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Thermal Processing of Packaged Foods

Third Edition

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This book is dedicated to our wives, Margaret and Anita, and family, Christopher, Martin, Giles, Sarah and José Ignacio, María Jesús, and Enrique.

S. Donald Holdsworth and Ricardo Simpson

Foreword

The first edition of this book "*Thermal Processing of Packaged Foods*" was published in 1997, in which Professor D. Holdsworth gave response to a need of understanding *thermal processing* from an engineering point of view, incorporating concepts such as lethality and food quality. In the second edition published in 2007, Professor Holdsworth in collaboration with Professor Ricardo Simpson made an actualization of the book, which included different topics under a renewed vision, especially in those aspects related to process evaluation techniques, engineering aspects, and optimization techniques for thermal processing.

Presently, during 2015 this third edition was totally renewed and updated including new concepts and areas that are relevant for modern thermal food processing. This new edition is acquiesced by 22 chapters—that retain great part of the first and second edition—which are divided into five parts. The first part, entitled "Fundamentals of Thermal Food Processing," includes five chapters where different topics associated with heat transfer mechanisms, kinetics of microbial death, sterilization criteria, and safety aspects of thermal processing are analyzed. The second part, entitled "Thermal Food Process Evaluation Techniques," includes six chapters, in which Chap. 7 deeply analyzes the *General Method* and its application and similarly Chap. 8 analyzes *Formula Methods* and analytical techniques. It is also remarkable the incorporation of new chapters, such as Chap. 11 entitled "Software of Thermal Food Processing Evaluation and Optimization," where the development of a new software to optimize and estimate the thermal processing time is presented, including a downloadable file. Part III, entitled "Engineering Aspects of Thermal Food Processing," comprises six chapters where subjects related to pressure buildup in containers, simultaneous sterilization, and thermal food processing equipment, amongst other, are presented. Part IV, "Mathematical Modeling, Simulation, Optimization, Control, and Automation," includes four chapters, of which both Chap. 18, dedicated to computational fluid dynamics as a tool for thermal food processing modeling, and Chap. 20, which incorporates the use of multiobjective optimization in thermal food processing, are totally new.

Finally, Part V, entitled "Innovative Thermal Food Processing," includes a chapter focused on two innovative processes used for food sterilization, such as combination of High Pressure and High Temperature sterilization and the application of Ohmic Heating. Both methods are applied to reduce the process time and the effect of temperature on food quality factors.

It is a great pleasure to have the third edition of *Thermal Processing of Packaged Foods*. I strongly believe that this book will be useful for academics, researchers, engineers, and students that are involved in this thrilling world of thermal food processing.

Valparaíso, Chile Sergio Almonacid

Preface (Second Edition)

In this new edition, the historical perspective of the development of thermal processing has been retained and much new additional material has been added. The development of the subject, as indicated by the amount of research that has been done during the last ten years, has been remarkable and shows that the technology is very viable and expanding worldwide.

The main developments that have been included are as follows: (a) the increased use of new packaging materials, including retortable pouches and the use of containers made from other plastic composite materials, (b) the application of newer processing methods which use heat transfer media such as hot water, air/steam, and steam/water, which are necessary for the newer forms of packaging material, (c) new methods of theoretically calculating the heat transfer characteristics during processing, including three-dimensional modeling and application of computerized fluid dynamics (CFD) techniques, (d) implications of newer models for microbial destruction, (e) revised techniques for process evaluation using computer models, including CD software, (f) development of process schedules for quality optimization in newer packaging materials, and (g) important new aspects of methods of retort control.

Unlike other texts on thermal processing, which very adequately cover the technology of the subject, the unique emphasis of this text is on processing engineering and its relationship to the safety of the processed products.

The authors hope that they have produced an adequate text for encouraging research workers and professional engineers to advance the operation of the manufacturing processes to ensure the production of high quality products with assured safety.

Stretton-on-Fosse, Gloucestershire, UK — S. Donald Holdsworth
Valparaíso, Chile — Ricardo Simpson

Preface (First Edition)

My credentials for writing this book are three decades of experience in the canning industry, the research that has supported it, and the establishment of a specialized training course on the thermal processing of packaged foods. My first encounter with the industry was to accompany Tom Gillespy around the various factories of the members of Campden Research Association. He took his annual leave for many years visiting the industry and was dedicated to ensuring that the requirements of good manufacturing practice were observed. The occasion on which I accompanied him was his last trip before retirement, and I shall always be grateful to him for the kindly advice he gave me on all aspects of canning and food processing. Nobody could have had a better introduction to the industry. In a small way, this book is an appreciation and a memorial to some of his work. He was greatly respected in academic and industrial circles.

This book is concerned with the physical and engineering aspects of the thermal processing of packaged foods—i.e., the heating and cooling of food products hermetically sealed in containers. The two commonest types of container used for this process are glass bottles and cans, although more recently a variety of plastic containers has been added to the list. The main aim of the book is to examine the methods that have been used to establish the time and temperature of processes suitable to achieve adequate sterilization or pasteurization of the packaged food.

It is written from the point of view of the food process engineer, whose principal role is to design, construct, and operate food processing equipment to produce food of acceptable quality and free from public health hazards. The engineering approach requires a knowledge of the microbiological and physicochemical factors required to solve the necessary equations to establish the safety of the process. In some ways, the canning process is unique, in as much as it requires a mathematical model of the sterilization value to determine the adequacy of the process. Over the last 70 years, a considerable amount of time and energy has been spent around the world on developing suitable mathematical methods to calculate the effectiveness of various processing regimes in order to ensure the safe production of foods. In this book, the various methods and theoretical models on which they are based, for determining adequate times and temperatures for achieving sterility, are discussed and examined.

Most books on canning tend to deal with this subject either by means of a generalized technological description of the process, containers, and products, or from a bacteriological point of view. This book, however, attempts to deal with the more fundamental engineering aspects of the heating and cooling process and the mathematical modeling of the sterilization operation—aspects that are dealt with more briefly elsewhere. Many hundreds of papers have been published on this subject and an untold amount of thermal processing experimental work carried out. Each canning company usually has a person specializing in thermal processing, as well as microbiological laboratory and pilot plant facilities. Much of the academic research work reported is essentially an extension of basic principles and the development of new, and alternative methods of calculation rather than the discovery of new principles. Some of the work makes a critical comparison of various authors' work and assesses the improvements or otherwise that accrue from using a particular method. Some of it uses new mathematical techniques to perform already established methods, while other work analyzes the errors resulting from the use of different methods of heat penetration. The research and development work is important in training people in the principles of one of the best and well-established methods of making shelf-stable food products.

This book will be of interest to technical managers, process engineers, and research workers as a guide to the literature and the principles underlying thermal processing. It will be of use to those in the industry who are concerned with achieving adequate processes as well as to those who are concerned with the development of equipment. It will also act as a guide to those who are concerned with the development of legislation and help them to assess the realities of whatever they wish to impose on the manufacturing industry. Finally, it is hoped that this book will inspire and enthuse research workers to even greater endeavors in this area.

I am most grateful for advice and help from former colleagues and also to many friends throughout the world.

Stretton-on-Fosse, Gloucestershire, UK S. Donald Holdsworth

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Part I

Fundamentals of Thermal Food Processing

Chapter 1
Introduction

1.1 Thermal Processing Principles

1.1.1 Thermal Processing

A generation ago the title of this book would have contained such terms as *canning*, *bottling*, *sterilization*, and heat *preservation*; however, with the passage of time it has become necessary to use a more general title. The term *thermal processing* is used here in a general sense and relates to the determination of heating conditions required to produce microbiologically safe products of acceptable eating quality. It conveys the essential point that this book is concerned with the heating and cooling of packaged food products. The only attempt to produce a generic title has been due to Bitting (1937), who used the term *appertizing*, after the process developed and commercialized by Nicholas Appert (1810) to describe the canning and bottling process. Despite the need for a generic term, rather surprisingly, this has never been used to any great extent in the technical press (Larousse 1991).

The phrase *packaged foods* is also used in a general sense, and we shall be concerned with a variety of packaging materials, not just tin-plate, aluminum, and glass, but also rigid and semirigid plastic materials formed into the shape of cans, pouches, and bottles. The products known originally as canned or bottled products are now referred to as heat-preserved foods or thermally processed foods.

Thermal Processing is part of a much wider field—that of industrial sterilization—which includes medical and pharmaceutical applications. Those concerned with these subjects will find that much of the information in this book will apply directly to their technologies.

S.D. Holdsworth, R. Simpson, *Thermal Processing of Packaged Foods*,
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1.1.2 The Process

It is necessary to define the word *process*. Generally in engineering, a process is defined as the sequence of events and equipment required to produce a product. Here, however, *process* is a time–temperature schedule, referring to the *temperature* of the heating medium (condensing steam) and the *time* for which it is sustained. Tables of processing schedules are available: In the USA, the National Food Processors' Association produces guides (e.g., NFPA 1996; GMA 2007). In France such schedules are referred to as *Barèmes de Sterilization* (e.g., Institut Appert 1979). In the UK various guidelines are available from Campden BRI, which are discussed in later chapters of this text.

1.2 Canning Operations

1.2.1 General

Figure 1.1 *Illustrates the canning process which consists of five main stages*:

Stage 1. Selecting suitable foods, taking them in prime condition at optimum maturity, if appropriate, followed by preparation of the foods as cleanly, rapidly, and perfectly as possible with the least damage and loss with regard to the economy of the operation.
Stage 2. Packing the product in hermetically sealable containers—together with appropriate technological aids—followed by removing the air and sealing the containers.
Stage 3. Stabilizing the food by heat, while at the same time achieving the correct degree of sterilization, followed by cooling to below 38 °C.
Stage 4. Storing at a suitable temperature (below) 35 °C to prevent the growth of food spoilage organisms
Stage 5. Labeling, secondary packaging, distribution, marketing, and consumption

The instability of foods at the time they are sealed in containers is due to the presence of living organisms that, if not destroyed, will multiply and produce enzymes that will decompose the food and in some cases produce food-poisoning toxins. Stability, i.e., the production of shelf-stable products, is attained by the application of heat, which will kill all the necessary organisms (For further details, see Sect. 3.2.1). Of the above listed operations only the stabilization operation, Stage 3, commonly known as processing, will be covered in this text. The technological aspects of the subject are well covered by many texts, among them Downing (2013), Jackson and Shinn (1979), Hersom and Hulland (1980), Lopez (1987), Rees and Bettison (1991), and Footitt and Lewis (1995). Most of these texts do not elaborate on the subject of this book, which is dealt with only in the classical works of Ball and Olson (1957) and Stumbo (1973), as well as in the individual

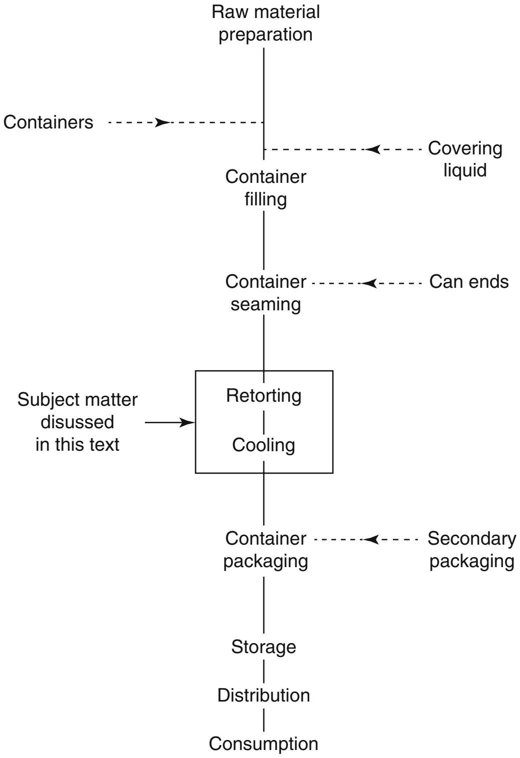

Fig. 1.1 General Simplified flow diagram for a canning line

specialized texts (Pflug 1982) and other publications from the various food processing centers. A particular important basic text, used in training courses, has been published by Tucker and Featherstone (2010).

1.2.2 Methods of Processing

The most widely used systems are vertical batch retorts, with a lid at the top, which are cylindrical pressure vessels operating at temperatures usually between 100 and 140 °C. The sequence of operations consists of putting the cans in baskets, placing them in the retort and closing the lid. Steam is then introduced, leaving the vent valve open, so that the air in the retort can be suitably expelled, thereby leaving an atmosphere of almost pure steam. When the processing temperature has been reached the vent is closed and the temperature maintained for the appropriate time dictated by the given *process*. After the time and temperature requirements have been achieved, cooling water is introduced while maintaining the pressure in the retort using air. Pressurized cooling of this type is required for larger-sized cans so that the pressure differential on the cans is reduced slowly in order not to cause irreversible can deformation. When the pressure has been reduced to atmospheric and the cans sufficiently cooled, the retort is opened and the cans removed. The subsequent operations involve drying, labeling and packaging the cans in the required manner for marketing.

Modifications to the above processing are the use of hot water made by steam injection, either in the retort or externally, and the use of air–steam mixtures for processing retortable pouches of food.

Batch retorts also come in a horizontal format with either square or circular cross-sections, with trolleys on wheels for handling the baskets. Some retorts also have facilities for internal rotation of the cans, or external rotation by end-over-end motion of the retort.

High-speed continuous retorts are now widely used in modern production. There are two main types. With *rotary sterilizers*, the cans pass through mechanical valves into a horizontal, cylindrical steam chamber and rotate around the periphery of the shell. Special pressure valves allow the passage of the heated cans into the cooling shell prior to discharge. *Hydrostatic cookers* are valveless sterilizers in which the pressure in the vertical steam chamber is balanced by water legs of appropriate height to match the temperature of the processing steam. The cans are conveyed through the system on horizontal carrier bars, which pass vertically upwards through the preheating leg and vertically downwards through the precooling section. Various different types are available, including facilities for rotating cans in the carrier bar system. Details of the heat transfer in these cookers, and the achievement of the correct processes, are given in Chap. 17.

1.3 Packaging Materials

1.3.1 Introduction

The packaging material and its ability to prevent recontamination (*integrity*) are of paramount importance to the canning industry. A large number of spoilage incidents have been attributed to leaker spoilage, subsequent to processing, due to incorrect sealing or the use of unchlorinated water for cooling the cans. The use of the double-seaming technique and can-lid-lining compounds has been effective in reducing leaker spoilage.

1.3.2 Metal Containers

Cylindrical cans made of metal are the most widely used and in the highest production world-wide. Containers made of tin-plated steel are widely used, although lacquered tin-free steels are gradually replacing them. Aluminum cans, and also thin steel cans with easily opened ends, are widely used for beer and beverage packing. The standard hermetically sealable can, also known as a sanitary can in some countries, has various geometries and consists of a flanged body with one or two seamable ends. In the three-piece version one of the ends is usually—but not always—seamed to the body, and the other is seamed after filling. In the two-piece version, which has steadily increased in use, the body is punched out or drawn in such a way that only one flange and lid are necessary. Cans are usually internally lacquered to prevent corrosion of the body and metal pick-up in the products.

Full details of the fabrication of containers are given in Rees and Bettison (1991) and Footitt and Lewis (1995). Some typical container sizes are given in Tables 1.1, 1.2, and 1.3.

Recent developments have reduced the amount of material used in can manufacture, including the necked-in can, which has the advantage of preventing seam-to-seam contact during storage and handling and has cost-saving benefits. New can seam designs—for example the Euroseam and the Kramer seam, which reduce the seam dimensions, especially the length—have been reported (Anon 1994). There is also interest in the design of easy-open ends, especially made of less rigid material such as foil seals (Montanari et al. 1995). Two examples, are the Impress Easy Peel® lid, (Isensee 2004) and the Abre-Facil produced by Rojek of Brazil. The latter is a vacuum seal like a closure for a glass jar (May 2004).

The effect of different types of process, e.g., hydrostatic and reel and spiral pressure cookers on can performance, in terms of can distortion, has been discussed by Pape (2008).

1.3.3 Glass Containers

Glass jars are also widely used for packing foods and beverages. They have the advantages of very low interaction with the contents and visibility of the product. However, they require more careful processing, usually in pressurized hot water, and handling. Various types of seals are available, including venting and non-venting types, in sizes from 30 to 110 mm in diameter, and made of either tin or tin-free steel. It is essential to use the correct overpressure during retorting to prevent the lid being distorted. It is also essential to preheat the jars prior to processing to prevent shock breakage.

1.3.4 Rigid Plastic Containers

The main requirement for a plastic material is that it will withstand the rigors of the heating and cooling process. Again it is necessary to control the overpressure correctly to maintain a balance between the internal pressure developed during

Table 1.1 A guide to UK and US can sizes (1995 revised 2005)

Imperial size[a] (in)	Metric size[b] (mm)	Gross liquid volume (ml)	Common name
Cylindrical cans			
202 × 108	52 × 38	70	70 g tomato paste
202 × 213	52 × 72	140	Baby food
202 × 308	52 × 90	180	6Z (US) or Jitney
202 × 314	52 × 98	192	6 oz juice
202 × 504	52 × 134	250	25 cl juice
211 × 202	65 × 53	155	5 oz
211 × 205	65 × 58	175	6 oz milk
211 × 300	65 × 100	234	8Z Short (US)
211 × 301	65 × 77	235	Buffet or 8 oz picnic
211 × 304	65 × 81	256	8Z Tall (US)
211 × 400	65 × 100	323	No. 1 Picnic (US)
211 × 400	65 × 101	315	Al–10 oz
211 × 414	65 × 124	400	Al tall – 14 oz
			No. 211 Cylinder (US)
300 × 108	73 × 38	125	
300 × 201	73 × 515	185	
300 × 204.5	73× 57.5	213	Nominal ¼ Kg
300 × 207	73 × 61	230	8 T—U8
300 × 213	73 × 71	260	250 g margarine
300 × 303 ½	73 × 82	310	400 g (14 oz) SCM
300 × 401	73 × 103	405	14Z (E1)
300 × 405	73 × 110	425	Nominal ½ kg
300 × 407	73 × 113	449	No. 300 (US)
300 × 408 ¾	73 × 115	445	UT
300 × 410	73 × 118	454	16 oz
300 × 509	73 × 146	572	No. 300 Cylinder (US)
300 × 604	73 × 158	630	
301 × 407[c]	74 × 113	440	
301 × 409	74 × 116	459	No. 1 Tall (UK)
301 × 411	74 × 118	493	No. 1 Tall (US)
303 × 406	74 × 113	498	No. 303 (US)
303 × 509	74 × 141	645	No. 303 Cylinder (US)
307 × 113	83 × 46	215	7 oz
307 × 201	83 × 52	235	
307 × 306	83 × 82	434	No. 2 Vacuum (US)
307 × 403	83 × 106	540	
307 × 408	83 × 114	580	A2
307 × 409	83 × 115	606	No. 2 (US)
307 × 510	63 × 142	761	Jumbo (US)

(continued)

Table 1.1 (continued)

Imperial size[a] (in)	Metric size[b] (mm)	Gross liquid volume (ml)	Common name
307 × 512	63 × 144	780	No. 2 Cylinder (US)
401 × 200	99 × 51	325	No. 1.25 (US)
401 × 206	99 × 60	190	
401 × 210	99 × 66	445	
401 × 212	99 × 69	475	1 lb flat
401 × 407	99 × 113	815	
401 × 411	99 × 119	880	A 2½/nominal kilo No. 2.5. (US)
401 × 509	99 × 141	1025	Liter
401 × 609	99 × 166	1215	Quart (US)
401 × 711	99 × 195	1430	
404 × 307	104 × 88	571	No. 3 Vacuum (US)
404 × 700	104 × 177	1455	A3 (UK)
404 × 700	104 × 177	1525	No. 3 Cylinder (US)
502 × 510	127 × 140	1996	No. 5 (US)
502 × 612	127 × 172	2040	Milk powder
602 × 700	151 × 178	3709	No. 10 (US)
603 × 304	153 × 83	1335	3 lb
603 × 402	153 × 105	1755	
603 × 600	153 × 152	2630	A6
603 × 700	153 × 178	3110	A10
603 × 910	153 × 245	4500	Nominal 5 kg
606 × 509[c]	159 × 141	2570	6 lb tongue
Rectangular cans			
312 × 115 × 309	93 × 47 × 91	345	12 oz rect. (PLM)
301 × 205 × 311	74 × 56 × 93	345	12 oz corned beef
Beverage cans/beer cans (necked in)			
200/202 × 308	50/52 × 88	150	15 cl
200/202 × 504	50/52 × 134	250	25 cl
209/211 × 315	63/65 × 100	275	10 fl oz
209/211 × 409	63/65 × 115	330	12 fl oz
209/211 × 514	63/65 × 149	440	16 fl oz
209/211 × 610	63/65 × 168	500	½1

[a] External diameter × height. Imperial sizes are quoted with three digits and a possible following fraction: the first refers to whole inches and the rest to sixteenths of an inch. For example, 211 means $2\frac{11}{16}$ in., while 408¾ means $4 + \frac{8.75}{16} = 4\frac{35}{64}$ in.

[b] Internal diameter × height

[c] Non-ISO standard

Sources: A.I.D. Packaging Services (UK) Ltd, Worcester, Crown Company, Wantage, and Can Manufacturers Institute, USA

Table 1.2 A guide to some European can sizes

Metric size[a] (mm)	Gross liquid volume (ml)	Common name
55 × 67.8	142	1/6 haute
86 × 35.5	170	1/5
65 × 71.8	212	1/4
83 × 57	283	1/3
65 × 100.1	314	3/8
71.5 × 115.5	425	1/2 haute
73 × 109.5	425	1/2 haute dia. 73
99 × 118.2	850	1/1 dia. 99
100 × 118.5	850	1/1
100 × 225	1700	2/1
153 × 151	2550	3/1
153 × 246	4250	5/1

[a] Internal diameter × height
Source: Institute Appert, Paris

Table 1.3 A guide to some European large rectangular can sizes for meat products

	Size (m)		Description
105	169	323	12 lb oblong
103	164	305	12 lb oblong LANGEN
95	105	318	Ham mold
105	82	400	Ham mold (long)
115	115	545	16 lb Pullman
115	115	385	11 lb Pullman
100	100	400	8 lb Pullman
100	100	303	6 lb Pullman
100	100	207	4 lb Pullman

Source: Eszes and Rajkó (2004)

processing and the pressure of the heating system. The main plastic materials used for heat-processed foods are polypropylene and polyethylene tetraphthalate. These are usually fabricated with an oxygen barrier layer such as ethylvinylalcohol, polyvinylidene chloride, and polyamide. These multilayer materials are used to manufacture flexible pouches and semi-rigid containers. The current interest is mainly in the latter, which are used to pack microwavable products. This will be an area of rapid expansion during the next few decades, and thermally processed products, especially ready meals, will have to compete with their chilled and frozen counterparts.

More recent developments have been (1) a cylindrical container which has a polypropylene (PP)/aluminum laminate body with molded ends that are welded together, *Letpak*–Akerlund and Rausing; (2) ethylene vinyl alcohol (EVOH) oxygen-barrier laminate with double-seamed ends, *Omni Can*—Nacanco; (3) a bowl shaped plastic container with a double-seamed metal easy-open lid, *Lunch* *bowl*—Heinz; (4) a clear plastic can with double-seamed end, *Stepcan*—Metal Box; (5) laminated polypropylene (PP)/ethylene vinyl alcohol (EVOH) bottles with foil laminated caps. and polyvinylidene chloride (PVC)/polypropylene (PP) containers, both with a shelf-life of approximately 12 months; and (6) polyethylene terephthalate (PET) bottles, which can be hot-filled up to 92 °C or pasteurized up to 75 °C (May 2004).

1.3.5 Retortable Pouches

The retortable pouch is a flexible laminated pouch that can withstand thermal processing temperatures and combines the advantages of metal cans and plastic packages. These consist of laminated materials that provide an oxygen barrier as well as a moisture barrier. Flexible retortable pouches are a unique alternative packaging method for sterile shelf-stable products. Recently, important US companies have commercially succeeded with several products. Pouches may be either premade or formed from rolls-stock—the more attractive price alternative. Alternately, the premade process permits an increased line speed over that of roll-stock, and mechanical issues of converting roll-stock to pouches at the food plant disappear (Blakiestone 2010).

A typical four ply pouch would have an outer layer of polyethylene terephthalate (PTFE) for heat resistance, aluminum foil for oxygen/light barrier, biaxial orientated nylon for resilience, and an inner-cast polypropylene for pack sealing. Each layer has an adhesive in between it and the next layer. Clear pouches are also made by using a silicate SiOx layer instead of aluminum foil, and these may be reheated using microwaves. Some typical thicknesses for high-barrier pouch laminate films are PTFE 12–23 μm, aluminum 9–45 μm, SiOx (Ceramis®—Alcan-Amcor) 0.1 μm, and o-polyamide 15–25 μm, with either polyethylene or polypropylene sealants 50–150 μm.

Other similar materials are Silaminat® and Techbarrier™—Mitsubishi (Potter 2008; Lagaron et al. 2008). The possible use of liquid crystal polymers, which have superior oxygen and water vapor barrier properties compared with other polymer films, has drawn considerable interest recently (Taylor 2004).

Various types of pouch geometry are available, such as the *pillow pouch*, which consists of a rectangular-shaped container with one side left open for filling and subsequent sealing. Pillow pouches, which have been manufactured and successfully marketed in Japan, e.g., Toyo Seikan, Yokohama, for many years, are usually distributed in cardboard boxes for outer covers. Apart from products for military purposes, the development and acceptance of pillow pouches has been slow. Another pouch geometry is the *gusset pouch*, which is similar to the above but has a bottom on which the container can stand.

The most important feature of these packages is to produce a contamination-free seal, which will maintain the shelf life of the product. Filling and sealing are, therefore, slow processes if an effective seal is to be achieved. Various tests are used to assess the integrity of the seal: (1) a bursting test by injecting gas under pressure, (2) seal-thickness measurements, and (3) seal-strength tests. Pouches are usually sterilized in over-pressure retorts.

A retortable plastic laminated box *Tetra-Recart* has been developed and marketed by Tetra Pack (Bergman 2004). This is a more heat resistant carton compared with the company's aseptic packs, and the filled and sealed cartons are processed at temperatures up to 130 °C for up to 3 h, in over-pressure retorts. A number of commercial products have been presented in this pack, including in-pack sterilized vegetables, hot-filled tomato products and a range of sauces.

Retorts used in processing pouches can be batch or continuous, agitating or non-agitating, and they require air or steam overpressure to control pouch integrity (Blakiestone 2010).

Retortable pouches have several advantages over traditional cans. Slender pouches are more easily disposed of than comparatively bulky cans. Shipping them is easier. In addition, the "fresher" retortable pouch product obviously required significantly less heat to achieve commercial sterility. Furthermore, cooking time is about half that required for traditional cans, resulting in tremendous energy savings. Now that retort pouches of low-acid solid foods appear to have attained some commercial acceptance and recognition of their superior quality and more convenient packaging, the expectation is that other heat-sterilized foods will appear in pouches, creating a new segment within the canned foods category (Brody 2003).

1.4 Some Historical Details

The process of glass packing foods was invented and developed on a small commercial scale by the Frenchman Nicholas Appert in 1810, for which he received a financial award from the French government. Subsequently other members of his family continued the business and received further awards and honors. The original work (Appert 1810) describes the process in excellent detail; however, the reason the process achieved stability of the food and its indefinite shelf-life was not known at that time. It was not until 1860 that Pasteur explained that the heating process killed (nowadays we would say "inactivated") the micro-organisms that limited the shelf-life of food. Very shortly after Appert's publication, an English merchant, Peter Durand, took out a patent—subsequently purchased by Donkin, Hall and Gamble—for the use of metal canisters, which inaugurated the canning industry. The industry developed on a large scale in the USA when an English immigrant, William Underwood, opened a cannery for fruit products in Boston in 1819. The next major development was the production of continuously seamed cans with the use of the double seam. The American industry developed rapidly after this innovation. It was not until the 1920s that the newly developed technology was available in the USA. A can-body maker was installed in 1927 in Williamson's factory in Worcester on the recommendation of the staff at the Bristol University Research Station, at Chipping Campden, whose staff at that time included Alfred

Appleyard and Fred Hirst. Much of the subsequent technical development of the industry was due to the untiring efforts of Hirst and his colleagues, Bill Adam and Tom Gillespy, as well as the field service staff of The Metal Box Co., the subsequent owners of Williamson's factory.[1]

During the 1920s W.D. Bigelow, the first director of the National Canners' Association in Washington, and colleagues developed a method of determining thermal processes based on heat-penetration measurements in cans of food (Bigelow et al. 1920). One of these colleagues, Charles Olin Ball, subsequently developed theoretical methods for the determination of thermal processes (Ball 1923, 1928) and became the acknowledged expert in this subject (Ball and Olson 1957). Subsequent developments in the subject have been largely based on these workers' early concepts.

Following the lead set by the Americans, research workers in the USA and the UK applied these methods to their canning industries. In the UK the pioneering work on process determination was done by T.G. Gillespy at Campden Research Station. The establishment of safe procedures in the British canning industry owes much to his scholarship, devotion, and integrity. He devoted much of his time to recommending safe processes for each type of sterilizer as it was introduced into the industry. His guide to processes for canning fruits and vegetables (Gillespy 1956) is a model of his clear approach to the subject. He was also very much concerned with the heat resistance of microorganisms, as well as problems of leader spoilage and sanitation in canneries. In fact, he was one of the first workers to identify spoilage by post-process can seam leakage rather than understerilization. Although by today's standards he published relatively little (in fact he regarded much of the published literature with disdain), the clarity of his thought was illustrated by his paper on the principles of heat sterilization (Gillespy 1962), and his two papers on the mathematics of process calculations (Gillespy 1951, 1953). While the nomenclature is often daunting, these publications are well worth mastering as an introduction to the subject.

The contributions of other workers are documented in various parts of this book. It would be an invidious task to detail all the contributions of the world's experts; consequently selection has been necessary. An indexed bibliographic guide to process calculations, which covers much of the work, formed the basis for this book, including heat inactivation of microorganisms, heat transfer to and in cans, and thermal process calculations (Overington and Holdsworth 1974; Holdsworth 2006).

Some additional books and articles of importance to this text have been produced by Ahmed and Rahmann (2012), Heldman and Moraru (2010), Jun Weng (2006), Peleg (2006), Ramaswamy and Singh (1997), Richardson (2001, 2004, 2008), Simpson (2009), Simpson et al. (2010), Sun (2006), Teixeira (1992, 2006), Teixeira et al. (2006), and Tucker and Featherstone (2010).

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[1] For further historical information see Bitting (1937), Ball and Olson (1957), Metal Box (1960), Adam (1980), and Thorne (1986).

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Chapter 2
Heat Transfer

2.1 Introduction

2.1.1 General Aspects

The main object of this chapter is to give a brief account of the mathematical methods of determining the temperature distribution with time and position in packaged foods while being heated and cooled. This is a prerequisite to establishing a *process* which will ensure the microbiological safety of the product and is also organoleptically acceptable. This requires an examination of the modes of heat transfer in different parts of the processing operation.[1]

2.1.2 Mechanisms of Heat Transfer

There are three modes of heat transfer, which contribute to the overall heat transfer process in differing proportions: conduction, convection and radiation. Conduction is the transfer of heat by molecular motion in solid bodies. Convection is the transfer of heat by fluid flow, created by density differences and buoyancy effects, in fluid products. Radiation is the transfer of electromagnetic energy between two bodies at different temperatures. In Fig. 2.1 the main modes for heat transfer in the processing of packaged foods are illustrated.

The first mode is heat transfer to the container or packaging from the heating and cooling medium; the main modes of heat transfer to be considered for the various

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[1] The reader is encouraged to consult the very useful text on heat transfer and food products by Hallström et al. (1988). This is an excellent guide to the basic principles of heat transfer and its application to food processing.

S.D. Holdsworth, R. Simpson, *Thermal Processing of Packaged Foods*,
Food Engineering Series, DOI 10.1007/978-3-319-24904-9_2

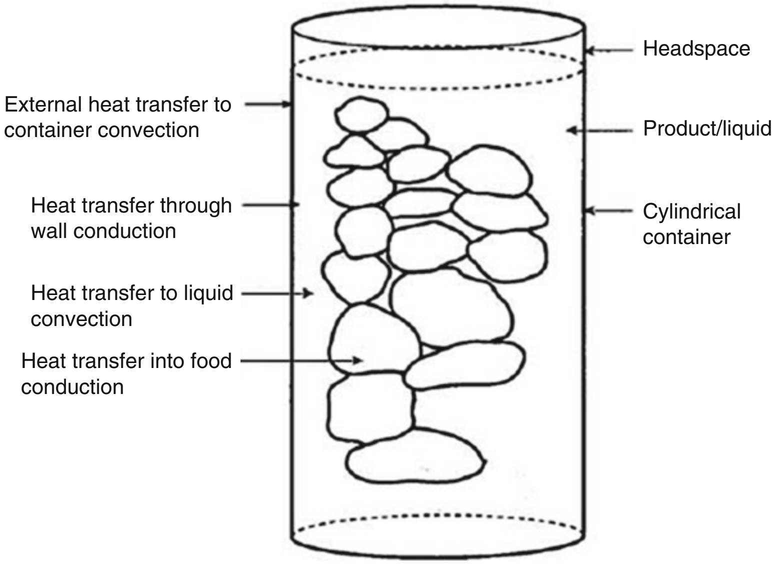


Fig. 2.1 Heat transfer to food product in a cylindrical container

Table 2.1 Heat transfer modes for containers being heated or cooled

Media	Main mode	Resistance
Steam (air-free)	Condensation	Effectively none
Steam–air mixtures	Convection	Increases with increasing air content
Air	Convection	High
Water, boiling	Convection	Low
Water, hot	Convection	Decreases with increasing water velocity
Water, cold	Convection	Medium
Flame/infrared	Radiation	Low
Fluidized bed	Convection	Medium, depends on degree of agitation
Microwave	Radiation	None

heating media are given in Table 2.1. Heating with pure steam, or microwaves, is very effective and does not present any appreciable resistance to heat transfer; consequently, it does not need to be taken into account in the overall heat transfer. In the case of all other media it is necessary to take the convective or radiative heat-transfer coefficient into account. Convective-heat transfer rates depend largely on the velocity of flow of the media over the container, and this is an important factor to be controlled in all processing operations. This subject is dealt with in more detail in Part III.

The second mode of heat transfer is through the container wall; for metallic containers of normal thickness, the thickness and the thermal conductivity of the material are such that there is no appreciable resistance to heat transfer. However, for glass bottles and plastic containers there is a significant resistance, and this should be considered in determining the overall heat transfer resistance.

The third mode of heat transfer is into the product from the container wall; this depends on the consistency of the food material and is discussed in detail elsewhere (see Chap. 6). Fluid products or solid particulates covered with a fair amount of fluid heat or cool rapidly by convection, while other products of a more solid consistency heat mainly by conduction. In between there are products that heat/cool by a combination of conduction and convection, and some that start with convection heating and finish in conduction mode because of physicochemical changes. Thus the internal mechanisms of heat transfer are complicated. From a theoretical point of view it is only possible at the present time to deal with simple heat transfer mechanisms; however, empirical methods (see Chap. 6) allow the processor to calculate temperature distributions without being too concerned about the mechanism.

When dealing with heat transfer theory, it should be noted that a distinction is made between (a) steady-state heat transfer, which involves constant temperatures of heat transfer media, and the product, e.g., heating and cooling in continuous-flow heat exchangers; and (b) unsteady-state heat transfer, which implies that the temperatures are continuously changing. It is type (b) with which we are concerned in this book, i.e., the determination of time–temperature profiles at specified points in the container. From a practical point of view, a satisfactory process is determined at the slowest point of heating in the packaged food, and this makes calculation easier, since with conduction heating products, the center point of the food mass is taken as the slowest point of heating, or critical point. It is not sufficient in processing packaged foods just to achieve a given temperature at the slowest point of heating, but to achieve it for a given time, specified either by calculation or experimental investigation.

2.2 Heat Transfer by Conduction

2.2.1 Introduction

Energy transfer by conduction takes place when different parts of a solid body are at different temperatures. Energy flow in the form of heat takes place from the hotter, more energetic state, to the colder, less energetic state. The quantity of heat transferred under steady-state conditions is given by

$$Q = k\frac{T_1 - T_2}{x}At, \qquad (2.1)$$

where

Q = quantity of heat (J or N m);
T = temperature (K or °C), with subscripts 1, 2 referring to the two parts of the body;
t = time (s);
x = the distance (m) of separation of the two points;
A = the cross-sectional area (m^2) for heat flow;
k = the thermal conductivity (W m^{-1} K^{-1}).

Differentiating with respect to time gives the rate of heat flow:

$$\dot{Q} = k\frac{T_1 - T_2}{x}A, \tag{2.2}$$

This equation can be written more simply in a differential form

$$\dot{Q} = -kA\frac{dT}{dx}. \tag{2.3}$$

This relates the rate of heat flow dQ/dt to the temperature gradient in the material dT/dx, and is known as the one-dimensional heat conduction equation expressed in Cartesian coordinates. The quantity $(dQ/dt)/A$ is known as the heat flux, and is measured in joules per square meter per second.

2.2.2 Formulation of Problems Involving Conduction Heat Transfer

The main object of this section is to indicate the mathematical basis of the problems encountered in the determination of the temperature distribution in heating canned foods by conduction. The treatment is necessarily brief, and further information can be found in the standard texts, e.g., Ingersoll et al. (1953), Carslaw and Jaeger (1959), Arpaci (1966), Luikov (1968), and Ozisik (1980).

The basis of all unsteady-state conduction heat transfer equations is Fourier's equation, established by the French physicist Jean Baptiste Joseph Fourier (1768–1830) (Fourier 1822) and written as

$$\rho c\frac{\partial T}{\partial t} = \nabla k \nabla T \tag{2.4}$$

where ρ is the density (kg m^{-3}), c the specific heat or heat capacity (J kg^{-1} K^{-1}), and ∇ the differential operator (del, also known as nabla), where

$$\nabla = \partial/\partial x + \partial/\partial y + \partial/\partial z.$$

Equation (2.4) implies that the thermal conductivity is a function of temperature, an assumption which is not usually made in heat transfer calculations in order to simplify the calculations. Consequently, a simpler equation is generally used,

$$\rho c \frac{\partial T}{\partial t} = k \nabla^2 T$$

or

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T, \tag{2.5}$$

where α is the thermal diffusivity, $k/\rho c$ ($\mathrm{m}^2\ \mathrm{s}^{-1}$) and ∇^2 is the Laplace operator, given by

$$\nabla^2 = \partial^2/\partial x^2 + \partial^2/\partial y^2 + \partial^2/\partial z^2.$$

The physical significance of this property is associated with the speed of heat propagation into the solid. Materials with high values, such as metals, heat rapidly, whereas food materials and water have comparatively low values and heat much more slowly. Table 2.2 gives some data for food products. More extensive data are found in the publications of Singh (1982), Okos (1986), Lewis (1987), George (1990), and Eszes and Rajkó (2004). The determination of physical properties from thermometric measurements and a finite element model has been reported by Nahor et al. (2001). A computer program, COS-THERM, was developed to predict the thermal properties of food products based on their composition (van Beek and Veerkamp 1982; Miles et al. 1983). Many foods of high moisture content have values of α ranging from 1.4 to $1.6 \times 10^{-7}\ \mathrm{m}^2\ \mathrm{s}^{-1}$. Palazoglu (2006) has reported an interesting study on the effect of convective heat transfer on the heating rate of materials with differing thermal diffusivities including cubic particles of potato and a polymethylpentene polymer. Using the analytical solution for heating a cube with external heat transfer it was shown that the rate of heating depended very much on the combination of heat-transfer coefficient and the thermal conductivity.

Equation (2.5) can be expressed in a variety of forms depending upon the coordinate system being used. Cartesian coordinates—x, y, z—are used for heat transfer in flat plates (Eq. 2.4), including slabs where the length is greater than the width, e.g., food in flexible pouches and trays, and for rectangular parallelepipeds or bricks (Eq. 2.6), e.g., rectangular containers both metallic and plastic:

$$\frac{dT}{dt} = \alpha\left[\frac{d^2T}{dx^2} + \frac{d^2T}{dy^2} + \frac{d^2T}{dz^2}\right]. \tag{2.6}$$

Cylindrical coordinates—$x = r\cos b$, $y = r\sin b$, and z—where b is the angle and r the radius for transformation from a Cartesian coordinate system, are used for all containers with a cylindrical geometry, i.e., most canned foods. When transformed the previous equation becomes

Table 2.2 Some values of thermal diffusivities of various products

Product	Temperature (°C)	Thermal diffusivity ($\times 10^7$ m^2 s^{-1})	Reference
(1) Food products Apple sauce	105	1.61	Uno and Hayakawa (1980)
Apple pulp: Golden Delicious	29	1.50–1.62	Bhowmik and Hayakawa (1979)
Cherry tomato pulp	26	1.46–1.50	Bhowmik and Hayakawa (1979)
Tomato ketchup	—	1.20 ± 0.02	Gouvaris and Scholefield (1988)
Tomato: Ace var.	42.9	1.22–1.88	Hayakawa and Succar (1983)
Carrots	138	1.82–1.88	Chang and Toledo (1990)
Pea purée	—	1.59	Bhowmik and Tandon (1987)
Pea purée	—	1.54	Lenz and Lund (1977)
Pea and potato purée	—	1.48	Masilov and Medvedev (1967)
Potato purée	—	1.30 ± 0.04	Gouvaris and Scholefield (1988)
Potato (78 % water)	60–100	1.39–1.46	Tung et al. (1989)
Potato	42.9	1.42–1.96	Hayakawa and Succar (1983)
French bean and chicken purée	—	1.62	Patkai et al. (1990)
Mixed vegetables and beef purée	—	1.63	Patkai et al. (1990)
Tuna fish/oil	115	1.64	Banga et.al. (1993)
Mushrooms in brine	—	1.18	Akterian (1995)
Ham, processed	—	0.94	Smith et al. (1967)
Ham salami	—	1.52	Choi and Okos (1986)
Beef purée	—	1.75	Lenz and Lund (1977)
Meat hash	—	1.52	Choi and Okos (1986)
Meat sauce	69–112	1.46 ± 0.05	Olivares et al. (1986)
Meat croquette	59–115	1.98 ± 0.22	Olivares et al. (1986)
Meat, ground	20	1.26–1.82	Tung et al. (1989)
Pork purée	—	1.94	Lenz and Lund (1977)
Meat/tomatoes/potatoes	65–106	1.57 ± 0.20	Olivares et al. (1986)
Meat/potatoes/carrots	58–113	1.77 ± 0.15	Olivares et al. (1986)
Cooked chickpeas/pork sausages	71–114	1.90 ± 0.03	Olivares et al. (1986)
Chicken and rice	65–113	1.93 ± 0.21	Olivares et al. (1986)
Chicken/potatoes/carrots	72–109	1.70 ± 0.03	Olivares et al. (1986)
Lasagne (73.6 % water)	60–100	1.32–1.70	Tung (1989)
Water	0–100	1.338–1.713	Evans (1958)
(2) Simulants			
Acrylic plastic ellipsoids	—	1.19	Smith et al. (1967)
Ammonium chloride	40–100	1.53–1.47	Tung et al. (1989)
Agar-starch/water gels 3–3.5 %	40–60	1.38–1.25	Tung et al. (1989)

(continued)

Table 2.2 (continued)

Product	Temperature (°C)	Thermal diffusivity ($\times 10^7$ m^2 s^{-1})	Reference
Agar-water 5 %	54	1.53	Evans (1958)
Bean-bentonite 75 % water	115.6	1.72	Evans (1958)
Bentonite 10 Bentonite 10 %	120	1.77	Uno and Hayakawa (1980)
Bentonite 10 %	—	1.90	Bhowmik and Tandon (1987)
Bentonite	—	1.86	Peterson and Adams (1983)
Ethylene glycol/water/ agar 5 %	—	1.11	Evans (1958)
(3) Container materials			
Polypropylene (PP)		0.071	Shin and Bhowmik (1990, 1993)
Polycarbonate		0.013	Shin and Bhowmik (1990, 1993)
Polyvinylidene chloride (PVDC)		0.062	Shin and Bhowmik (1990, 1993)
Laminate (PP:PVDC:PP)		0.068	Shin and Bhowmik (1990, 1993)

$$\frac{dT}{dt} = \alpha\left[\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr^2} + \frac{1}{r^2}\frac{d^2T}{db^2} + \frac{d^2T}{dz^2}\right]. \tag{2.7}$$

For radial flow of heat, i.e., neglecting axial heat flow, the last two terms may be neglected, so that the basic equation to be solved for radial heat transfer into a cylindrical container is (Fig. 2.2):

$$\frac{dT}{dt} = \alpha\left[\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr}\right]. \tag{2.8}$$

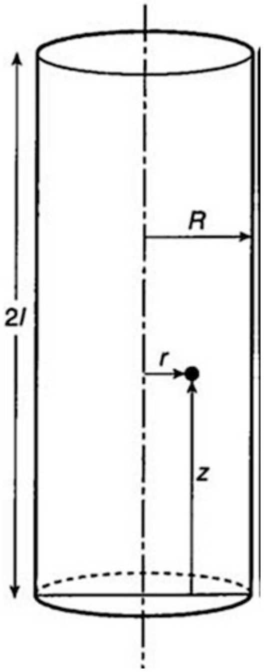
If the temperature is only required at the point of slowest heating, i.e., the center, where at $r = 0$, $dT/dr = 0$, and $dT/rdr = d^2T/dr^2$ (see Smith 1974), then Eq. (2.8) simplifies for the purposes of computation to

$$\frac{dT}{dt} = 2\alpha\left[\frac{d^2T}{dr^2}\right]. \tag{2.9}$$

While there are no containers that approximate to a spherical shape, spherical coordinates—$x = r\cos a \cos b$, $y = r\cos a \sin b$ and $z = r\sin a$—are useful for predicting the temperature distribution in spherical-shaped food particulates, e.g., canned potatoes in brine. The basic equation (2.5) in spherical coordinates is

$$\frac{1}{\alpha}\frac{dT}{dt} = \frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dT}{dr}\right) + \frac{1}{r^2\sin b}\frac{d}{db}\left(\sin b\frac{dT}{db}\right) + \frac{1}{r^2\sin^2 b}\frac{d^2T}{da^2}. \tag{2.10}$$

Fig. 2.2 Coordinate system for a cylindrical can of height $2l$ and diameter $2R$



If the temperature is only required in the radial direction, the angular terms can be neglected and Eq. (2.10) may be simplified to give

$$\frac{1}{\alpha}\frac{dT}{dt}=\frac{1}{r^2}\frac{d}{dr}\left(r^2\frac{dT}{dr}\right)$$

or

$$\frac{dT}{dt}=\alpha\left[\frac{d^2T}{dr^2}+\frac{2}{r}\frac{dT}{dr}\right]. \tag{2.11}$$

For the central point only, $r=0$, the equation becomes

$$\frac{dT}{dt}=3\alpha\left[\frac{d^2T}{dr^2}\right]. \tag{2.12}$$

In all these cases the problems have been simplified; for more complicated cases the reader is referred to the texts previously mentioned.

A full treatment of the term $\nabla\cdot k\nabla$ is given by Bird et al. (1960); for details of the equations in cylindrical and spherical coordinates, see Ruckenstein (1971).

2.2.3 Initial and Boundary Conditions

Temperature representations are often expressed simply as T. However, a more formal method is to give the coordinates of space and time in brackets. Thus a simple one-dimensional temperature distribution would be represented as $T(x, t)$ or $T(r, t)$, two-dimensional distributions as $T(x, y, t)$ and three-dimensional distributions as $T(x, y, z, t)$. For center distributions, where $x = y = z = r = 0$, $T(0, t)$ is used, and for conditions at time zero $T(x, 0)$. Since it is usually obvious what is intended from the context of the equations, this practice is often dispensed with. It is used in the following discussion where appropriate.

There are two *initial* conditions that may apply to a particular problem:

1. The contents of the container are initially at a uniform temperature T_0 throughout, which is expressed as follows:

$$T = T_0 \text{ at } t = 0 \text{ or } T = T(x, y, z, 0).$$

In good canning practice this condition should be achieved, and in calculations it is nearly always assumed.

2. The contents of the container have an initial temperature distribution in space. This is usually expressed as follows:

$$T = f(x) \quad \text{at} \quad t = 0,$$

or in other suitable ways, e.g.

$$T(x, y, z, 0) = f(x, y, z) \quad T(r, 0) = f(r),$$

where $f(x)$ is some function of x. This initial condition is used at the beginning of the cooling period for canned products that have not achieved a uniform temperature distribution at the end of the heating period. It usually applies to large container sizes with conduction-heating products.

Other conditions that have to be taken into account for solving the heat transfer equations are the *boundary* or *end* conditions, the conditions to which the can is exposed during processing. The following boundary conditions are encountered in heat transfer work:

1. The surface temperature is prescribed and does not vary with time, i.e., a surface is exposed to an instantaneous change in temperature. This is referred to as a boundary condition of the first kind by some workers. It applies to steam heating and is often assumed in heat transfer modeling work. It is the simplest condition to apply and is expressed as

$$dT(x, t)/dx = 0,$$

where x represents the external can diameter, or

$$T(x,t) = \text{constant}.$$

2. The surface temperature is governed by a convective heat coefficient, often referred to as a boundary condition of the third kind. Such a condition applies to cases where the heating medium is not condensing steam, e.g., hot water, a steam–air mixture, or a cooling fluid. The surface temperature in these cases depends on the heat-transfer coefficient, which in turn depends on the velocity of the fluid over the surface (see Sect. 2.3). This condition is expressed as follows:

$$-dT(x,t)/dx + h[T_\mathrm{R} - T(x,t)] = 0. \tag{2.13}$$

3. The surface temperature is a function of time, i.e., the heating medium heats or cools while the containers are being processed. Three specific cases are used to illustrate this condition:
   (a) Retort temperature change is a *linear function* with time: for example,

   $$T_\mathrm{R}(t) = T_0 + bt, \tag{2.14}$$

   where T_0 is the initial temperature, T_R is the processing medium temperature, i.e., retort temperature, and b is a constant depending upon the magnitude of the gradient.
   (b) Retort temperature change is an *exponential function* of time:

   $$T_\mathrm{R}(t) = T_\infty - (T_\infty - T_0)e^{-kt}, \tag{2.15}$$

   where T_∞ is the maximum temperature reached and k a constant. This applies to the initial heating period of cans when placed in a static retort.
   (c) Retort temperature a *harmonic function* of time:

   $$T_\mathrm{R}(t) = T_\infty \cos(2\pi nt), \tag{2.16}$$

   where n is the frequency of oscillation.

2.2.4 Mean or Volume Average Temperatures

It is necessary to know the exact temperature distribution inside packaged foods in order to calculate the sterilization value; however, there are circumstances in which mass-average temperatures are appropriate—in particular, the determination of a heat-vulnerable component, e.g., a vitamin; for determining some cooling processes; and for determining energy changes.

The average temperature is signified by putting a bar over the temperature term, and thus the volume-average temperature is given by

$$\overline{T}(t) = \frac{1}{V}\int_0^V T(x,t)dV, \tag{2.17}$$

where V is the volume and dV is the volume element. So for a slab of dimensions $2x$, $2y$, $2z$, we have

$$\overline{T}(t) = \frac{1}{2x2y2z}\int_{-x}^{x}\int_{-y}^{y}\int_{-z}^{z} T(x,y,z,t)dx,dy,dz; \tag{2.18}$$

for a one-dimensional slab thickness $2x$:

$$\overline{T}(t) = \frac{1}{2x}\int_{x}^{-x} T(x,t)dx = \frac{1}{x}\int_0^x T(x,t)dx; \tag{2.19}$$

for a sphere of radius R at any point r:

$$\overline{T}(t) = \frac{3}{R^3}\int_0^R r^2 T(r,t)dr; \tag{2.20}$$

and for a cylinder of radius R:

$$\overline{T}(t) = \frac{2}{R^2}\int_0^R rT(r,t)dr. \tag{2.21}$$

The mean temperature may also be used to determine the energy changes in a processing system:

$$Q = c\left(\overline{T}(t) - T_0\right) \tag{2.22}$$

where Q is the amount of energy supplied during time t, c is the specific heat and T_0 is the initial uniform temperature.

2.2.5 Summary of Basic Requirements

The following points need to be considered when attempting to formulate a model to predict the temperature distribution in a packaged food product which is being heated and cooled:

1. Is the product isotropic, i.e., does it have properties the same in all directions? If not, use k_x, k_y, k_z.

2. Do the physical properties vary with temperature, or any other prevailing condition? If so, then use $k(T)$.
3. Is the product at a uniform initial temperature? If not, use $T = f(x, y, z)$.
4. Is the product heated uniformly on all sides? Is the headspace taken into account?
5. Does the container or package change shape during the processing? If so, use appropriate dimensions.
6. Is it necessary to consider the resistance to heat transfer through the container wall? If so, use x_w/k_w.
7. Does the heating or cooling medium impose a low heat-transfer coefficient? If so, use heat-transfer boundary condition equation (2.12).
8. Is the surface temperature variable? If so, use $T_R(t)$ as in Eqs. (2.13) and (2.14).

A general rule for proceeding is to apply a simple model first, usually in one dimension, and then a more complex model if the predictions are not in agreement with the experimental results. For many practical factory applications simple models suffice.

2.2.6 Some Analytical Methods for Solving the Equations

There are many methods for solving partial differential equations, and it suffices here to mention some of those that have been used by researchers in this subject without going into any detail. The first group are the analytical methods and the functions that they use.

2.2.6.1 Method of Separation of Variables

This method assumes that the solution to the partial differential equation, e.g., the simplest one-dimensional unsteady-state equation for the temperature distribution in a slab equation,

$$\frac{\partial T(x,t)}{\partial t} = \alpha \frac{\partial^2 T(x,t)}{\partial^2 x}, \tag{2.23}$$

can be represented as the product of a spatial function $X(x)$ and a time function $T(t)$, viz.

$$T(x,t) = X(x) \cdot T(t). \tag{2.24}$$

Substituting the differentiated forms of (2.24) in (2.23) and separating the variables on either side of the equation results in:

$$\frac{1}{\alpha}\frac{\partial T}{T\partial t}=\frac{1}{X}\frac{\partial^2 X}{\partial x^2}. \tag{2.25}$$

Putting each side equal to a constant, e.g., $-b^2$, it is possible to obtain solutions for $T(t)$ and $X(t)$, viz.

$$T(t)=Ae^{-b^2 t}$$
$$X(x)=B\cos(bx)+C\sin(bx).$$

Using Eq. (2.23), the general solution becomes

$$T(x,t)=[D\cos(bx)+E\sin(bx)]e^{-b^2 t}. \tag{2.26}$$

Using the initial and boundary conditions, a particular solution can then be found for the problem. This involves the use of Fourier sine series, which is discussed in Sect. 2.2.6.3.

2.2.6.2 Operational Methods: Integral Transforms and the Laplace Transform

In this method each term of the differential equation is multiplied by $e^{-\beta t}$ and integrated with respect to time from $t = 0$ to $t = \infty$. For the one-dimensional slab this results in

$$\int e^{-\beta t}\cdot\frac{\partial T}{\partial t}\cdot dt=\alpha\int e^{-\beta t}\frac{\partial^2 T}{\partial x^2}\cdot dt. \tag{2.27}$$

The Laplace transform L[$f(t)$] is defined by

$$f(s)=\mathrm{L}[f(t)]=\int f(t)e^{-st}dt, \tag{2.28}$$

and Eq. (2.27) may be written as

$$L\left[\frac{\partial T}{\partial t}(x,t)\right]=\alpha L\left[\frac{\partial^2 T}{\partial x^2}(x,t)\right]. \tag{2.29}$$

By integrating the terms in Eq. (2.27) from 0 to ∞ or from standard tables, the partial differential equation is transformed to a second-order differential equation, viz.

$$\alpha\frac{d^2T}{dx^2}(x,s)-sT(x,s)=0, \tag{2.30}$$

which has solution

$$T(x,s) = A\cosh\left(\frac{s}{a}\right)^{1/2} + B\sinh\left(\frac{s}{a}\right)^{1/2}. \tag{2.31}$$

This can be transformed back to the original system using the reverse transformation $f(t) = L^{-1}[f(s)]$, resulting in the Fourier series solution.

Tables of transforms are found in all standard texts on heat transfer, e.g., Carslaw and Jaeger (1959), Luikov (1968), Mickley et al. (1957), and Ozisik (1980).

Hayakawa (1964) made elegant use of integral transforms for handling complex boundary conditions experienced in standard canning operations. Various other types of transform are available for handling different situations. The Fourier sine transform is useful for dealing with situations with a prescribed boundary condition and the Hankel transform for dealing with cylindrical geometry (Magnus et al. 1966). The main problem with the integral transform method is finding the reverse function to convert the solution of the derived differential equation.

2.2.6.3 Some Special Transcendental Functions Involved in the Solution of Differential Equations

Fourier series. Many of the analytical solutions to heat transfer problems involve the use of series, in particular series of trigonometrical functions. For example, a relationship $y = f(x)$ may be represented, between the limits of $x = 0$ and $x = \pi$, as follows:

$$y = f(x) = a_1\sin(x) + a_2\sin(2x) + \cdots + a_n\sin(nx) \tag{2.32}$$

or

$$y = f(x) = a_n\sin(x)$$

and

$$n = \frac{2}{\pi}\int f(x)\sin(mx)dx$$

If $f(x)$ is a constant, e.g., initial temperature T_0, then

$$a_n = \frac{2}{\pi}T_0\int\sin(mx)dx = \frac{2}{\pi n}T_0[1-(-1)^n]$$

If n is even, then $a_n = 0$, and if n is odd, $a_n = 4T_0/\pi n$ and

$$f(x) = 4T_0\left(\frac{\sin(x)}{1} + \frac{\sin(3x)}{3} + \frac{\sin(5x)}{5} + \cdots\right). \tag{2.33}$$

Similar Fourier series are available with cosine terms. The standard analytical solutions for simple slab geometry involve combinations of sine and cosine series. For ease of computation it is essential that the series converge rapidly: In many cases a first-term approximation is satisfactory, especially where long times are involved.

Bessel functions. For problems involving cylindrical geometry—in particular, food and drink cans—the linear second-order equation representing the temperature distribution with time and space is known as Bessel's equation. The analytical solution of this equation requires the use of Bessel functions designated $J_v(x)$, where v is the order.

Bessel functions are defined by

$$J_v(x) = \frac{x^v}{2^v v!}\left[1 - \frac{x^2}{2(2v+2)} + \frac{x^4}{2 \times 4(2v+2)(2v+4)} - \cdots\right]. \tag{2.34}$$

When $v = 0$ the function $J_0(x)$ is known as a Bessel function of the first kind and of order zero, i.e.

$$J_0(x) = 1 - \frac{x^2}{2^2} + \frac{x^4}{2^2 \cdot 4^2} - \frac{x^6}{2^2 \cdot 4^2 \cdot 6^2} + \cdots \tag{2.35}$$

$J_0(x_n)$ is a continuous function of x and cuts the $y = 0$ axis at various points known as the roots, x_n:

Root number n	1	2	3	4	5
Roots of $J_0(x_n)$	2.405	5.520	8.654	11.792	14.931
Roots of $J_1(x_n)$	3.832	7.015	10.173	13.324	16.470

The first differential of $J_0(x)$ is $-J_1(x)$, known as a Bessel function of the first kind and of the first order.

Bessel functions may be calculated using the following equations:

$$J_0(x) = A\cos(x - 0.25\pi) \tag{2.36a}$$

$$J_1(x) = A\cos(x - 0.75\pi), \tag{2.36b}$$

where $A = (2/\pi x)^{1/2}$.

2.2.6.4 Duhamel's Theorem

A useful method of dealing with time-dependent boundary conditions, e.g., ramp and exponential functions, is to use Duhamel's theorem to convert the step-response solution to the required solution. This method has been widely used in the solution of canning problems (Riedel 1947; Gillespy 1953; Hayakawa 1964; Hayakawa and Giannoni-Succar 1996).

If the step-function temperature distribution is given by $\Phi(t)$ and the required solution for a time-dependent boundary condition $\Theta(t)$, then Duhamel's theorem states that the relationship between the two is given by

$$\Theta(t) = \int_0^{\tau} f(t) \cdot \frac{\partial \Phi}{\partial t}(x, t - \tau) d\tau, \tag{2.37}$$

where $f(t)$ is the temperature distribution equation for the time-dependent boundary condition and τ is the time limit for integration.

Duhamel's theorem has also been used in a direct approach to decoupling temperature data from specific boundary conditions, in order to predict data for different experimental conditions. A theoretical inverse superposition solution for the calculation of internal product temperatures in containers in retorts subjected to varying retort temperature profiles (Stoforos et al. 1997).

2.2.7 *Some Numerical Techniques of Solution*

2.2.7.1 Introduction

Many of the mathematical models for heat transfer into cylindrical containers have complex boundary conditions which do not permit simple analytical solutions to be obtained in a form which can easily be manipulated. Consequently, numerical methods have been developed and are now extensively used because of their suitability for modern computing. They require neither the solution of complex transcendental equations nor the functions outlined above. These methods are based on iterative estimations of temperatures using approximate methods. It is not possible to obtain directly solutions that show the interrelationship of the variables, and the solutions are essentially in the form of time-temperature data. In view of the fact that the temperature distributions obtained are used to determine the achieved lethality, it is necessary to check that the method used is of sufficient accuracy to prevent a sub-lethal process being recommended. There is always a possibility of cumulative error.

2.2.7.2 Finite-Difference Approximation Method

In the finite-difference methods the derivative functions are replaced by approximate values expressed by values of a function at certain discrete points known as "nodal points." The result of this operation is to produce an equivalent finite-difference equation which may be solved by simple algebraic or arithmetic manipulation.

For unsteady-state heat transfer it is necessary to construct a space–time grid (see Fig. 2.3) in which the temperatures at the nodal points are defined in terms of time (t) and space (x) coordinates.

Considering the basic one-dimensional heat transfer equation:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial^2 T}{\partial x^2}. \tag{2.38}$$

Using a Taylor series expansion the value of $T(x, t)$ may be expressed as

$$T_{(x,t+\Delta t)} = T_{(x,t)} + \Delta T.\frac{\partial T}{\partial t} + \frac{\Delta T^2}{2}\cdot\frac{\partial^2 T}{\partial t^2} + \frac{\Delta T^3}{3}\cdot\frac{\partial^3 T}{\partial t^3}. \tag{2.39}$$

If the increment is sufficiently small then the terms higher than T may be neglected, thus

$$\frac{\partial T}{\partial t} = \frac{T_{(x,t+\Delta t)} - T_{(x,t)}}{\Delta t} = \frac{T_{i,n+1} - T_{i,n}}{\Delta t}. \tag{2.40}$$

Two series are required for $\partial^2 T/\partial x^2$: these are the expansion of $T_{(x+\Delta x,t)}$ and $T_{(x-\Delta x,t)}$, from which

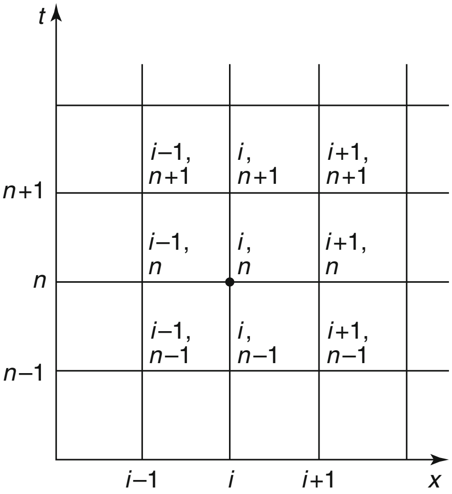


Fig. 2.3 Temperature nodal points on space–time grid

$$\frac{\partial^2 T}{\partial x^2} = \frac{T_{(x+\Delta x,t)} - 2T_{(x,t)} + T_{(x-\Delta x,t)}}{\Delta x^2} = \frac{T_{i+1,n} - T_{i,n} + T_{i-1n}}{\Delta x^2}. \tag{2.41}$$

Equation (2.39) then becomes

$$T_{i,n+1} = T_{i,n} + \frac{\alpha \Delta t}{\Delta x^2}[T_{i+1,n} - 2T_{i,n} + T_{i-1,n}]. \tag{2.42}$$

For a better approximation the term $T_{(x,t+2\Delta T)}$ can be expanded in the same way.

Two important aspects of this method of solution are the convergence and the stability criteria, without which full confidence in the solution cannot be guaranteed. Convergence implies that the finite-difference solution will reduce to the exact solution when the size increments, e.g., Δx and ΔT, are infinitesimally small. Stability implies that the errors associated with the use of increments of finite size, round-off errors, and numerical mistakes will not increase as the calculations proceed. Tests for these are given in the standard books on numerical analysis.

This method is usually referred to as the *explicit* method. The time step t has to be kept very small and the method is only valid for $0 < t/\Delta x^2 \leq 1/2$, i.e., $\Delta t \leq 1/2\Delta x^2$, and Δx has to be kept small in order to obtain reasonable accuracy.

A more suitable, but computationally more demanding, method is the *implicit* method in which the nodal points are replaced by the values taken at $n+1$ rather than n, although this results in three unknown temperatures, and N equations, where N is the number of spatial nodes representing the conductive body. The nodal temperatures are obtained by simultaneous solution of the equations. The basic equation for the relationship between the nodal points is given by

$$T_{i,n+1} = T_{i,n} + \frac{\alpha \Delta t}{\Delta x^2}[T_{i+1,n+1} - 2T_{i,n+1} + T_{i-1,n+1}]. \tag{2.43}$$

Several other methods, which are intermediate between the explicit and implicit methods, have been developed, e.g., the Crank–Nicholson method, Jacobi method, Gauss–Seidel method, and "over-relaxation" methods. Discussions of the application finite-difference methods are available in a large number of text-books: See Smith (1974), Adams and Rogers (1973), Croft and Lilley (1977), Carnahan et al. (1969), and Minkowycz et al. (1988).

The finite-difference technique has been applied to a wide range of canning problems (see Tables 2.3, 2.4 and 2.5). Tucker and Badley (1990) have developed a commercial center temperature prediction program for heat sterilization processes, known as CTemp.

Welt et al. (1997) have developed a no-capacitance surface node NCSN procedure for heat transfer simulation, which can be used for process design. This method when used with simulation steps of 10 s was found to provide a better fit to the experimental data compared with capacitance surface node technique (CNS). Chen and Ramaswamy (2002a, b, c) have also developed a method of modeling and optimization based neural networks and genetic algorithms.

Table 2.3 Some conduction-heating models for predicting temperatures in cylindrical cans of food

Form of solution	Product/ container	Process conditions	Comments	Reference
Analytical equations	Geometrical objects	Linear surface heating and step-change	Any position and center	Williamson and Adams (1919)
Analytical equations	Metal cans and glass jars, fruit and vegetables	Linear surface heating and step-change	Determination of effective thermal diffusivity	Thompson (1919)
Analytical equations	Cans: fruit and vegetables	Variable surface temperature	Duhamel's theorem	Thompson (1922)
Analytical equations	Cans: various fish	Step-change	Thermal properties	Langstroth (1931)
Analytical equations	Cans: fish	Step-change	Based on Langstroth (1931) first-term approximation	Cooper (1937)
Analytical equations	Cans: fish	Step-change		Tani (1938a)
Analytical equations	Cans: fish	Step-change	Cooling	Okada (1940a)
Analytical equations	Cans: food	Step-change	Based on Williamson and Adams (1919)	Taggert and Farrow (1941, 1942)
Tables of numerical values	Geometrical objects	Step-change	Very useful method	Olson and Schultz (1942)
Analytical equations	Cans: food	Step-change and initial temperature distribution	Classical equation for cylindrical can	Olson and Jackson (1942)
Analytical equations	Cans: food	Various heating profiles	Duhamel's theorem	Riedel (1947)
Analytical equations	Cans: food	Step-change and initial temperature distribution	Heating and cooling Duhamel's theorem	Hicks (1951)
Analytical equations with numerical tables	Cans: food	Step-change and variable surface temperature	Duhamel's theorem	Gillespy (1951, 1953)
Analytical equations	Cans: meat	Step-change and initial temperature distribution	Heating and cooling derivation given	Hurwicz and Tischer (1952)
Analytical equations	Cans: food	Step-change and finite-surface heat-transfer coefficient	Effect of head-space on temperature distribution	Evans and Board (1954)
Analytical equations	Cans: food	Step-change	Hyperbolic secant	Jakobsen (1954)

(continued)

Table 2.3 (continued)

Form of solution	Product/ container	Process conditions	Comments	Reference
Analytical equations	Cans: food	Variable surface temperature profiles	A major contribution to the theoretical analysis	Hayakawa (1964, 1969, 1970)
Analytical equations	Cans: food	Step-change	f_h/j analysis	Hayakawa and Ball (1968)
Analytical equations	Cans: food	Step-change	Heating and cooling	Hayakawa and Ball (1969a)
Analytical equations	Cans: food	Step-change	Cooling curve	Hayakawa and Ball (1969b)
Numerical solution	Cans: food	Step-change	2D finite-difference equation	Teixeira et al. (1969)
Analytical equations	Cans: food	Step-change	Jakobsen's equation (1954)	Shiga (1970)
Analytical equations	Cans: food	Variable surface temperature profiles	Based on Hayakawa (1964)	Hayakawa and Ball (1971)
Analytical equations	Cans: food	Variable surface temperature profiles	Duhamel's theorem	Hayakawa (1971)
Analytical equations	Cans: food	Step-change	Heating and cooling	Flambert and Deltour (1971, 1973a, b)
Analytical equations	Cans: food	Multiple step-changes	Duhamel's theorem	Wang et al. (1972)
Response charts	Cans: simulant and food	Variable surface temperature	Comparison with Gillespy (1953); mass average temps	Hayakawa (1974)
Analytical equations and response charts	Cans: food	Step-change	Central and average temperatures	Leonhardt (1976a, b)
Analytical and numerical solutions	Cans: food	Step-change	Lethality-Fourier number method	Lenz and Lund (1977)
Analytical equations	Cans: food	Variable surface temperature	f_h/j concept	Ikegami (1978)
Finite-element solution	Cans: model	Surface heat-transfer coefficient	Galerkin residual method of transform used	De Baerdemaeker et al. (1977)
Analytical equations	Cans: food	Step-change, center temperature	Second-order linear system	Skinner (1979)
Analytical equations	Cans: food	Surface heat-transfer coefficient	Simplified equations	Ramaswamy et al. (1982)

(continued)

Table 2.3 (continued)

Form of solution	Product/ container	Process conditions	Comments	Reference
Analytical equations	Cans: food	Surface heat-transfer coefficients	Thermocouple errors	Larkin and Steffe (1982)
Finite-element solution	Glass jar: apple sauce, can: salmon	Surface heat-transfer coefficient	Cooling effects	Naveh et al. (1983b)
Analytical equations	Cans: food	Heating and cooling	Lethality-Fourier number method	Lund and Norback (1983)
Analytical equations, computer programs	Geometrical objects	Heating and cooling	Based on Olson and Schultz (1942)	Newman and Holdsworth (1989)
Analytical equations	Cans: food	Surface heat-transfer coefficient	Cooling effects	Datta et al. (1984)
Analytical equations	Cans: food	Nonhomogeneous food	Effective thermal diffusivity	Olivares et al. (1986)
Analytical solution	Cans: food	Surface heat-transfer coefficient	Effect of air on the can base coefficient	Tan and Ling (1988)
Finite difference	Cans: food	Surface heat-transfer coefficient	Applicable for process deviations	Mohamed (2003)
Numerical solution	Cans: food	Surface heat-transfer coefficient	Finite-difference model	Richardson and Holdsworth (1989)
Analytical equations, computer programs	Geometrical objects, cans: potato purée	Surface heat-transfer coefficient	Effect of *l*/*d* ratio	Thorne (1989)
Finite difference	Cans: simulant	Surface heat-transfer coefficient	Cooling	Tucker and Clark (1989, 1990)
Finite element	Cans: fish/oil	Step-change	Anisotropic model, solid and liquid layer	Perez-Martin et al. (1990)
Finite difference	Plastic: 8 % bentonite	Wall resistance	ADI technique	Shin and Bhowmik (1990)
Finite difference	Cans: model	Surface heat-transfer coefficient	Step process	Silva et al. (1992)
Finite element	Cans: fish/oil	Step-change, solid and liquid layer	Anisotropic model	Banga et al. (1993)
Analytical equations	Cans: sea food	Surface heat-transfer coefficient	*z*-transfer function	Salvadori et al. (1994a, b)
Analytical	Model	Finite surface resistance	3D model	Cuesta and Lamua (1995)
Analytical equations	Cans: mashed potato	Step change	Linear recursive model	Lanoiseuille et al. (1995); Chiheb et al. (1994)

(continued)

Table 2.3 (continued)

Form of solution	Product/ container	Process conditions	Comments	Reference
Numerical	Cans: fruit/ syrup	Variable boundary conditions	*z*-transfer function	Márquez et al. (1998)
Zone Modeling	Cans: baked beans	Heating and cooling	Uncertain data	Johns (1992a, b)
Zone Modeling	Cans	Heating and cooling	Simple model	Tucker et al. (1992)
Finite element	Cans: tomato concentrate	Surface heat-transfer coefficient	Stochastic boundary conditions	Nicolai and De Baerdemaeker (1992)
Finite element/Monte Carlo	A1 can: tomato concentrate	Surface heat-transfer coefficient	Parameter fluctations	Nicolaï and De Baerdemaeker (1997); Nicolaï et al. (1998)
Various	Cans: model	Various	Comparison of techniques	Norohna et al. (1995)

2.2.7.3 The Finite-Element Method

With this method the body under investigation is divided up into an assembly of subdivisions called *elements* which are interconnected at *nodes* (see Fig. 2.4). This stage is called *discretization*. Each element then has an equation governing the transfer of heat, and system equations are developed for the whole assembly. These take the form

$$q = kT \tag{2.44}$$

where $\boldsymbol{k}$ is a square matrix, known as the stiffness or conductance matrix, $\boldsymbol{q}$ is the vector of applied nodal forces, i.e., heat flows, and $\boldsymbol{T}$ is the vector of (unknown) nodal temperatures.

In the case of one-dimensional heat conduction, the heat in is given by

$$q_i = -\frac{kA}{L}\left(T_j - T_i\right)$$

and the heat out by

$$q_j = -\frac{kA}{L}\left(T_i - T_j\right)$$

which in matrix form is

$$\begin{bmatrix} q_i \\ q_j \end{bmatrix} = \frac{kA}{L}\begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix}\begin{bmatrix} T_i \\ T_j \end{bmatrix}.$$

Table 2.4 Some conduction-heating models for predicting temperatures in slab- or brick-shaped containers of food

Form of solution	Product/ container	Process conditions	Comments	Reference
Analytical equations	Cans: fish	Finite surface resistance	3D model	Okada (1940c)
Analytical equations	Cans: fish	Thermal conductivity varies with temperature	ID nonlinear model	Fujita (1952)
Analytical equations	Pouches: food	Finite surface resistance	3D model	Chapman and McKernan (1963)
Analytical/ numerical	Model	Time-variable boundary conditions	ID model	Mirespassi (1965)
Finite difference	Model	Step-change	3D model	Manson et al. (1970)
Analytical equations	Model	Step-change	3D model	Alles and Cowell (1971)
Analytical equations	Model	Center and average temperatures	3D Model	Leonhardt (1976a, b)
Analytical equations	Model	Finite surface resistance	ID nonsymmetric model	Uno and Hayakawa (1979)
Analytical equations	Pouches: simulant	Step-change	3D model	Castillo et al. (1980)
Analytical equations	Metal brick	Retort profile	3D model	Ramaswamy et al. (1983)
Finite differencer	Pouches: bentonite	Finite surface resistance	3D model	McGinnis (1986)
Finite difference	Pouches: bentonite	Finite surface resistance	3D model	Bhowmik and Tandon (1987)
Finite difference	Cans: food	Finite surface resistance and wall thickness	3D model	Tucker and Holdsworth (1991a, b)
Finite difference	Model	Ramp/hold/step-cool	ID model	Hendrickx et al. (1993)
Analytical equations	Model	Finite surface resistance	*z*-transfer function	Salvadori et al. (1994a, b)
Finite difference	Pouches: model	Step-change	2- and 3D model	Silva et al. (1994)
Analytical	Model	Finite surface resistance	3D model	Cuesta and Lamua (1995)
Finite element	Lasagne: brick	Finite surface resistance	3D model	Nicolai et al. (1995), Nicolai and De Baerdemaeker (1996)

Table 2.5 Some conduction-heating models for predicting temperatures in arbitrary-shaped products and containers

Geometry	Product/ container	Process conditions	Comments	Reference
Any shape	Model	Finite surface resistance	Analytical solution	Smith et al. (1967)
Any shape	Model	Series of step-changes, finite surface resistance	Analytical solution	Wang et al. (1972)
Any shape	Model	Finite surface resistance	Analytical solution	Thijssen et al. (1978), Thijssen and Kochen (1980)
Any shape	Model	Finite surface resistance	Analytical solution	Ramaswamy et al. (1983)
Any shape	Model, particulates in cans	Finite surface resistance	Numerical solution	Lekwauwa and Hayakawa (1986)
Any shape	Model	Finite surface resistance	Analytical solution based on Smith et al. (1968)	Hayakawa and Villalobos (1989)
Any shape	Model	Finite surface resistance	Finite element	Akterian and Fikiin (1994)
Any shape	Model	Finite surface resistance	Analytical solution	Cuesta and Lamua (1995)
Cubes	Polycarbonate/ heated in water	Step-change	Finite difference	Kim and Teixeira (1997)
Cylinders	Polycarbonate/ heated in water	Step-change	Finite difference	Kim and Teixeira (1997)
Ellipsoidal	Sweet potato	Finite surface resistance	ADI: finite difference	Wadsworth and Spardaro (1970)
Ellipsoidal	Plastic model, processed ham	Finite surface resistance	Analytical solution	Smith (1966), Smith et al. (1967, 1968), Clary and Nelson (1970), Clary et al. (1971)
Elliptical cross-section	Shrimp	Finite surface resistance	Heat flow lines	Erdogdu et al. (1998a, b)
Oval-shaped	Cans	Step-change	Analytical solution	Iwata (1940)
Oval-shaped	Cans	Step-change	Finite difference	Simpson et al. (1989)
Oval-shaped	Solid shape	Surface heat transfer	volume element	Erdogdu et al. (2001)

(continued)

Table 2.5 (continued)

Geometry	Product/ container	Process conditions	Comments	Reference
Oval-shaped	Polycarbonate/ heated in water	Step-change	Finite difference	Kim and Teixeira (1997)
Pear-shaped	Cans	Step-change	Based on Smith et al. (1966)	Manson et al. (1974)
Mushroom-shaped	Model	Finite surface resistance	Finite difference	Sastry et al. (1985)
Mushroom-shaped	Model	Finite surface resistance	Finite difference	Akterian (1995)
Shrimp-shaped	Shrimp	Finite surface resistance	Finite difference	Chau and Snyder (1988)
Elliptical cross-section	Shrimp	Finite surface resistance	Heat flow lines	Erdogdu et al. (1998a, b)
Elliptical cylinders	Solid shape	Infinite surface resistance	Volume element	Erdogdu et al. (2001)
Conical shape	Acrylic cones	Finite surface resistance	Volume element	Pornchaloempong et al. (2001, 2003)
Cone frustrums	Fish/pouch	Finite surface resistance	Finite difference	Simpson et al. (2004)
Bowl-shaped, plastic	Apple sauce, bentonite	Finite surface resistance	ADI: finite difference	Sheen et al. (1993)
Irregular shaped particles/liquid	Model	Finite surface resistance	Numerical	Califano and Zaritzky (1993)

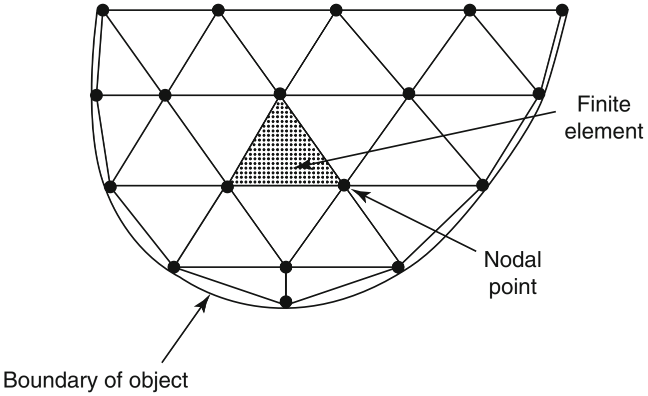


Fig. 2.4 Discretization of an object into finite elements

The stages in developing a finite-element model are as follows:

1. *Discretization*. For two-dimensional solid bodies that are axisymmetrical, triangular or rectangular elements may be used, whereas for three-dimensional objects, cubes or prisms may be used. In problems involving curved areas, shells of appropriate curved geometry are chosen.
2. *Size and number of elements*. These are inversely related: As the number of elements increases, the accuracy increases. It is generally more useful to have a higher density of mesh elements, especially where temperatures are changing rapidly. This requires careful planning at the outset of the analysis. It is important that all the nodes are connected at the end of the mesh.
3. *Location of nodes*. It is essential that where there is a discontinuity in the material, the nodes should join the two areas.
4. *Node and element numbering*. Two different methods are used, either horizontal or vertical numbering for the nodes; the elements are given numbers in brackets.
5. *Method of solution*. Most finite-element computer programs use wavefront analysis; however, the Gaussian elimination technique may also be used. The reader is recommended to consult the texts by Segerlind (1984) and Fagan (1992) for further information in relation to the application of the method. The ANSYS (1968) computer software package is very useful for problem-solving.

Relatively few applications of the technique to food processing problems have been reported. General discussions and overviews have been given by Singh and Segerlind (1974), De Baerdemaeker et al. (1977), Naveh (1982), Naveh et al. (1983a), Puri and Anantheswaran (1993), and Nicolai et al. (2001).

The method has been applied to the heating of baby foods in glass jars (Naveh 1982) and the heating of irregular-shaped objects, e.g., canned mushrooms in brine (Sastry et al. 1985). The temperature distribution during the cooling of canned foods has been analyzed by Naveh et al. (1983b), and Nicolai and De Baerdemaeker (1992) have modeled the heat transfer into foods, with stochastic initial and final boundary conditions. Nicolai et al. (1995) have determined the temperature distribution in lasagne during heating.

2.2.7.4 Some Other Methods

Hendrickx (1988) applied transmission line matrix (TLM) modeling to food engineering problems. This method, like the finite-difference model, operates on a mesh structure, but the computation is not directly in terms of approximate field quantities at the nodes. The method operates on numbers, called pulses, which are incident upon and reflected from the nodes. The approximate temperatures at the nodes are expressed in terms of pulses. A pulse is injected into the network and the response of the system determined at the nodes.

For systems with complex boundary conditions, such as those found in canning operations, the equations have been solved using the response of the linear system to a disturbance in the system, in this case a triangular or double ramp pulse. The solution uses both Laplace transforms and z-transfer functions. The formal solution of the heat-transfer equation for a finite cylinder with complex boundary conditions was derived by Salvadori et al. (1994a, b). Márquez et al. (1998) have applied the technique to the study of a particulate/liquid system, viz., pasteurizing fruit in syrup.

2.2.8 Some Analytical Solutions of the Heat Transfer Equation

2.2.8.1 Simple Geometrical Shapes

The simplest cases are the temperature distributions in one dimension for an infinite slab, an infinite cylinder and a sphere. From the first, two more complex solutions can be obtained (see Sect. 2.2.8.2).

The Infinite Slab

The one-dimensional flow of heat in a slab is given by

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \tag{2.46}$$

(see Eq. 2.38). The general form of the solution $F(t)$ is given by

$$T = T_\mathrm{R} - (T_\mathrm{R} - T_0)F(t), \tag{2.47}$$

where T is the temperature distribution at space coordinate x and time t, often written as $T(x, t)$; T_R is the retort temperature and T_0 is the initial temperature of the solid body, at time $t = 0$.

For a slab of thickness $2X$, the solution at any point is

$$F(t) = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{2n-1} \cos\left((2n-1)\frac{\pi x}{2X}\right) e^{\left[-(2n-1)^2 \pi^2 \alpha t / 4X^2\right]}, \tag{2.48}$$

which, at the center, becomes

$$F(t) = \frac{4}{\pi} \sum_{n=1}^{\infty} \frac{(-1)^{n+1}}{2n-1} e^{\left[-(2n-1)^2 \pi^2 \alpha t / 4x^2\right]}. \tag{2.49}$$

It is often conveniently designated by $S(\theta)$, where θ is the dimensionless Fourier number $\alpha t/l^2$ where l is the thickness of the body, i.e., $2X$:

$$S(\theta) = \frac{4}{\pi}\sum_{n=1}^{\infty}\frac{(-1)^{n+1}}{2n-1}e^{\left[-(2n-1)^2\pi^2\theta\right]} \tag{2.50}$$

$$= \frac{4}{\pi}\left[e^{-\pi^2\theta} - \frac{1}{3}e^{-9\pi^2\theta} + \frac{1}{5}e^{-25\pi^2\theta} - \cdots\right]. \tag{2.51}$$

This subject is discussed in detail by Ingersoll et al. (1953), Olson and Schultz (1942), and Newman and Holdsworth (1989). The latter includes a range of useful computer programs in BASIC.

If the body has an initial temperature distribution $f(\lambda)$, then the temperature distribution is given by

$$T_{\mathrm{R}} - T = \frac{2}{l}\sum_{n=1}^{\infty}(n\pi x/l)\int_0^{\lambda} f(\lambda)\sin(n\pi\lambda/l)d\lambda \cdot e^{-n^2\pi^2\theta}. \tag{2.52}$$

This equation ultimately reverts to (2.50), when $f(\lambda)$ is a uniform temperature $T_0 - T_{\mathrm{R}}$.

If the body has a surface heat-transfer coefficient, h, then the temperature distribution is given by

$$F(t) = 2\sum_{n=1}^{\infty}\frac{\sin M_n \cos(M_n(x/X))}{M_n + \sin M_n \cos M_n} e - M_n^2\theta \tag{2.53}$$

and for the center temperature, this becomes

$$F(t) = 2\sum_{n=1}^{\infty}\frac{\sin M_n}{M_n + \sin M_n \cos M_n} e - M_n^2\theta \tag{2.54}$$

where M_n is obtained from the solution of $M_n = Bi \cot M_n$ and Bi is the Biot number hX/k. This is also known as the Nusselt number in heat-transfer correlations.

Infinite Cylinder

The basic one-dimensional heat transfer equation is given by

$$\frac{dT}{dt} = \alpha\left[\frac{d^2T}{dr^2} + \frac{1}{r}\frac{dT}{dr}\right]. \tag{2.55}$$

The solution for a rod of radius $2a$, at any radial point r, for a constant retort temperature T_{R} and a uniform initial temperature distribution T_0 is given by

$$F(t) = \sum_{i=1}^{n} A_i J_0(R_i r/a) e^{-R_i^2 \theta}, \tag{2.56}$$

where $A_n = 2/[R_n J_1(R_n)]$, $J_0(x)$ is a Bessel function of zero order, $J_1(x)$ a Bessel function of the first order (see Sect. 2.2.6.3), R_n is the nth root of the characteristic equation $J_0(x) = 0$, and $\theta = \alpha t/a^2$ is the dimensionless Fourier number.

For the center point it is possible to define $C(\theta)$, similarly to $S(\theta)$ in Eq. (2.50):

$$C(\theta) = 2\sum_{i=1}^{n} A_i e^{-R_i^2 \theta}, \tag{2.57}$$

i.e.

$$C(\theta) = 2\left[A_1 e^{-R_1^2 \theta} + A_2 e^{-R_2^2 \theta} + A_3 e^{-R_3^3 \theta} + \cdots\right].$$

If the initial temperature distribution at time $t = 0$ is $f(r)$, then the temperature distribution after time t is given by

$$T_\mathrm{R} - T = \sum_{i=1}^{n} A_i' J_0(R_i r/a) e^{-R_i^2 \theta} \cdot \int_0^r r f(r) J_0(R_n r/a) dr, \tag{2.58}$$

where $A_n' = 2/[a^2 J_1(R_n)]$.

If there is a finite surface heat coefficient on the outside, then the temperature distribution is given by

$$F(t) = A_n'' J_0(R_n \cdot r/a) e^{-\left[R_n^2 \theta\right]}, \tag{2.59}$$

where

$$\begin{aligned} A_n'' &= \left[2J_1(R_n)/R_n\left[J_0^2(R_n) + J_1^2(R_n)\right]\right], \\ R_n J_1(R_n) &= J_0(R_n) Bi, \\ Bi &= hr/k. \end{aligned}$$

A Spherical Object

The basic heat transfer equation for determining the temperature distribution in a spherical object of radius a is given by

$$\frac{dT}{dt} = \alpha\left[\frac{d^2 T}{dr^2} + \frac{2}{r}\frac{dT}{dr}\right]. \tag{2.60}$$

The solution for the simplest case of a step function is given by

$$F(t) = (2a/\pi r)\sum_{n=1}^{\infty}(-1)^{n+1}\sin(n\pi r/a)e^{-n^2\pi^2\theta}. \tag{2.61}$$

where $\theta = \pi t/a^2$.

For the central temperature only the equation reduces to

$$F(t) = 2\sum_{n=1}^{\infty}(-1)^{n+1}e^{-n^2\pi^2\theta}. \tag{2.62}$$

A function $B(x)$ is defined in terms of $F(t)$ for later use as follows:

$$F(t) = B(x), \tag{2.63}$$

where $x = \pi^2\theta$.

For the case of external heat transfer the following equation is applicable:

$$F(t) = \frac{2r}{a}\sum_{n=1}^{\infty}\frac{\sin M_n - M_n\cos M_n}{M_n - \sin M_n - \cos M_n}\cdot\frac{\sin(M_n(r/a))}{M_n}e^{-\left[M_n^2\theta\right]}, \tag{2.64}$$

where $\tan M_n = M_n/(1 - Bi)$.

2.2.8.2 More Complex Geometries

Rectangular Parallelepiped or Brick

The simple analytical solution for this case is obtained using the $S(\theta)$ function given in Eq. (2.50). The temperature distribution is given by

$$F(t) = S(\theta_x)S(\theta_y)S(\theta_z), \tag{2.65}$$

where $S(\theta_n) = \alpha t/n^2$ and n is the overall side dimension. For a cube of side a, the temperature is given by

$$F(t) = [S(\theta)]^3. \tag{2.66}$$

Applications of these formulae to various conditions for heating canned foods in rectangular metallic or plastic containers are presented in Table 2.4.

Finite Cylinder

The simple analytical solution for a cylinder of radius r and length l is given by

$$F(t) = S\left(\alpha t/l^2\right)C\left(\alpha t/r^2\right). \tag{2.67}$$

Tables for $S(\theta)$, $C(\theta)$ and $B(x)$ are given in Ingersoll et al. (1953), Olson and Schultz (1942), and Newman and Holdsworth (1989).

The complex analytical equations that are required to interpret heat penetration data are as follows. For a can with infinite surface heat-transfer coefficient and uniform initial temperature, radius a and length $2l$ (Cowell and Evans 1961)

$$F(t) = \frac{8}{\pi}\sum_{n=0}^{\infty}\sum_{m=1}^{\infty}\frac{(-1)^n}{2n+1}\cos\,(2n+1)\frac{\pi x}{2l}\,\frac{J_0(R_m r/a)}{R_m J_1(R_m)}e^{-\psi\alpha t}, \tag{2.68}$$

where

$$\psi = \frac{(2n+1)^2\pi^2}{4l^2} + \frac{R_m^2}{a^2}.$$

At the center point

$$F(t) = \frac{8}{\pi}\sum_{n=0}^{\infty}\sum_{m=1}^{\infty}\frac{(-1)^n}{2n+1}\frac{1}{R_m J_1(R_m)}e^{-\psi\alpha t}. \tag{2.69}$$

A slightly different form of this equation is given by Hurwicz and Tischer (1952).

For a can with infinite surface heat-transfer coefficient and initial temperature distribution $f(r, \theta, z)$, radius a and height $2b$, where z is any point on the height axis and r is any point on the radial axis, the equation takes the form given by Ball and Olson (1957), based on Olson and Jackson (1942) (see also Carslaw and Jaeger 1959):

$$\begin{aligned} F(t) = &\sum_{j=1}^{\infty}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\left[A_{jmn}\cos\,(n\theta) + B_{jmn}\sin\,(n\theta)\right] \\ &\times J_n\left(R_j r/a\right)\sin\left(\frac{m\pi}{2b}(z+b)\right)e^{-\psi'\pi t}, \end{aligned} \tag{2.70}$$

where

$$\psi' = \frac{m^2\pi^2}{b^2} + \frac{R_j^2}{a^2}$$

and A_{jmn} and B_{jmn} are factors depending upon the initial temperature distribution. For the center point $r = 0$

$$F(t) = A_{110} \sin\left(\frac{\pi(z+b)}{2b}\right) J_0(R_1 r/a) e^{-\psi'' \alpha t}, \tag{2.71}$$

where

$$\psi'' = \frac{\pi^2}{4b^2} + \frac{R_1^2}{a^2}$$

and

$$\begin{aligned} A_{110} = {} & \frac{2}{\pi^2 a^2 l \left[J_0'(R_n)\right]^2} \int_0^a R J_0(R_1 r/a) dr \int_{-b}^{+b} \sin\left(\frac{\pi(z+b)}{2b}\right) dz \\ & \times \int_{-\pi}^{+\pi} (\cos\theta) f(r,\theta,z) d\theta. \end{aligned} \tag{2.72}$$

For a can with finite surface heat-transfer coefficient and an initial constant temperature,

$$F(t) = \sum_{n=1}^{\infty} \sum_{m=1}^{\infty} A_{n,1} A_{m,2} J_0(R_{n,1} r/a) \cos(R_{m,2z}/l) e^{-\psi''\alpha t}, \tag{2.73}$$

where

$$A_{n,1} = \frac{2Bi_1}{J_0(R_{n,1})\left(R_{n,1}^2 + Bi_1^2\right)}$$

(for tables, see Luikov 1968, p. 273),

$$A_{m,2} = (-1)^{n+1} \frac{2Bi_2\left(Bi_2^2 + R_{m,2}^2\right)^{1/2}}{R_{m,2}\left(Bi_2^2 + Bi_2 + R_{m,2}^2\right)}$$

(for tables, see Luikov 1968, p. 224), $R_{n,1}$ and $R_{m,2}$ are the roots of the corresponding characteristic equations (for extended tables, see Hayakawa 1975; Peralta Rodriguez 1987b), and

$$\psi''' = \frac{R_{n,1}^2}{a^2} + \frac{R_{m,2}^2}{l^2}.$$

For cans with other boundary conditions, Table 2.4 lists a number of models which have been used to determine the temperature distribution in canned foods with a wide range of boundary conditions. The effect of variable surface temperature profiles, including various combinations of exponential and linear heating profiles for heating and cooling phases, has been dealt with analytically by Hayakawa (1964). The effect of air in the headspace has been analyzed by Evans and Board (1954).

In many solutions to heat transfer problems it has often been assumed that the solution for a solid body may be reasonably approximated by an infinite body. For example, Olson and Schultz (1942) considered that a length 4× the diameter of a cylinder or 4× the shortest dimension of a square rod would be sufficient to use the infinite geometry approximation. Erdogdu and coworkers have shown that the infinite assumption ratio depends on the Biot number (hd/k) and the above assumptions do not always hold, Turhan and Erdogdu (2003, 2004) and Erdogdu and Turhan (2006).

Other Geometrical Shapes of Container

A number of other shapes for containers are used, e.g., pear- or oval-shaped cans for fish products and tapered cans for corned beef and fish products. Table 2.5 lists the solutions to the heat transfer equation which have been obtained.

Smith et al. (1967) used a generalized temperature distribution model,

$$F(t) = Ce^{-M^2\theta}, \tag{2.74}$$

where C is a pre-exponential factor and M a general shape modulus given by

$$M^2 = G\pi^2, \tag{2.75}$$

in which G is the geometry index, which takes the value 1.000 for a sphere, 0.836 for a cylinder and 0.750 for a cube. A general formula for G is

$$G = 0.25 + 3C^{-2}/8 + 3E^{-2}/8, \tag{2.76}$$

where $C = R_s/(\pi a^2)$ and $E = R_1/(\pi a^2)$, in which R_s is the smallest cross-sectional area of the body which includes the line segment a, R_1 is the largest cross-sectional area of the body which is orthogonal to R_s. This approach has been discussed in detail by Hayakawa and Villalobos (1989) and Heldman and Singh (1980).

2.2.8.3 Heating and Cooling

While it is important to know the temperature distribution during heating and to establish an adequate *process* on this basis, it is also important to know what contribution the cooling phase makes in order to prevent overheating and to optimize the process for maximum quality retention. For smaller-sized cans the contents of the can reach the processing temperature during the heating period; however, for larger cans there is a temperature distribution within the can at the onset of cooling. In fact the temperature of the center point continues to rise for some time before the effect of the cooling of the outer layers is felt. This being so, it is necessary to know at what stage to commence cooling to achieve a satisfactory process. This can best be done by studying the equations which govern the heating and cooling process. The technique used is to derive an equation for the cooling period with an initial temperature distribution, and substitute the temperature distribution at the end of heating in this equation. A rigorous derivation of the equation for a cylindrical container has been given by Hurwicz and Tischer (1952).

The heating stage is represented by the equation

$$T = T_{\mathrm{R}} - (T_{\mathrm{R}} - T_0)F(t_{\mathrm{h}}), \tag{2.76a}$$

where t_{h} is the time for heating, T the temperature at time t at the center (or spatially distributed), T_{R} the retort temperature, i.e., process temperature, and T_0 the initial temperature of can contents. Heating followed by cooling is given by

$$T = T_{\mathrm{R}} - (T_{\mathrm{R}} - T_0)F(t) + (T_{\mathrm{C}} - T_{\mathrm{R}})(1 - F(t - t_{\mathrm{h}})), \tag{2.77}$$

where t is the total heating and cooling time, i.e., $t_{\mathrm{h}} + t_{\mathrm{c}}$, and T_{C} the temperature of the cooling water, assumed to be constant at the surface of the container. This equation has been used to study the location of the point of slowest heating by various workers: see Hicks (1951), Hayakawa and Ball (1969a), and Flambert and Deltour (1971, 1973a, b). It should be noted that if first-term approximation of the heat-transfer equation for the heating effect is used, it is less reliable to use the same for the cooling period. The first-term approximation is only applicable for determining the temperature after the long heating times and is not applicable to estimating the temperatures during the early stages of the cooling period. The latter require many terms in the summation series of the solution in order to obtain convergence.

In general, and especially for large sized containers, the temperature distribution at the end of heating is not uniform and therefore the condition of a uniform initial temperature does not apply.

2.2.8.4 Computer Programs for Analytical Heat Transfer Calculations

Newman and Holdsworth (1989) presented a number of computer programs in BASIC for determining the temperature distributions in objects of various geometric shapes. These were based on the analytical solutions for the case of infinite surface heat-transfer coefficients and applied essentially to the case of a finite cylinder and a parallelpiped. The programs also calculate the lethality of the process (see Part II Chap. 6). Thorne (1989) extended the range of available computer programs to the case of external heat-transfer coefficients. These programs operated under MS-DOS. A number of computer simulation programs used for engineering applications are given in Part II Chap. 11.

2.2.9 Heat Transfer in Packaged Foods by Microwave Heating

The applications of microwave heating in the food industry are numerous, and several processes, including tempering and thawing, have been developed commercially (Metaxas and Meredith 1983; Decareau 1985; Decareau and Peterson 1986). However, applications to the pasteurization and sterilization of food products are at present in the early stages of development.

The interaction of microwave energy and food products causes internal heat generation. The rapidly alternating electromagnetic field produces intraparticle collisions in the material, and the translational kinetic energy is converted into heat. For many food products the heating is uneven; the outer layers heat most rapidly, depending on the depth of penetration of the energy, and the heat is subsequently conducted into the body of the food. Current research is concerned with achieving uniform heating, especially in relation to pasteurization and sterilization of foods, where nonuniform heating could result in a failure to achieve a safe process. For materials that are electrical conductors—e.g., metals, which have a very low resistivity—microwave energy is not absorbed but reflected, and heating does not occur. Short-circuiting may result unless the container is suitably designed and positioned. Metallic containers and trays can effectively improve the uniformity of heating (George 1993; George and Campbell 1994). Currently most packages are made of plastic materials which are transparent to microwave energy.

The amount of heat generated in microwave heating depends upon the dielectric properties of the food and the loss factor (see below), which are affected by the food composition, the temperature and the frequency of the microwave energy. For tables of electrical properties of food, and discussion of their application, see Bengtsson and Risman (1971), Ohlsson and Bengtsson (1975), Mudgett (1986a, b), Kent (1987), Ryynänen (1995), and Calay et al. (1995).

Many mathematical models have been developed for microwave heating. The most basic are Maxwell's electromagnetic wave propagation equations. These are difficult to solve for many applications, and a simpler volumetric heating model involving the exponential decrease of the rate of heat generation in the product is used. The basic equation for this model is

$$q = q_0 e^{-x/\delta} \tag{2.78}$$

where q is volumetric heat generation (W m^{-3}), q_0 heat generated in the surface (W m^{-3}), x the position coordinate in the product, and δ the penetration depth based on the decay of the heating rate.

The general equation for the temperature distribution based on microwave heating and conduction into the product is

$$\partial T/\partial t = \nabla^2 T + q_0 e^{-x/\delta}. \tag{2.79}$$

The rate of heat generation is given by

$$q_0 = \pi f \varepsilon_0 \varepsilon'' \left| E^2 \right|, \tag{2.80}$$

where f is frequency (Hz), ε_0 the permittivity of free space (F m^{-1}), ε'' the dielectric loss, and $|E^2|$ the root-mean-square value of the electric field (V m^{-1}).

The penetration depth x in the product is obtained from the equation

$$x = \lambda_0 / \left[2\pi (\varepsilon' \tan \delta)^{1/2} \right]. \tag{2.81}$$

The term tan δ is the ratio of the dielectric loss ε'' to the dielectric constant ε', and is known variously as the loss tangent, loss factor, or dissipation constant. It is listed in tables of physical property data, e.g., Kent (1987).

The main frequency bands used are 2450 and 896 MHz in Europe and 915 MHz in the USA. Greater penetration and more uniform heating are obtained at the longer wavelengths for food products with low loss factors.

Datta and Liu (1992) have compared microwave and conventional heating of foods and concluded that microwave heating is not always the most effective method, especially for nutrient preservation. The effect depends on a variety of properties of the system.

Burfoot et al. (1988) examined the microwave pasteurization of prepared meals using a continuous tunnel device. The product was heated to 80–85 °C for a few minutes, sufficient to inactivate vegetative pathogenic bacteria, e.g., Salmonella and Campylobacter, but not bacterial spores. The latter are controlled by storing the product below 10 °C. This type of product is not shelf-stable at room temperature and a full sterilization process would be necessary with low-acid products of this type to obtain a stable product. Microwave tunnels for this purpose would have to be pressurized to maintain the integrity of the package when sterilizing temperatures (121 °C) had been achieved. A general-purpose plant known as Multitherm has been developed by AlfaStar Ab, Tumba, Sweden (Hallström et al. 1988). Burfoot et al. (1996) have modeled the pasteurization of simulated prepared meals in plastic trays with microwaves. Large differences between actual and predicted temperatures were found at some points.

For measuring temperatures in microwave systems an invasive fiber-optic probe has been developed, which uses the change in color with temperature of a crystal situated at the end of a glass fiber. Fluoroptic probes are manufactured by Luxtron Corp., CA, USA.

2.2.10 Dielectric Heating

Dielectric heating is performed at radio frequencies of 13.56, 27.12, or 40.68 MHz. This distinguishes from microwave heating, which uses ≅900 or 2450 MHz (Rowley 2001). Wang et al. (2004) have emphasized the advantage of the volumetric heating characteristics of dielectric heating, especially for heating sealed polymeric and pouches. In a study on the heating of 6 lb capacity polymeric trays filled with whey protein gels, the production of M-1 (see Sect. 6) was used as a chemical marker to determine the degree of lethality and cooking value achieve by RF dielectric heating and steam.

2.3 Heat Transfer by Convection

2.3.1 Introduction

Convective heat transfer inside containers results either from the natural effects of changes in density in the liquid induced by changes in temperature at the container walls (free or natural convection) or by creating motion in the container contents by axial or end-over-end rotation (forced convection).

The process of natural convection initially involves heat transferred by conduction into the outer layers of fluid adjacent to the heated wall; this results in a decrease in the density, and the heated fluid layer rises. When it reaches the top of the liquid at the headspace, the induced fluid motion causes it to fall in the central core, the displaced hot fluid at the wall being replaced by colder fluid in the core. As the temperature of the can contents becomes more uniform and the driving force smaller, the fluid velocity tends to decrease and eventually, when the fluid becomes uniformly heated, the motion ceases.

The mechanism can also be represented by an initially thin boundary layer of liquid in which the fluid is rising, the thickness of which increases as the process continues. According to experimental investigations by Datta and Teixeira (1988), after 30 s heating the thickness of this layer was 2 mm and the temperature drop from the can wall to the boundary layer edge was from 121 to 45 °C.

With more viscous fluids the process is somewhat slower, although the viscosity and the density are, in general, reduced by a rise in temperature. There will also be an increase in the conductive component with thicker fluids. Ball and Olson (1957) devised a qualitative method of determining the intensity of convection currents in containers based on the ratio of the conductive to convective heat transfer components. This situation should not be confused with the following phenomenon.

For both pure convection and pure conduction heating in canned foods the "heating curve" plot of the logarithm of the reduced temperature against time is more or less linear, after an initial lag period (see Part III Chap. 6). However, for some products the plot shows two lines with differing slope, known as a "broken heating curve". Products showing this type of effect usually start as convective heating packs, but due to physicochemical changes, e.g., starch gelation, they finally heat by a highly conductive mechanism.

Convection currents inside a container can be visualized, in an idealized form, as shown in Fig. 2.5. In the upper part of the container the hot liquid is being pumped

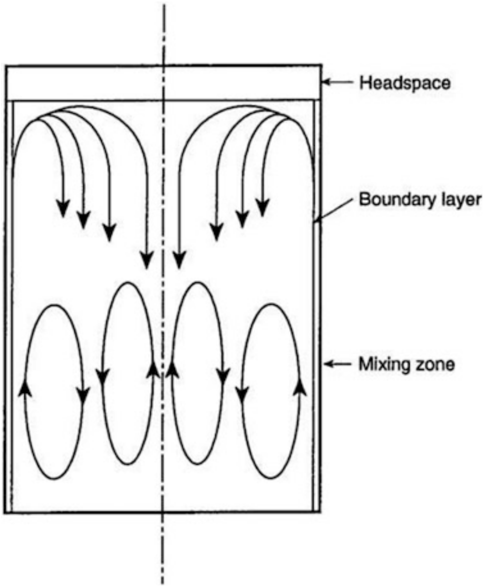


Fig. 2.5 Idealized representation of convection currents in a can of liquid

by the heated fluid rising in the boundary layer, and being placed on the cold liquid in the core. Simultaneously, in the case of a vertical container, there is also heat rising from the bottom end of the can, which produces mixing eddies in the bulk of the fluid. Datta (1985) has shown that as result of instabilities in the temperature distribution, regular bursts of hot liquid occur on the base of the container. This phenomenon is known as Bernard convection.

The mechanism of unsteady-state convection is very complex and varies with time of heating and/or cooling; consequently it is very difficult to model precisely. Hiddink (1975) used a flow visualizing technique with metallic powders in liquids in containers with light-transmitting walls, to highlight the streamlines in the bulk of the fluid. Other workers, e.g., Blaisdell (1963), have used thermocouples at several points in the containers to plot the temperature profiles.

Guerrei (1993) has discussed the internal flow patterns in convection-heating bottles of cylindrical and square shape, using the concept of a double-layer system of rising hot liquid on the wall of the container which discharge into a central volume. The point-of-slowest-heating was shown to be 0.006 m from the wall of an 0.06 m internal diameter container.

The most important point, from a practical safety point of view, is where the slowest heating point is situated. This subject is dealt with in Chap. 6.

While the discussion has been concerned with convection heating/cooling inside containers, there is also the problem of convection heating on the outside, from the heating or cooling medium to the container wall. In the case of pure steam heating, condensation of steam on the container wall surface raises the temperature of the surface almost immediately to that of the steam and, consequently, no problem arises. If, however, the steam contains air, either as an adulterant or intentionally, then the velocity of the mixture over the surface will affect the temperature of the surface and a more complex situation will arise. Similarly, if water is used for heating, and also for cooling, then the wall temperature will be affected by the velocity of the heat transfer medium. In all cases, except for condensing pure steam, it is necessary to consider external convective heat transfer to the outer surface of the container.

2.3.2 Basic Concepts in Convection Heat Transfer

Mathematical models for the prediction of temperatures in the heating of canned foods by convection are necessary in order to determine the process requirements. However, they are much less easy to obtain than in the case of heating by conduction. There are three approaches to convective heat transfer: the film theory; the use of dimensionless numbers; and the more rigorous mathematical treatment of the basic fluid dynamic and heat transfer models. Reviews of this subject have been presented by Ball and Olson (1957), Holdsworth and Overington (1975), Rao and Anantheswaran (1988), as well as in various theses, e.g., Blaisdell (1963), Stevens (1972), Hiddink (1975), and Zechman (1983).

2.3.2.1 Film Theory

The basic heat transfer equation for convection is

$$Q = h_s A(T_b - T_s), \tag{2.82}$$

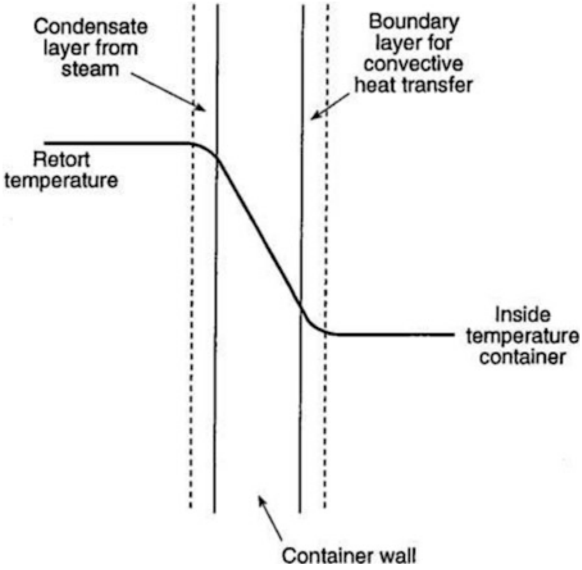
where Q is the quantity of heat flowing (J s^{-1}), h_s is the surface heat-transfer coefficient (W m^{-2} K^{-1}), A is the surface area (m^2), T_b is the bulk fluid temperature (K), and T_s is the surface temperature.

The idealized temperature profile for a material being heated by a fluid and separated by a container wall is shown in Fig. 2.6. On either side of the wall boundary layers or films may be visualized, through which the bulk of the temperature drop takes place. Thus if T_1 is the temperature of the heating medium and T_4 is the temperature in the bulk of the fluid being heated, and the average film temperatures are T_2 and T_3, then an overall heat-transfer coefficient U (alternatively denoted by H) can be defined as follows

$$Q = UA(T_1 - T_4), \tag{2.83}$$

where

Fig. 2.6 Temperature profile across container wall



$$\frac{1}{U} = \frac{1}{h_s} + \frac{x_w}{k_w} + \frac{1}{h_b}, \tag{2.84}$$

and h_s and h_b are the heat-transfer coefficients for the surface being heated and the bulk of the fluid, x_w is the thickness of the wall (m), and k_w is the thermal conductivity of the wall material (W m^{-1} K^{-1}).

Some typical values for h_s (W m^{-2} K^{-1}) are: steam, 12,000; steam + 3% air, 3500; steam + 6% air, 1200; cold water, 500; air moving at 3 m s^{-1}, 30; still air, 6. From these values it can be seen that the resistance to heat transfer, the reciprocal of the heat transfer coefficient, is extremely small for condensing steam; consequently this can be ignored in all heat transfer calculations.

Some values for the thermal conductivities of container materials (W m^{-1} K^{-1}) are: ferrous metal containers, 40–400; aluminum, 220; glass, 1–2; polyvinylchloride, 0.29; polyethylene, 0.55; water, 0.57. From these values it can be seen that it may be necessary, when using container materials other than metals, to consider the x_w/k_w term in the overall heat transfer equation.

2.3.2.2 Correlations for Predicting Heat-Transfer Coefficients

Engineering practice makes use of dimensionless numbers for correlating heat-transfer coefficients with the physical circumstances of heat transfer and the physical properties and flow conditions of the fluids involved. The four dimensionless numbers used in heat transfer studies are:

(a) Reynolds number, used for flow characterization,

$$Re = vd\rho/\mu;$$

(b) Nusselt number, ratio of the heat transferred by convection to that transferred by conduction,

$$Nu = hd/k;$$

(c) Prandtl number, influence of physical properties

$$Pr=c\rho/k;$$

(d) Grashof number, influence of buoyancy forces in natural convection

$$Gr = d^3\rho^2\beta g\Delta T/\mu^2;$$

(e) Rayleigh number, product of Grashof and Prandtl numbers

$$Ra = Gr \cdot Pr$$

where

c = specific heat at constant pressure (J kg^{-1} K^{-1});
d = characteristic linear dimension—thickness, length, or diameter, as appropriate (m);
g = gravitation constant (m s^{-2});
h = heat-transfer coefficient (W m^{-2} K^{-1});
k = thermal conductivity (W m^{-1} K^{-1});
T = temperature difference (K);
v = velocity (m s^{-1});
β = coefficient of thermal expansion (K^{-1});
μ = dynamic viscosity (Pa s);
ρ = density (kg m^{-3}).

For example, for forced convection we have the correlation

$$Nu = A(Re)^a(Pr)^b.$$

For gas flow across cylinders, with Re in the range 10^3–10^5, values of $A = 0.26$, $a = 0.60$ and $b = 0.30$ have been obtained. For liquids, with Re between 4×10^3 and 4×10^4, we have $A = 0.193$, $a = 0.618$ and $b = 0.333$. For natural convection, the relationship is

$$Nu = A(Pr)^c(Gr)^d.$$

For horizontal or vertical cylinders with streamline flow and $Re < 2100$, values of $A = 0.47$ and $c = d = 0.25$ have been obtained. With turbulent flow and $Re > 10000$, we have $A = 0.10$, and $c = d = 0.33$. All the fluid properties are measured at the mean film temperature $1/2(T_w + T_b)$, where the subscripts b and w to the temperature refer to the bulk fluid and the wall respectively.

Several other dimensionless numbers are encountered in heat transfer studies and these are defined where appropriate.

Since the numerical values for the indices and coefficients are determined from experimental results, it is unwise to use dimensionless correlations outside the ranges for which the experimental results have been obtained. Extrapolation of the data requires careful consideration.

For methods of deriving dimensionless correlations and for further information on different applications, the standard engineering texts should be consulted, e.g., Burmeister (1983), Coulson and Richardson (1985), Hallström et al. (1988), Jaluria (1980), and Perry and Green (1984).

2.3.3 Models for Convection Heat Transfer

Some of the models that have been used to predict temperature distributions and velocity profiles in heated and cooled can liquid products are shown in Tables 2.6–2.9.

The models may be classified as follows:

2.3.3.1 Energy Balance Model

This is the simplest of the models; it was first proposed by Jones (1931) and subsequently used by many other workers. It is often known as the Schultz–Olson model in recognition of the contribution of the American Can Company workers (Schultz and Olson 1938).

By equating the overall rate of heat transfer into the can with the rate of accumulation of heat inside the can, an energy balance equation can be established. For the heat transfer into the can,

$$Q = UA(T_\mathrm{s} - T_\mathrm{m}), \tag{2.85}$$

and the rate of accumulation of heat

$$Q = mc\frac{dT}{dt}, \tag{2.86}$$

where

Q = rate of heat transfer (W);
U = overall heat-transfer coefficient (W m^{-2} K^{-1});
A = surface area (m^2);

Table 2.6 Some studies on convection heat transfer for non-agitated homogeneous canned foods

Product	Process	Model	Comments	Reference
Water	100 °C: No. 2 and No. 3 cans	Energy balance	Film model	Jones (1931)
Water	Cooling: No. 2 and No. 3 cans	Energy balance	Newton's law	Jones (1932)
Water	100 °C: 1 lb tall glass	Conduction (modified)	Apparent thermal diffusivity	Tani (1938b)
Water	100 °C: 1 lb tall glass	Navier–Stokes equation	Dimensionless; data from Tani	Okada (1940b)
Water/aluminum powder	100° C: 1 lb glass, two sizes	Energy balance	Flow visualization	Ban and Kaziwara (1941)
Ideal fluid ($Pr = 1$)	Heating and cooling	Navier–Stokes equation	Analytical solution	Hammitt and Chu (1962)
Water/glycerol, butanol, methanol	100 °C: 2″ and 2.5″ d cylinders	Energy balance	Dimensionless groups, heat transfer coefficients	Evans and Stefany (1966)
Water	Heating: closed container	Semiempirical model	Turbulent free convection	Tatom and Carlson (1966)
Ideal fluid	Heating: closed container	Navier–Stokes equation	Laminar natural convection	Barakat and Clark (1966)
Water and glycerol	Heating: cylinder	Energy balance	Mixing/main core study	Evans et al. (1968)
Water/sucrose solution	<83 °C: 8–22 oz glass jars	Navier–Stokes equation	Dimensionless groups, flow visualization	Blaisdell (1963)
Ethylene glycol	100 °C:401 × 411 can	Navier–Stokes equation	Velocity and temperature profiles	Stevens (1972)
Water and sucrose solution	100 °C: 300 × 410 can	Energy balance	Rayleigh nos v. temperature	Jowitt and Mynott (1974)
Water and siliconc fluid	115 °C: half cylinder	Energy and stratification	Flow visualization	Hiddink (1975), Hiddink et al. (1976)
Water	100 °C: 3 kg can 156 × 150 mm	Energy balance	Temperature distribution	Miglioli et al. (1983)
Beer	100 °C: bottle	Finite-element model (CFD)	Temperature/velocity profiles	Engelman and Sani (1983)
Water	121 °C: 303 × 406 can	Navier–Stokes equation	Temperature/velocity profiles	Datta and Teixeira (1987, 1988)
Water, xanthan gum, oils	120 °C: 300 × 401 can	Conduction (modified)	Apparent thermal diffusivity	Bera (1988)
Water/CMC	121 °C: 81 × 111 mm can	Finite volume model (CFD)	Temperature distributions	Ghani et al. (1999a, b)

(continued)

Table 2.6 (continued)

Product	Process	Model	Comments	Reference
Liquid	121 °C: 4 × 12 × 22 cm pouch	Finite volume model (CFD)	Temperature distributions	Ghani et al. (2002)
Starch/water	121 °C: 303 × 406 can	Fluid dynamics analysis	Viscosity study of gelation	Yang and Rao (1998)
3.5 % corn starch/water	121 °C: 303 × 406 can	2D-finite element	Energy balance	Tattiyakul et al. (2001, 2002a)
3.5 % starch/water	110–121 °C: 162 × 111 mm can	2D-finite element	Energy balance	Tattiyakul et al. (2002b)
5 % waxy maize starch/water	110–121 °C: 162 × 111 mm can	2D-finite element	Energy balance	Tattiyakul et al. (2002b)
5.6° Brix tomato juice	110–121 °C: 162 × 111 mm can	2D-finite element	Energy balance	Tattiyakul et al. (2002b)
5 % Tomato paste solids	121 °C: cans	Distributed parameter model	Energy balance	Bichier et al. (1995)
Carrot/orange soup	121 °C: can	Finite volume model (CFD)	Velocity/temperature profiles	Ghani et al. (2002)
Carrot/orange soup	121 °C: 4 × 12 × 22 cm pouch	Finite volume model (CFD)	Temperature distributions	Ghani et al. (2001a, b)
Carrot/orange soup	121 °C: 72 × 106 mm can	CFD PHOENICS	Temperature/flow profile	Ghani et al. (2001a, b); Ghani et al. (2002)
Tomato dip product	Holding 90 °C and cooling 70, 50, 20 °C: 690 g jars	Finite difference	Temperature distribution	Plazl et al. (2006)
Non-Newtonian simulant	121 °C: 303 × 406 can	Finite-element model (CFD)	Temperature/velocity profiles	Kumar et al. (1990) Kumar and Battacharya (1991)
Non-Newtonian, CMC/water	125 °C: 75 × 115 mm	CFD; CFX-4	Transient natural convection	Quarini and Scott (1997)
CMC. 0.85 % w/w	121 °C: 307 × 408 and conical can	Finite element model (CFD)	Temperature/velocity profiles	Varma and Kannan (2006)

T_s = temperature of the heating medium (K);
T_m = temperature of the product (mass average) (K);
c = specific heat (J kg^{-1} K^{-1});
t = time (s);
m = mass (kg).

Equating the left-hand sides of (2.85) and rearranging we obtain:

$$\frac{mc}{A}\frac{dT}{T_s - T_m} = U\,dt. \tag{2.87}$$

Table 2.7 Some studies on convection heat transfer for agitated homogeneous canned foods

Product	Process	Model	Comments	Reference
Sucrose solution, juices and fruit purées	Spin-cooker/cooler 98 °C: axial rotation 300 × 406; 401 × 411; 604 × 614 cans	Energy balance	Heat transfer coefficients	Quast and Siozawa (1974)
Silicone oil	Laboratory device 120° C: axial and end-over-end	Energy balance	Heat-transfer coefficients – duration of a transfer unit	Bimbenet and Michiels (1974)
Water and sucrose solution	FMC Steritort 121 °C: axial rotation 303 × 406; 608 × 700	Energy balance	Temperature profiles, heat-transfer coefficients	Lenz and Lund (1978)
Aqueous and organic liquids	Hydrolock pilot sterilizer 130 °C: end-over-end 54 × 90; 73 × 52; 73 × 107; 99.4 × 111.2 mm cans	Energy balance	Heat-transfer coefficients, surface tension consideration	Duquenoy (1980, 1984)
Glucose syrup 84° brix	Stork simulator; various modes 125 °C: 105 × 112 mm can	Energy balance modified for process deviations	Heat-transfer coefficients	Naveh and Kopelman (1980)
Water, glycerol and sucrose solutions 30, 50 and 60 %	Agitating sterilizer 100 °C: 303 × 406 can; end-over-end	Energy balance	Heat-transfer coefficients, dimensionless analysis	Anantheswaran and Rao (1985a)
3.5 % corn starch/ water	FMC Steritort. Intermittent agitation 121 °C: 303 × 406 can	Energy balance	2D-finite element	Tattiyakul et al. (2001, 2002a)
3.5 % starch/water	FMC Steritort: 110–121 °C: 162 × 111 mm can	Energy balance	2D-finite element	Tattiyakul et al. (2002b)
5 % waxy maize starch/water	FMC Steritort: 110–121 °C: 162 × 111 mm can	Energy balance	2D-finite element	Tattiyakul et al. (2002b)
5.6° Brix tomato juice	FMC Steritort: 110–121 °C: 162 × 111 mm can	Energy balance	2D-finite element	Tattiyakul et al. (2002b)
5 % Tomato paste solids	FMC Steritort: 5 rpm: 121 °C: cans	Energy balance	Distributed parameter model	Bichier et al. (1995)
Aqueous solution guar gum, various conc.	Agitating sterilizer 100 °C: 303 × 406 can; end-over-end	Energy balance	Heat-transfer coefficients, dimensionless analysis	Anantheswaran and Rao (1985b)

(continued)

Table 2.7 (continued)

Product	Process	Model	Comments	Reference
Water, silicone oil	Rotary simulator 100° C: axial rotation 303 × 406; 401 × 411; 404 × 700 cans	Energy balance	Heat-transfer coefficients	Soule and Merson (1985)
Aqueous solution guar gum	Rotary device/batch retort 121 °C; end-over-end; 303 × 406 can	Energy balance	Heat-transfer coefficients	Price and Bhowmik (1994)

Table 2.8 Some studies on convection heat transfer for non-agitated heterogeneous canned foods

Product	Process	Model	Comments	Reference
Glass spheres/water/silicone fluid	115 °C: half cylinder	Fluid dynamic model	Temperature distribution	Hiddink (1975)
Bamboo shoots, sausages, baby clams, mushrooms/liquid	JCS Nos. 1, 2, 4 and 7 cans	f_h and j model	Heat penetration data	Ikegami (1977)
Mushroom-shaped aluminum, mushrooms	115.6–126.7 °C: 211 × 212 can	Energy balance	Heat transfer coefficients, effect of temperature and particle size	Sastry (1984)
Aluminum, PTFE and potato spheres/liquids	100 °C: see Hassan (1984)	Energy balance–particles/liquids	Heat transfer coefficients	Rumsey (1984)
Mushroom-shaped aluminum in water	80 °C: heating bath	Energy balance	Heat transfer coefficients	Alhamdan et al. (1990)
Mushroom-shaped aluminum in carboxymethylcellulose	80 °C: heating bath	Energy balance	Dimensionless correlations	Alhamdan and Sastry (1990)
Mushrooms/brine	121 °C: pilot retort Omnia jars 0–8	Energy balance–thermal inertia	Temperature profile	Akterian (1995)
Fruits in syrup	93.3 °C: retort; Omnia jars 105 mm diam	Empirical model	f_h and heat-transfer coefficients	Akterian (1996)
Vegetables in brine	121 °C: retort; Omnia 105 mm diam	Empirical model	f_h and heat-transfer coefficients	Akterian (1996)
Food particles/CMC	Cans	Energy balance	Surface heat-transfer coefficients	Awuah et al. (1993)

Table 2.9 Some studies on convection heat transfer for agitated heterogeneous canned foods

Product	Process	Model	Comments	Reference
Silicone oil, sausage	Laboratory device, 120 °C: axial and end-over-end	Energy balance and particle conduction	Heat-transfer coefficients – duration of transfer unit	Bimbenet and Michiels (1974)
Water and sucrose solution, peas and lead shot	FMC Steritort, 121 °C: axial rotation 303 × 406; 608 × 700 can	Energy balance and particle conduction	Temperature profiles – heat-transfer coefficients	Lenz and Lund (1978)
Potatoes/water	Stock Pilot Rotor-900, 121 °C: end-over-end 307 × 409 cans	Energy balance and particle conduction	Effect of size distribution and surface heat transfer	Lekwauwa and Hayakawa (1986)
Water, silicone fluid, PTFE, aluminum, potato	Rotary single can simulator, 50 °C: axial rotation	Energy balance and particle conduction	Analytical solution, heat-transfer coefficients	Deniston et al. (1987), Stoforos (1988), Merson and Stoforos (1990)
Spheres	303 × 406 can			Stoforos and Merson (1990, 1992)
Water, sucrose solution, raw snap beans and aluminum	FMC Steritort, 115.6 °C: axial rotation 303 × 406	Energy balance and particle conduction	Heat-transfer coefficients – dimensionless correlation	Fernandez et al. (1988)
Sucrose syrup/particles	100 × 119 mm cans; axial rotation; ambient temperature	Position emission particle tracking	Head space and mixing study	Cox et al. (2003)
Spheres, cylinders, cubes/liquid	Stock Rotomat-PR 900	Flow visualization	Heat-transfer coefficients-mixing studies	Sablani and Ramaswamy (1998)
Nylon spheres/water and /oil	Stock Rotomat-PR 900	Experimental correlations	Heat-transfer coefficients- influence of particle size and concentration	Sablani and Ramaswamy (1997)
Polypropylene spheres/water	110–130 °C: full immersion water sterilizer	Experimental correlations	Heat-transfer coefficients; effect of head space	Sablani and Ramaswamy (1996)
Spheres, cylinders, cubes/liquid	Stock Rotomat-PR 900	Flow visualization	Heat-transfer coefficients and mixing studies	Sablani and Ramaswamy (1993, 1998)
Potato shape 7 aluminum spheres	Axial rotation	Energy balance and particle conduction	Heat-transfer coefficients and 4th order Runge–Kutta model	Stoforos and Merson (1992, 1995)

Integrating,

$$\int_{T_0}^{T_\mathrm{m}} \frac{mc}{A}\frac{dT}{T_\mathrm{s}-T_\mathrm{m}} = \int_0^t U\,dt. \tag{2.88}$$

leads to

$$\log_\mathrm{e}\frac{(T_\mathrm{s}-T_\mathrm{m})}{(T_\mathrm{s}-T_0)} = \frac{UA}{mc}t \tag{2.89}$$

or

$$T_\mathrm{m} = T_\mathrm{s} - (T_\mathrm{s}-T_0)e^{-[(UA/mc)]t} \tag{2.90}$$

This equation shows that the rate of heating is an exponential function, which depends on the overall heat-transfer coefficient U (or the internal heat-transfer coefficient h_int when steam is used as the heating medium with metallic cans), the surface area A, the mass of the contents and their specific heat, as well as the temperature of the heating medium and the initial temperature of the contents T_0.

This approach has been modified by Videv (1972) and applied by Akterian (1995) to a range of canned and bottled foods heating by convection. Their approach uses the concept of thermal inertia E for the term mc_p/UA. This characterizes the temperature lag between the liquid temperature and the heating medium. The theoretical treatment has been extended to the case of an external linear heating profile (Videv 1972). The variation in heat transfer rate into canned products has been discussed theoretically by Dincer et al. (1993).

Slow Come-Up Time with Perfect Mixing

Equation (2.91) has been derived from Eq. (2.87), solving an ordinary differential equation and assuming a linear retort temperature profile (i.e., simulating temperature profile during come-up time) (Simpson et al. 2003).

$$\begin{aligned} T_\mathrm{m} &= a\left(1-\exp\left(-\frac{UA}{mc}t\right)\right) + b\left(t-\frac{mc}{UA}\right) + b\frac{mc}{UA}\exp\left(-\frac{UA}{mc}t\right) \\ &\quad + T_0\exp\left(-\frac{UA}{mc}t\right) \end{aligned} \tag{2.91}$$

where retort temperature is time dependent and expressed as: $T_\mathrm{S}(t) = a + bt$ and Eq. (2.91) is valid for: $0 < t \leq CUT$. For $t > CUT$, temperature T (or T_m) can be expressed by Eq. (2.89) using an appropriate initial temperature (constant T_S).

Provided that f_{h} is defined as ln 10 × [MCp/UA] (Merson et al. 1978), Eq. (2.91) can be rearranged and expressed as:

$$T_{\mathrm{m}} = (a + bt) - b\frac{f_{\mathrm{h}}}{\ln 10} + \left(-a + b\frac{f_{\mathrm{h}}}{\ln 10} + T_0\right)\exp\frac{-t\ln 10}{f_{\mathrm{h}}} \tag{2.92}$$

Further working on Eq. (2.92) renders:

$$\frac{T_{\mathrm{m}} - (a + bt) + b\,\frac{f_{\mathrm{h}}}{\ln 10}}{\left(-a + b\,\frac{f_{\mathrm{h}}}{\ln 10} + T_0\right)} = \exp\frac{-t\ln 10}{f_{\mathrm{h}}} \tag{2.93}$$

From Eq. (2.93), the dimensionless temperature ratio can be expressed as:

$$\frac{T_{\mathrm{m}} - (a + bt) + b\left(\frac{f_{\mathrm{h}}}{\ln 10}\right)}{T_0 - a + b\left(\frac{f_{\mathrm{h}}}{\ln 10}\right)} = \frac{T'_{\mathrm{m}} - \left(a' + b't\right) + b'\left(\frac{f_{\mathrm{h}}}{\ln 10}\right)}{T'_0 - a' + b'\left(\frac{f_{\mathrm{h}}}{\ln 10}\right)} = \text{Constant} \tag{2.94}$$

2.3.3.2 Effective Thermal Diffusivity Model

This model, first discussed by Thompson (1919), makes use of the unsteady-state conduction model solutions and an apparent or effective thermal diffusivity. Thompson found that this depended on the ratio of solids to liquid in the container. Tani (1938b) also used this approach to studying the temperature profiles in heated 1 lb tall cans filled with water. More recently, Teixeira et al. (1992) have used a similar method with the *j*-value concept (see Chap. 6). Early Japanese work was discussed by Olson (1947).

2.3.3.3 Transport Equation Model

This is the most rigorous approach to determining the temperature distributions and the velocity profiles in containers filled with liquids. The early work in this area was reviewed by Ede (1967) and particularly useful work was reported by Evans and Stefany (1966) and Evans et al. (1968). The form of the equations depends on the geometry of the container; care should be taken to use the most appropriate coordinate system (Bird et al. 1960; Ruckenstein 1971).

The equations which have to be solved in relation to the container boundaries are the equation of continuity:

$$\frac{1}{r}\frac{d}{dr}(r\rho v) + \frac{d}{dz}(\rho u) = 0; \tag{2.95}$$

the equation of momentum in the radial direction:

$$\rho\left(\frac{du}{dt}+v\frac{du}{dr}+u\frac{du}{dz}\right)=-\frac{dP}{dz}+\mu\left\{\frac{1}{r}\frac{d}{dr}\left(r\frac{d\mu}{dr}\right)+\frac{d^2\mu}{dz^2}\right\}+\rho g; \tag{2.96}$$

the equation of momentum in the radial direction:

$$\rho\left(\frac{dv}{dt}+v\frac{du}{dr}+u\frac{du}{dz}\right)=-\frac{dP}{dz}+\mu\left\{\frac{d}{dr}\left(\frac{1}{r}\frac{d}{dr}(rv)\right)+\frac{d^2v}{dz^2}\right\}; \tag{2.97}$$

and the energy equation to determine the temperature distribution:

$$\frac{dT}{dt}+v\frac{dT}{dr}+u\frac{dT}{dz}=\frac{k}{\rho c_{\mathrm{p}}}\frac{1}{r}\frac{d}{dr}\left(r\frac{dT}{dr}\right)+\frac{d^2T}{dz^2}. \tag{2.98}$$

The boundary conditions required for the solution are, for the side wall,

$$r=R,\quad 0<z<H,\quad T=T_1,\quad u=0,\quad v=0;$$

for the center line,

$$r=0,\quad 0<z<H,\quad dT/dr=0,\quad du/dr=0;$$

for the bottom wall,

$$0<r<R,\quad z=0,\quad T=T_1,\quad u=0,\quad v=0;$$

and for the top wall,

$$0<r<R,\quad z=H,\quad T=T_1,\quad u=0,\quad v=0.$$

The initial conditions are that the fluid is at rest and at a uniform temperature:

$$0<r<R,\quad 0<z<H,\quad T=T_0,\quad u=0,\quad v=0.$$

Numerical solutions for these equations have been attempted (see Table 2.6). The work of Datta (1985) and Datta and Teixeira (1987, 1988) represents the most advanced approach at the present time.

2.3.4 Some Experimental Work and Correlations

Here some of the experimental work to determine internal heat-transfer coefficients are considered. Both homogeneous and heterogenous products heated in static and rotary retorts are mentioned. Tables 2.6–2.9 give further references to work in this area.

2.3.4.1 Homogeneous Products Heated in Batch Systems

Much of the early work on heat penetration into cans of liquid products was aimed at determining the time–temperature profiles. Jones (1931) was one of the first workers to apply a simple model to determine temperature profiles in canned liquid products. Blaisdell (1963) made an extensive survey of the literature and carried out experimental work on the heating of a 50 % sucrose solution in glass jars of varying sizes. The results were correlated using the heat penetration parameters f_{h} and j (see Chap. 6). Evans and Stefany (1966), using a range of liquids, obtained a simple correlation for predicting internal heat-transfer coefficients,

$$Nu = 0.55(Gr \cdot Pr)^{0.25},$$

using the length of the container as the characteristic length. Hiddink (1975), in a similar study, obtained a correlation

$$Nu = 0.31(Gr \cdot Pr)^{0.268}.$$

Verboven et al. (2004) have described various applications of CFD to optimizing thermal processes and have given details of the techniques used in various applications.

Further work is listed in Table 2.6.

2.3.4.2 Homogenous Systems Heated with Agitation

Many products are now processed in retorts (see Chap. 17) that impart either axial or end-over-end motion to the container contents. By choosing a suitable headspace it is possible to increase the rate of heat transfer and thereby reduce the time required for processing. The success of this type of process depends on the suitability of the product and careful control of the headspace during the filling operation. Table 2.7 gives some examples of the types of correlation which have been applied to the estimation of heat-transfer coefficients. Some important studies have been carried out, from which quantitative correlations for heat-transfer coefficients have been obtained. Some of these are now discussed briefly; however, other matters relating to external heat-transfer coefficients from the heating medium are dealt with in Chap. 17.

Naveh and Kopelman (1980) studied a variety of rotational modes, based on end-over-end and axial rotation modes, some in off-set positions, using 105 × 112 mm containers of glucose syrup 84° brix. A modified energy balance model was used to determine the overall heat-transfer coefficient, using a modified energy balance model, as follows:

$$U = \frac{1}{n}\sum_{i=1}^{n} \frac{mc_{\mathrm{p}}}{At_i} \log\left(\frac{T_{\mathrm{R}} - T}{T_{\mathrm{R}} - T_0}\right)_i \tag{2.99}$$

where U is the average momentary overall heat-transfer coefficient, taken at intervals of time t_i, m is the mass of can and contents, c_p is the specific heat of the product, A is the surface area for heat transfer, T is the temperature of the food, T_R is the retort temperature, and T_0 is the initial temperature of the product.

Duquenoy (1980, 1984) determined heat-transfer coefficients for cans containing a range of aqueous and organic liquids agitated in end-over-end mode. The correlation obtained included a dependence on surface tension of the liquid as well as filling ratio.

Anantheswaran and Rao (1985a) determined heat-transfer coefficients for end-over-end can rotation for a range of Newtonian fluids in 303 × 406 cans. They obtained the correlation:

$$Nu = 2.9Re^{0.436}Pr^{0.287}, \tag{2.100}$$

where $Nu = h_\mathrm{i}d_\mathrm{r}/k,\ Re{=}d_\mathrm{r}^2N\rho/\mu$ (rotational), and $Pr = \mu/k$, in which d_r is the diameter of rotation, and N the speed of rotation (s^{-1}).

The correlation was not improved by trying to incorporate natural convection effects, length to diameter ratio, or headspace volume. The arithmetic average heat-transfer coefficient was determined from instantaneous heat-transfer coefficients by integration of the basic energy equation.

Subsequently these workers (Anantheswaran and Rao 1985b) reported experimental work using non-Newtonian fluids (guar gum of various concentrations) and obtained a general correlation:

$$Nu = 1.41GRe^{0.482}GPr^{0.355}, \tag{2.101}$$

where the generalized Reynolds GRe and Prandtl GPr numbers were obtained using the non-Newtonian apparent viscosity term $(8/N)^{n-1}\ K[(3n+1)4n]^n$ in place of the viscosity term. N is the rotational speed (s^{-1}). It was found that other factors, e.g., can length to diameter ratio and the flow index, had no statistically significant influence on the heat-transfer coefficient.

Soule and Merson (1985) obtained an overall heat transfer correlation for axial rotation of cans filled with water and silicone oils of varying viscosity. They found a dependency on both the can dimension ratio L/D and the viscosity ratio $\mu b/\mu_\mathrm{w}$, where the subscripts b and w refer to the viscosities evaluated at the average bulk temperature and can wall temperature, respectively, taken over the whole process. Their correlation is:

$$Nu = 0.434Re^{0.571}Pr^{0.278}(L/D)^{0.3565}(\mu_\mathrm{b}/\mu_\mathrm{w})^{0.154}. \tag{2.102}$$

The average internal heat-transfer coefficient, h_i, was estimated from the overall coefficient, U, from the following equation:

$$h_\mathrm{i} = (1.07 \pm 0.04)U. \tag{2.103}$$

Datta and Teixeira (1987, 1988) solved the basic fluid flow and heat transfer equations numerically. The solution compared well, both qualitatively and quantitatively, with the available experimental data. The fluid flow patterns revealed liquid rising at the wall because of the buoyancy of the heated boundary layer, radial flow and mixing at the top of the liquid and uniform core flow near the axis.

Kumar et al. (1990) used a finite-element technique and computational fluid dynamics to study the flow of a thick viscous liquid heated in cans. The liquid had non-Newtonian flow characteristics and obeyed a simple power law model. A flow model with the viscosity dependent on temperature was used.

Further examples are referred to in Table 2.7

2.3.4.3 Heterogeneous Products Heated in Batch Retorts

To estimate the ratio of conduction/convection heat transfer within the container, the following equation has been proposed (Ball and Olson 1957):

$$K_{\mathrm{va}} = \frac{K_{\mathrm{v}} f_{\mathrm{h}} - f_{\mathrm{h}'}}{f_{\mathrm{h}} K_{\mathrm{v}} - f_{\mathrm{h}} K_{\mathrm{a}}} \tag{2.104}$$

where

K_{va}: conduction-convection heat transfer index (dimensionless)
K_{v}: can conduction index (dimensionless)
K_{a}: can convection index (dimensionless)
f_{h}: slope index of the first can (min)
$f_{\mathrm{h}'}$: slope index of the second can (min)

According to Eq. (2.104), when K_{va} index tends to 1 the heat transfer is mainly carried out by conduction. On the other hand, if K_{va} index tends to 0 the main heat transfer mechanism is convection.

2.3.4.4 Heterogeneous Products Heated in Batch Retorts

Most workers, dealing with convection packs consisting of particulates in a covering liquid, carry out experimental trials to determine process safety with a thermocouple placed at a convenient point, often considered to be the point of slowest heating in the liquid. While this is adequate for particulates of small size, larger-sized constituents may not receive an adequate process at their centers. For some vegetable products this could result in a sub-botulinum process (see Chap. 4). Potatoes have been shown to receive inadequate processes in their centers (Thorpe and Atherton 1969; Atherton et al. 1970). While, in practice, it is necessary to make a judgement on the efficacy of a given process, it may well be, as in the case of canned carrots, that many years of industrial practice dictate that this criterion is not always essential. However, with many other products, e.g., artichoke hearts, microbiological challenge tests are required to establish the safety of the process.

Models for predicting the temperature distributions in both the particulates and the covering liquid have been developed by relatively few workers. However, some of the work is briefly mentioned here; other works are listed in Table 2.8.

Ikegami (1977) developed an equation based on heat transfer parameters f_h and j for both solid and liquid phases, which could be used to predict the temperature profile:

$$\frac{T_\mathrm{s} - T_\mathrm{R}}{T_0 - T_\mathrm{R}} = \frac{jj_2 f_2}{f_2 - f} 10^{-t/f_2}, \tag{2.105}$$

where j and f are the heat transfer parameters for the solid, and j_2 and f_2 for the liquid, and T_s, T_R, and T_0 are, respectively, the solid food, retort, and initial food temperatures.

Rumsey (1984) used a numerical approach to solve an energy balance model, which had been modified by the addition of a term representing the temperature gradient in the particulate:

$$m_1 c_1 \frac{dT_1}{dt} + n_\mathrm{p} m_\mathrm{p} c_\mathrm{p} \frac{dT_\mathrm{p}}{dt} = U_\mathrm{c} A_\mathrm{c} (T_\mathrm{R} - T_1), \tag{2.106}$$

where m is the mass, c is the specific heat, t the time, T the temperature, n the number of particulates; the subscripts referring to 1 the liquid, p the particulate, R the retort and c the container. The temperature distribution in the particulate, T_p, is obtained using the solution of the unsteady-state heat conduction equation for the particular geometry.

One of the more important studies was due to Lekwauwa and Hayakawa (1986), who developed a model assuming an initially uniform temperature in the particulates, which was not necessarily the same as the covering liquid; the solid and liquid components had homogeneous, isotropic and temperature-independent properties; the particulate sizes were statistically distributed (approximately gamma); the heat-transfer coefficient between the solid surface and the bulk liquid was constant; and the heat-transfer coefficients for cooling conditions were different from those for heating. The technique used for determining the particle temperature distributions was to apply Duhamel's theorem (.ion 2.2.6.4) to the conduction step response (modeled in terms of f_h and j) with the change in liquid temperature. The energy balance on the whole system was established considering the heat transfer between the external heating medium and the liquid in the container, and also between the liquid and the particulates. A computer algorithm was presented for this model. Experimental results for the heating of aspheroidally shaped white potatoes in distilled water were in good agreement with those from the theoretical models, for both analytical and numerical solutions. Hayakawa et al. (1997) have used Duhamel's theorem to determine the temperature distribution in irregular shaped objects, subjected to an external heat transfer coefficient. This involved using the experimentally determined values of f_h and j (see Part I Chap. 3) The method was also applicable to deviant processes.

The energy balance model was also used by Sastry (1984) to determine heat-transfer coefficients to canned aluminum mushroom-shaped particles packed in water. The heat-transfer coefficients were correlated using the relationship:

$$Nu = 0.015\,61(Gr \cdot Pr)^{0.529}.$$

The convective heat-transfer coefficient was found to be time-dependent, increasing to a maximum during the early stages of heating and steadily declining. The mean heat-transfer coefficients varied between 396 and 593 W m^{-2} K^{-1}.

Another application of the energy balance model was to determine the heat-transfer coefficients between irregular-shaped particulates and Newtonian as well as non-Newtonian covering liquids (Alhamdan et al. 1990; Alhamdan and Sastry 1990). For water, dimensionless correlations were, for heating,

$$Nu = 5.53(Gr \cdot Pr)^{0.21},$$

and for cooling,

$$Nu = 0.08(Gr \cdot Pr)^{0.27}.$$

The average heat-transfer coefficients ranged between 652 and 850 W m^{-2} K^{-1} for heating and 384–616 W m^{-2} K^{-1}. For a non-Newtonian liquid, carboxymethyl cellulose solution, the heat-transfer coefficients were for heating 75–310 W m^{-2} K^{-1} and for cooling 22–153 W m^{-2} K^{-1}. The heat-transfer coefficients decreased with increasing apparent viscosity.

Stoforos and Merson (1990) developed a technique for estimating heat-transfer coefficients in liquid/particulate canned foods using only liquid temperature data. They solved the energy balance equation, modified for particulates, analytically using Laplace transformations.

2.3.4.5 Heterogeneous Products Heated with Agitation

In this category there are a large number of products containing particulates and covering liquid, which can benefit from being processed in rotary retorts (see Chap. 17). Processes are shorter, energy can be saved, and textural and other quality attributes can be improved. Using rotary processes requires the contents of each container to receive the same rotary motion; this means that the ratio of solids to liquids and the headspace in each container have to be carefully controlled. Table 2.9 gives some examples of experimental work that has been done to investigate the heat transfer into rotating and agitated containers. Relatively little work has been done on the quantitative aspects of the subject: three theses by Hassan (1984), Deniston (1984), and Stoforos (1988) and an overview by Stoforos and Merson (1990) cover what has been done. The technology has received a thorough treatment in the work of Manfried Eisner (1988). Some of the more important contributions are now discussed.

Lenz and Lund (1978) derived a useful heat-transfer correlation for spherical particulates 9.65–38.1 mm in diameter and void fraction 0.32–0.41 in covering liquids of both water and 60 wt% sucrose solution using 303 × 406 and 608 × 700 cans. These were processed in an FMC Steritort pilot simulator. The correlations were, for liquids only

$$Nu = 115 + 15Re^{0.3}Pr^{0.08}, \tag{2.107}$$

for liquids and particulates,

$$Nu = -33 + 53Re^{0.28}Pr^{0.14}X, \tag{2.108}$$

where $X = D_p/[S(1-\varepsilon)]$ and D_p is the particle diameter, S is the radius of the reel in the simulator, and ε is the fraction of the container volume occupied by the fluid. Values for the particulate–liquid heat-transfer coefficients ranged from 180 to 970 W m^{-2} K^{-1}.

Fernandez et al. (1988) used the simple energy balance model to determine the heat-transfer coefficients between canned snap beans and the covering liquid in 303 × 406 cans. The best correlation obtained for the experimental data was

$$Nu = 2.7 \times 10^4 Re^{0.294}Pr^{0.33}(S_f)^{6.98}, \tag{2.109}$$

where the Reynolds number was in a rotational form $D^2N\rho/\mu$, in which D is the can diameter and N the number of rotations per minute, and S_f is a shape factor given by $\pi(6V_p/\pi)^{2/3}A_p^{-1}$, with V_p and A_p being, respectively, the particulate volume and area.

Merson and Stoforos (1990) studied the effect of axial rotation on heat-transfer coefficient and the effect of the relative velocity between the particle and the liquid. They obtained a more complex correlation, in which the first term on the right includes particulate conduction, the second, heat transfer in the laminar boundary layer on the upstream side of the sphere, and the third term is the heat transfer in the turbulent wake.

$$Nu = 2 + 0.4Re^{0.5}Pr^{0.4}(\mu/\mu_s)^{0.25} + 0.06Re^{0.66}Pr^{0.4}(\mu/\mu_s)^{0.25}. \tag{2.110}$$

A semi-analytical solution for determining particle temperature and a semi-numerical solution for determining fluid temperature has been applied to the solution of heat transfer in axially rotating liquid/particle canned foods. The time dependent boundary condition was modeled using Duhamel's theorem and a 4th-order Runge–Kutta technique was used for the solution of the finite difference mode (Stoforos and Merson 1995).

This measurement of particulate temperatures is difficult. The presence of a thinwire thermocouple prevents free motion in the particle, and consequently could seriously affect the actual value of the heat-transfer coefficients. Liquid crystal sensors incorporated in the particulates have been used, which allows unrestricted movement of the monitored particulates (Stoforos and Merson 1991, 1992). For a critical overview concerning heat-transfer coefficients to particulates, see Maesmans et al. (1992).

Sablani et al. (1997) have used dimensionless correlations to determine the heat-transfer coefficients for a range of different plastic particles in both oil and water undergoing end-over-end agitation. The correlation for multiparticles involves the ratio of the particle diameter (d_{e}) to that of the can diameter (D_{c}) see Eq. (2.111).

$$Nu = 0.71\mathrm{Re}^{0.44}\mathrm{Pr}^{0.36}(\varepsilon/100 - \varepsilon)^{-0.37}(d_{\mathrm{e}}/D_{\mathrm{c}})^{-0.11}\Psi^{0.24} \tag{2.111}$$

where ε is the particle concentration and Ψ is the particle sphericity.

2.3.5 Conclusions

While a considerable amount of effort has been put into modeling convective heating of liquids and liquids/particulates in containers, there are wide discrepancies in the results obtained by different workers. With the development of more advanced techniques for monitoring temperatures inside containers and with the ability to solve coupled hydrodynamic and heat transfer problems using finite-element techniques and computational fluid dynamics, it should be possible in the future to obtain more reliable models capable of extrapolation to a range of can sizes. At the present time the work on convective heating has led to a better understanding of the heat-transfer regimes inside canned foods. This in turn has given us a better understanding of the factors that must be considered in order to be assured of the microbiological safety of canned foods. This is particularly important in reducing the severity of processes to give better-quality products, where this is appropriate, and to reduce the energy requirements. It is important to consider carefully the meaning of heat-transfer coefficients; whereas it is relatively easy to obtain an overall coefficient, which includes the internal coefficient from the wall to the covering liquid, the average heat transfer from the liquid to the particulate, the container wall resistance and the external heat-transfer coefficient from the heating medium to the external wall, it is more difficult to quantify the instantaneous local distribution of heat transfer depending upon the particle motion relative to the fluid motion. It may be, because of the unpredictability of the relative liquid/particulate motion inside cans, that we have reached the limit of the usefulness of this approach.

2.4 Radiation Heating

Thermal radiation has a wavelength from 0.8 to 400 μm and requires no medium to transmit its energy. The transfer of energy by radiation involves three processes: first, the conversion of the thermal energy of a hot source into electromagnetic waves; second, the passage of the waves from the hot source to the cold receiver; and third, the absorption and reconversion of the electromagnetic waves into thermal energy.

The quantity of energy radiated from the surface per unit time is the emissive power E of the surface. For a perfect radiator, known as a black body, the emissive power is proportional to the fourth power of the temperature T:

$$E = \sigma T^4, \tag{2.112}$$

where σ is the Stefan–Boltzmann constant, 5.670×10^{-8} W m^{-2} K^{-4}, and the heat-transfer equation for the net exchange of heat between two bodies at temperatures T_1 and T_2, respectively, is given by

$$Q = \varepsilon\sigma\left(T_1^4 - T_2^4\right), \tag{2.113}$$

where Q is the net radiation per unit area, and ε is the emissivity, i.e., the ratio of the energy emitted by a grey body to that emitted by a black body. For a highly polished surface ε can be as low as 0.03, and for a black body ε is 1.

The heat-transfer coefficient for radiation can be obtained from Eq. (2.113) as follows:

$$\begin{aligned} Q &= h_\mathrm{r}(T_1 - T_2) \\ h_\mathrm{r} &= \frac{Q}{T_1 - T_2} = \frac{\varepsilon\sigma}{T_1 - T_2}\left(T_1^4 - T_2^4\right). \end{aligned} \tag{2.114}$$

The main application for radiation theory is in relation to can sterilization using gaseous flames. The cooling of cans to the atmosphere also involves loss of heat by radiation as well as convection.

A more complex heat-transfer model for canned foods heated in a flame sterilizer was developed by Peralta Rodriguez and Merson (1983). The following assumptions were made in developing the model:

1. The flow of combustion gases past the can surface is uniform.
2. A single average heat-transfer coefficient applies to the whole of the can surface.
3. Heat transfer through the end of the can is neglected.
4. The flame is considered to be a regular-shaped gaseous body.
5. Radiation from the hot gases after they have left the flame is neglected.
6. Radiation exchange only occurs between the flame and the can, and from the can to the surroundings.
7. The temperature of the flame is the adiabatic temperature calculated on the dissociation of the combustion species.
8. The dissociated species do not combine on the can surface.

The heat balance equation is

$$Q_{\mathrm{T}} = Q_{\mathrm{C}} + Q_{\mathrm{R}}, \tag{2.115}$$

where Q is the rate of heat transfer and the subscripts T, C, R refer to total, convection and radiation, respectively.

The convective contribution is given by

$$Q_{\mathrm{C}} = h_{\mathrm{c}} A_{\mathrm{c}} \left(T_{\mathrm{g}} - T_{\mathrm{sur}} \right), \tag{2.116}$$

where h_{c} is the average film heat-transfer coefficient for the surface, A_{c} is the surface area of the can, T_{g} is the gas temperature, and T_{sur} is the temperature of the surface of the can.

The radiative contribution is given b

$$Q_{\mathrm{R}} = Q_{\mathrm{i}} - Q_{\mathrm{e}} - Q_{\mathrm{r}}, \tag{2.117}$$

where Q_{i} is the radial energy reaching the surface, Q_{e} is the energy reemitted, and Q_{r} is the reflected energy. These three terms are given by the following equations:

$$Q_{\mathrm{i}} = \varepsilon_{\mathrm{f}} A F_{\mathrm{fc}} \sigma T_{\mathrm{f}}^4, \tag{2.118}$$

where the subscript f refers to the flame properties and F_{fc} is the dimensionless view factor from the flame to the can;

$$Q_{\mathrm{e}} = \varepsilon_{\mathrm{c}} A_{\mathrm{c}} \sigma T_{\mathrm{sur}}^4, \tag{2.119}$$

where the subscript c refers to the can; and

$$Q_{\mathrm{r}} = \rho_{\mathrm{c}} \varepsilon_{\mathrm{f}} A_{\mathrm{f}} F_{\mathrm{fc}} \sigma T_{\mathrm{f}}^4, \tag{2.120}$$

where ρ_{c} is the reflectivity of the can. Combining these equations we obtain

$$Q_{\mathrm{R}} = (1 - \rho_{\mathrm{c}}) \varepsilon_{\mathrm{f}} A_{\mathrm{f}} F_{\mathrm{fc}} \sigma T_{\mathrm{f}}^4 - \varepsilon_{\mathrm{c}} A_{\mathrm{c}} \sigma T_{\mathrm{sur}}^4. \tag{2.121}$$

From Kirchhoff's laws of radiation, the absorptivity α_{c} is equal to the emissivity ε_{c}. This, and using the reciprocity relation, $A_{\mathrm{f}} F_{\mathrm{fc}} = A_{\mathrm{c}} F_{\mathrm{cf}}$, give

$$Q_{\mathrm{R}} = \alpha_{\mathrm{c}} A_{\mathrm{c}} \sigma \left(\varepsilon_{\mathrm{f}} F_{\mathrm{cf}} T_{\mathrm{f}}^4 - T_{\mathrm{c}}^4 \right). \tag{2.122}$$

Using these equations and other basic heat-transfer equations, the temperature of the liquid T_1 was derived:

$$\frac{T_1 - T_{\mathrm{g}}}{T_0 - T_{\mathrm{g}}} = \exp(-Xt) - \Psi[1 - \exp(-Xt)], \tag{2.123}$$

where T_0 is the initial temperature of the fluid, T_g is the temperature of the radiating gas, and

$$X = A_c U_c / Mc$$

$$\Psi = \left[\alpha_c \sigma\left(\varepsilon_f F_{cf} T_f^4 - T_{sur}^4\right)\right] / \left[h_c\left(T_g - T_0\right)\right],$$

in which M is the mass of fluid, c is the specific heat, and U_c is the overall heat-transfer coefficient, based on the log mean cylindrical area.

For a 60 % sucrose solution in a 304 × 406 can and using an average flame temperature up to 1000 °C, the external heat-transfer coefficient was 26.38 W m^{-2} K^{-1} and the internal coefficient ranged from 220 to 621 W m^{-2} K^{-1}, depending on the rotational speed of the can. The overall heat-transfer coefficient, U_c, varied from 23.86 to 25.12 W m^{-2} K^{-1} and did not increase with increasing rotational speeds above 60 rpm. The flame emissivity was taken as 0.0241 and the absorptivity of the can body 0.055. From this work it was concluded that the external heat-transfer coefficient, unlike steam sterilization, was the rate-controlling step. Table 2.10 gives some information about other work on heat transfer to cans being sterilized by flame heating. Further aspects of flame sterilization are dealt with in Chap. 17.

Table 2.10 Some heat transfer studies for radiation heating from flames

Product	Container size	Process conditions	Comments	Reference
Water	401 × 411 (A2 1/2)	Flame sterilization	Heating curves	Paulus and Ojo (1974)
Bentonite/water 4 % and 10 %		Single can Axial rotation 0–60 rpm	External temperature Profile	
Bentonite 1 %	303 × 406 (1/2 kg)	Flame sterilization	Energy balance model	Merson et al. (1981)
Sucrose syrup 60 %		Single can Axial rotation 30 and 50 rpm	Internal heat transfer Coefficients	
Sucrose syrup 60 %	303 × 406 (1/2 kg)	Flame sterilization	Radiation and convective	Peralta Rodriguez (1982, 1987a)
Silicone fluids		Single can Axial rotation 10–200 rpm	Convective model Heat-transfer coefficients	Peralta Rodriguez and Merson (1982, 1983)
Water	303 × 406 (1/2 kg)	Flame sterilization	Energy balance model	Teixeira Neto (1982)
Carboxymethylcellulose/water 1.5–2.5 %		Single can	Heat-transfer coefficients	
Bentonite/water 1 %	209 × 413 (aluminum)	Axial rotation 50–200 rpm Flame pasteurization	Energy balance model	Noh et al. (1986)
		Single can Axial rotation 40 rpm	Temperature profiles Heat-transfer coefficients	

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Chapter 3
Kinetics of Microbial Death and Factors for Quality Attributes

3.1 Introduction

The successful thermal processing of packaged food products requires sufficient heat to inactivate microorganisms, both those which cause spoilage and those which cause food poisoning. For this purpose it is necessary to know how heat-resistant microorganisms are in order to establish a time and temperature for achieving the objective. In the canning trade this time and temperature relationship is known as the *process* and should not be confused with the sequence of engineering operations.

The heat applied to the food product not only inactivates microorganisms but also facilitates the cooking of the product to give an acceptable texture and destroys active enzymes. In addition, it has the effect of destroying the nutrients, color, and other quality attributes. The balance between excessive heating and underprocessing, known as *optimization*, is discussed later in Chap. 19.

However, when food is heated for the purpose of destroying microorganisms, several types of chemical and physicochemical reactions also occur, some desirable but often excessive (e.g., enzyme destruction, cooking, texture softening), others less desirable but often inevitable to some degree (e.g., nutrient destruction and loss of organoleptic quality, color, texture, and flavor). These reactions are essentially chemical and less heat-dependent than microbial destruction. The art of canning depends on being able to choose processes which are microbiologically safe but result in the least loss of quality. In this section some of the kinetic factors for these changes are discussed. Much of the earlier work on quality retention has been discussed by Teixeira (2006) and Awuah et al. (2007) have reviewed the subject in detail.

In this chapter the thermal kinetics of microbial inactivation, enzyme inactivation, and quality changes are discussed.

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3.2 Kinetics of Microbial Death

3.2.1 The Nature of Microbial Behavior

The structure, chemical composition, and behavior of bacteria have been the subjects of extensive investigation and the reader wishing for a comprehensive treatment of the subject should consult advanced microbiology textbooks. More specific treatments are given in the standard canning texts, such as Ball and Olson (1957), Hersom and Hulland (1980), and Stumbo (1973).

In canning the primary concern is with bacteria, which are unicellular organisms less than 3 μm in size. These are spherical (cocci), cylindrical (rods), or helical in shape and can multiply by binary fission. Bacteria are divided into families and genera, the members of the latter being subdivided into species. Two of the more important genera are *Bacillus* and *Clostridium*, whose species have the ability to form endospores, which are more commonly referred to as *spores*. These are durable cells that can exist with little or no metabolic feed, are extremely resistant to chemical and physical treatments, and can accomplish rapid but controlled release of the dormant condition through activation and germination, under anaerobic conditions. In the case of *Clostridium botulinum*, this can lead to the production of a deadly toxin and cause the disease of botulism, which can be fatal. The purified toxins of *Clostridium botulinum* can be destroyed by heating at 80 °C for 10 min; the presence of a food substrate may modify the conditions required (Hersom and Hulland 1980).

Bacterial endospores have a very variable and usually high heat resistance, those of *Clostridium botulinum* being among the most resistant for pathogenic microorganisms. Table 3.1 shows some heat resistance data. More extensive heat resistance data are given in Appendix A.

Useful reviews which are of importance to the processing of heat-processed foods, concerning emerging pathogens and problems associated with the reduction of severity of heat treatment, have been produced by McClure (2008) and Stringer and Peck (2008).

Table 3.1 Some typical heat resistance data

Organism	Conditions for inactivation
Vegetative cells	10 min at 80 °C
Yeast ascospores	5 min at 60 ° C
Fungi	30–60 min at 88 ° C
Thermophilic organisms	
Bacillus stearothermophilus	4 min at 121.1 ° C
Clostridium thermosaccharolyticum	3–4 min at 121.1 ° C
Mesophilic organisms	
Clostridium botulinum spores	3 min at 121.1 ° C
Clostridium botulinum toxins Types A and B	0.1–1 min at 121.1 ° C
Clostridium sporogenes	1.5 min at 121.1 ° C
Bacillus subtilis	0.6 min at 121.1 ° C

3.2.2 *Other Factors Affecting Heat Resistance*

3.2.2.1 Water Activity

It should be noted that dry heat resistance data are generally much higher than those for wet conditions; however, with conventional canning this condition rarely arises. It can exist under adverse conditions of mixing powders into formulated products. Heat resistance for oily and fatty products is also higher. This emphasizes the point that it is necessary to determine the heat resistance of bacteria in the presence of food substrate.

3.2.2.2 pH

The acidity of the substrate or medium in which microorganisms are present is an important factor in determining the degree of heating required. For products with a pH less than 4.5 (high-acid products), a relatively mild pasteurization process is all that is necessary to stabilize the product. This category includes acid fruits and acidified products. Some spore formers may cause spoilage, for example, *Bacillus coagulans*, *Clostridium butyricum*, and *B. licheniformis*, as well as ascospores of *Byssoclamys fulva* and *Byssoclamys nivea*, which are often present in soft fruit such as strawberries. For pH values greater than 4.5, so-called low-acid products, it is necessary to apply a time–temperature regime sufficient to inactivate spores of *C. botulinum*. In the industry the process is referred to as a botulinum process. Ito and Chen (1978) have reviewed the evidence for the pH required to prevent the growth of *C. botulinum* and concluded that a pH of 4.6 or less is the necessary requirement. The widely used and accepted pH value of 4.5 falls within this criterion.

It is possible to identify at least four groups of products:

Group 1: Low-acid products (pH 5.0 and above)—meat products, marine products, milk, some soups, and most vegetables.
Group 2: Medium-acid products (pH 5.0–4.5)—meat and vegetable mixtures, specialty products, including pasta, soup, and pears.
Group 3: Acid products (pH 4.5–3.7)—tomatoes, pears, figs, pineapple, and other fruits.
Group 4: High-acid products (pH 3.7 and below)—pickles, grapefruit, citrus juices, and rhubarb.

Table 3.2 gives a range of typical pH values. It should be noted that the classification is not rigorous, but only intended for guidance (Hersom and Hulland 1980). The pH of some marginal fruit products can vary with growing conditions, variety, and season, and similarly formulated products can have a wide range of pH. It is important to check the products in marginal cases to ensure that an adequate heating regime is applied. When necessary, especially in the case of

Table 3.2 Some typical heat resistance data

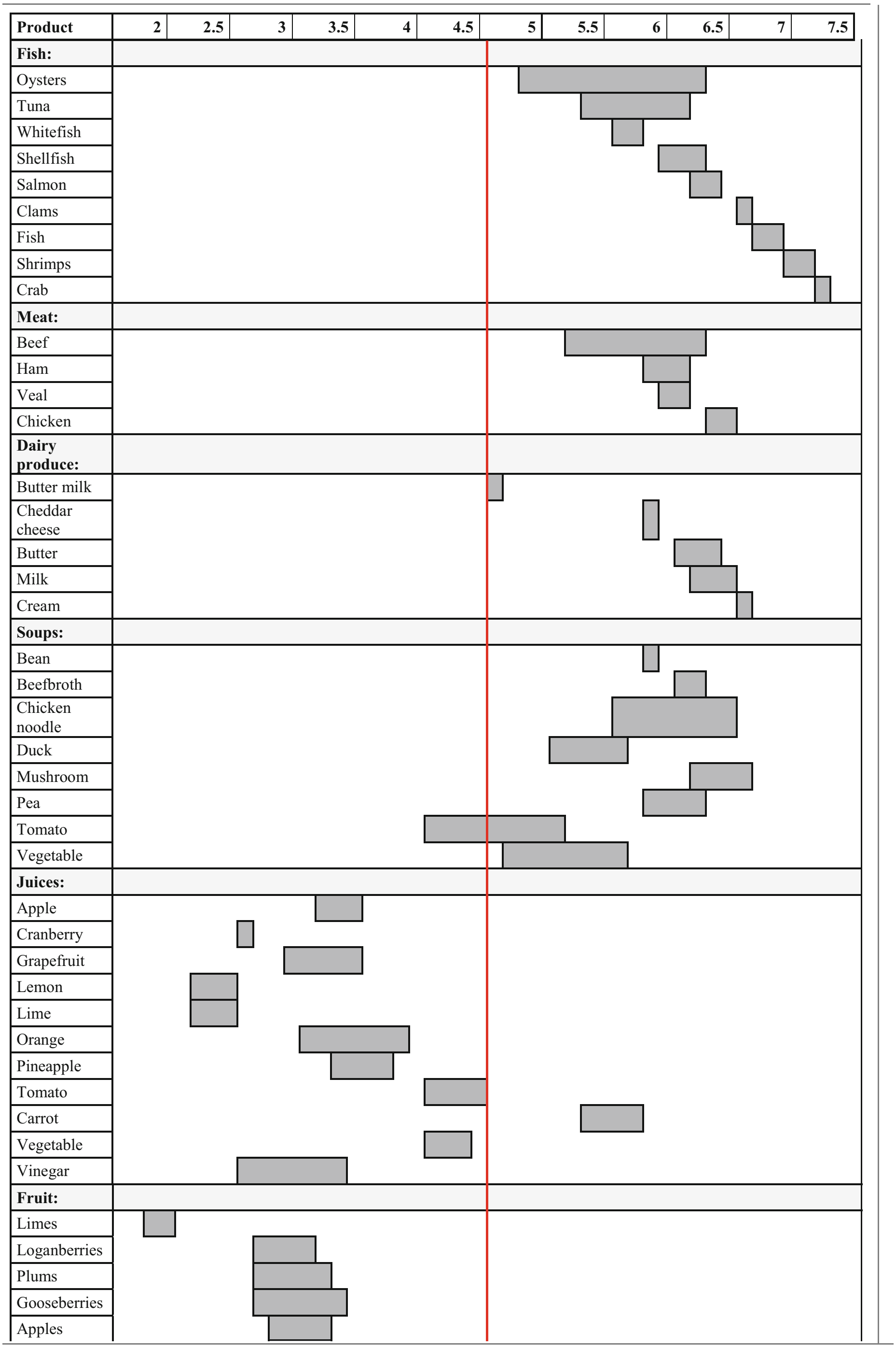
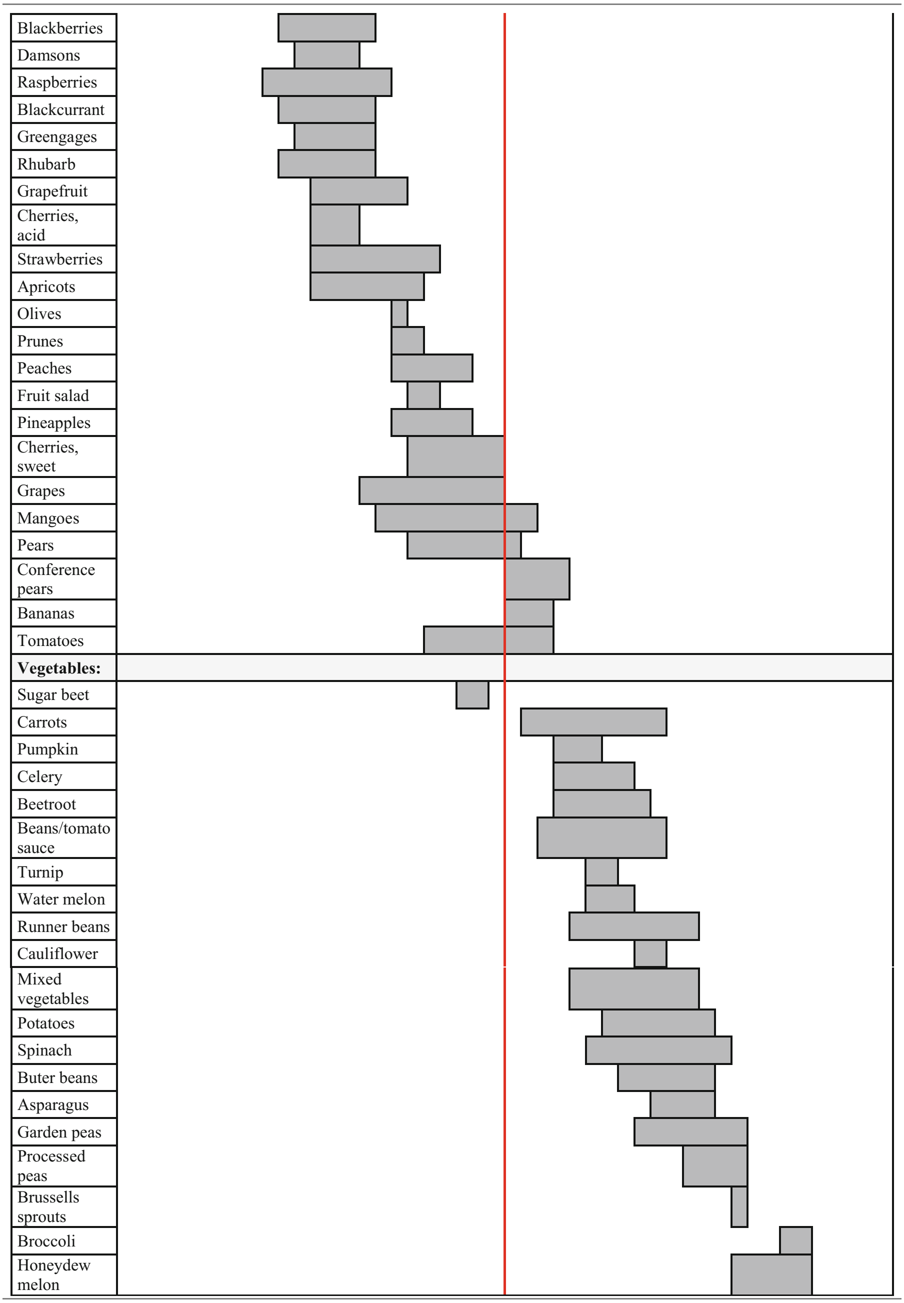


Table 3.2 (continued)



new product formulations, microbiological advice should be sought from a competent canning organization.

The US Food and Drug Administration currently defines low-acid canned foods as having a pH greater than 4.6 and a water activity greater than 0.85.

3.2.2.3 Other Factors

A number of other factors affect the heat resistance, including lipids and oily materials, dielectric constant, ionic species, ionic strength, oxygen level, organic acids, and antibiotics. Details of these are found in Hersom and Hulland (1980) and Vas (1970).

3.2.3 Measuring Heat Resistance

This is a specialized technique, and the reader should consult standard microbiological texts for details. Brown (1991) has tabulated the various methods which are available.

The two most popular ways of measuring heat resistance in the range 60–135 °C are the end-point method and the multiple-point method. The end-point method involves preparing a number of replicate containers containing a known number of spores and heating them for successively longer times until no survivors are obtained by culturing each container. The multiple-point method involves heating a batch of spore suspension continuously and withdrawing samples at selected intervals, followed by determination of the number of survivors.

Simplified equations for calculating the lethality of the heating and cooling phases for capillary tube techniques have been presented by Dickerson (1969) and a programmed heating technique has been developed by Hayakawa (1969). A computerized method of estimating microbial inactivation parameters is described by Hayakawa et al. (1981).

One of the major problems of heating spore suspensions is allowing for the time it takes for the heat to be transferred through the container walls. For temperatures in the range 100–120 °C it is relatively easy to correct for the "come-up" time; however, for higher temperatures, where the heating times can be as short as the wall penetration lag times, the problem is more difficult. Consequently, the standard capillary tube method becomes less accurate.

A thermoresistometer may be used for determining the heat resistance of spores (Stumbo 1948, 1973; Brown et al. 1988; Brown 1992a, b; Gaze and Brown 1990). This has the advantages of carefully controlling the residence time and direct exposure of the microbial suspension to the steam heating medium. Brown et al. (1988) have produced some of the most reliable data available for heat-resistant spores, especially *Clostridium botulinum*, for the temperature range 120–150 °C.

Rodrigo et al. (1993) have also used a thermoresistometer to determine the kinetics of *Clostridium sporogenes PA 3679*. Indirect heating methods have also been applied to determining the TDT of microorganisms (Haas et al. 1994).

Flow methods have also been devised, although again these tend to be used for the higher-temperature processing region (Swartzel 1984, 1989; Swartzel and Jones 1985; Srimani et al. 1990; Cole and Jones 1990). Computerized methods of experimental design for the determination of D-values for inactivating bacterial spores have been recommended by Hachigian (1989).

Teixeira (2002, 2004) has discussed dynamic methods of determining heat resistance including Paired Equivalent Isothermal Exposures (PEIE), which make use of end-point reaction data and temperature/time data from continuous sterilization experiments. The method has been shown to be superior to estimating resistance from traditional survivor curves, especially at higher processing temperatures.

3.2.4 The Statistical Nature of Microbial Death

Bigelow (1921) and Ball (1923) developed the theory of thermal process evaluation on the basis of the direct killing or inactivation of microorganisms. However, other workers, among them Stumbo (1973), Gillespy (1946), and Jakobsen (1954), showed that there was a statistical basis for the thermal inactivation of microorganisms.

The theory was based on the concept that spores die at all temperatures; however, the higher the temperature, the more likely it is that death will occur. Every spore has an inherent probability of escaping death, which does not change with time. This probability defines the heat resistance of a microorganism. If P is the probability of escaping death for unit time, then the possibility of escaping for t units of time is P^t.

3.2.4.1 Spores of Equal Heat Resistance

If N spores of equal heat resistance are considered, then the number of survivors S expected after time t is given by

$$S = NP^t \tag{3.1}$$

Taking logs gives

$$\log S = \log N + t \log P.$$

This indicates that bacterial death is of a logarithmic order, and a plot of log S versus t will give a straight line, with slope $d(\log S)/dt = \log P$ (a constant). Since P takes values from 0 to 1, i.e., $0 < P < 1$, then log P is negative.

If log $P = -1/D$ then

$$S = N \times 10^{-t/D}. \tag{3.2}$$

D is known as the *decimal reduction time*, usually measured in minutes (see Sect. 3.2.2 for further discussion).

Substituting for S from Eq. (3.1), we have

$$P^t = 10^{-t/D}. \tag{3.3}$$

If $t = D$, then $P^t = P^D = 0.1$, i.e., a 10 % survival would be expected, and if $t = 2D$, then $P^D = 0.01$ and a 1 % survival would result.

The survival equation may also be written in exponential terms, i.e., if $\log_e P = \ln P = -k$, then

$$S = Ne^{-kt}. \tag{3.4}$$

3.2.4.2 Spores of Unequal Heat Resistance

For a collection of spores of varying heat resistance the survival equation becomes

$$S = N_1 e^{-k't} + N_2 e^{-k''t} + N_3 e^{-k'''t} + \cdots, \tag{3.5}$$

where $\Sigma N_i = 1$, $k' = \ln P'$, etc.

Assuming that ln k is normally distributed among the population of spores, then

$$S = (1 + akt)^{-1/a}$$

or

$$\ln S = -(1/a)\ln(1 + akt), \tag{3.6}$$

where a is the variance of ln k, i.e., $(\mathrm{var}k)/k^2$.

T above equations may be written in base 10 notation as follows:

$$\begin{aligned} S &= 10^{-Kt} \\ S &= (1 + aKt/M)^{-1/a} \\ \log S &= -(1/a)\log(1 + aKt/M) \end{aligned} \tag{3.7}$$

where $M = \log e = 0.4343$. Whereas Eq. (3.1) indicated that the survivor relationship between log S and t was rectilinear, Eq. (3.6) or (3.8) shows that the curve is concave upwards. This is observed in practice for many microbial systems. A more extensive treatment of the topic is given by Aiba and Toda (1967).

More recently a technique has been described that uses the number of active microbial survivors in the food. This is based on the principle that the number and concentration of active survivors can be assessed from the number of spoiled heat treated out of the initial sample. The method has been validated using spores of *Clostridium sporogenes* in pea purée (Körmendy and Mohácsi-Farkas 2000).

3.2.5 Practical Aspects

The practical implications of this logarithmic order of death are as follows: It is impossible to give a time and temperature that will guarantee to kill every spore in a can of food, or indeed every spore in every can of a batch. Increasing the process increases the likelihood that an individual will be sterilized.

In order to produce canned foods which are adequately processed to prevent them being a public health hazard, it is necessary to establish a very low probability of spore survival. For low-acid foods the aim is to attain a probability of spore survival of one in 10^{12} or better. This corresponds to a $12D$ process, and is known as a *minimum process*. Processes established on this basis do not always destroy heat-resistant thermophiles; consequently, a process which deals adequately with pathogenic organisms is called a commercial process and the operation of applying the process is called *commercial sterilization*. These processes are adequate provided the cans are stored at temperatures below 35 °C, since above this temperature residual thermophiles may grow and produce a spoiled can. Cans destined for hot climates may require increased processes.

The level of initial infection, N, of a can is very important, as can be seen from Eq. (3.2), since the greater the value of N the higher the value of the survival S for given values of t and D. In practice, this means that raw materials must be examined carefully and every precaution taken to reduce the spore loading to a minimum by using hygienic handling conditions.

3.2.6 Methods of Representing Kinetic Changes

3.2.6.1 Basic Kinetic Equations

The most general equation for studying the kinetics of reactions, whether microbial inactivation, enzyme inactivation, the degradation of a heat-labile component, or the effects of cooking, is given by

$$-dc/dt = k_n c^n, \tag{3.8}$$

where c is the concentration of a reacting species at any time t, k_n is the specific reaction rate, with units $[\text{concentration}]^{1-n}$ $[\text{time}]^{-1}$, and n the order of the reaction. The concentration of reactants can be either the number of microorganisms or the concentration of a compound in grams per liter or other appropriate molar units.

When studying the kinetics of a thermal treatment it is essential to determine the order of the reaction, so that an appropriate kinetic equation can be obtained for subsequent use. This is done by obtaining the rate term $-dc/dt$, plotting c against t and then using the logarithmic form of Eq. (3.8), i.e.

$$\ln(-dc/dt) = \ln k_n + n \ln c. \tag{3.9}$$

A typical plot is shown in Fig. 3.1, from which the reaction order n can be found from the slope and the value of k from the intercept on the y-axis. A least-squares statistical approach should be used for the accurate determination of the constants and their statistical significance.

1. *Zero-Order Reactions ($n = 0$)*

   The reaction rate is independent of the concentration, and the reaction rate constant, k_0, can be found from the equation

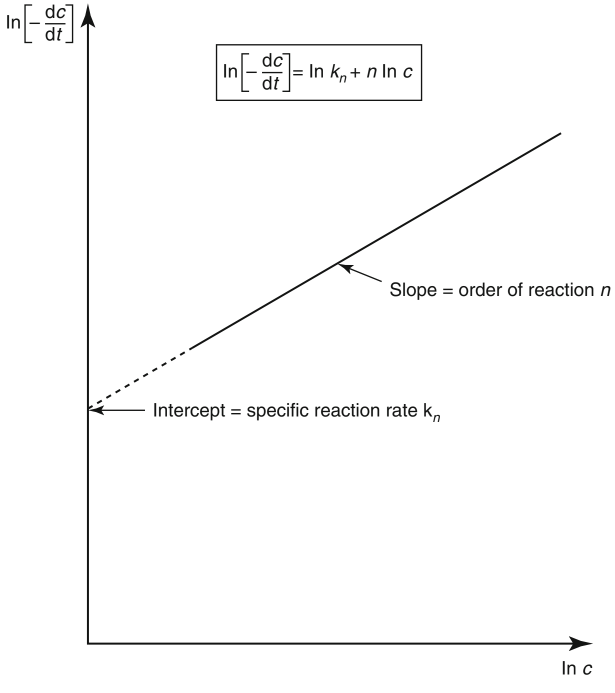


Fig. 3.1 Determination of reaction order n from Eq. (3.9)

$$-dc/dt = k_0. \tag{3.10}$$

Integration gives

$$c_0 - c = k_0 t, \tag{3.11}$$

where c_0 and c are the concentrations at times 0 and t, respectively. The units of k_0 are [concentration] [time]$^{-1}$.

Zero-order reactions are encountered infrequently in thermal processing; some examples are the caramelization of sugars (Buera et al. 1987a, b), and vitamin C degradation in model meat systems of different water activities (Laing et al. 1978).

2. *First-Order Reactions (n = 1)*

The reaction rate is proportional to the concentration of the reacting species or the number of microorganisms, and the reaction constant, k_1, can be found from the equation

$$-dc/dt = k_1 c. \tag{3.12}$$

Integration gives

$$\ln(c/c_0) = -k_1 t \tag{3.13}$$

or

$$\ln(c_1/c_2) = k_1(t_2 - t_1), \tag{3.14}$$

where c_1 and c_2 are the concentrations at times t_1 and t_2 respectively. The units of k_1 are [time]$^{-1}$ and are independent of concentration.

The majority of reactions, including microbial inactivation, encountered in thermal processing obey, or are assumed to obey, first-order (or pseudo-first-order) kinetics. In this text the subscript giving the reaction order is omitted, and thus in the various forms of the first-order reaction equation the reaction rate constant is signified by k, and Eq. (3.13) takes the form

$$\ln(c/c_0) = -kt$$

or

$$c/c_0 = e^{-kt}. \tag{3.15}$$

3. *Second-Order Reactions (n = 2)*

The reaction rate is proportional to the square of the concentration in the case of a single reactant and the product of the concentrations for two reactants. For the single reactant case, the reaction constant, k_2, can be found from the equation

Table 3.3 Reaction orders for the effect of heat on some quality factors for green peas and white beans (Van Loey et al. 1995)

Product	Attribute	Reaction order *n*
Peas (*Pisum sativum*)	Color	1.31 ± 0.18
	Hardness	1.13 ± 0.20
Beans (*Phaseolus vulgaris*)	Hardness	0.36 ± 0.17
	Appearance	0.44 ± 0.16

$$-dc/dt = k_2c^2. \tag{3.16}$$

Integration gives

$$c^{-1} - c_0^{-1} = k_2t. \tag{3.17}$$

The units of k_2 are [concentration]$^{-1}$ [time]$^{-1}$. Second-order reactions are infrequently encountered in thermal processing; however, the destruction of thiamin in milk was shown to be second-order by Horak and Kessler (1981).

4. *Other Orders*

Van Loey et al. (1995) have shown that reaction orders may be fractional or not whole integers for some types of degradation reaction, for example the color and texture of peas and the texture and appearance of beans. Table 3.3 shows the *n*-values obtained from experiments on peas and beans. These values reveal the care that should be taken in establishing the reaction order, so that the correct equations may be used for determining the effect of thermal processing on the heat-labile components in the food products.

Readers requiring further information on reaction kinetics should consult standard textbooks and monographs, such as Atkins and Paula (2014), Moore (1972, 1983), Steinfeld and Fransisco (1989), and Stevens (1961). A particularly useful text on mathematical models for microbial destruction has been presented by Teixeira (2007).

3.2.7 Decimal Reduction Time

For microbial inactivation the number of viable organisms, N_0 at time zero and N at time t, is used as a measure of the concentration. Equation (3.15) thus becomes

$$\ln(N/N_0) = -kt, \tag{3.18}$$

which can also be expressed as

$$\log_{10}(N/N_0) = -kt/2.303 \tag{3.19a}$$

or

$$N/N_0 = e^{-kt}. \tag{3.19b}$$

The standard convention in thermobacteriology has been to define a *decimal reduction time*, D, which is the heating time in minutes to give an expected inactivation of 90 % of organisms, or 10 % survival (Katzin et al. 1942). This can be determined from heat resistance experiments by plotting $\log N$ against t and using the equation

$$\log N = \log N_0 - t/D. \tag{3.20}$$

The term $\log(N/N_0)$ is also known as the germ reduction value, G (see Machmerth 1983; Swartzel 1986).

From Eq. (3.19b), the interrelation between the kinetic factors results in Eq. (3.21):

$$D = 2.3/60k, \tag{3.21}$$

where D is in minutes and k in seconds. Note that the interrelation between kinetics factors (D and k in Eq. (3.21)) has been derived for a first-order kinetics and is not valid for different kinetics orders.

A typical microbial inactivation curve, known as the *survivor curve* or *thermal death curve*, is a plot of $\log N$ against time, and is shown in Fig. 3.2. D is the time, in minutes, to traverse one log cycle and the slope is $-1/D$.

The logarithmic relationship between microbial inactivation and heating time was originally established by Esty and Meyer (1922), before the D-value concept was used, for spores of various strains of *Clostridium botulinum*.

3.2.8 More Complex Inactivation Models

Figure 3.3 shows some of the different types of survivor curve often encountered in experimental work. It can be seen that it is often difficult to determine the initial number of spores accurately from the non-rectilinear nature of these curves. Curves that show a concave downwards behavior are considered to be due to the clumping of organisms; the true inactivation level can be obtained from the part of the curve following the initial lag period. Curves that are concave upwards are due to organisms of different heat resistance (see Sect. 3.2.4.2). The true rate of inactivation can be obtained from the latter part of the curve where the most heat resistance is located. A review of the different types of curve, including shoulder, sigmoidal, upward concave, and biphasic types, has been presented by Cerf (1977). One of the commonest types of curve encountered shows an initial shoulder, considered to be

Fig. 3.2 Semilogarithmic survivor curve from Eq. (3.20)

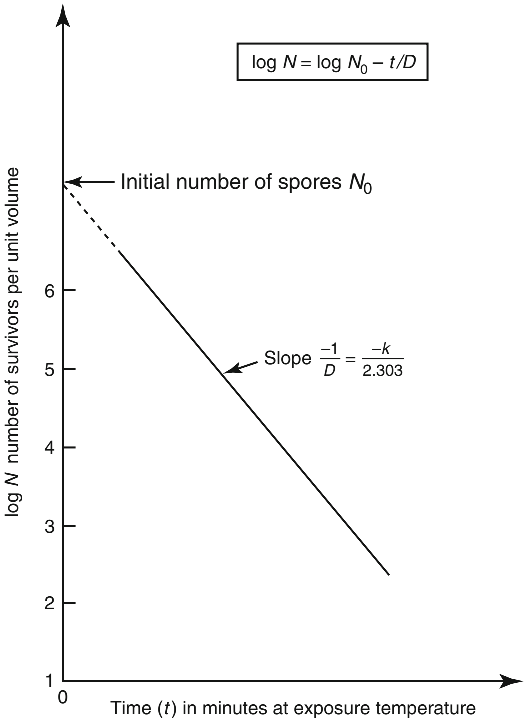
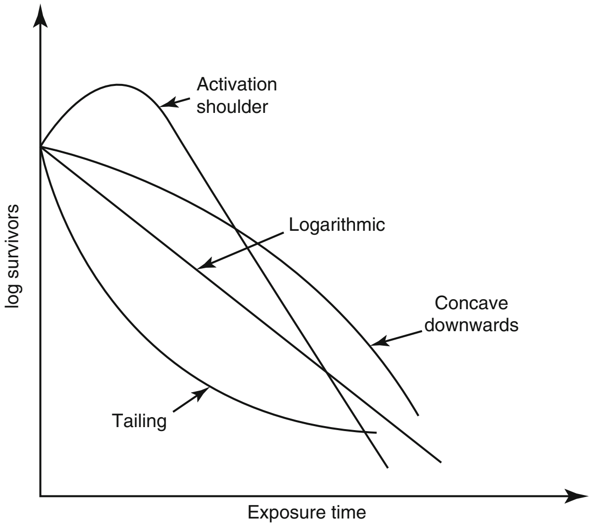


Fig. 3.3 Examples of different types of spore survivor curves



due to activation of organisms, followed by a constant period of inactivation, and then a residual tailing.

A more complex model, which includes heat activation, injury, preliminary inactivation of the less heat-resistant fraction, and inactivation of the remainder, has been developed (Rodriguez et al. 1988; Teixeira et al. 1990; Teixeira 2007). The model has three terms and allows for the accurate prediction of the thermal inactivation behavior of microbial populations. The first term describes the rapid decay of the least resistant fraction of the organisms:

$$N_{\mathrm{A}} = N_0 e^{-k_{\mathrm{a}} t}, \tag{3.22}$$

where k_{a} is the reaction rate for activation. The second term is a combination of thermal activation and subsequent destruction of dormant spores initially present:

$$N_{\mathrm{B}} = N_0 \left(1 - e^{-k_{\mathrm{a}} t}\right) e^{-k_{\mathrm{d}} t} \tag{3.23}$$

where k_{d} is the reaction rate constant for destruction. This is the term which generates the “shoulder” of the inactivation curve. It represents a pulse rising rapidly from an initial value of zero, peaking, and then decaying slowly towards zero. The third term describes the inactivation of initially active spores:

$$N_{\mathrm{C}} = N_0 e^{-k_{\mathrm{d}'} t}. \tag{3.24}$$

The total number of survivors can be obtained by summation

$$N_{\mathrm{t}} = N_{\mathrm{A}} + N_{\mathrm{B}} + N_{\mathrm{C}}.$$

Rodriguez et al. (1988), using spores of *Bacillus subtilis*, showed that a two-term model, $N_{\mathrm{B}} + N_{\mathrm{C}}$, was adequate for predicting the spore inactivation, especially for shorter times and higher temperatures. The values for the rate constants, k_{a}, k_{d}, and $k_{\mathrm{d}'}$, for spores of *Clostridium botulinum* are 1.4×10^{-2}, 1.6×10^{-3}, and $0.16\ \mathrm{s}^{-1}$, respectively.

Abraham et al. (1990) showed that a mathematical model based on one proposed by Shull et al. (1963) was applicable to experimental survivor curves that were basically nonlinear. The model, represented by the following equation, contains two terms, one for activation of dormant spores (specific reaction rate k_{A}) and the other for inactivation (specific reaction rate k_{D}):

$$N/N_0 = \phi e^{-k_{\mathrm{D}} t} + (1 - \phi) e^{-k_{\mathrm{A}} t}, \tag{3.25}$$

where

$$\phi = 1 - \left[k_{\mathrm{A}}/\left(k_{\mathrm{D}} - k_{\mathrm{A}}\right)\right]\left(N_{\mathrm{D}}/N_{\mathrm{A}}\right)$$

and N_{D} and N_{A} are the number of dormant and activated spores respectively.

Empirical formulae have been developed (Hayakawa et al. 1969; Hayakawa 1982) for estimating nonlinear survivor curves of thermally vulnerable factors. The method proposed was simpler than the traditional method of Stumbo (1973); it was based on programmed heating and included cases where the thermal death time (TDT) curve was a linear relation with heating time. Teixeira (2004) has used this model for determining the heat resistance factors for survivor curves showing "shoulders" and "tails," considered to be the result of activation and deactivation of subpopulations of microbial species. This uses as many terms as are required to fit the survival curve, using a number of terms as in Eq. (3.25a).

$$N(t) = N_{10}e^{-k_1 t} + N_{20}e^{-k_2 t} + N_{30}e^{-k_3 t} + \cdots + N_0 e^{-k_n t} \tag{3.25a}$$

3.2.9 *Temperature Dependence of Death Rate*

The fact that the death rate varies with temperature is very important in all aspects of thermal processing, especially in establishing adequate processes. This section examines the most important of these models and their applicability in design, simulation, and modeling situations.

Thermal inactivation of mixed microbial populations has been studied theoretically by Körmendy et al. (1998). This showed that the nth-order time constant and survivor ratio are independent of the initial microbial concentration.

Körmendy and Körmendy (1997) have shown that when the semilogarithmic thermal inactivation models are nonlinear, the Bigelow model can be used for calculating thermal processes if $t\{T, N\} = g\{T\} \cdot F\{N\}$, where t is the heat treatment time at constant temperature; T is the temperature, and N is the number of surviving microorganisms at time t. The function $g\{T\}$ depends only on T and the function $F\{N\}$ depends only on N. A simple graphical method is presented for determining whether semilogarithmic curves correspond to a $g\{T\} \cdot f\{N\}$ type function.

An alternative concept to the kinetic theory of microbial inactivation is the statistical approach, i.e., using a cumulative form of the temporal distribution of lethal events. These are capable of handling nonlinear survival curves with upward and downward concavity as well as "shoulders" and "tails." This is briefly discussed in Sect. 3.2.4.1, where the early work of the 1940s is discussed.

A number of new approaches have been examined:

(a) *Weibull Distribution* (Peleg and Cole 1998; Peleg and Penchina 2000; Peleg et al. 2002, 2003a, b, c; Peleg 2004; Van Boekel 2002; Corradini et al. 2005; Albert and Mafart 2005, Mafart et al. 2002).

This model is essentially a power-law distribution of the form $\log_{10} S(t) = -b(T).\ t^{n(T)}$ where $S(t)$ is the survival ratio of microorganisms with time t, i.e., Nt/N_0, $b(T)$, the scale or steepness factor, is a temperature (T) dependent coefficient (between 0.1 and 6.0), and $n(T)$, the shape or curvature factor, is a temperature dependent coefficient (approximately 0.4). When $n(t)$ is unity the equation resolves to the linear Arrhenius model. When $n(t) < 1$, the curve is upward concave and when $N(t) > 1$ it is downward concave. The equation has been applied satisfactorily to the interpretation of the inactivation *Clostridium botulinum* spores (Campanella and Peleg 2001).

The Weibull model has been applied to study on-line correction for continuous sterilizers, e.g., hydrostatic cookers (Campanella and Chen 2008).

Nonlinear inactivation kinetic models (nine different types) have also been discussed by Corradini et al. (2006, 2009). For isothermal survivor curves that show a residual survival ratio a non-Weibullian model is proposed.

(b) *Log-Logistic Model* (Campanella and Peleg 2001; Peleg et al. 2002; Anderson et al. 1996)

This empirical model is represented by the following equation:

$b(T) = \log_e\{1 + \exp[k(T - T_c)]\}$, where k and T_c are constants

(c) *Prentice Model* (Prentice 1976; Kilsby et al. 2000; Mycock 2002)

This is a seven-parameter model, which has been used successfully to model the kinetic behavior of *C. Botulinum* 213B and *Salmonella Bedford.* Mycock (2002) showed that the heat resistance data for *Clostridium botulinum* 213B was found to be modeled by the Prentice function and *Salmonella Bedford* 286 by a log normal distribution, both using a log time scale. The z-value in °C (Celsius degrees) for *C. botulinum* was found to be dependent on temperature, viz., 8.7 at 110 °C; 10.6 at 121 °C and 13.2 at 135 °C. It is interesting that the z-value increases considerably with increasing temperature, above the standard processing temperature of 121.1 °C. This could have implications on the processing times required for processes at higher temperatures.

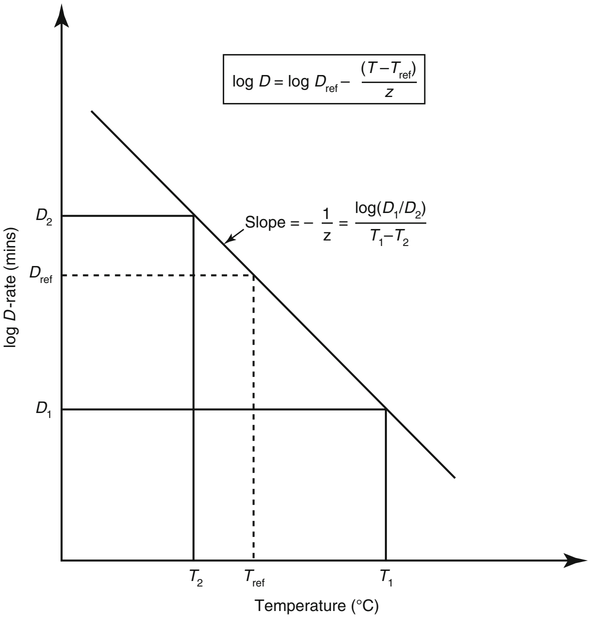
(d) *Other Models:*

Geeraerd et al. (2004) have discussed a number of other models, including a Biphasic model and a Sigmoidal model. For the latter a freeware for Microsoft® Excel known as GinaFiT (*G*eeraerd et al. 2004*I*nactivation *M*odel *Fi*tting *T*ool) has been developed for the Sigmoidal model. A discontinuous linear model (Corradini et al. 2005), which considers that no inactivation takes place below a specified temperature and that the increase in the rate parameter above this temperature is linear. The capabilities in predicting the survival patterns for *Clostridium botulinum* and *Bacillus sporothermodurans* are shown to be superior to the Arrhenius model. Estimation of kinetic parameters for non-isotherm processes have been developed by Dolan (2003), Dolan et al. (2007), Jiménez et al.(2011), Teixeira(2007) and Teixeira and Rodriguez (2009).

3.2.9.1 Thermal Death Time Method: *D–z* Model

Some of the earliest work on the heat resistance of microorganisms was done by W.D. Bigelow of the National Canners' Association, Washington, USA (see Bigelow and Esty 1920; Bigelow 1921), who first used the term 'thermal death

Fig. 3.4 Thermal death time curve to obtain z-value



time' in connection with the minimum time required for the total destruction of a microbial population. When the temperature was plotted against the log time a straight-line relationship was observed. Subsequent to this work the D-value—obtained from the slope, $-1/D$, of the log survivor curve against time—was used to quantify heat resistance (see Fig. 3.2). When the D-value is plotted against the temperature a linear relationship is observed; this is generally referred to as the *thermal death time curve*. The slope of the log D versus temperature curve, i.e., $d(\log D)/dT$, is $-1/z$, where z is the temperature change necessary to alter the TDT by one log-cycle. From Fig. 3.4 it can be seen that for any two values of D and the corresponding temperatures T, z can be determined from the relationship

$$\log(D_1/D_2) = (T_2 - T_1)/z. \tag{3.26}$$

An important and unique value of D measured at a reference temperature is designated D_{ref} or D_r; this is defined by

$$\log(D/D_{ref}) = -(T - T_{ref})/z. \tag{3.27}$$

The standard reference temperature was 250 °F, but its exact Celsius equivalent, 121.1 °C, is now in more common usage, though less satisfactory since the ".1" represents a recurring decimal. The use of 120 °C or 121 °C has been rejected on the grounds that it could lead to misunderstanding and errors in using existing F-values. A more theoretical treatment of the use of reference temperatures is given by

Holdsworth and Overington (1975), who suggested the use of an absolute standard of 400 K and processing times in seconds.

The ratio of D_{ref}/D is known as the *lethal rate L*; this is a quantitative measure of the rate of inactivation of organisms at a given temperature:

$$L = (D_{\mathrm{ref}}/D) = 10^{(T-T_{\mathrm{ref}})/z}. \tag{3.28}$$

An important property of lethal rates is that they are additive, so it is possible to quantify the process over the temperature range used. The integrated lethal rate is known as the F-value (see Sect. 4.1.2).

3.2.9.2 Arrhenius Kinetic Approach: *k–E* Model

One of the most important approaches to modeling the effect of temperature T (in kelvin) on the specific reaction rate k (s^{-1}) was produced by Svante Arrhenius in a paper discussing the kinetics of the inversion of sucrose (Arrhenius 1889). He suggested an equilibrium existed between inert and active molecules and that the inversion reaction only took place with molecules that were energetically activated by heat. Using the van't Hoff isochore and applying it to the equilibrium, the following classical equation was obtained:

$$\ln k = \ln A - E/RT$$

or

$$k = Ae^{-E/RT}. \tag{3.29}$$

From the activation energy theory A is a constant known as the pre-exponential factor, collision number or frequency factor (s^{-1}), E is the activation energy (kJ mol^{-1}), and R is the molar gas constant (8.135 J mol^{-1} K^{-1} or 1.987 cal mol^{-1} K^{-1}). The activation energy can be conceived as the minimum energy that molecules must possess before reaction can occur, and the exponential term $e^{-E/RT}$ is the fraction of the molecules that collectively have minimum energy. The fundamental basis for this theory is extremely well expounded in the text by Glasstone et al. (1941). Other work that is relevant to the subject can be found in the papers of Karplus et al. (1965) and Truhlar (1978).

The values of A and E may be determined from a plot of ln k versus $1/T$. The values of A for unimolecular chemical reactions vary from 10^{14} to 10^{20} s^{-1}, for bimolecular reactions from 10^{4} to 10^{11} s^{-1}, with intermediate values for chain reactions.

When applied to the thermal inactivation of microbial spores, Eq. (3.29) is written in a form which eliminates the factor A by using a reference temperature, T_{ref}, and the corresponding specific reaction rate constant, k_{ref}:

$$\ln k = \ln k_{\mathrm{ref}} - (E/R)[1/T - 1/T_{\mathrm{ref}}]. \tag{3.30}$$

For heat-resistant bacterial spores A is extremely large, of the order of 10^{30}–10^{60} s^{-1}, and E can be up to 500 kJ mol^{-1} (see Appendix 1 for a table of values). For *Clostridium botulinum* spores, Simpson and Williams (1974) concluded that the most appropriate value for k was obtained by using $A = 2 \times 10^{60}$ s^{-1} and $E = 310.11 \times 10^{3}$ J mol^{-1} K^{-1} for temperatures in the range $373 < T < 423$ K. Casolari (1979) has commented critically on the meaning of such high A-values. He concludes that equilibrium thermodynamics is neither a fruitful field nor a satisfying approach to determining reaction rates in rapidly increasing temperature fields. The factors A and E are assumed in the theory to be independent of temperature; however, this may not always be the case. Casolari (1981) has proposed a modified version of the Arrhenius equation to deal with nonlinear forms of inactivation curves. This includes a term showing the dependence of k on the concentration of cells, and this has been tested by Malmborg (1983).

3.2.9.3 Absolute Reaction Rate Theory

The Arrhenius model can be developed further using the theory of absolute reaction rates and a thermodynamic evaluation of the constants. Thus the variation of k with temperature T can be expressed by the equation

$$k = (k_{\mathrm{B}}/h_{\mathrm{P}})Te^{\left(\Delta S^{*}/R\right)}e^{\left(\Delta H^{*}/RT\right)}, \tag{3.31}$$

where k_{B} is the Boltzmann constant (1.381×10^{-23} J K^{-1}), h_{P} the Planck constant (6.626×10^{-34} J s), ΔS^* the entropy of activation (kJ kmol^{-1} K^{-1}), and ΔH^* the enthalpy of activation (kJ kmol^{-1}).

Comparing Eq. (3.31) with (3.29), the pre-exponential factor, A, and the activation energy, E, are

$$A = (k_{\mathrm{B}}T/h_{\mathrm{P}})e^{(\Delta S^{*}/R)}$$
$$E = \Delta H^{*}.$$

The theory is based on the fact that spores will die when they are activated to a sufficiently high level by increasing the probability of collision. The rate constant, k, increases with temperature and makes the probability of death greater.

For many systems, including microbial inactivation by heat, an empirical relationship between ΔS^* and ΔH^* has been observed. This is known as the *compensation law* because, as can be seen from the following equation, one factor compensates the other:

$$\Delta S^{*} = a\Delta H^{*} + b. \tag{3.32}$$

When $T = a^{-1}$, the two thermodynamic entities are equal; this temperature is known as the *compensation* or *isokinetic* temperature. The model can be used, within experimental limits, for the prediction of entropies of activation from enthalpies. The reader requiring further information should consult the papers by Banks et al. (1972), Kemeny and Rosenberg (1973), Boon (1973), Harris (1973), and Rudra et al. (2008).

Warren (1973) developed a more extensive model which accounts for the effects of temperature and pH on the thermal death rate of spores. The validity of the model was tested using the data of Gillespy (1947, 1948) for the inactivation kinetics of *Clostridium thermosaccharolyticum* and that of Xezones and Hutchings (1965) for *C. botulinum*. The predicted results were in good agreement with the experimental ones. The model is sufficiently important to justify further refinement and use as a predictive tool.

Other models have also been developed for the combined effect of pH and temperature on microbial inactivation:

(a) *The Davey—linear Arrhenius model* D-LA (Davey 1993a, b; Davey et al. 1995; Chiruta et al. 1997; Davey 1994; Davey and Cerf 1996; Davey et al. 2001) and this is given by Eq. (3.33):

$$\ln k = C_0 + C_1 T^{-1} + C_2\,\mathrm{pH} + C_3\,\mathrm{pH}^2. \tag{3.33}$$

For *C. botulinum*, in spaghetti/tomato sauce, the values of the constants were $C_0 = 105.23$, $C_1 = -3.704 \times 10^4$, $C_2 = -2.3967$, and $C_3 = 0.1695$, using the data of Xezones and Hutchings (1965).

This equation has been extended by Gaillard et al. (1998) and Khoo et al. (2003) to include a second temperature dependent term:

$$\ln k = C_0 + C_1 \mathrm{T}^{-1} + C_2 \mathrm{T}^{-2} + C_3\,\mathrm{pH} + C_4\,\mathrm{pH}^2. \tag{3.34}$$

This shows that the value of k is a maximum when $\mathrm{pH}_{\max} = -C_3/2C_4$.

(b) *Square-root model* is a special form of the Ratowsky-Belehradek model (Belehradek 1926; McMeekin et al. 1993a, b; Khoo et al. 2003)

This is represented by multiplicative equation:

$$(k)^{1/2} = b\left(T - T^*\right) \times \left(\mathrm{pH} - \mathrm{pH}^*\right). \tag{3.35}$$

where the * terms are conceptual values. This is a three-term model which includes T, pH, and TpH and is more complex to apply than the classical log-linear and D-LA models.

(c) *nth order polynomials*—noP These have been widely used to model bacterial growth (McMeekin et al. 1993a, b). They take the form:

$$\ln k = \alpha_0 + \alpha_1 T^1 + \alpha_2 T^2 + \alpha_3 T^3 + \alpha_4\,\mathrm{pH} + \alpha_5\,\mathrm{pH}^2 + \alpha_6\,\mathrm{pH}^3 + X \tag{3.36}$$

where α_n are the coefficients of the cubical model and X are any interactive terms.

(d) *The Mafart Model* The model has been used to extend the generalized sterilization chart for combined temperature and pressure (Davey 1993b). Gaillard et al. (1998), Mafart (1999), Mafart and Leguérinel (1999), and Mafart et al. 2002) have presented an extended model, the Mafart model, for the prediction of the heat resistance of *Bacillus cereus* spores, which include water activity as well as pH.

3.2.9.4 Quotient Indicator Method

Another method used to express the temperature dependence of specific reaction rate is the *quotient indicator*, Q. This is the ratio of two specific reaction rates measured at different temperatures, such as T and $T = 10$ °C:

$$Q_{10} + k_{T+10}/k_T. \tag{3.37}$$

The Q_{10} ratio has values of 1.8–4 for chemical reactions, 8–20 for inactivation of microorganisms, and 10–100 for denaturation of proteins. The higher the Q_{10}-value, the more sensitive the inactivation rate is to temperature change.

The Q_{10} method can be compared with the D–z method, and can be converted using the formula

$$Q_{10} = D_T/D_{T+10} = 10^{10/z}. \tag{3.38}$$

For *C. botulinum*, $z = 10$ °C, $Q_{10} = 10$.

The Q_{10} is extensively used in milk pasteurization and sterilization practice (see Burton 1988), and for biochemical and sensory changes induced by heating; it is rarely used in conventional canning technology.

3.2.9.5 Equivalence of the Models

For first order kinetics the thermal death time D–z model as expressed in Eq. (3.27) can be directly compared with the Arrhenius k–E model equation (3.30) to give the following identities:

$$D = \ln 10/(60k) = 2.303/(60k), \tag{3.39}$$

where k is in reciprocal seconds and D is in minutes; and

$$E = 2.303RTT_{\mathrm{ref}}/z, \tag{3.40}$$

where E is in kilojoules per mole and z in Kelvin or degrees Celsius. Equation (3.40) is often expressed in the approximate form:

$$E = 2.303RT_{\mathrm{ref}}^2/z, \tag{3.41}$$

which is satisfactory when processing temperatures are near to the reference temperature 121.1 °C. It also implies that the z-value is a function of temperature. Datta (1993) examined the errors associated with using $T_{\mathrm{ref}} = 121$ °C, and showed that errors of the order of 1.3 % at 116 °C, 8 % at 80 °C, and 62 % at 151 °C were inherent. Nunes et al. (1993) used Eq. (3.40) to determine the most appropriate T_{ref} to minimize the errors. For a z-value of 10 °C and values of E from 320 to 350 kJ mol^{-1}, T_{ref} was between 140 and 150 °C. Hallström et al. (1988) have examined the errors in Arrhenius kinetic factors as a function of processing temperature. Several workers, among them Haralumpu et al. (1985a, b), Cohen and Saguy (1985a, b), and Arabshahi and Lund (1985), have dealt with the problems of statistical fit of kinetic data using the two models. Three least-square regression models—a separate linear model, a multiple linear model and a nonlinear model—have been examined and the third found to be the best fit. The two models, however, are essentially different; the D-value is proportional to the temperature, whereas k is proportional to $1/T$. Despite the differences, experimental results for *Bacillus stearothermophilus* (Gillespy 1947; Navani et al. 1970; Jonsson et al. 1977; Perkin et al. 1977; Ocio et al. 1994) fit both models with a high degree of correlation. For the heat inactivation of *Saccharomyces uvarum*, Manji and Van De Voort (1985) found that the data fitted the Arrhenius model better than the D–z model. Jones (1968) showed significant differences between the two approaches for calculating process lethalities; however, the data used were inconsistent and invalidated the results (Cowell 1968). Ramaswamy et al. (1989), extending the work of Lund (1975) and Cleland and Robertson (1985), concluded that over a limited range of processing temperatures, 115–135 °C, near to the reference temperature 121.1 °C, there is little to choose between the two approaches. The D–z model predicts greater lethality values than the k–E model for temperatures below T_{ref} and vice versa.

The practical and theoretical aspects of alternatives to the D–z concept have been discussed by Brown (1992b) and Casadei and Gaze (1994). The different methods of determining heat resistance are reviewed, including indirect, particle, mixing, direct steam, and electrical methods. The conclusion was reached that in relation to non-logarithmic survivor curves, the D–z approach was less appropriate for determining thermal processes. The authors recommended the use of the logistic model or the Gompertz exponential models.

Sapru et al. (1993) have compared a number of predictive models, applicable mainly to higher processing temperatures. Cunha et al. (1997a, b) have shown that for isothermal heating the Bigelow D–z model gives results in good agreement with the Arrhenius E_{A}–k model; however, this is not the case for non-isothermal heating, where the initial temperature plays an important role.

Table 3.4 Statistical accuracy of some *D*- and *z*-values

Reference	Statistical parameter	*D*-value	*z*-values
Lewis (1956)	Coefficient of variation	10 %	–
Hicks (1961)	Standard error of the mean	–	2 %
Stumbo et al. (1950)	Coefficient of variation	–	2 %
Kaplan et al. (1954)	Coefficient of variation	–	9 %
Kaplan et al. (1954)	Mean value [PA 3679]	–	10.4 °C
Lenz and Lund (1977)	Standard deviation	10 % (0.10*D*)	1.11 °C
Patino and Heil (1985)	Standard deviation	3.6 % (0.03– 0.06*D*)	0.28–0.55 °C

3.2.9.6 Errors in Experimental Kinetic Factors

In the previous section the differences between two kinetic models were discussed, as well as the errors arising from these approaches. It is, however, necessary to look at the inherent error in the experimental results. Hicks (1961) considered that the following factors contributed to the variations encountered in experimental results: the nature of the organism; the history of the spore prior to use; the conditions of sporulation; the nature of the substrate in which the spores are heated; and the substrate used for detecting survivors. Discussion of these factors is beyond the scope of this book, and the practicing technologist should seek information from microbiological sources. It is, however, important for the process engineer and the food technologist to appreciate the sources of error in the data that they have to use.

The errors found in some of the experimental kinetic factors and their effect on process evaluation have been widely discussed—see, for example, Lewis (1956), Hicks (1961), Lund (1978, 1983), Patino and Heil (1985), and Datta (1993). Table 3.4 gives some data on the accuracy of experimental *D*- and *z*-values.

3.3 Factors for Quality Attributes

3.3.1 *Kinetic Representation*

Both the *D*–*z* and *k*–*E* methods, discussed before have been used to express the temperature dependence of reaction rate.

From Eq. (3.12), the basic kinetic equation for a first-order reaction is

$$-dc/dt = kc, \tag{3.42}$$

where *c* is the concentration of the species being studied and *dc*/*dt* is the rate of change of concentration with time. This yields the familiar relation

$$c_1/c_2 = e^{-k_c(t_1 - t_2)}$$

or

$$\ln(c_1/c_2) = k_c(t_2 - t_1), \tag{3.43}$$

where c_1 and c_2 are the concentrations at times t_1 and t_2, respectively, and k_c refers to a chemical constituent or physical attribute.

The temperature dependence is given by the Arrhenius equation

$$k_c = Ae^{-E/RT}. \tag{3.44}$$

The *D*–*z* concept is also used for heat-vulnerable factors. These can be determined using the equations used for decimal reduction time (3.18–3.19). The D_{ref}-value, often designated as D_c, is taken at the reference temperature T_{ref}, and represents 90 % destruction of a thermolabile component; the corresponding *z*-value is designated z_c. Equation (3.45) is used to determine *D*-values for thermolabile components:

$$\log(D/D_{\mathrm{ref}})_c = -(T - T_{\mathrm{ref}})/z_c, \tag{3.45}$$

where the subscript c refers to a chemical compound or physical attribute.

Adams (1978) compared experimental results for the thermal inactivation of horseradish peroxidase with the theoretical predictions of the *D*–*z*, *k*–*E* and absolute reaction rate models, but found little difference between them. This is probably because there is less temperature sensitivity with these compounds than with bacterial spores. Cohen and Saguy (1985a, b) have statistically evaluated the applicability of the Arrhenius model to food quality losses. Cronin et al. (2007) have discussed the effect of minimizing temperature variability on product quality.

3.3.2 Kinetic Factors

For chemical constituents of food the rates of degradation reactions are slower than for the destruction of microbial species. Table 3.5 shows these differences in general terms. For more detailed information the reader should consult Villota and Hawkes (1986, 1992).

Table 3.5 Some comparative *z*-values for heat-vulnerable constituents

Vulnerable factor	*z*-value (°C)	Tables
Bacterial spores	7–12	Table A.1
Vegetative cells	4–8	Table A.1
Vitamins	25–30	Table B.1
Proteins	15–37	Table B.2
Enzymes	10–50	Table B.3
Overall sensory quality	25–45	Table B.4
Texture and cooking	17–47	Table B.5
Color degradation	17–57	Table B.6

3.3.3 *Experimental Procedures*

The main experimental methods used to determine the kinetics of the effect of temperature on quality attributes and heat-vulnerable components of food are as follows:

3.3.3.1 Steady-State Methods

These use blended samples of the food, or food and an added component, which are heated to a constant temperature for constant periods of time, the time being increased for each successive experiment. The reaction mixture is then analyzed for the component being studied at each period of time, and the results studied to determine the kinetic factors, using either the *D*–*z* or the *k*–*E* model. The main problem with this method is that a considerable period of time is required to analyze the large number of samples required. For further discussion of the technique and error analysis, see Lenz and Lund (1980) and Hill and Grieger-Block (1980).

3.3.3.2 Unsteady-State Methods

With these methods the samples are submitted to a variable time–temperature heating profile, either similar to those encountered in commercial canning or to a programmed sequence. The kinetic factors are determined using a trial-and-error method, which can be computerized and the average retention of a component or components obtained. For further details, the reader is referred to the work of Hayakawa (1969), Nasri et al. (1993), and Nunes et al. (1991).

A linear gradient technique has been developed by Cunha and Oliviera (2000) for the kinetics of the acid hydrolysis of sucrose. A theoretical equation was developed for a linearly rising temperature gradient and an analytical solution was derived using exponential integrals. Values of $k_{77^\circ\mathrm{C}}$ varied from 0.10 to 1.47.

The large differences in the values of kinetic factors found in the literature (see Appendix B for some tabulated data) often result from differing experimental methods (Sadeghi and Swartzel 1990; Swartzel 1982; Nunes et al. 1993). Considerable care needs to be taken in obtaining reproducible and satisfactory results that may be used with confidence in optimizing process conditions.

3.3.4 *Specific Components*

3.3.4.1 Vitamin Destruction

The destruction of nutrients and vitamins during the processing of canned foods is detrimental to their nutritional value. It is necessary to know the kinetics of destruction in order to determine the conditions of processing necessary for minimizing this effect (Lund 1977). There has been a continuous trend in thermal processing to reduce process times and increase temperatures in order to reduce nutrient degradation. Similarly, attempts have been made to utilize thin-profile heat-stable plastic pouches and containers.

Greenwood et al. (1944) showed that the rate of thiamine destruction during processing meat doubled with a 10 °C increase in temperature compared with a tenfold increase in the rate of inactivation of heat-resistant bacteria. The most extensively quoted data on thiamine destruction in puréed meats and vegetables was reported by Feliciotti and Esselen (1957), who determined *D*-values, specific reaction rates and half-life values, for temperatures ranging from 108 to 150 °C at pH values from 3.5 to 7. Hayakawa (1977) has compared experimentally obtained results for thiamine degradation in canned puréed meats and puréed vegetables with computer predictions using kinetic models and heat transfer data. He concluded that theoretical predictions could be used as a good indicator of the effect of differing processes on nutrient retention. Mauri et al. (1989) have reviewed the existing data on thiamin degradation in foods and model solutions of high water activity.

Davey and Cerf (1996) have studied the effect of combined temperature and pH on the kinetics of destruction of vitamins B_1 and C and shown that the model represented by Eq. (3.33) can be used to predict the degree of denaturation satisfactorily.

Some kinetic data for the thermal destruction of nutrients are given in Table B.1 (Appendix B).

3.3.4.2 Protein Denaturation

Relatively little information is available on the kinetics of protein destruction in thermally processed foods; mostly it relates to milk proteins, and hemoglobin in meat products. The processing of fish products, e.g., sardines, has been discussed in relation to optimizing nutrition and sensory quality (Skipnes and Hendricks 2008). Some kinetic data are presented in Table B.2.

3.3.4.3 Enzyme Inactivation

Enzymes in many food products control the deteriorative reactions in fresh produce and it is necessary, when handling raw materials such as vegetables, to inactivate the enzymes prior to processing. This is one of the objectives of the heat treatment known as *blanching*; for a recent excellent review, see Selman (1989), and for earlier work on the nature of thermal destruction of enzymes and their regeneration, see Leeson (1957). Apart from this, many other products require adequate enzyme inactivation to stabilize them, especially at higher processing temperatures, where the process times for bacterial destruction may be less than those for enzyme inactivation (Adams 1978). Some kinetic data for thermal destruction of enzymes are given in Table B.3.

3.3.4.4 Quality Attributes

The effect of thermal processing on sensory and other factors (e.g., color, texture, flavor, and visual appearance) has received only limited treatment despite the importance of the subject. Overall sensory effects have been studied by several workers, among them Cho and Pyun (1994), Mansfield (1974), Hayakawa et al. (1977), and Ohlsson (1980). Cooking effects have been more extensively covered because of the importance of mouth-feel and chewing requirements (Paulus 1984; Rao and Lund 1986). Some kinetic data are given in Table B.4 for overall sensory quality, in Table B.5 for texture and softening, and in Table B.6 for color degradation. Ávila and Silva (1999) have produced an extensive list of kinetic parameters for color degradation in fruits and vegetables.

3.4 Summary

Pflug (1982), an international authority on food sterilization, recommends the TDT method as an objective tool for use in the laboratory, in the manufacturing plant, and in validation and monitoring of sterilization processes. For the purposes of this book it should be recognized that discrepancies exist; however, provided the processing temperatures are not excessive, the problem can be minimized. Care should be taken to examine the original experimental microbiological data to make sure they are consistent with the application envisaged. The situation is more complex at the higher processing temperatures encountered in continuous flow sterilization for aseptic packaging applications (Holdsworth 1992). This also applies to high-temperature, short-time (HTST) processing of packaged foods, where it is practicable.

Despite the adverse effects of heat on thermally processed foods, many products are commercially in high demand and produce a significant contribution to the diet. Many products are esteemed as brand image products in their own right, without reference to the initial raw material or product. There is, however, a considerable need to be able to quantify the effects of heat on food components in order to be able to predict the effect of different thermal processes. Much of the difficulty in experimental work comes from the variability of the composition of raw materials and prepared products ready for canning and the reliability of the experimental techniques. It is essential to have statistically well-designed experiments in order to account for the variability. This is an important area for future research, especially considering the need to conserve energy and natural resources.

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Chapter 4
Sterilization, Pasteurization, and Cooking Criteria

4.1 Sterilization Value

4.1.1 Definitions

The need for a criterion against which to judge the efficacy of a process is paramount in thermal processing technology. First it is necessary to decide on a target organism, which in the case of sterilization is usually *Clostridium botulinum*, with a z-value of 10 °C, and then it is necessary to know the temperature history to which the package has been submitted or the temperature distribution obtained at the point of slowest heating in the food product during the process.

The unit of processing value is known as the F-value, and was originally developed from the pioneering work of Bigelow et al. (1920) at the National Canners' Association in Washington, and developed subsequently by Ball (Ball and Olson 1957). It is a system that was adopted by the canning industry in the USA and later the UK and is in universal use in other countries, which were influenced by the pioneering American work. The general principles of sterilization have been briefly mentioned in Sect. 1.2.1; more recent publications include Campden BRI (1998), Tucker and Featherstone (2010), and Simpson et al. (2012).

4.1.2 Lethal Rates

A measure of the lethal effect of heat on microorganisms at a given temperature has already been discussed in Sect. 3.2.9.1—the lethal rate L, in minutes, which is defined by the equation

$$L = 10^{(T - T_{\mathrm{ref}})/z}, \tag{4.1}$$

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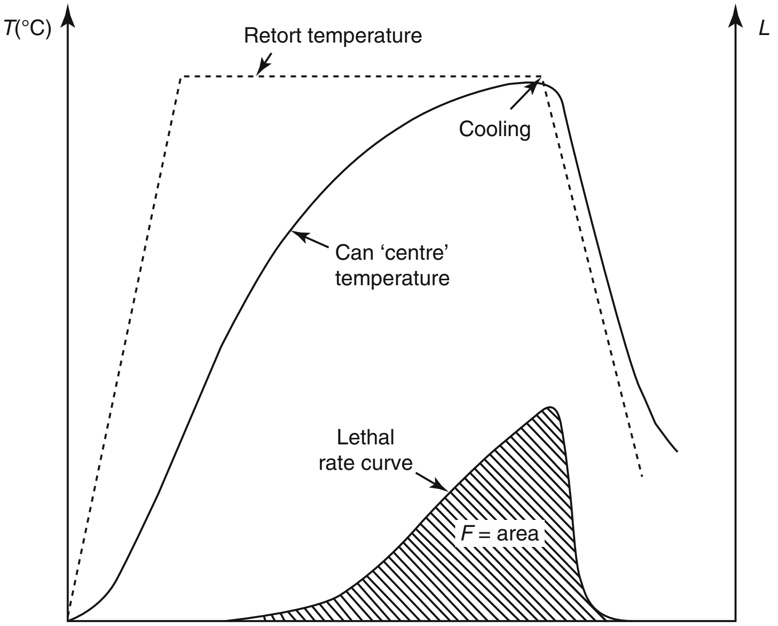

Fig. 4.1 Graph of temperature (T) and lethal rate (L) against time

and is the ratio of the D-value at a particular temperature, T, to the D-value at the reference temperature T_{ref}. For a constant temperature T the F-value is equal to the L-value; however, if the temperature varies from an initially ambient temperature to the retort temperature, or the reverse on cooling, then it is necessary to integrate the achieved lethal rates at the various temperatures (Fig. 4.1). The basic equation for calculating F-values for processes is given by:

$$F = \int_0^t L dt, \tag{4.2}$$

or, in the classical form,

$$F_{\mathrm{r}} = \int_0^t 10^{\frac{T - T_{\mathrm{ref}}}{z}} dt \tag{4.3}$$

The value of $T - T_{\mathrm{ref}}$ is always negative when the processing temperature, and hence the internal temperature, T, is less than the reference temperature.

If the relationship between temperature and time at the point of slowest heating is in a mathematical form, then the equation can be analytically integrated. However, it is more usual, from heat penetration experiments, to know the time–temperature relationship in numerical form. The equation may then be integrated by a mathematical technique such as the trapezium rule. An important property of lethal rates is that they are additive and use can be made of lethal rate tables (Table 4.1), calculated using Eq. (4.1), to determine F-values. Table 4.2 lists lethal

Table 4.1 Lethal rate tables ($T_{\mathrm{ref}} = 121.1$ °C and $z = 10$ °C)

T (°C)	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
90	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
91	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001
92	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002
93	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
94	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002	0.002
95	0.002	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003	0.003
96	0.003	0.003	0.003	0.003	0.003	0.003	0.004	0.004	0.004	0.004
97	0.004	0.004	0.004	0.004	0.004	0.004	0.004	0.005	0.005	0.005
98	0.005	0.005	0.005	0.005	0.005	0.005	0.006	0.006	0.006	0.006
99	0.006	0.006	0.006	0.007	0.007	0.007	0.007	0.007	0.007	0.008
100	0.008	0.008	0.008	0.008	0.009	0.009	0.009	0.009	0.009	0.010
101	0.010	0.010	0.010	0.010	0.011	0.011	0.011	0.011	0.012	0.012
102	0.012	0.013	0.013	0.013	0.013	0.014	0.014	0.014	0.015	0.015
103	0.015	0.016	0.016	0.017	0.017	0.017	0.018	0.018	0.019	0.019
104	0.019	0.020	0.020	0.021	0.021	0.022	0.022	0.023	0.023	0.024
105	0.025	0.025	0.026	0.026	0.027	0.028	0.028	0.028	0.029	0.030
106	0.031	0.032	0.032	0.033	0.034	0.035	0.035	0.036	0.037	0.038
107	0.039	0.040	0.041	0.042	0.043	0.044	0.045	0.046	0.047	0.048
108	0.049	0.050	0.051	0.052	0.054	0.055	0.056	0.058	0.059	0.060
109	0.062	0.063	0.065	0.066	0.068	0.069	0.071	0.072	0.074	0.076
110	0.078	0.079	0.081	0.083	0.085	0.087	0.089	0.091	0.093	0.095
111	0.098	0.100	0.102	0.105	0.107	0.110	0.112	0.115	0.117	0.120
112	0.123	0.126	0.129	0.132	0.135	0.148	0.141	0.145	0.148	0.151
113	0.155	0.158	0.162	0.166	0.170	0.174	0.178	0.182	0.186	0.191
114	0.195	0.200	0.204	0.209	0.214	0.219	0.224	0.229	0.234	0.240
115	0.245	0.251	0.257	0.263	0.269	0.275	0.282	0.288	0.295	0.302
116	0.309	0.316	0.324	0.331	0.339	0.347	0.355	0.363	0.372	0.380
117	0.389	0.398	0.407	0.417	0.427	0.437	0.447	0.457	0.468	0.479
118	0.490	0.501	0.513	0.525	0.537	0.550	0.562	0.575	0.589	0.603
119	0.617	0.631	0.646	0.661	0.676	0.692	0.708	0.724	0.741	0.759
120	0.776	0.794	0.813	0.832	0.851	0.871	0.891	0.912	0.933	0.955
121	0.977	1.000	1.023	1.047	1.072	1.096	1.122	1.148	1.175	1.202
122	1.230	1.259	1.288	1.318	1.349	1.380	1.413	1.445	1.479	1.514
123	1.549	1.585	1.622	1.660	1.698	1.738	1.778	1.820	1.682	1.905
124	1.950	1.995	2.042	2.089	2.138	2.188	2.239	2.291	2.344	2.399
125	2.455	2.512	2.570	2.630	2.692	2.754	2.818	2.884	2.952	3.020
126	3.090	3.162	3.236	3.311	3.388	3.467	3.548	3.631	3.715	3.802
127	3.890	3.981	4.074	4.169	4.266	4.365	4.467	4.571	4.677	4.786
128	4.898	5.012	5.129	5.248	5.370	5.495	5.623	5.754	5.888	6.026
129	6.166	6.310	6.457	6.607	6.761	6.918	7.079	7.244	7.413	7.586
130	7.762	7.943	8.128	8.318	8.511	8.710	8.913	9.120	9.333	9.550

Further values may be calculated from the formula $L = 10^{(T - 121.1)/z}$

Table 4.2 Some tables of lethal rates

T_{ref}	z-value	Temperature range	Smallest ΔT	Reference
250 °F	18 °F	191–218 °F	0.25 °F	Patashnik (1953)
250 °F	21 °F	181–205 °F	0.50 °F	Patashnik (1953)
250 °F	17–23 °F	180–260 °F	2.00 °F	Patashnik (1953)
250 °F	10–26 °F	180–260 °F	2.00 °F	Ball and Olson (1957)
250 °F	18 °F	200–264 °F	0.10 °F	Sleeth (1978)
250 °F	18 °F	190–270 °F	0.10 °F	Lopez (1987)
250 °F	12–23 °F	200–264 °F	0.25 °F	Stumbo (1973)
250 °F	12–23 °F	200–264 °F	0.25 °F	Hersom and Hulland (1980)
120 °C	10 °C	100–121.9 °C	0.10 °C	Brennan et al. (1976)
120 °C	10 °C	90–155 °C	0.10 °C	Shapton et al. (1971)
121.0 °C	10 °C	90–130 °C	1.00 °C	Lewis (1987)
121.1 °C	10–26 °C	90–125 °C	0.10 °C	Cheftel and Thomas (1963)
121.1 °C	10 °C	90–130 °C	0.10 °C	See Table 4.1
121.11 °C	10 °C	100–121.9 °C	0.01 °C	Brennan et al. (1976)
121.11 °C	7–12 °C	90–124 °C	0.10 °C	Hersom and Hulland (1980)
85 °C[a]	10 °C	65–94 °C	0.10 °C	Shapton et al. (1971)

[a] For pasteurization purposes

rate tables available for different temperature systems and different reference temperatures; however, it is easier to construct a table using Eq. (4.1) for the particular conditions being used.

4.1.3 Reference Temperatures

While it has become established practice to use a reference temperature in degrees Celsius, it was the practice at first to use the Fahrenheit system.

Thus much of the literature in canning uses a reference temperature of 250 °F; subsequently the industry has moved to use the direct Celsius equivalent of 121.1 °C or, less frequently, 121.11 °C, rather than 120 °C or 121 °C. In time the processes of standardization will probably settle on one of the more rational values.

It is usual to be more specific in defining F-values by using adscripts z and T_{ref}, so that the commonest value is $F^{10}_{121.1}$ or F^{18}_{250}, designated F_0. Thus Eq. (4.3) becomes

$$F_0 = \int_0^t 10^{(T-121.1)/10} dt \equiv \int_0^t 10^{(T-250)/18} dt. \tag{4.4}$$

The system of using F-values with adscripts defining the conditions is particularly useful and avoids confusion. It can be extended to other processes, such as the heat destruction of yeast spores in beer, a pasteurization process, using $F^{12.5}_{212}$ or F^{7}_{100}. It is, however, necessary when using this system to state at what point the value has been determined. An alternative system uses subscripts alone, e.g., F_c when the F-value has been determined at the center point in the food mass. This is also known as the point of slowest heating or critical point. When this system is not used it may be assumed, unless stated to the contrary, that the F-value has been determined from time–temperature data obtained at this unique point.

The original unit of process was 1 min at 250 °F and, although the system still exists, there is a continuing change to 1 min at 121.1 °C. Whichever system is used, the F-value is not affected, provided that z-values and temperatures are in consistent units. If a process has an F-value of 4 min, the process is said to be equivalent in sterilizing value to 4 min at 121.1 °C, assuming instant attainment of this temperature at the start and instant cooling to sub-lethal temperatures at the end. This is very useful, since it means that different processes can be compared for their lethal effects. For every F-value there is a range of combinations of time and temperature that will produce the equivalent sterilizing value. In practice, there are limits to the suitability of a process; for sterilizing processes, temperatures are generally in the range 115–130 °C (240–270 °F), and for pasteurization processes a temperature of 70–100 °C (160–212 °F) is the normal value.

Like the lethal rate, the F-value is additive; thus the various stages may be evaluated separately, and their contributions to the total F-value for a complete heating-holding-cooling cycle may be obtained from the Eq. (4.5)

$$F_{\text{total}} = F_{\text{heating}} + F_{\text{holding}} + F_{\text{cooling}} \tag{4.5}$$

4.1.4 A Processing Point of View to Derive **F** *Value*

When defining a closed system (canned food, retortable pouches, a particle in a moving system, etc.) and doing a survivor balance, we obtain Eq. (4.7):

In general, for an open system in non steady state condition the survivor balance can be expressed as

$$[QN]_{\mathrm{i}} - [QN]_{\mathrm{o}} + M\left[\frac{dN}{dt}\right]_{\mathrm{I}} = \left[\frac{dMN}{dt}\right]_{\mathrm{S}}. \tag{4.6}$$

where

N: microorganisms concentration (p/p)
M: mass of the system
Q: mass flow
t: time

Subscripts
i, o: input and output
I: inactivation
S: system

Applying Eq. (4.6) for the particular case of a closed system, the above general survivor balance is reduced to

$$\left[\frac{dN}{dt}\right]_{\mathrm{I}} = \left[\frac{dN}{dt}\right]_{\mathrm{S}} \tag{4.7}$$

Considering first-order kinetics for a microorganism's inactivation and replacing into Eq. (4.7):

$$-kN = \left[\frac{dN}{dt}\right]_{\mathrm{s}} \tag{4.8}$$

Separating variables and integrating, taking into account the D value definition:

$$-\int_0^D k dt = \int_{N_o}^{\frac{N_o}{10}} \frac{dN}{N} \text{ and, therefore, } \quad k = \frac{\ln 10}{D}. \tag{4.9}$$

Given that D values can be expressed as a function of temperature according to Eq. (4.26),

$$D = D_{\mathrm{r}} 10^{\frac{T_{\mathrm{r}}-T}{z}}. \tag{4.10}$$

Replacing Eq. (4.10) into Eq. (4.9) and then into Eq. (4.8), we obtain

$$-\frac{\ln 10}{D_{\mathrm{r}} 10^{\frac{T_{\mathrm{r}}-T}{z}}} N = \left[\frac{dN}{dt}\right]_{\mathrm{s}}. \tag{4.11}$$

where

T_{r}: reference temperature
D_{r}: decimal reduction time at reference temperature
z: temperature change necessary to alter TDT by one log-cycle

Integrating, Eq. (4.11), from N_0 to $N_0/10^x$ for microorganisms (where x represents the number of decimal reductions) and from 0 through t for time:

$$x \cdot D_{\mathrm{r}} = \int_0^t 10^{\frac{T-T_{\mathrm{r}}}{z}} dt \tag{4.12}$$

where the product xD_{r} was denominated as F_{r}, then

$$F_{\mathrm{r}} = \int_0^t 10^{\frac{T-T_{\mathrm{r}}}{z}} dt. \tag{4.13}$$

In the case of $T_{\mathrm{r}} = 121.1$ °C (250 °F), F_{r} has been denominated as F_{o}.

$$F_{\mathrm{r}} = F_{\mathrm{o}} \text{ at } T = 250\,^{\circ}\mathrm{F} \tag{4.14}$$

$$F_{\mathrm{o}} = \int_0^t 10^{\frac{T-121.1}{z}} dt \tag{4.15}$$

Note that Eq. (4.15) was derived for closed systems and first order inactivation kinetics.

4.1.5 Integrated F-*Values,* $\mathbf{F}_S$

Stumbo (1948, 1949) considered that in order to evaluate a process properly it was necessary to consider the probability of survival of microorganisms throughout the pack and not just at the center. In this method (Stumbo 1953), the pack was divided into iso-F regions, i.e., regions that received the same thermal process, which formed a nest of concentric shells of geometry corresponding to that of the pack. Using the F-value for any particular region λ, denoted by F_{λ}, and for the center F_{c}, Stumbo showed that there was a linear relation between $(F_{\lambda} - F_{\mathrm{c}})$ and υ, the fraction of the total pack volume enclosed by λ, for values of from 0 to 0.4. This is adequate since the region for which the probability of survival is significant is generally less than $\lambda = 0.15$. The relation is given by

$$F_{\lambda} = F_{\mathrm{c}} + m\upsilon, \tag{4.16}$$

where m is the slope of the line.

Using F_{s} for the total integrated sterilizing value, also known as the mass-average value, for cylindrically shaped cans, the following equation was obtained:

$$F_{\mathrm{s}} = F_{\mathrm{c}} + 1.084 D_{\mathrm{r}} + \log[(F_{\lambda} - F_{\mathrm{c}})/D_{\mathrm{r}}], \tag{4.17}$$

where D_{r} is the D-value of the target organism at T_{ref}. This equation sums up all the probabilities from the center of the can to $\upsilon = 0.19$ of the can volume. In practice, F_{λ} is the value of F_0 at a point whose j-value is $j_{\mathrm{c}}/2$, and the value of 1.084 is $\log \upsilon + \log 2.303$.

The F_{S}-value can be obtained experimentally from the number of organisms present at the start of the process n_0 and the number surviving at the end of the process n_t, using the equation

$$F_{\mathrm{s}} = D_{\mathrm{r}} \log(n_0/n_t) \tag{4.18}$$

The method is described fully with examples of application in Stumbo (1973), and extensions to the subject have been reported by Stumbo and Longley (1966), Manson and Zahradnik (1967), and Skinner and Urwin (1971). A critique of the method is given by Holdsworth and Overington (1975). An application to nutrient retention is reported by Jen et al. (1971), which gives a slightly different formula than Eq. (5.17) and is discussed in Sect. 5.2. Newman and Holdsworth (1989) have derived equations for other geometries, in relation to food particulate sterilization; however, these are also applicable to containers.

In 1951, two researchers, Gillespy (1951) and Hicks (1951), independently published a mathematical derivation for the integrated sterilizing value. In the first of these the F_S-value is given by the equation

$$F_s = F_c + D_r \log(2.303 f_h q/D), \tag{4.19}$$

where f_h is the reciprocal of the slope to the heating curve and q is the slope of the curve of $(F_\lambda - F_c)$ against v. This equation is similar to Stumbo's inasmuch as it shows the dependence of Fs on the D_r-value.

In the second, using a different technique involving the first-order approximation of the heat transfer equation for both heating and cooling, the following equation was obtained:

$$F = f_h \exp[b(T_R - T_{\text{ref}})] E_i\left(-Abe^{-\gamma t'}\right) - E_i(-Ab), \tag{4.20}$$

where A and γ relate to the heat transfer equation (see Chap. 2) and t' is the heating time at temperature T_R, b the inactivation rate for a specified microorganism and media, and $E_i(x)$ is the exponential integral (see Chap. 8). The total number of survivors in the whole can, n_f, is obtained by integrating c_f, the concentration of spores at the end of the process, with respect to the volume element dV:

$$n_f = \int_0^v c_f \, dV. \tag{4.21}$$

4.1.6 F-*Values for Cans of Differing Sizes*

An important relation between the F-value and the size of containers was obtained by Gillespy (1951). If two series of equal volumes of the same food are packed into A2 and A10 cans, the number of cans will be approximately in the ratio 11:2. If the cans receive processes of equal F-values, then the degrees of sterility with respect to spores will be the same for each pack, but the degrees of sterility with respect to cans will differ. Therefore a higher F-value would have to be attained in the A10 cans to give the same degree of sterility as in the A2 pack.

Given the original mean number of spores, N, in each of the two series of equal volumes of the same food packed in cans of volume V_1 and V_2, then the mean spore survivals m_1 and m_2 would be given by

$$m_1 = N10^{-F_1/D_{\text{ref}}}$$
$$m_2 = N10^{-F_2/D_{\text{ref}}}$$

Since $m_1/m_2 = V_1/V_2$, then

$$\begin{aligned} F_1 - D_{\text{ref}}\log V_1 &= F_2 - D_{\text{ref}}\log V_2 \\ F_2 &= F_1 + D_{\text{ref}}\log(V_2/V_1). \end{aligned} \tag{4.22}$$

This can be used to determine the required F-value for a new can size, when the F-value is known for a given can size.

4.1.7 Arrhenius Approach

The Arrhenius equation for microbial death given in Chap. 3 is also used for deriving a measure of the lethal effect of heat. The approach is widely used in continuous sterilization (Holdsworth 1992), but less so in canning process calculations.

The basic equation relates the microbial reduction to the temperature coefficient of microbial destruction:

$$\ln(n_0/n_t) = \int_0^t k\,dt, \tag{4.23}$$

where n_0 and n_t represent the concentrations of microorganisms at times 0 and t; using the Arrhenius equation, this becomes

$$\ln(n_0/n_t) = A\int_0^t e^{-E/RT}\,dt. \tag{4.24}$$

One of the difficulties of using this equation is that the values of A are extremely large and difficult to handle. This is overcome by using a reference temperature, so that the equation becomes

$$\ln(n_0/n_\text{t}) = \int_0^t e^{-(E/RT - E/RT_{\text{ref}})}dt \tag{4.25}$$

The F-value is obtained from

$$F = D_{\text{ref}}\log(n_0/n_t).$$

Deindoerfer and Humphrey (1959a, b) used the symbol ∇ to represent the term ln (n_0/n_t), while Nunes and Swartzel (1990) used the letter G for A^{-1} ln(n_0/n_t), where A is the pre-exponential factor of the Arrhenius equation (4.25). Maesmans et al. (1995), have examined Nunes' and Swarztel's method, known as the equivalent point method, and concluded that for time-variable process conditions the concept is less satisfactory than for isothermal heating used in continuous sterilization.

4.2 Cooking Values

4.2.1 Historical Perspective

The application of heat during the processing operation causes not only microbial destruction but also nutrient degradation, texture changes (usually softening) and enzyme inactivation. The final quality of the canned product thus depends on the amount of heat it has received. Biochemical reactions proceed at a substantially slower rate than microbial inactivation, and this is reflected in the higher z-values, which are given in Table 4.3.

The degree of heat treatment with respect to these factors can be represented by C-value equations similar to the F-value equations, beginning with

$$C = \int_0^t 10^{(T - T_{\mathrm{ref}})/z_{\mathrm{c}}}\, dt, \tag{4.26}$$

where z_{c} is the thermal destruction rate analogous to the z-factor for microbial inactivation. This concept originated from the work of Mansfield (1962), at FMC, San Jose, CA, and is now standard nomenclature. The E-value of Ball and Olson (1957) does not seem to have been used extensively and has been superseded by the C-value concept. Reichert (1977) used E for enzyme inactivation to distinguish it from the C-value for cooking. Definitions of C_0 vary, but the general reference temperature is 100 °C or 212 °F and the z_{c} is appropriate to the heat vulnerable factor being considered. It is probably best if the C-value is quoted with the adscripts depicting the z_{c}-value (super) and T_{ref} (sub), i.e., $C_{T_{\mathrm{ref}}}^{z_{\mathrm{c}}}$.

Table 4.4 shows how the F-value and the C-value vary with temperature. It can be seen that the sterilizing values rise by a factor of 10 for every 10 °C rise in temperature.

Table 4.3 Values of z for heat-vulnerable components

Heat-vulnerable component	Approximate range of z-value (°C)	Detailed tables
Bacterial species	7–12	Table A.1
Vegetative cells	4–8	Table A.1
Enzymes	10–50	Table B.1
Vitamins	25–30	Table B.2
Proteins	15–37	Table B.3
Sensory factors		
Overall	25–47	Table B.4
Texture and softening	25–47	Table B.5
Color	25–47	Table B.6

The detailed tables in the Appendices are extended versions of those given in Holdsworth (1992)

Table 4.4 Variation of F- and C-values with temperature and reference temperature

Temperature (°C)	$F_{121.1}^{10}$(min)	$C_{100}^{33.1}$(min)	$C_{121}^{33.1}$(min)
100	7.76×10^{-3}	1.00	0.23
110	7.76×10^{-2}	2.15	0.46
121.1	1.00	5.05	1.00
130	7.76	10.00	1.85
140	77.60	21.50	3.71
150	776.00	46.40	7.42

While point values, F_c are applicable to microbial inactivation, it is the total integrated or mass-average values that are most appropriate for cooking; thus we can define a C_s-value by

$$C_s = D_{ref}\log(c_0/c) \tag{4.27}$$

where c_0 and c are the concentrations of heat-vulnerable species at times 0 and t, respectively, and D_{ref} is the D-value corresponding to the z_c value, and

$$\log(c_0/c) = \frac{1}{D_{ref}}\int_0^t 10^{(T-T_{ref})/z_c}dt. \tag{4.28}$$

Jen et al. (1971) developed the Stumbo equations (4.17) and (4.18) to take into account the nature of the distribution of heat-vulnerable components, and indicated that Stumbo's distribution equation $(F_\lambda - F_c) = mv$ does not apply to the outer portions of the can; consequently, a new relation equation (4.29) was developed, which encompassed the whole volume,

$$\ln(1-v) = -m(F_\lambda - F_c). \tag{4.29}$$

Using this equation in the F_s equation,

$$C_s \equiv F_s = F_c + D_r\log\left[\frac{D_r + A(F_\lambda - F_c)}{D_r}\right] \tag{4.30}$$

where A depends on the geometry. Jen et al. (1971) indicated that A was 10.9 for a cylindrical can, while Newman and Holdsworth (1989) obtained values of $A = 9.28$ for a spherical object, 10.73 for a cylindrical object and 11.74 for a cube-shaped object.

The art of canning consists of selecting times and temperatures which achieve the desired purpose of microbial destruction and adequate cooking without undue loss of nutrients. The C-value concept, combined with optimization theory, helps to put this on a more scientific basis.

4.2.2 Origin and Rationale of Cooking Value

Cooking value was derived from the F_o definition. To have a clear understanding of it usefulness as a quality indicator, we shall first take a close look at the derivation of the F_o value (see Sect. 4.1.4).

In the same manner, with the same constraints and rationale as was derived F_o (Eq. 5.15), if a quality factor has first order inactivation kinetics, it is possible to obtain the following expression for a quality factor in a closed system:

$$x \cdot D_r^c = \int_0^t 10^{\frac{T-T_r}{z_c}} dt \tag{4.31}$$

where D_r value is the reference D value for the target attribute and z_c is the corresponding z value for the target attribute. As was the case for F_r, we can define:

$$x \cdot D_r^c = C_r \tag{4.32}$$

Then:

$$C_r = \int_0^t 10^{\frac{T-T_r}{z_c}} dt \,\text{or, in its common form:}\; C_o = \int_0^t 10^{\frac{T-100}{z_c}} dt. \tag{4.33}$$

One alternative, a practical use of the aforementioned equation, is the calculation of the cooking value on the surface. But, as mentioned in the beginning it will be necessary to have a z_c value and, in addition, a corresponding value for D_r. Without knowing D_r the obtained value for C_r is not interpretable and understandable. Depending on the target attribute (D_r), C_r will have different meanings.

Clearly, the calculation of cooking value (C_r) at the cold spot is not important because it is reflecting the minimum cooking value in the whole food product. To calculate the cooking value, besides the temperature history, the only requirement is z_c value. According to its definition z value represents the temperature dependency but has no relation to the thermal resistance of a given attribute. On the other hand, D value has a direct relation with the thermal resistance of the target attribute, and it is not required to calculate the cooking value. Then, the intricate problem will be how to interpret the obtained cooking value. Clearly, it will have different meanings depending on the target attribute. According to the Appendices B.4 and B.5, D_{121} values vary widely from 0.45 through 2350 min.

How, for example, can one interpret a cooking value of 30 min ($T_r = 100$ °C)? Choosing real values for quality factors from the appendix (pea purée and green beans) with the same z_c (32.5 °C) but with different D_r (4 and 115 min at 121 °C), the following results were obtained: In the case of the less resistant attribute, we obtained 0.8 decimal reductions and surface retention of 15.84 %, and for the most resistant attribute, 0.028 decimal reductions and a surface retention of 93.8 %.

Another critical aspect of the utilization of cooking value is the fact that z_c presents a wide range among different target attributes. It would seem difficult to accept a universal value of 33.1 °C for z_c. According to Appendices B.4 and B.5, z_c ranges from 2.66 through 109.7 °C. A quite small difference of 5 °C in z_c will account for a cooking-value difference in the range of 10–15 %, with the remaining problem of its particular interpretation.

In addition, the cooking value concept, like quality retention, has been strongly linked to a *first order kinetic* and *closed system*.

4.2.3 *Quality Retention*

A better way to examine the impact on quality of a given process—with the specified constraints—is the evaluation of the target attribute retention. Starting, again, from Eq. (5.7) and assuming first-order kinetics for the attribute deterioration, we can obtain an equation for surface retention:

$$\%\text{Surface-retention} = 100e^{-\frac{\ln 10}{D_r}\int_0^t 10^{\frac{T_S - T_r}{z_c}}} dt, \tag{4.34}$$

and relating the surface retention (Eq. 5.34), with the cooking value (Eq. 5.33), we obtain:

$$\%\text{Surface-retention} = 100e^{-\frac{\ln 10}{D_r}C_r} \tag{4.35}$$

The main difference between Eq. (5.34) and the equation for cooking value is that the surface retention is a direct calculation of the process-impact over the food product's surface. To do the calculations for surface retention it is necessary to know, not only the value z_c, but also the D_r value.

In addition, in the case of retention, it is also possible to derive an equation for the average retention. The volume-average quality retention value is given by:

$$\%\text{Average} = \frac{100}{V}\int_0^V e^{-\frac{\ln 10}{D_r}\int_0^t 10^{\frac{T - T_r}{z}} dt} dV \tag{4.36}$$

The main drawback of Eq. (5.36) is the requirement of information. It is imperative to have temperature data for the whole container for the whole process.

4.3 Pasteurization Value

For products with a pH less than 4.5, so-called acid products, food poisoning organisms of the type *Clostridium botulinum* do not germinate; consequently it is only necessary to inactivate molds and yeasts. This can be done at much lower temperatures, with the result that the F_0-values are very low, since the lethal rate at a temperature of 80 °C is 7.76×10^{-5} min^{-1}. A more practical unit for quantifying the lethal effect of this type of process is the pasteurization unit P (Shapton 1966; Shapton et al. 1971) given by

$$P_{65}^{10} = \int_0^t 10^{(T-65)10}\, dt \tag{4.37}$$

where the reference temperature is 65 °C.

For the pasteurization of beer, the PU, i.e., pasteurization unit, has been suggested (Ball and Olson 1957) and defined by

$$PU = \exp[2.303(T - 140)/18], \tag{4.38}$$

which is equivalent to P_{140}^{18} in Fahrenheit units. This has been developed into a standard pasteurization unit. 1 PU is equivalent to a process of 1 min at 140 °F (60 °C) (Portno 1968), with $z = 7$ °C for beer spoilage organisms. Using these criteria, Fricker (1984) suggested that a satisfactory process for stabilizing beer was 5.6 PU.

Horn et al. (1997) have used the concept of PUs for pasteurizing beer, adopting a reference temperature of 60 °C and z value of 6.94. The experimental results showed that the average PU was of the order of 20 min. The authors also discussed staling of the beer and the development of a quality unit based on chemiluminescence analysis.

For the milk industry, Kessler (1981) proposed a P^*-value, based on a reference temperature of 72 °C and z-value of 8 °C with Eq. (5.37), where a satisfactory milk process was $P^* = 1$.

The pasteurization of tomato products has been investigated by Tucker and Emond (2000), Plazl et al. (2006).

The general principles of pasteurization have been reviewed by Silva and Gibbs (2009) and Tucker (2012). Practical guides for the food industry are also available see Campden BRI (1992, 2006).

4.4 Minimally Processed Foods

The current trend in the food industry is to reduce the thermal process used for sterilizing food products and hence improve the overall quality. For this purpose much research work has been carried out on using processes that reduce the heating time. Some of these processes are discussed in this section.

4.4.1 Acidified Products

Apart from those products which fall naturally into this class, acidification, where organoleptically acceptable, is a method of reducing the heat process. The extent to which this is possible depends on the actual pH (see Sect. 5.5). It is essential with acidification processes that the acid penetrates the product completely; otherwise, there would be a danger of under sterilization in the regions where the acid had not penetrated. The effect of pH on the heat resistance of bacteria has been thoroughly discussed by Palop and Martnez (2006).

A hot-fill technique, which is used with acid fruit products, heats the product to or near to boiling, fills the preheated container, seals it rapidly, inverts the container to heat the lid, then uses air to cool it. The heat is sufficient to inactivate spoilage organisms likely to grow under the acid conditions. The pasteurization value given to the product depends on the most heat-resistant microorganism or spoilage enzyme present. Sandoval et al. (1994) have produced a mathematical model for the process that involves calculating the temperature–time profile of the product, i.e., tomato purée, during the cooling process in air, and the effect of the external heat transfer coefficient. Several workers have also studied the process, including Nanjunaswamy et al. (1973) with mango products, Nath and Ranganna (1983) with guava pulp, and Silva and Silva (1997) with cupuaça (*Theobroma grandiflorum*) purées. See Table 4.5 for heat treatment recommendations for some pasteurized acid products.

4.4.2 Pasteurized/Chilled Products

Pasteurized foods, so-called *sous vide* products, are stored and retailed at low temperatures. Generally they have had a 6*D* process, which is equivalent to a thermal treatment of 12 min at 70 °C. While this is adequate for inactivating the human pathogen *Listeria monocytogenes*, it is far from adequate for the inactivation of *Clostridium botulinum* spores. It is therefore necessary to hold the product at a chilled temperature to prevent the growth of botulinum spores. At 5 °C type E

Table 4.5 Heat treatment recommendations for some pasteurized acid products

Product	pH	${}^{z}F_{T}$-value min
Tomato	3.9–4.6	${}^{8.8}F_{93} > 20$
Green olive	3.6	${}^{20}F_{62.5} > 15$
Pickles 1–2 % acetic acid. no sugar:		
Onion, cucumber and capers	<3.7	${}^{7}F_{87} > 5$
Pickles 1–2 % acetic acid with sugar:		
Leek and carrot	3.7–3.9	${}^{7}F_{87} > 20–25$

Data from Perez (2002) Centro Técnico Nacional de Conservas Vegetales, Spain spores regenerate in 42 h and type B spores in 30.3 h. Thus these products have a very limited shelf-life in the distribution chain. Considerable advantage has been taken, during the last few years, of microwave heating to achieve a low thermal process with recipe products packaged in plastic trays. The standards to be achieved in controlling this type of product have been extensively discussed (Betts and Gaze 1993; Chilled Foods Association 1998). It is necessary with this type of product to exercise every care in their manufacture, distribution, storage and reuse. Good manufacturing practices for pasteurized foods have been developed (Anon 1992).

4.4.3 Electrical Methods of Heating

Ohmic and microwave types of heating have been widely developed during the last few years. Jun and Sastry (2005) have used pulsed ohmic heating for the sterilization and reheating of food packaged in flexible pouches, e.g., chicken noodle soup and black beans. A 2-D thermal-electric model was developed for optimizing the design and layout of electrodes to ensure uniform heating using a CFD package FLUENT v. 6.1 software.

For packaged foods the only practical method that has been used to any large extent is microwave heating (see Chap. 2). This can only be applied at the present time in batch processes or continuous tunnels at ambient pressures; consequently, sterilization temperatures cannot be achieved. Because of the advantages of microwave heating for achieving low-impact thermal processes, there is considerable interest in extending microwave heating to sterilization processes (George 1994). Provided that a suitable method of control can be established to ensure that uniform heating can be reproducibly attained, then the process may be used to produce ambient shelf-stable products in plastic containers (Mullin 1995).

4.4.4 Other Processes

There are other methods of reducing the required thermal process, which involve using either water activity control or special additives such as antimicrobials, nitrites, and sorbates. The bacteriocin nisin has been used to control clostridium spore outgrowth in a range of low-acid canned foods, including carrot purée, sausages, mushrooms, legumes, soups, hams, and pasta products (De Vuyst and Vandamme 1994).

4.5 Process Achievement Standards

4.5.1 Sterilization

The foregoing sections have indicated the necessary criteria for determining F-, C- and P-values. While the details of determining these are discussed in other chapters, it is necessary to decide whether the value obtained for a process is adequate for the required purpose. In this section the standards used in commercial practice are discussed.

A simple method of determining the efficacy of a process is to relate the F-value to the change in the microbial contamination using the equation

$$\begin{aligned} F &= D_{\mathrm{ref}} \log(N_0/N) \\ &= D_{\mathrm{ref}} \log 10^n, \end{aligned} \tag{4.38}$$

where D_{ref} is the decimal reduction time at the reference temperature for the target organism, N_0 is the initial number of organisms, N the final number and n is the number of log-cycles for the reduction in microbial population. The equation has been modified by Kyzlink (1990) to take into account the effect of nonlinear survivor curves:

$$F = D_{\mathrm{ref}} \log[(N_0/N) + t_x], \tag{4.39}$$

where t_x is usually of the order of 1 min.

Gillespy (1962) used the principle to establish minimum processes for low-acid canned foods on the basis of a maximum value for $D_{121.1}$ for *Clostridium botulinum* of 0.3 min. A process should aim at a microbial survival rate of one spore in 10^{12}, corresponding to 12 decimal reduction times, often referred to as a 12D process; this gives a minimum F-value of 3.6 min. A process that achieves this standard is often referred to as a “botulinum cook.” For a critique of the system, the reader is referred to Kilsby (1985).

More recently Teixeira (2002) has discussed the origins of the 12-D concept, outlining the original work of Esty and Meyer (1922) and concluding that Stumbo (1948) was the first to recognize the logarithmic nature of TDT curves. The latter showed the D-value derived from a plot of the logarithm of survivors versus time.

Pflug and Odlaugh (1978) reviewed the literature on D-values for *C. botulinum* and concluded that a $D_{121.1}$-value of 0.25 min is adequate. Current US practice (Pflug 1987) and UK practice (Department of Health 1994) recommend $F_{\mathrm{min}} = 3$ min.

Pflug et al. (1985) have suggested that for foods with pH in the range 4.6–6.0 and processing temperatures in the range 110–118 °C the minimum F-value should be as given in Table 4.6. It is recommended that extreme care should be taken in using this concept; adequate experimental work should be carried out with individual products to ensure that the minimum processes are entirely adequate. It is also

Table 4.6 Relationship between pH and minimum target F-values in minutes

pH	7.0	6.0	5.7	5.5	5.2	5.0	4.6
$F_{\min}$	3.0	3.0	2.6	2.3	1.9	1.6	1.2

important to ensure that specified processes will deal with the microbial loads encountered in practice.

The F-values achieved in actual commercial processes are always significantly higher than the minimum value, due to safety margins and the cooking requirements of some products. Some values are tabulated in Table 4.7

4.5.2 A Guide to Sterilization Values

Several definitive sources are available for the selection of suitable processes. The ones that are used world-wide are those produced by the National Food Processors' Association, USA, in particular *Bulletin 26-L* (NFPA 1982), which gives recommendations for thermal processes for low-acid canned foods in metal containers; and *Bulletin 30-L* (NFPA 1971), which gives recommendations for thermal processes for low-acid canned foods in glass containers. These are extremely valuable since they not only give recommended processes but also refer the processor to their laboratories for further advice on difficult products.

In the UK the publications of Campden BRI are widely used and respected. The main ones are: *Technical Bulletin No. 4* (Atherton and Thorpe 1980), which gives a wide range of equivalent process times and temperatures for both sterilizing and cooking a range of fruit and vegetable products, for both rotary and static process; and *Technical Manual No. 6* (Atherton 1984), which deals with the processing of uncured meat products. The statistical variability of lethality distribution and F_0-values has been discussed by Hall (1997)

In France the main source of information is "*Barèmes de Sterilisation pour Aliments Appertisés*" (Institut-Appert 1979), which gives a time and temperature for given can sizes of specific products.

Some general principles are as follows. For low-acid products (pH 4.5) the minimum process is taken as $F_0 = 3$ min, but more severe processes equivalent to $F_0 = 6$ min or longer are usually applied to control spoilage organisms. There are a number of low-acid products that receive special treatment by virtue of statutory legislation, e.g., milk and dairy products. In the UK there are Statutory Instruments (SIs) that deal with pasteurization and sterilization of milk (SI 1033 of 1977), cream (SI 1509 of 1983), and milk-based drinks (SI 1508 of 1983). The process for sterilized milk is that it should be maintained at a temperature above 100 °C for such a period so that it complies with the turbidity test. Sterilized cream and milk-based drinks should be heated to a temperature not less than 104 °C for not less than 45 min. For UHT sterilization, milk should be heated for not less than 1 s at a

Table 4.7 Some F_0-values for canned foods[a]

Product	Can size	Min F_0
Meat based:		
Curled meats and vegetables	Up to 16Z	8–12[b]
Ham 3.3 % brine	–	0.3–0.5[c]
Ham 4.0 % brine	–	0.1–0.2[c]
Ham "sterile"	1 and 2 lb	3–4[b]
Luncheon meat 3–4 % brine	–	1.0–1.5[c]
Luncheon meat 4–4.5 % brine	–	1.0[c]
Luncheon meat 5–5.5 % brine	–	0.5[c]
Meat in gravy	All	12–15[b]
Meat (sliced) in gravy	Oval	10[b]
Meat loaf	A2	6[d]
Meat pies	Tapered, flat	10[b]
Pet food	A2	12[d]
Pet food	Up to 16Z	15–18[b]
Pet food	A10	6[d]
Sausages 2.5 % brine	–	1.5[c]
Sausages Vienna in brine	–	5[d]
Sausages in fat	Up to 1 lb	4–6[b]
Sausages Frankfurters	Up to 16Z	3–4[b]
Vegetables:		
Asparagus	All	2–4[d]
Beans in tomato sauce	All	4–6[b]
Carrots	All	3–4[b]
Celery	A2	3–4[b]
Chili con carne	–	6[d]
Corn, whole-kernel in brine	A2	9[d]
Corn, whole-kernel in brine	A10	15[d]
Corn, cream-style	A2	5–6[d]
Corn, cream-style	A10	2.3[d]
Green beans in brine	A2	3.5[d]
Green beans in brine	Up to A2	4–6[b]
Green beans in brine	A10	6[d]
Green beans in brine	A2–A10	6–8[b]
Mushrooms in brine	A1	8–10[b]
Peas, in brine	A2	7[d]
Peas, in brine	Up to A2	6[b]
Peas, in brine	A2–A10	6–8[b]
Peas, in brine	A10	10[d]
Fish:		
Mackerel in brine	301 × 411	3–4[d]
Herrings in tomato sauce	Oval	6–8[b]

(continued)

Table 4.7 (continued)

Product	Can size	Min F_0
Poultry:		
Chicken, boned	–	6–8[d]
Chicken breast in jelly	Up to 160 oz	6–10[b]
Poultry/game, whole in brine	$A2\frac{1}{2}$ – A10	15–18[b]
Other:		
Baby foods	1/6	3–5[b]
Meat soups	Up to 16Z	10[b]
Tomato soup, non-cream	All	3[b]
Cream soups	A1 to 16Z	4–5[b]
Cream soups	Up to A10	6–10[b]
Milk puddings	Up to 16Z	4–10[b]
Cream	4 and 6 oz	3–4[b]
Cream	16Z	6[b]
Evaporated milk	up to 16 oz	5[b]

[a] Extensive tables of recommended F_o-values (American and European) are given in Eisner (1988)
[b] Collected UK data
[c] Codex Alimentarius (1986)
[d] Alstrand and Ecklund (1952)

temperature not below 132.2 °C, and cream should be heated for not less than 2 s at a temperature not below 140 °C.

Another group of products that receive subminimal processes are canned cured meats, which contain salt or sodium nitrite as an inhibitor and some of which must be further protected by storage at refrigerated temperatures. These generally receive processes between $F_0 = 0.5$ and 1.5 min, the severity of the process being inversely proportional to the concentration of the inhibitor. These products require careful processing and, in particular, special control of the initial spore loadings.

For acid products, with pH below 4.5, the risk of growth and production of toxin by *C. botulinum* is highly unlikely. For products with pH 4.0–4.5 processes are designed to control the survival and growth of spore-forming organisms, e.g., *Bacillus coagulans*, *B. polymyxa*, *B. macerans*, and butyric anaerobes, e.g., *C. butyricum* and *C. pasteurianum*. A process of $F^{10}_{121.1} = 0.7\text{min}$ is recommended by Hersom and Hulland (1980) for this purpose. Townsend et al. (1954) recommended a process of $F^{8.3}_{93.31} = 10\text{min}$ for products with pH in the range 4.3–4.5 and $F^{8.3}_{93.31} = 5\text{min}$ for pH 4.0–4.3. For products with lower pH, temperatures below 100 °C are usually adequate; however, heat-resistant molds, e.g., *Byssoclamys fulva* and *B. nivea*, may be present, which, if they survive and germinate to produce enzymes, can cause structural breakdown of fruit products, in particular strawberries.

Table 4.7 gives a guide to sterilization values which are used for some products. It is important to treat these as guidance only, since the specific conditions of the process, in particular the hygienic aspects, may be entirely different from the conditions being used in another factory. Whichever process is chosen, it is essential that the process is checked and verified under appropriate conditions, especially if there has been a change in container size, product specification or operating procedures. Stumbo (1983) have produced an extensive and valuable guide for lethalities for both conduction and convection packs.

4.5.3 Cooking

There are no standards for cooking in the same sense as there is a minimum F-value. While it is possible to determine C_s-values for acceptable sterilization processes (see Tucker and Holdsworth 1991), each commercial process is set to a quality control standard established as a brand image. Consequently, different manufacturers use different processes. There is a need to be able to quantify organoleptic attributes, and this may be done by determining the C_s-value.

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Chapter 5
Safety Aspects of Thermal Processing

5.1 Introduction

The aim of this text is to consider some of the engineering aspects of the thermal processing of packaged foods. These include the establishment of a thermal process through mathematical and experimental techniques, and the delivery of the thermal process, involving the correct operation and control of the process equipment. Many aspects of the complete process outlined in Fig. 1.1 have not been dealt with, in particular the food preparation operations, filling and seaming or sealing, can-handling procedures, and hygienic aspects of equipment design and operation. However, an attempt has been made to cover the main aspects of the thermal process and to review developments. In conclusion, it is necessary to consider some of the procedures used in what is today referred to as "good manufacturing practice" (GMP) in terms of legislation and processing guidelines. The aim of thermal processing of packaged foods is to assure that the food is free of microorganisms that can produce foodborne illness. In the case of canned food, the target microorganism is *Clostridium botulinum*, which produces a toxin responsible for serious illness in humans, called botulism. This toxin can affect the nervous system, causing paralysis and sometimes death. At the industrial level and because of legislation and code practices, foodborne botulism is uncommon and is a more complex trouble at the home canning level due to leakage of thermal processing. However, in the past, in the early stages of the canning industry and for close to half a century, the rapid spread of canned foods and evidence that they were causing illness led to recognition of the need to establish a means of assuring the safety of food products. For example, in 1918 in the USA, the first botulism commission was created. In 1922, it published its findings on the extent of botulism from commercially canned food. In 1922, Esty and Meyer determined the heat resistance of clostridium botulinum spores, establishing the basis of a microbiologically safe process for canned food. The recommendations proposed in this work for low-acid canned food were accepted by the US canning industry and later worldwide (Baird-Parker 1995).

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From this pioneering work, the health authorities together with the canning industry have developed some procedures that must be conducted during thermal processing to reduce the risk associated with *Clostridium botulinum* presence inside the can.

5.2 Information Sources

5.2.1 Legislation and Codes of Practice

One of the most important legislative documents relating to the canning industry is the US Food and Drug Administration document titled *Thermally Processed Low-acid Foods Packaged in Hermetically Sealed Containers* (Regulations 21, Part 113, 1983), which deals with definitions, GMP, establishing scheduled processes, operations in the thermal processing room, instrumentation and control for batch, agitating and hydrostatic retorts, processing and production records, and process deviations. Part 114 of the same regulation relates to acidified foods.

In the UK a code of practice has been established by the industry titled *Guidelines for the Safe Production of Heat Preserved Foods*, published by HMSO in 1994 for the Department of Health. This covers similar topics to the US legislation; it is not mandatory but recommended.

Another legislative document, adopted by the European Commission, is the Codex Alimentarius document Vol. G CAC/RCP23–1978, titled *Recommended International Code of Practice for Low-acid and Acidified Low Acid Canned Foods*, published in Rome by the World Health Organization.

5.2.2 GMP Guidelines and Recommendations

In the USA, The National Food Processors' Association produces a number of booklets of which the following are important: "Thermal Processes for Low-Acid Canned Foods fn Metal Containers" (Bulletin 26L); "Thermal Processes for Low-Acid Canned Foods in Glass Containers" (Bulletin 30L); "Flexible Package Integrity Bulletin" (Bulletin 41L) and "Guidelines For Validation Of Automatic Retort Control" (Bulletin 43L 2nd Ed. 2002).

The American Society for Testing Materials has produced a useful guide to the flexible packages: Designation: F 1168–88 "Standard Guide For Use In The Establishment Of Thermal Processes For Foods Packaged In Flexible Containers" (F1168–88).

A major reference work, published annually, for US legislation and standards is *The Almanac of the Canning, Freezing Preserving Industries*, published by Edward E. Judge & Sons, Inc., Westminster, MD.

The UK has developed a considerable number of GMP guidelines, many of which have already been mentioned. These include a range of documents from Campden and Chorleywood Food Research Association, in particular, the following Technical Manuals: “Canning Retorts and Their Operation” (No. 2); “Guidelines for the Establishment of Scheduled Processes for Low-Acid Foods” (No. 3); “Guidelines on GMP for Sterilisable Flexible Packaging Operations for Low-Acid Foods” (No. 4); “Process Control in Hydrostatic Cookers” (No. 5); “The Heat Processing Of Uncured Canned Meat Products” (No. 6); “Guidelines for the Establishment of Procedures for the Inspection of Canneries” (No. 12); “Operation of Batch Retort Systems–Fully Water Immersion, Raining Water and Steam/Air” (No.13); “Process Control in Reel and Spiral Cooker/Coolers” (No. 26); “Food Pasteurization Treatments” (No. 27); “The Processing of Canned Fruits and Vegetables” (No. 29); “The Shelf Stable Packaging of Thermally Processed Foods in Semi-Rigid Plastic Barrier Containers” (No 31); and “HACCP: A Practical Guide” (No. 38).

5.2.3 *Technical Training*

The technical complexity of the canning operation demands that all types of operatives are thoroughly trained in the aspects of the subject to the appropriate level. This is particularly true as new methods of processing and packaging develop. The training is carried out at appropriate institutions that have close connections with the industry. At the present time courses include cover factory operations, canning principles, and thermal process calculations. Most institutions produce documentation for their courses of instruction, which is generally confidential to the recipients. However, a number of general training documents are available from US sources. The Food Processors’ Institute publishes a joint NFPA/FPI document *Canned Foods—Principles of Thermal Process Control, Acidification and Container Closure Evaluation*, the latest edition being the 5th (1989). The Institute of Food Technologists publishes a course book titled *Introduction to the Fundamentals of Thermal Processing*. Finally, the Environmental Sterilization Laboratory publishes I.J. Pflug’s *Textbook for an Introductory Course in the Microbiology and Engineering of Sterilization Processes* (6th edition, 1987).

5.3 Some Techniques for the Implementation of GMP

5.3.1 *HACCP Techniques*

The technique known as hazard analysis critical control points (HACCP) involves several stages:

(a) Hazard identification and analysis;
(b) Identification of critical control points (CCPs);

(c) The establishment of CCP criteria;
(d) The monitoring of CCPs;
(e) The development of protocols for CCP deviations and verification.

The basis for HACCP is hazard analysis, and this deals with all aspects of the manufacturing and distribution operations. It includes the determination of the hazards and assessment of risks and the effects of each hazard as determined by using an engineering flow sheet of the operations. The CCPs are then selected on the basis of the degree of risk to which the consumer would be exposed, and where a breakdown in control would lead to a consumer being subjected to risk. The number of CCPs should be about six: more would indicate an increase in the degree of complexity of the process, and less would indicate that something may have been missed. The choice is critical to the success of the operation of the system. Each CCP should be capable of being effectively monitored, preferably in real time; this method replaces end-of-line sampling. This is not always possible with microbiological techniques, which take time to deliver results. A monitoring system should include careful recording to identify deviations and their correction. The protocols that must be followed when deviations occur must then be established, and plans implemented to correct the system. Verification should also be included, since this is often required by regulatory agencies or process audit investigators. The stages of HACCP analysis are as follows. First, the details of the process, factory, operation, and management routines are obtained and clearly displayed. Second, the essential characteristics of the product are obtained and analysis made of the requirements to safeguard the product at various stages in the operation. Third, all the process operations are examined for process deviations and then the CCPs can be identified. To determine whether a control point is critical or not, two parameters are used to determine the "severity" of the process, i.e., the magnitude of the potential hazard and an estimate of the likely occurrence of the hazard and the risk. Risk analysis may be achieved by one of three methods: probabilistic, comparative, or pragmatic.

The probabilistic method of risk analysis involves an assessment of the probability of an event occurring, e.g. a failure. It is also necessary to be able to define the chance accurately; this can be done with machinery failures if performance records are kept. The probabilistic concept is embodied in the classical 1 in 10^{12} concept for the survival of spores of *Clostridium botulinum*, used in the canning of low-acid foods.

In cases where information on risks is not available, e.g., in the case of a new product formulation or a new process, it is possible to use the comparative method, comparing the product with related products that have proved by long experience to be acceptable. The related property must show a relationship or accepted process criteria, e.g., pH or water activity.

The pragmatic method is used when information on the process is not available; it relies on expert judgement as to whether a risk is acceptable or not. Stage 3 requires a high degree of expertise and experience and should only be carried out by suitably qualified persons.

In the fourth stage the various control options are decided. The education and training element is particularly important. Monitoring procedures can also involve visual inspection without the use of measurements, and the observations should be carefully recorded using suitable checklists. These should show details of the location of the CCP, the monitoring procedures, the frequency of monitoring, and satisfactory compliance criteria.

Further details of the basic aspects of the technique are given in the following texts and documents: Bauman (1974), NRC (1985), CCFRA (1987, 1989), ICMSF (1988), Buchanan (1990), USDA (1990), and Williams (2004).

Another technique, process analysis critical control points (PACCP), extends the former concepts to include mechanical, physical, chemical, and contamination aspects (Peri 1991).

5.3.2 Process Audits

An audit is defined in BS 4778/ISO 8402 (1986) as "a systematic and independent examination to determine whether quality activities and related results comply with planned arrangements and whether these arrangements are implemented effectively and are suitable to achieve objectives."

Factory audits involve investigating the operation of the factory to ensure the effectiveness of the factory system. It is an objective method which uses comparison with recognized standards, and it can be used internally as well as with factory customers. The system requires auditors free from any pressures that may bias the report.

5.4 Aspects of GMP

5.4.1 Identification of Critical Factors

While the principles of HACCP apply to the whole process, it is important in relation to this text to look at the components of the process to which this technique may be applied. The delivery of the scheduled process is paramount in ensuring the safety of the processed packaged food. It is therefore important to consider all relevant factors in assessing the relative importance and the risks involved:

1. Food product characteristics including:
    (a) Formulation of components and weight distribution;
    (b) Filled weight and volume;
    (c) Consistency/viscosity of sauce or covering liquid;
    (d) Drained weight before process;
    (e) Size of particulates;

   - (f) Size of conglomerate;
   - (g) pH, a_w, and other physical properties;
   - (h) Location of slowest point of heating in the product.

2. Microbiological load on the product: This is what the process sets out to inactivate and eliminate; consequently it must be a major factor. The microbiological status of all the ingredients must be assessed, especially when new product formulations are being developed. Delays in handling the products and the filled cans must be evaluated for increased microbiological load. While the conditions of handling material in factories have greatly improved over the last four decades, and on-site analytical facilities have become available and more sophisticated, it is still necessary to consider this as a factor of high priority. The scheduled process must be capable of achieving a shelf-stable product.
3. Headspace and filling control: The headspace in cans being retorted should be kept constant and at a predetermined value. This is especially critical in cans that will undergo an agitated process, the severity of which is determined by the motion of the headspace bubble. The effect of deviations in the filling process should be noted.
4. For steam retorting in batch retorts, the following are critical to the delivery of the scheduled process:
   - (a) Correct venting schedule as predetermined for can stacking pattern;
   - (b) Correct process schedule for appropriate container/product;
   - (c) Correct steam temperature;
   - (d) Correct time;
   - (e) Cooling water temperature;
   - (f) Appropriate cooling time;
   - (g) Correct functioning of controller/valves;
   - (h) Steam distributor unblocked and adequate condensate removal facilities. Other factors such as compressed air supply, chlorinated cooling water, and can handling operations are important factors for the integrity of the container and product.
5. Other heating media and batch retorts: steam–air mixtures and hot water. In addition to the points raised above, it is essential that the correct steam–air mixture at the scheduled temperature is used, and that in the case of both heating media, the flow rates, directions of flow and flow distribution are correctly maintained.
6. Agitating batch retorts: In addition to points 3–5 above it is essential to maintain the rate of rotation at the prescribed rate.
7. For continuous reel-and-spiral pressure cooker/coolers, all the above factors are appropriate. An important point is the prevention of excessive condensate buildup due to incorrect operation of steam condensate valves, so that the cans passing through the lower part of the cooker are not immersed in water.
8. For hydrostatic cooker/coolers, again all the above points are relevant, with the additional requirement of having the legs at the correct levels and maintaining the correct speed of the carrier bars.

5.4.2 *Process Deviations*

In the event of a process being incorrectly performed due to, for example, steam supply failure, thermometer inaccuracies, time curtailment, or power supply interruption, it is necessary to determine what course of action is necessary. This generally requires expert judgement, following reassessment of the F-value achieved by the deviant process. Studies range from deviant processes (Houtzer and Hill 1977); to conduction-heating packs (Giannoni-Succar and Hayakawa 1982); to convection-heating packs (McConnell 1952; Huang and Hayakawa 1983); to convection-heating packs with agitation (Denys et al. 1996): and to broken-heating packs (Stroup 1982).

Tucker et al. (1996) made a study of the effect of deviant processes on the sterilization of a number of canned foods (conduction heating—beans in tomato sauce, broken heating—cream of chicken soup and convection heating—peas in brine) using the *CTemp* model see page 24 (first edition). This work showed that both the conduction model and the *CTemp* model were suitable for predicting heating profiles for the canned foods.

Chen and Rhamaswamy (2003) studied a range of critical processes variables, e.g., retort temperature (RT), initial temperature T_i, cooling water temperature T_w, f_h, j_h, and j_c, using article neural networks. The results showed that for the process lethality F, $RT > f_\mathrm{h} \cdot j_\mathrm{h} \cdot T_\mathrm{i} T_\mathrm{w} > T_\mathrm{i} \cdot RT\ T_\mathrm{i} > T_\mathrm{i} f_\mathrm{h} > RT\ T_\mathrm{i} > j_\mathrm{c} RT j_\mathrm{h}$; for process time PT, $RT > f_\mathrm{h} \gg j_\mathrm{h} > T_\mathrm{i} > j_\mathrm{c} > T_\mathrm{i} T_\mathrm{w}$; for cooling time CT, $j_\mathrm{c} > T_\mathrm{w} > f_\mathrm{h}$; and for total process time TT, $RT > f_\mathrm{h} > j_\mathrm{h} > j_\mathrm{c} > T_\mathrm{w} > T_\mathrm{i} > T_\mathrm{i} j_\mathrm{c} > T_\mathrm{i} T_\mathrm{w}$.

With the development of computer control this will ultimately be done automatically (see Chap. 21).

5.5 Thermal Process Validation

5.5.1 *Process Establishment*

The first stage in thermal process validation is to consider process evaluation. Some of the major factors that need to be considered in the establishment of scheduled processes have already been listed in Sect. 5.4. The identification of retorting and product preparation conditions is necessary in order to determine the likely extremes that will occur during production. These are known as “worst case” conditions and must be evaluated to establish the ultimate safety of the process. For heat penetration determinations, these include product formulation and properties; initial temperature; container size and shape; thermocouple location and point of slowest heating in the product. For retorting operations they include container stacking; temperature distribution; slowest heating location in retort; retort control conditions; thermal load; and process service supplies (steam, water, and air pressure) (Tucker 2001).

5.5.2 Lethality Assurance

This is the second stage in process validation. It requires comparison of the scheduled process as established by experimental trials and the delivered process in the production environment. The various factors to be considered include raw material specification and monitoring to the standard required, monitoring the food preparation stages, and establishing the correct thermal process conditions.

The time–temperature conditions should be recorded on a chart recorder for future reference, as well as for process operation, and a manual record of the time and temperature of the master temperature indicator should be kept. The importance of calibration of the temperature indicator against a known traceable standard is paramount.

It is important to ensure in batch operations that each retort crate of cans has been processed. This is done by using either striped retort tape, the stripes going black/brown when the tape has been heated, or Cook-Chex indicators, cardboard tags impregnated with a purple indicator ink that turns green when exposed to wet steam heating (no reaction to dry heating). These indicators can also be altered to have an F_0 range from 2 to 90 min, and by selecting a particular value the process can be controlled to a particular value.

5.5.3 Records

It is necessary to keep full and accurate records of the sterilization history of any production batch or run as part of the quality assurance routine. These records should contain details of all the critical factors concerned with the scheduled process time and temperature, product and production details and container.

The US Food and Drug Administration has an elaborate system of process filing which requires complete information about the equipment, installation, and product, packaging and process details, including critical factors and scheduled process. Electronic records and signatures are the legal equivalents of paper records and handwritten signatures and are required to comply with *FDA Guidance Document 21* CFR Part 11 (www.fda.gov/ora/compliance_ref/part11) (Spinak 2002).

Cook-room audits should also be performed at regular intervals, so that there is an independent confirmation of safety assurance. A periodic survey or compliance audit should be made of equipment, procedures, and personnel training. For further details see NFPA/FPI (1989), Shapton (1986), Shapton and Shapton (1991), and BSI (1987).

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Part II
Thermal Food Process Evaluation Techniques

Chapter 6
Heat Penetration in Packaged Foods

6.1 Introduction

This chapter is concerned with the measurement and interpretation of heat penetration curves, obtained from temperature measurements inside the food in the container or package. It is the most important part of determining an adequate process for sterilizing or pasteurizing food products. However, because of the complex nature of food products, the number of different packages and the variety of methods of processing them, the interpretation of the data is often difficult. All thermally processed packaged foods require a validated process schedule which is traceable to heat penetration measurements. The methods of doing this and the treatment of the experimental data are outlined in Sect. 6.2.

An important protocol for doing heat penetration studies has been established by the Institute for Thermal Processing Specialists (IFTPS 1995, 2014). Similarly May (1997) has produced an industrial laboratory guideline for performing heat penetration tests, which includes guidance on the procedures and for the interpretation of the results. It also highlights the critical control points for a canning operation.

Table 6.1 gives an outline of the factors which affect the rate of heat penetration in canned foods; these are discussed in greater depth in Sect. 6.5.

6.1.1 Heat Transfer and Product Characteristics

The way in which heat is transferred in the food inside the container or package depends on the nature of the food product and the style of packing the components. Some of the earliest published work on heat penetration into cans of food was carried out by Bigelow et al. (1920) at the National Canners' Association in Washington. The now-classical document, *Bulletin 16-L*, revised many times, is well worth study even after more than 85 years. Equally worth reading is the work

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Table 6.1 Factors affecting heat penetration and process severity

Factors	Comment
(a) Process-related	
1. Retort temperature and profile	The higher the temperature the faster the heating rate Depends on sterilizer type: in static retorts and hydrostatic cookers the temperature rises slowly and there is a lag in heating the cans; in rotary cookers the heating starts instantaneously
2. Process time	The longer the process time the greater the heat penetration and the nearer to processing temperature the pack contents become
3. Heat transfer medium	The external heat transfer coefficient, h, governs the temperature at the surface of the container. Steam has a very high h, but h for water or steam–air mixtures depends on the velocity and geometry factors
4. Container agitation	Agitation and rotation improve the internal heat transfer, depending on the amount of headspace, and degree of agitation and rotation
(b) Product-related	
5. Consistency	The composition, consistency, and rheological behavior control the rate of heat penetration. For products of a thin nature or in thin covering liquid, convection heating occurs, while for thicker products heat transfer is mainly by conduction. Some products (broken-heating) show both types of heating
6. Initial temperature	The higher the initial temperature of the contents the shorter the processing. The process is very sensitive to the initial temperature, especially for conduction-heating products, which often do not reach process temperature by the end of the process
7. Initial spore load	The severity of the process depends on the initial spore load; good factory hygiene keeps this low
8. Thermophysical properties	The thermal diffusivity is the controlling factor. This approximates to that of water for most products, but is lower for those which are oil-based and those of low water activity
9. Acidity pH	The severity of the process depends on the pH of the product. Products with $\text{pH} > 4.5$ require the severest processes, whilst products with $\text{pH} < 4.5$ can be pasteurized; this includes acidified products
10. Additives	Certain additives, e.g., nisin, nitrite, salt, and sugar, reduce the process time
(c) Packaging-related factors	
11. Container materials	These include: tin plate, aluminum, glass, and plastic and laminated materials. The thermal conductivity and thickness of the material determine the rate of heat penetration. The lower the conductivity and the thicker the material, the slower the heating
12. Container shape	The external surface area and thickness of the container determine the heat penetration rate. The most rapidly heating packages have the highest surface area and thinnest profile

by Magoon and Culpepper (1921), which deals with heat penetration into canned fruits and vegetables, and all the factors affecting it. Both documents show the remarkable perspicacity of these pioneers, and while there have been many changes in technique and products, and subsequent mathematical development of the subject, these documents form the foundation of this subject.

Table 6.2 Heat transfer in canned foods

Rapid convection	Convection	Convection *f* Conduction broken-heating	Conduction $\alpha \approx \alpha$ water	Conduction $\alpha < \alpha$ water
Type 1:	Type 2:	Types 3 and 5:	Type 4:	Type 6:
Juices	Liquid	Cream soups (starch gel)	Cream style corn	High fat/oil
Broths	Spinach/brine	Noodle soups	Thick purées	Meat and marine packs
Milk	Cabbage/brine	Tomato juice	Solid pack apples/vegetables	High sugar products
Type 2:	Low-starch purée		Jams	Low-moisture puddings
Fruits/syrup	Vegetable soups		Vegetables/meat in sauce	
Vegetables/brine	Sliced vegetables/brine		Marine/sauce	
Meat and marine	Macédoine		Beans in tomato sauce	
Products/brine	Type 7: Vapor Vacuum-packed vegetables Sweetcorn Whole kernel corn		Spaghetti Rice Pet foods	

The various types described are in Sect. 6.1.1

Table 6.2 gives an idealized representation of some of the types of canned foods; it should be taken as guidance only since the formulation of packs can vary considerably. The main factors are the packing style of the components in the cans and the rheological properties of the foods. The basis for the classification was developed by workers at the American Can Co. (Jackson 1940; Jackson and Olson 1940). The table identifies seven types:

1. Thin liquid products which heat extremely rapidly due to internal convection, e.g., fruit juices, beverages, milk, and thin soups. The thicker the consistency becomes, the slower the heating rate.
2. Liquid products containing solid food. The liquid portion heats rapidly by convection and transfers the heat into the particulate by conduction. For products such as peas in brine and strawberries in syrup, the process is determined by heat penetration into the covering liquid. The rate of heat penetration is determined to a large extent by the solid–liquid ratio and packing style. For larger products, such as whole potatoes or celery hearts in brine, heat penetration into the center of the product is necessary to ensure an adequate process and sufficient cooking.
3. Solid products in thick covering liquids, such as beans in tomato sauce and thick soups. Depending on the formulation, heating is first by convection and then,

after thickening by starch gelation, by a conductive mechanism. These products show a heat penetration curve with two different rates of heating, known as a broken-heating curve. The reverse process also occurs (see type 5).

4. Thick products which heat by conduction, and whose thermal diffusivities are about the same as water, there being insufficient or no covering liquid. This covers a wide range of products in thick sauces and gravies and solid pack products.
5. Products which start by heating with a conductive mechanism and then, because of thinning due to structure and rheological changes, heat by convection, e.g., some thickened puddings and some tomato juices. Again this produces a broken-heating type of heat penetration curve.
6. Thick products which heat by conduction but have thermal diffusivities less than water, i.e., they have a high fat or sugar content, e.g., fish in oil.
7. Vacuum-packed products. These contain very little water, sufficient to produce enough steam inside the can to heat the product, e.g., corn on the cob, wholegrain corn and some vegetables.

6.2 Experimental Determination

6.2.1 Temperature Monitoring

The measurement of the temperature at a selected point in the product in the container is paramount to process determination. Temperature sensors are usually thermocouples of various types.

The Ecklund system of thermocouples (Ecklund Custom Thermocouples, Cape Coral, FL, USA) is widely used since each thermocouple is designed to place the sensor element at the point most appropriate to the container size. A standard size is 1.6 mm in diameter, made of copper-constantan (copper/45 % nickel alloy) type T. For very accurate work thin wires are used to reduce the conduction errors.

There are several types of system available: (a) molded thermocouples made of rigid Bakelite insulation, which are available to suit specific can sizes; (b) stainless-steel needle thermocouples, which are relatively thin and rigid; (c) flexible thermocouples which can be used for measuring the heat penetration at the center of particulate materials; and (d) custom-made thermocouples, rigid rod-in-tube type, which can be made to any suitable length. The system allows for the thermocouple to be inserted prior to filling, using a non-projecting mounting with plug-in facilities for the leads.

The thermocouples can be attached to any suitable data-logging system or PC, and special programs can be introduced to give the heat penetration parameters, f_{h} and j, as well as F_0-value.

In Europe, while many laboratories use the Ecklund system, an alternative system, the Ellab heat penetration system, is widely used (Ellab A/S, Copenhagen, Denmark). This has type T thermocouples and has a dedicated system for f_n and j

parameters. The system uses self-threading receptacles which are placed in an opening in the filled and sealed container. A packing gland with a compression fitting allows for the location of the thermocouple sensor at the appropriate point (Eisner 1976).

For pilot-scale rotary cookers special slip-ring devices, commutators and rotary transformers can be supplied by the manufacturers for conveying the signal from the container to the data-logging device.

The historical development of the subject, which has moved rapidly with the development of electronic devices and made many previous devices out of date, has been dealt with by Charlett (1955), Holdsworth (1974, 1983, 1985), May and Cossey (1989), and May and Withers (1993).

For many years the major problem was to measure temperatures inside cans being processed in continuous cookers, e.g., rotary sterilizers and hydrostatic cookers. Various devices including radiotelemetry were used, with limited success. However, more recently a device with encapsulated data-logging facilities, the Ball Datatrace unit, has become available (Datatrace Division, Mesa Medical Inc., Wheat Ridge, CO, USA). This can be fitted inside the can for internal heat penetration or can go through the cooker measuring the environmental temperature. The unit consists of a completely self-contained miniature computer/temperature sensor. The Micropack version has a cylindrical body 1.38 in. in diameter and length varying from 2.16 to 6.16 in., with a probe 1–5 in. long. The temperature is a thermistor, with range 10–150 °C. The computer can store a maximum of 1000 readings and record at frequencies between 1 per second and 1 per day. The performance of this unit has been thoroughly examined and shown to be reliable for temperature measurements in canned foods (May and Cossey 1989; May 1991, 1992).

George and Richardson (2001) have described a noninvasive temperature sensor, which uses a passive electronic inductor-capacitor particle (<5 mm diameter) and an external detection coil. This will withstand temperatures up to 130 °C and has a reproducibility within ±1 °C.

Marra and Romano (2003) have made a study of the effect of the size and position of a radiotransmitting temperature-measuring device using cans of differing sizes. This involved the development of a sophisticated mathematical model, using finite element technique. The results showed that the presence of the measuring device influenced the measured-temperature profile, according to the relative dimensions of the can, especially with the smaller cans sizes as would be expected. A basal position for the sensor had least effect on the temperature profile at the point of slowest heating.

More recently Shaw (2004) has reviewed the use of data loggers for the validation of thermal processes. This includes new units, e.g., Datatrace Microack III (20 mm in length) and Ellab's Tracksence Pro Mini Logger (16 mm in length by 20 mm wide). Both these systems only give time-lapsed data. TechniCAL RTemp wireless data collection systems overcome the problem to some extent by providing real time data. Problems of getting the signal out of the thick-walled retort may be overcome by internal aerials.

For retort pouches special methods of sealing the wires into the package and for locating the thermocouple sensor have been devised (Bhowmik and Tandon 1987; Spinak and Wiley 1982). These use a folded strip welded to the pouch sides which straightens up across the pouch when filled, so that the thermocouple sensor is correctly centered. Alternatively, Peterson and Adams (1983) used machined PTFE blocks to support the thermocouple; Thorpe and Atherton (1972) recommended the use of a nylon cross spacer across the pouch to locate the thermocouple.

6.2.2 Thermocouple Errors

One of the main errors associated with thermocouples is the conduction of heat along the thermocouple wires. While this is of relatively little importance in convection heating packs, it can be very important in conduction heating packs. Conduction errors tend to be greatest during the initial heating and cooling periods. Errors are unimportant in the early stages of heating before the temperature has any significant lethal effect; however, they become significant during the rest of the processing. It is also important to note that the thermal conductivity of the copper wire is 17 times that of the constantan; consequently the main conduction errors occur with the copper wire.

Zang et al. (2002). have studied the effect of thermocouple and receptacle type on the f_h-value in a chicken/gravy pack showing conduction eating characteristics, in 202 × 204 and 211 × 300 cans. Three types of thermocouple were used, viz., flexible, with stainless steel receptacles, and with Delrin plastic receptacles, the latter two having stainless steel needle thermocouples. The highest j_h-value of 1.48 was observed for the plastic receptacles, and the lowest f_h for the stainless steel receptacle. The highest f_h of 22.4 min was observed for the flexible thermometers.

Ecklund (1956) investigated the thermocouples which he had designed, and compared them with a standard thermocouple, assuming that the latter was free from error. He found that the error was mainly associated with the lag factor j and devised a table of correction factors to be applied when using his thermocouples.

Cowell et al. (1959) investigated the conduction errors in simple thermocouples, using both theoretical and experimental results. They found that there was negligible error with very thin wires of thickness 40 s.w.g. (0.122 mm) diameter compared with thicker wires 27–20 s.w.g. (0.42–0.91 mm). They also confirmed Ecklund’s (1956) work concerning the effect on the j-value; however, they found that the rate of heating factor f was also affected when thicker wires were used. For accurate work, especially with the cooling phase, they recommended that wires of low thermal conductivity were used, rather than copper. Hosteler and Dutson (1977) showed a similar dependence on wire size during the cooking of meat samples.

Beverloo and Weldring (1969) examined the effect of thermocouple construction materials and mode of assembly and found that the effect of errors on the F_0-value was very low. The overestimation of the temperature during heating was compensated for during the cooling.

Packer and Gamlen (1974) considered the heat transfer lag from the surroundings to the sensor element in convection heating packs. They devised a mathematical analysis to determine the magnitude of the error.

A finite-element model was developed by Kanellopoulos and Povey (1991) and the results compared with those from a type *T* thermocouple with wires of diameter 0.56 mm (24 s.w.g.). They considered that the temperature during the heating phase could be overestimated by 2 °C and that the cooling corrections for the *j*-value were not always an adequate compensation for the cooling phase.

The important aspect of this work is the recommendation to use thin thermocouple wires of low thermal conductivity for accurate heat penetration work involving conduction heating and cooling products. For conventional type *T* thermocouples it is necessary to consider the effect of any errors involved, and to consider both heating and cooling phases when determining the achieved lethality.

6.2.3 Thermocouple Calibration

An important aspect of temperature measurement is the calibration of the thermocouples or other temperature measuring devices. It is essential for the purpose of process determination that the thermocouples are regularly checked against a traceable standard. This requires a constant temperature source, e.g., a molten salt or boiling water, and a thermometer calibrated to a national standard. Cossey and Richardson (1991) have described the use of a constant temperature block for the calibration of master temperature indicators, and Dobie (1993) discussed the methods of calibration. The ASTM guidelines (ASTM 1988) should be consulted for exact procedures.

6.2.4 Thermocouple Location: Slowest Heating Point

The main aim of process determination is to locate the thermocouple sensor at the point of slowest heating or critical point, in order to obtain the temperature history: Given that the critical point has been found, then all other points must have reached a higher temperature and received a greater lethal process. Consequently, if the process is safe at the critical point, then it will be safe at all other points in the container. The problem is how to locate this point. The usual method is to put a number of different thermocouples in the can at different points and thereby determine, by trial and error, the position of the slowest heating point. For small sized cans of conduction-heating food the critical point will be near to the center of the food mass, but for larger cans this may not be so, because the center point may go on heating (known as overshooting—Kopelman et al. 1982) after the cooling has started, until in fact the cooling is felt at the center. The geometrical center will always be the slowest heating point during heating but not necessarily during cooling. This tends to produce a circular or triangular cross-sectioned torus symmetrical about the vertical axis, of lowest temperature (Hurwicz and Tischer 1955). This was found to apply to the processing of meat in 300 × 308 cans at processing temperatures of between 107 and 157 ° C. Flambert and Deltour (1974) found that the position of the critical point depended upon the h/d ratio for the particular can. Under the conditions of their work they showed that for h/d ratios less than 0.3 and greater than 1.9 and for h/d about 0.95, the critical point was at the geometrical center. For lower values, $0.3 < h/d < 0.95$, the critical point was constituted by two points located symmetrically along the vertical axis with respect to the central plane. For higher values, $0.95 < h/d < 1.9$, the critical area is ring-shaped and lies within the central plane. Naveh et al. (1983a, b) used a finite-element model to investigate the overshooting phenomenon. They showed that the extent of overshooting was proportional to the value of g, the temperature difference between the critical point and the retort temperature at the end of heating, and decreased as the external heat-transfer coefficient increased. Silva and Korczak (1994) similarly showed that the packaging dimensions and the heating rates affected the position of the least-lethality point. For packs with $0.1 < h/r < 0.9$ the point was located along the central vertical axis, and for $0.9 < h/r < 4.0$ it was located along the radius.

May (2004) has described the location of the slowest heating point in a variety of differing situations, e.g., convection in thin liquids, mixed convection-conduction liquids showing broken heating curves, conduction packs and packs going through a hydrostatic cooker. Wiese and Wiese (1992) have studied the heat penetration characteristics of a range of vegetable products, e.g., beans in tomato sauce, which show broken heating curves.

A similar study was reported by Sumer and Esin (1992) who examined the effect of the arrangement of cans on the slowest heating point for a can filled with water, peas in brine and 28 % tomato paste. For the water the point was 10–15 % of the height of the can from the bottom, for the peas 20–25 % and around the geometric center for the tomato paste. A finite element model was developed for the distribution of temperature in the stacking patterns.

Ghani et al. (2002) have made a study of the destruction of *Bacillus stearothermophilus* in pouches containing a beef-vegetable soup. Simulations using PHOENICS packages were used to determine the relative concentration profiles of the spores and also the temperature profiles. It was shown that the slowest heating zone covered the whole cross section of the pouch at the early stages of heating after which it migrates and located itself about 30 % pouch height.

For convection packs Datta and Teixeira (1988) showed that the point of slowest heating moves during the processing; there are in fact a cluster of points located on either side of the center line low down in the can. The volume in which these points were located was doughnut-shaped. They suggested that the thermocouple should be placed 15 % of the height up from the base of the can. This is lower than the UK recommendation of 20 % (Campden BRI 1977).

It should be possible to demonstrate this effect by using a colored dye in a silicone rubber cylinder, which is decolorized by heating. There must be many dyes which have been examined as food colors and found to be unstable to heat. Alternatively there are chemicals that develop color on heating, e.g., leucoanthocyanins, as witnessed by the pinking of pears and some other fruits when processed in A10 cans. Doubtless there are many other chemicals which could be used to demonstrate this effect.

For a solid packed-product of fish in a cylindrical form, thermal images of the cross-section have been obtained using a thermal imaging camera (Skipnes and Hendricks 2008). These show that the hottest part of the contents was located in an annulus around the cooler edge and center parts.

For practical purposes the UK recommendations are that thermocouples are located as follows:

1. For conduction-heating packs, cylindrical and other shapes of can, the thermocouple should be arranged at the geometrical center of the food mass.
2. For convection-heating foods in cylindrical cans, the point of slowest heating is about one-fifth the height of the can up from the base. The exact point should be determined using multiple thermocouples for each can size and commodity.
3. For products heated in rotary retorts, the slowest heating point is in the geometric center of the food. The temperature should be fairly uniform in rotated and agitated packs, and therefore the actual position of the thermocouple is less critical.
4. For products which show a broken-heating curve, a similar position to that for convection heating products is used if the break occurs towards the end of the heating. For these cases the point of slowest heating should be determined experimentally. It will move upwards during the process when conduction heating starts.
5. For mixed products, which heat by both convection and conduction simultaneously, e.g., potatoes in brine, it is necessary to ensure that the center of the potatoes receive a satisfactory process and the thermocouple should therefore be located in the center of the potato with the largest dimensions.
6. Care should be taken to insert the thermocouple into the side of the can, if possible, since thermocouples inserted into the ends tend to change their position if the ends flex during the processing.

6.2.5 Model Systems

For the purposes of studying heat transfer in containers, obtaining thermocouple correction factors and demonstrating the various modes of heat transfer, simulants have been used. Food products are usually too variable for detailed experimental work, and the use of simulants removes this variability.

The most common of the simulants is known as bentonite (Jackson 1940; Jackson and Olson 1940). In one method of preparation the powder is mixed intimately with water to form a suspension, which is subsequently heated to boiling, cooled and allowed to stand for 24 h. Some workers prefer to use the cold suspension directly for their experiments. Robertson and Miller (1984) made a 10 kg batch of a suspension of calcium bentonite in water by adding it slowly to the vortex created in the water (c. 65 ° C) by a Silverson mixer. The suspension was mixed for 15 min to facilitate hydration and to prevent any clumping. The suspension was stored for 48 h to allow for full rehydration. A 1 % suspension is used for simulating convection-heating packs and suspension of 5 % or more for conduction-heating packs. Broken-heating packs can be demonstrated using a concentration of about 3.5 %. In practice, it requires a good deal of experimental skill to obtain packs which behave uniformly. The thermal diffusivity of bentonite suspensions is very sensitive to the exact composition, and the suspension deteriorates with repeated use. Tong and Lenz (1993) have determined the dielectric properties of bentonite pastes at different temperatures.

For studying convection, a wide range of materials have been used: water, solutions of ethylene glycol, sugar solution, oils with thermal properties independent of temperature and various solutions of known viscosity.

For conduction heating a range of suspensions, including agar, and starch-based materials are available. More recently, silicone elastomers (Dow Corning Ltd., Barry, South Glamorgan) have been used, e.g., Sylgard 170 and 184; although these are expensive materials, they give very reproducible results when used for simulating conduction-heating packs. The thermal diffusivity is, however, somewhat lower than that of water and water-based food products: 1.02×10^{-7} m^2 s^{-1} compared with $1.4–1.6 \times 10^{-7}$ m^2 s^{-1} (Bown et al. 1985).

The thermal diffusivities for some simulants are given in Table 2.2.

6.3 Graphical Analysis of Heat Penetration Data

6.3.1 *The Linear Plot*

The simplest method of plotting the results of a heat penetration experiment is to use linear graph paper. Figure 6.1 shows a typical heating and cooling curve, with the retort temperature profile and the corresponding temperature measured at the critical point. This type of plot is useful for observing the come-up of the retort and for converting the temperatures to a lethality curve for determining the F_0-value.

6.3.2 *The Semilogarithmic Plot*

If the temperature–time results from a heat penetration experiment are plotted on multi-cycle logarithmic-ordinary graph paper, it is possible to construct a straight

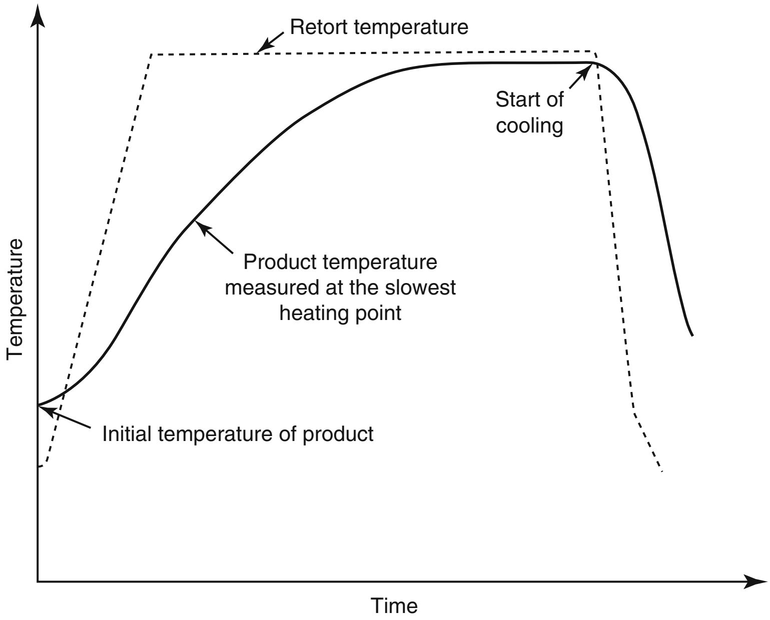


Fig. 6.1 Typical temperature profile for steam heating of canned foods in a batch retort

line through the points. The data for conduction-heating products usually have a lag period before linear heating is achieved, represented by a curved portion to the graph. The extent of this depends on the external heat-transfer coefficient and tends to increase in curvilinearity with increasingly slower heating media or thicker packaging material. The data for convection-heating packs often follow a slightly sigmoidal pattern, and are usually less uniform than those for conduction heating products.

Three methods of representing the results are in common use. The first is log $(T_R - T)$ vs. time t (Fig. 6.2). When the logarithm of the temperature difference between the retort temperature and the critical point temperature, known as the temperature deficit, $(T_R - T)$, is plotted against the time, then a plot is obtained with curvilinear and linear portions with negative slope. When the deficit is greater than one then three-cycle logarithmic paper is satisfactory; however, when the deficit is less than one four cycles will be required. This method is mainly used in theoretical work.

The second method is $\log[(T_R - T)/(T_R - T_0)]$ vs. time t (Fig. 6.3), where $(T_R - T)/(T_R - T_0)$ is the reduced temperature and T_0 the initial temperature of the food in the can; in this case a graph similar to Fig. 6.2 is obtained. This method is mainly used in theoretical work.

The third method is log T vs. t (Fig. 6.4). If the logarithmic scale is arranged to run in the opposite direction to the previous two (inverted scale), and the top line of the graph is numbered 1° below the retort heating temperature, the next line is

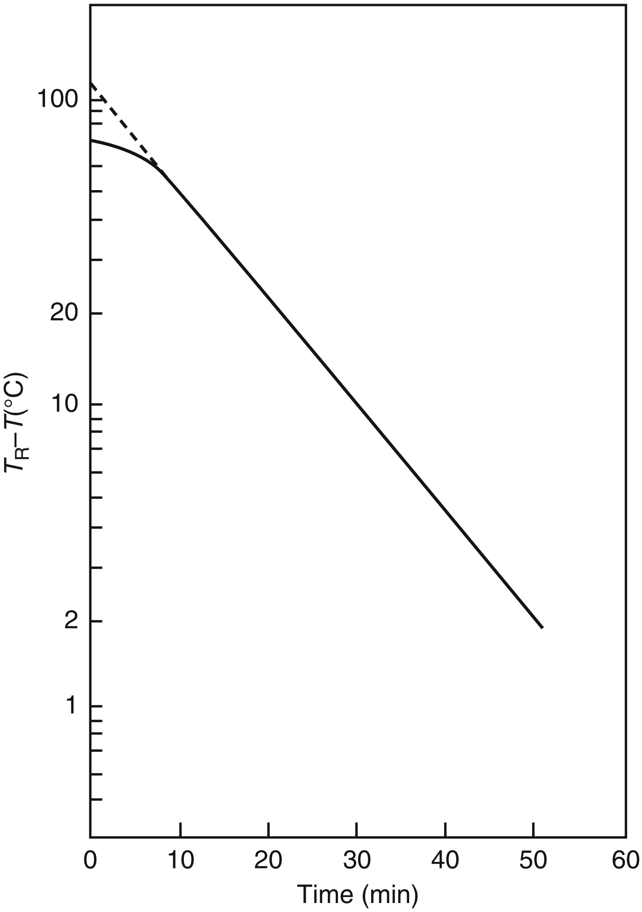


Fig. 6.2 Temperature deficit plot

numbered 2° below, and so forth, then a linear plot with positive slope is obtained. Using this method the lines are numbered with the actual temperatures and no conversion is necessary.

The cooling curves may be represented in a similar manner.

6.3.3 Analysis of Heat Penetration Graphs

A straight line can be obtained from the log temperature–time or semilog plots by drawing the asymptote to the curve (Olson and Jackson 1942; Ball and Olson 1957). The equation of this line is then fully defined by its intercept and slope.

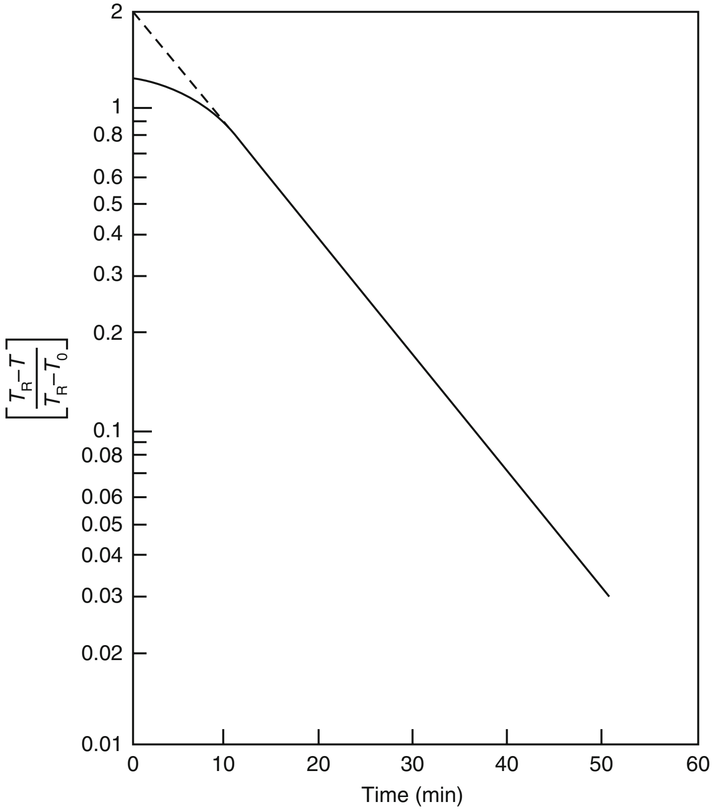


Fig. 6.3 Reduced temperature plot

The intercept is obtained by extrapolating the asymptotic line to the axis and defining a temperature T_A such that

$$T_R - T_A = j(T_R - T_0) \tag{6.1}$$

or

$$j = \frac{T_R - T_A}{T_R - T_0} \tag{6.2}$$

where j is known as the lag factor, since it measures the lag in establishing a uniform heating rate; it is also designated j_h to represent the heating part of the process, and j_c is the corresponding value for cooling. Part of the lag is due to the slow come-up of the retort, and this is accounted for by determining a new zero time for the process. Ball and Olson (1957) used 58 % of the come-up time as making a useful contribution to the process and this is widely accepted. It corresponds to adding 42 % of the come-up time to process time at retort temperature. The j-value

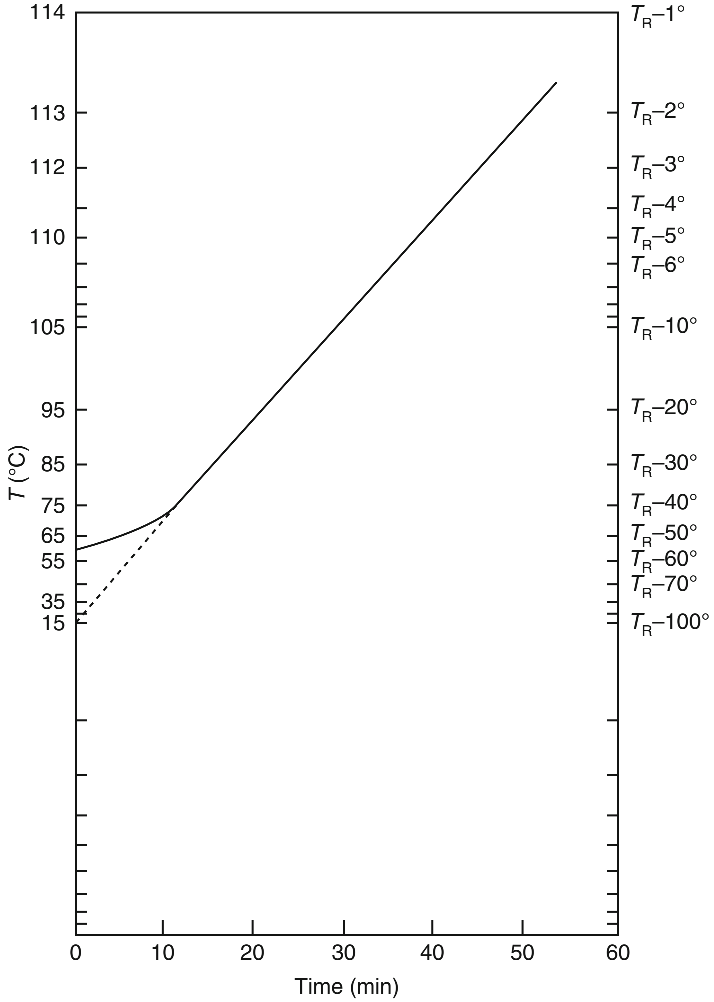


Fig. 6.4 Inverted scale plot for $T_R = 115$ °C and $T_0 = 62$ °C

for this process is found by using the intercept of the line with the new zero axis, T_I (see Fig. 6.5). For this purpose

$$j = \frac{T_R - T_1}{T_R - T_0} \tag{6.3}$$

The slope of the line is given by the tangent of the angle between the line and the t-axis, although it is best obtained as the time for the curve to traverse one logarithmic cycle. This time is known as the f-value and is the time to reduce a given temperature to one-tenth of its value. The f-value is the reciprocal of the slope and cotangent of the angle between the line and the time axis. For the heating phase it is designated f_h, and for the cooling phase f_c.

Combining these two heat penetration factors in the straight-line equation $y = mx + c$ gives the equation

$$\log u = -t/f + \log j, \tag{6.4}$$

where u is the reduced temperature, $(T_R - T)/(T_R - T_0)$, the slope is $-1/f$ and the intercept $\log j$. This equation may also be reexpressed as

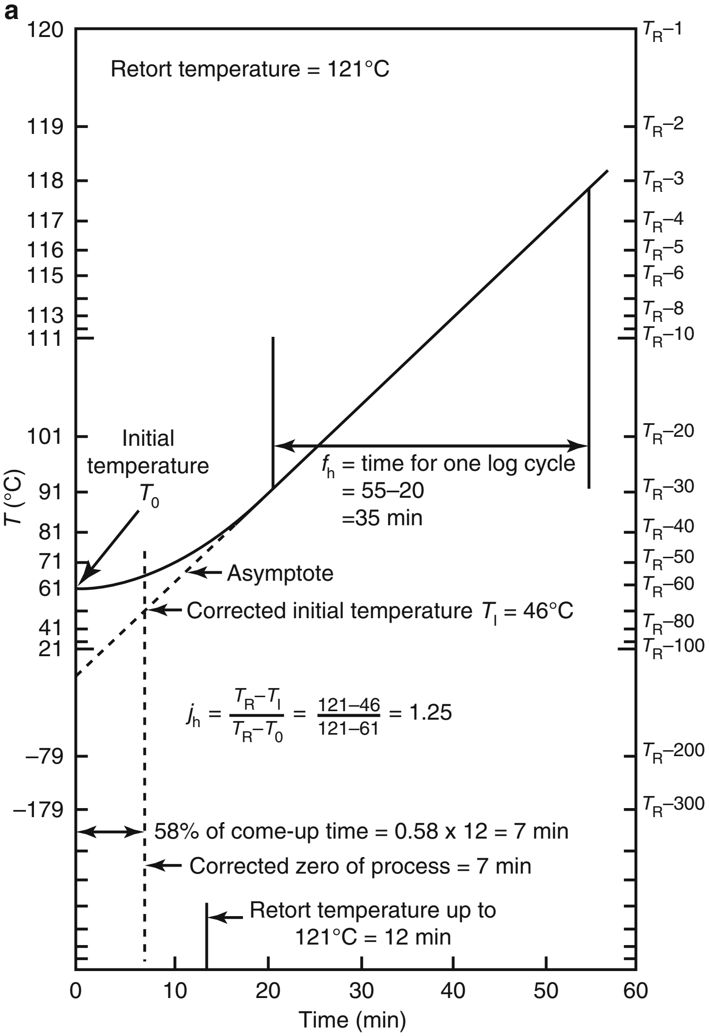
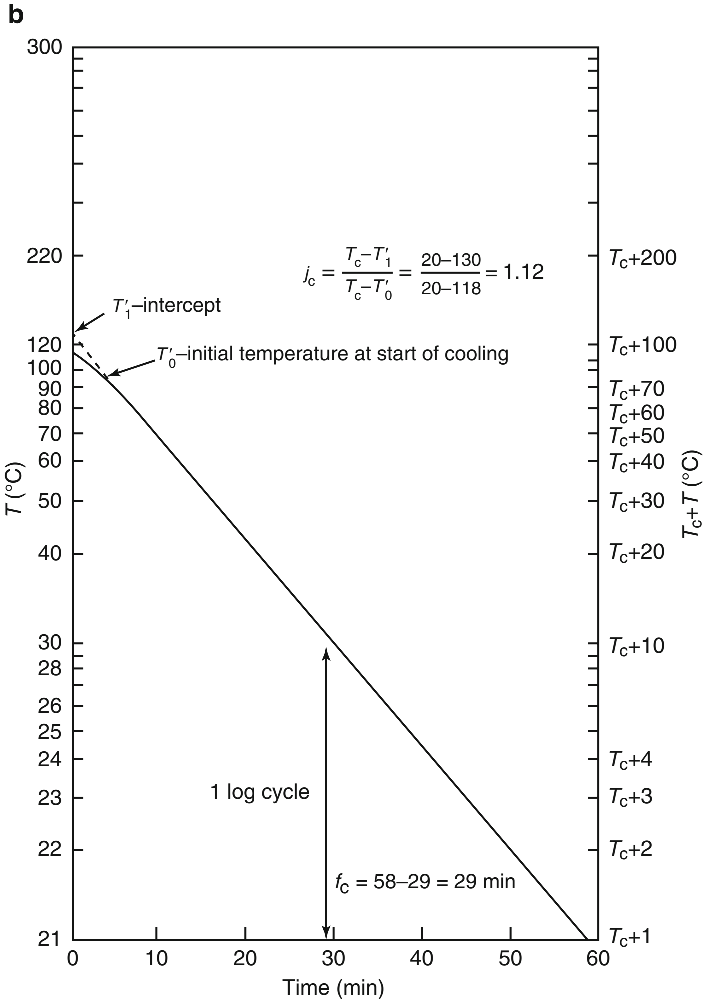


Fig. 6.5 Heat penetration curves: (**a**) heating phase, (**b**) cooling phase



$$j_c = \frac{T_c - T'_1}{T_c - T'_0} = \frac{20-130}{20-118} = 1.12$$

Fig. 6.5 (continued)

$$t = f\log(j/u) \tag{6.5}$$

or

$$u = j \times 10^{-t/f} = j\mathrm{e}^{-2.303t/f}. \tag{6.6}$$

The value of j ranges from approximately 1 to 2, although both smaller and larger values are found in practice. The value, as can be shown theoretically, depends on the position at which the temperature is measured, the shape of the container or body being heated and cooled, and the initial temperature distribution.

Table 6.3 Some typical f_h-values for products processed in static retorts using steam heating

Can size	Conduction heating (min)	Convection heating (min)
211 × 2025 oz	25	4.0
211 × 301 picnic	34	4.5
211 × 400 A1	39	5.0
300 × 2078T	34	4.5
300 × 408$\frac{3}{4}$UT	47	4.5
301 × 40916Z	52	5.5
307 × 408 A2	62	6.0
401 × 411A2$\frac{1}{2}$	83	7.0
603 × 700 A10	198	11.0

The value of f is expressed in minutes, and depends on the thermal properties, in particular the thermal diffusivity, and the dimensions of the object being heated. The faster the rate of heat penetration, the steeper the slope and the smaller the f-value. For most conduction-heating packs f_h is greater than 20 min, and for convection-heating packs values of between 4 and 11 min for the common sizes of cylindrical container are obtained. Table 6.3 shows some typical values of f_h for static steam-heating processes.

The values for f_c tend to be larger because of the slower heat transfer with water compared to steam. An empirical guideline is that $f_c = 1.3f_h$, which is confirmed from the work of Hurwicz and Tischer (1956) for the processing of beef. These workers also found a greater variance in the values of f_c compared with f_h.

For broken-heating curves (see Fig. 6.6) there are two f_h-values, usually designated f_1 and f_2, and a break point, T_p, at time t_p. The retort temperature tends to influence the value of f_2 and the break point parameters t_p and T_p. The closing temperature also affects the break point. The can size affects both f_1 and f_2. For a 3.5 % suspension of bentonite in water in No. 2 cans the values of j varied from 0.99 to 1.72; f_1 from 4.87 to 6.84 min; f_2 from 44.6 to 62.0, and t_p from 6.7 to 8.3 min (Jackson 1940; Jackson and Olson 1940). Baked beans in tomato sauce exhibit a broken heating curve; initially the pack shows typical convection heating behavior and then as the tomato thickens by gelation of the starch leached from the beans, the pack shows increasing conduction behavior. For an A10 can processed at 121.1 ° C, and heated for 35 min typical values for the heat penetration factors are $f_1 = 8.7$ min and $f_2 = 39.8$ min and $t_p = 10$ min. A typical broken heating curve for this type of product is shown in Fig. 6.6 (Tucker 2002). The problems associated with this type of process are dealt with in Sect. 8.2.4.

Giannoni-Succar and Hayakawa (1982) reported values $f_h = 29.37$ and $f_c = 34.45$ min for 8 % w/w bentonite in can size 307 × 115, with corresponding j values of 2.13 and 1.56 respectively. The ratio f_c/f_h was 1.17, which is in general agreement with the quoted value of 1.3.

Bichier et al. (1995) found that for tomato sauce in 300 × 407 cans in a batch retort the $f_h = 44.4$–45.2 min, $f_c = 45.2$ min, $j_h = 1.69$ and $j_c = 1.69$, whereas for an

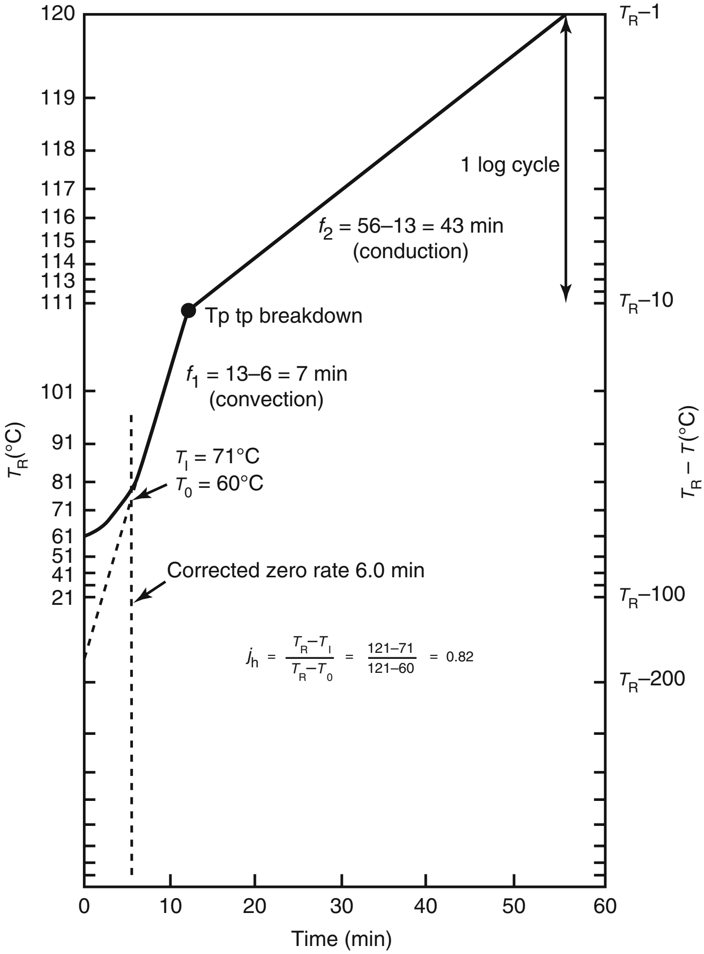


Fig. 6.6 Example of broken heating curve

agitated cook in a Steritort retort $f_h = 3.7$–4.45 min 7 $j_h = 1.44$–2.05 with the f_c and j_c very similar. The value for the stationary process agrees well with the value in Table 6.3.

6.4 Theoretical Analysis of Heat Penetration Curves

6.4.1 Conduction-Heating Packs

In Chap. 2 the general equation for determining the temperature distribution in a cylindrical container of conduction-heating food was presented (Olson and Jackson 1942; Ball and Olson 1957). From this series solution, a first-term approximation can be derived which applies to any point (r, z) in a cylinder of radius r and height $2b$:

$$u = A_{110} J_0(R_1 r/a) \sin\left(\frac{\pi(z + b)}{2b}\right) \mathrm{e}^{-\left(R_1^2/a^2 + \pi^2/4b^2\right)\alpha t}, \tag{6.7}$$

where $u = (T_\mathrm{R} - T(t))/(T_\mathrm{R} - T_0)$, A_{110} is a function of the initial temperature distribution (equal to 2.03970 for a uniform distribution), $J_m(x)$ is the $m$thorder Bessel function of x, R_n the nth positive root of $J_0(x)$ and α the thermal diffusivity. The first-term approximation is only valid for long processing times, and for the purposes of the cooling part it is necessary to examine whether this criterion applies.

Equation (6.7) is of the same form as the exponential heat penetration equation (6.6), viz.

$$u = j\mathrm{e}^{-2.303t/f}$$

from which

$$f = \frac{2.303}{\alpha\left[R_1^2/a^2 + \pi^2/4b^2\right]} \tag{6.8}$$

$$j = A_{110} J_0(R_1 r/a) \sin\left(\frac{\pi(z + b)}{2b}\right) \tag{6.9}$$

$$R_1 = 2.4048.$$

There are two important conclusions from this comparison: first, from Eq. (6.8) the f-value depends on the thermal diffusivity and the container dimensions; it is the same at all points inside the container, since it is independent of z and r. Second, from Eq. (6.9) the j-value depends on the initial temperature distribution and the position in the can; for conduction-heating packs the theoretical value of j at the center will be 2.03970.

The above analysis applies to containers heated by steam; if there is a finite heat-transfer coefficient on the surface of the container then the equations given in Chap. 2 should be used. This is discussed further in Sect. 6.5.6. A more detailed discussion of this subject has been developed by Eszes and Rajk (2004), who included a study of thermal diffusivity, heat transfer coefficients and other thermal parameters.

6.4.2 Convection-Heating Packs

Using the uniform internal temperature model, discussed in Chap. 2, the basic equation for the temperature in the fluid core is

$$u = 10^{-0.434Kt}, \tag{6.10}$$

where u is the reduced temperature $(T_R - T(t))/(T_R - T_0)$ and $K = UA/\rho V$, in which U is the overall heat-transfer coefficient, A is the internal surface area of the container, c is the specific heat and ρ is the density.

Comparing Eq. (6.10) with the heat penetration equation in the same form,

$$u = j \times 10^{-t/f}, \tag{6.11}$$

we obtain

$$f = 2.303/K = 2.303_{cp}V/UA \tag{6.12}$$

$$j = 1.$$

For many products the value of $c\rho$ is constant, so that f is directly proportional to the volume of the system and indirectly proportional to the internal area of the container and the heat-transfer coefficient. Although in theory $j = 1$, in practice a wide range of values, some less than 1, are observed. The reason put forward for this is that the U-value is initially high because of the high driving force ΔT, and with increasing time this decreases progressively to a constant value. The f_h-value will be small initially and will increase to a constant rate of heating. The initial low value will favor low values of j, which will be less than the theoretical value of 1.

Datta (1990) examined the case of natural convection in canned foods and concluded that there was no justification for the existence of an asymptotic straight-line temperature–time relationship, because of the complexity of the temperature field and the flow patterns. However, he concluded that over short ranges of processing time the errors would be sufficiently small to use the approximation for practical purposes. It should be remembered that the method is entirely empirical and care should be taken in the evaluation of convection heating.

Schmidt and Pflug (1966) studied the effect of solids (glass spheres of varying sizes) on the heat penetration factor f_h for jars of water/spheres. They found that the f_h-value decreased with increasing surface area-volume ratio for the spheres, but did not vary with sphere size. Jars of water alone had a higher f_h than filled jars.

Ikegami (1977) derived an empirical convection equation for heat transfer into a can of solids with a covering liquid:

$$u = \frac{jj'f_2}{f_2 - f} 10^{-t/f_2}, \tag{6.13}$$

where f and j apply to the solid portion and f_2 and j' to the liquid portion. From various experimental results the j-values for the solid portion were approximately 2.0, the j'-values for the liquid portion were below 0.5. The formula was rigorously derived in Ikegami (1978).

Akterian (1996) developed a model for predicting heat penetration data for convection heat fruits in syrup and vegetables in brine packed in glass jars. This was based on the uniform internal temperature model (Sect. 2.3), and used the used concept of the coefficient of thermal inertia $E = f_h/\log_e 10$. The values for the f_h calculated from E values ranging from 7 to 25 min are much greater than those given in Table 6.3 for canned products because of the thickness of the walls of the glass bottles and the effect of the external heat-transfer coefficient. A table giving experimental data, including process data, E- and F-values and heat-transfer coefficients, for 20 products is useful for manufacturers using glass jars.

6.4.3 Computer Modeling

A computer model, NumeriCAL—(see Chap. 11), has been developed by Manson (1992) for determining heating factors from heat penetration data. The program has the advantage of not using the Ball 42 % come-up time but calculating this effect from the actual processing conditions. This means that pilot-plant data can be used more reliably. An extension of this model to determine the f_c and j_c factors for the cooling phase was proposed.

6.5 Factors Affecting Heat Penetration

6.5.1 Effect of Container Shape and Dimensions

6.5.1.1 f_h-Value

The f_h for a Cylindrical Container of Conductive-Heating Product is given by the Eq. (6.14)

$$f_h = \frac{2.303}{\left[\alpha\left(2.4048^2/a^2 + \pi^2/4b^2\right)\right]}, \tag{6.14}$$

and is obtained by substituting the values for R_1 and π^2 in Eq. (6.8). This equation can be used for determining the f_h-value for a container of different dimensions, with the same food product. Thus if the first container has a value f_1 and dimensions radius a and height $2b$ and the second container an unknown f^2 and dimensions c and $2d$, respectively, then the value of f_2 can be obtained by eliminating the thermal diffusivity α from the respective equations, giving

$$f_2 = \frac{2.4048^2/a^2 + \pi^2/16b^2}{2.4048^2/c^2 + \pi^2/16d^2} f_1. \tag{6.15}$$

The container dimensions for this type of calculation should be based on the mass of product. Thus the diameter is the nominal can diameter less $\frac{1}{8}$in. and the height is the nominal can height less $\frac{1}{8}$in. less the headspace of the container. For two-piece cans with only one double seam $\frac{1}{16}$in. is subtracted. An easy system, using can factors, for conversion to various can sizes is given by Ball and Olson (1957) in tabular form. This only applies to cans with seamed lids at the top and bottom; consequently, for modern two-piece cans with one seamed end and for many other types of package it is more appropriate to calculate the conversion directly using Eq. (6.15).

A similar equation can be obtained for a brick-shaped container or pouch (Olson and Jackson 1942),

$$f = 0.933/\left\lfloor \alpha\left(1/a^2 + 1/b^2 + 1/c^2\right)\right\rfloor \tag{6.16}$$

and if f_1 applies to a container of dimensions $2a$, $2b$, $2c$, and f_2 applies to one with dimensions $2p$, $2q$, $2r$, then f^2 is given by

$$f_2 = \frac{1/a^2 + 1/b^2 + 1/c^2}{1/p^2 + 1/q^2 + 1/r^2} f_1. \tag{6.17}$$

The container dimensions are determined in the same way as before.

If the object can be approximated to a slab then only one term is necessary:

$$f_2 = p^2 f_1/a^2. \tag{6.18}$$

For convection heating, a similar conversion can be carried out using the general equation

$$f = 2.303\frac{cpV}{UA}, \tag{6.19}$$

from which the relation between the f-values for two cans of differing sizes with radii a_1 and a_2 and heights h_1 and h_2 can be obtained, by substituting for the volumes ($\pi a^2 l$) and surface areas ($2\pi a^2 + 2\pi a l$) of the cans:

$$f_2 = \frac{V_2A_1}{V_1A_2} f_1 = \frac{a_2 + l_2}{a_2 l_2}\,\frac{a_1 l_1}{a_1 + l_1} f_1, \tag{6.20}$$

where a and l are, respectively, the radius and height of the container, suitably adjusted for the seam and headspace dimensions. Ball and Olson (1957) have again produced tabular data for easy conversion of can sizes. Kopelman et al. (1981) developed conversion factors for a wider range of processing conditions and other containers, by expanding the overall heat-transfer coefficient so that the wall thickness and the outside heat-transfer coefficients could be considered. This allowed conversions to made from metal to glass containers and heating from steam to water.

6.5.1.2 Lag Factor *j*

The Lag Factor *j*, as Previously Discussed, Depends on the Position in the Object. The *j*-value for a Finite Cylinder is Derived from Eq. (6.9)

$$j = 2.03970 J_0(R_1 r/a) \cos(\pi y/2b), \tag{6.20a}$$

where a is the radial position, r is the radius of the can, y is the axial position and $2b$ the height of the can. $J_0(x)$ is a zero-order Bessel function of x and R_1 is the first positive root of $J_0(x) = 0$. The *j*-value for a brick-shaped object of dimensions $2a$, $2b$, $2c$ is given by

$$j = 2.06410 \cos(\pi x/2a) \cos(\pi y/2b) \cos(\pi z/2c). \tag{6.21}$$

Olson and Jackson (1942) also showed that, contrary to the theory, the *j*-value was related to the diameter-length ratio for a finite cylinder, attaining a maximum value of 1.68 when the length of the can was equal to that of the diameter. This was explained as being due to the fact that the *j*-value was taken from the tangent to the curve rather than the asymptote. This was further investigated by Cowell and Evans (1961), who showed that the *j*-value derived from the tangent equation was related to the height–diameter ratio squared. For theoretical work on this subject of the difference between tangents and asymptotes, the reader is referred to the work of Hayakawa (1964), Alles and Cowell (1971), and Flambert and Deltour (1974).

6.5.2 *Effect of Initial Temperature*

From Eq. (6.9) the factor A_{110} contained expressions for the initial temperature distribution in the product being heated. This meant that the *j*-value was dependent upon this condition. Olson and Jackson (1942) developed an expression for *j* to deal with nonuniform initial temperature distributions,

$$j = 1.27 + 0.77 \frac{T_R - T_W}{T_R - T_0}, \tag{6.22}$$

where T_R is the retort temperature, and T_W is the temperature about 0.1 in. (2.5 mm) from the wall just before heating begins. The equation was used to predict *j*-values for 603 × 700 cans of 5 % bentonite in water, which had different initial temperature distributions. Moderate agreement was shown between the experimental and the practical results. The equation does show the magnitude of the effect, and it is worth considering when doing practical work.

The effect of variable initial temperature distributions will be seen with the cooling phase of large cans, when the critical point temperature is considerably different from the retort temperature.

The effect of varying the initial temperature has also been studied. Berry and Bush (1989) showed that for whole-kernel corn packed in 603 × 700 cans the j_h-value for $T_0 = 25$ °C was 1.36, and for $T_0 = 70$ °C it was 1.66. With smaller-sized cans the effect was less noticeable. The f_h-values were relatively unaffected.

For products displaying broken-heating curves the effect of initial temperature differences was more pronounced on both heat penetration factors and the breakpoint time. The j-values increased and the f-values decreased with increasing initial and retort temperatures.

6.5.3 Effect of Position Inside the Container

It has already been seen from Eqs. (6.8) and (6.9) that the j-factor is dependent on position inside the container, whereas f_h is independent but depends on the container dimensions. The fact that the j-value varies is a very important property and was used by a number of workers to determine the total sterilizing value for the whole container, rather than just at the critical point. The method consisted of constructing a series of iso-j shells in the container and determining the corresponding lethalities.

Ball and Olson (1957) estimated the errors in the j-value associated with thermocouple positioning. For a 307 × 409 container of conduction-heating product, when the temperature sensor is located on the container axis, a displacement of 0.205 in. (5.21 mm) from the center towards either end will produce an error of 1 % in the j-value. If the sensor is located in a plane mid-way between the ends of the can, then a displacement of 0.138 in. (3.5 mm) will produce a similar error. It was concluded that the error in the j-value was slight when the thermocouple sensor was off-center.

6.5.4 Effect of Headspace

Evans and Board (1954) made a theoretical and practical study of the effect of headspace on f- and j-values. The results showed that the f-value is greater when the headspace is taken into account and the j-value slightly less, for both heating and cooling phases. The influence of trapped air on the heating characteristics of a model food packaged in a semirigid plastic container has been studied by Ramaswamy and Grabowski (1996).

6.5.5 Effect of Variation of Physical Properties with Temperature

Using physical property data for “immobilized” water at 20 and 120 °C, Evans (1958) showed that if the value of the thermal diffusivity α at 20 °C was used, the j-value was unaffected, but the f_h-value was decreased. However, when the correct data were used at the appropriate temperature, f_h was 7.5 % higher. It is, therefore, important to consider the effect of temperature on the value of α, since process calculations are very sensitive to small changes in α.

6.5.6 Effect of External Heat-Transfer Coefficients

The effect of using processing media other than saturated steam is to impose a heat transfer restriction on the process. This is measured by the magnitude of the external heat-transfer coefficient, h.

6.5.6.1 *j*-Value

For a finite cylinder, with an external heat-transfer coefficient, the j-value at the center is given by

$$j = \frac{2\sin M_1}{M_1 + \sin M_1 \cos M_1} \frac{2}{\left(1 + R_1^2/Bi^2\right) R_1 j_1(R_1)}, \tag{6.23}$$

where M_1 is the first positive root of

$$Bi \cot M_n = M_n,$$

R_1 is the first positive root of

$$J_0(R_n) = (1/Bi) R_n J_1(R_n),$$

and J_0 and J_1 are Bessel functions of zero and first order, respectively; Bi, the Biot number, is ah/k, where a is the radius, h the heat-transfer coefficient and k the thermal conductivity. Tabulated values are given by Ball and Olson (1957) for a finite cylinder, and Alles and Cowell (1971) for a rectangular container. Castaigne and Lacroix (1986) give tables of Bi against j-values for the center, surface and at the mean temperature for infinite slabs, infinite cylinders and spheres. The value of j for a finite cylinder was obtained from

$$j = j_{\text{slab}} \times j_{\text{cylinder}}.$$

For a brick-shaped package

$$j = j_{\text{thickness}} \times j_{\text{length}} \times j_{\text{width}}.$$

For a slab

$$j = \frac{2\sin M_n}{M_n + \sin M_n \cos M_n}. \tag{6.24}$$

If this is designated $2A_n$, then the *j*-value for a three-dimensional object will be given by

$$j = 2A_n \cdot 2A_m \cdot 2A_p.$$

The first root of M_n is $M_1 = 1.5708 (= \pi/2)$, and $A_1 = 1/M_1$, since $\sin(\pi/2) = 1$ and $\cos(\pi/2) = 0$. Therefore,

$$j = 8 \times 1.5708^{-3} = 2.06410.$$

The *j*-value decreases with decreasing values of the heat-transfer coefficient, i.e., greater resistance.

6.5.6.2 f_h-Value

The equation for the *f*-value corresponding to Eq. (6.23) is

$$f = \frac{2.303}{\left(M_1^2 + R_1^2\right)\alpha}. \tag{6.25}$$

Both M_1 and R_1 increase with increasing h, and consequently the value of f decreases with increasing surface conductance.

Tabulate values are given by Ball and Olson (1957) for a finite cylinder and Alles and Cowell (1971) for a rectangular container. Castaigne and Lacroix (1986) give tables of Bi against $f\alpha/R^2$ for infinite slabs, infinite cylinders and spheres. The values for a finite cylinder and a brick-shaped package are obtained as follows. For a finite cylinder:

$$1/f = 1/f_{\text{slab}} + 1/f_{\text{cylinder}}.$$

For a brick:

$$1/f = 1/f_{\text{thickness}} + 1/f_{\text{length}} + 1/f_{\text{width}}$$

and

$$f = \frac{2.303}{\alpha M_1^2\left[1/t^2 + 1/l^2 + 1/w^2\right]}, \tag{6.26}$$

which becomes, when M_1 is substituted,

$$f = \frac{0.9334}{\alpha\left(1/t^2 + 1/l^2 + 1/w^2\right)}. \tag{6.27}$$

6.5.7 *Effect of Container Material and Thickness*

Lu et al. (1991) compared heat penetration rates into metal and plastic cans (with metal lids) for a range of conduction-heating products. While the *j*-values were found to be about 10 % lower, the f_h-values were correspondingly higher, reflecting the slower heat penetration through the walls of the plastic container. The location of the slowest heating point in the plastic can depend on the orientation of the lid. When the headspace was in contact with the lid the heating rate was slower, i.e., f_h was greater, than when the cans were inverted and the product was in contact with the lid. The overall effect of using plastic cans was to produce much lower lethalities, and in some cases sub-lethal processes.

Kebede et al. (1996) studied heat transfer into high-barrier plastic trays containing an 8 % bentonite suspension. The containers had a net volume of 460 ml and had dimensions 35 × 97 × 142 mm and were made from (1) polypropylene/ethylene vinyl alcohol/polypropylene and (2) crystallized polyethylene terephthalate. The f_h values for the two types of tray were similar: 31.1 and 32.6 min respectively.

6.5.8 *Effect of Can Rotation*

In general, the effect of can rotation is to improve the internal heat transfer and reduce the f_h-value. This subject is discussed when rotary sterilization is considered in Chap. 13.

6.5.9 *Statistical Aspects of Heat Penetration Data*

The literature values for the variation of f_h-values show that the standard deviation was between 7 % and 25 % of the average f_h-value (Hicks 1951; Herndon 1971; Lund 1978; Patino and Heil 1985). For canned spaghetti in tomato sauce, histograms of the distribution of f_h showed that it was skewed to the right (inverse gamma distribution), whereas the distributions of j_{h} and j_{c} were skewed to the left and the f_{c} distribution was symmetrical (Hayakawa et al. 1988).

6.5.10 Extrapolation of Heat Penetration Data

The safety of canned foods depends upon adequate process determination by means of heat penetration experiments. The extrapolation of heat penetration data determined at one retort temperature and for a particular initial temperature to other temperatures should be undertaken with extreme care.

For products with straight-line semilogarithmic heating curves, the problems are less than with broken-heating type curves (Berry and Bush 1987, 1989). For rapidly heating products in small cans the process times measured at different retort temperatures were identical to extrapolated figures. However, for products of intermediate viscosity, or for larger can sizes, the effect of the retort temperature becomes more significant and less confidence can be placed in extrapolation.

The extrapolation to other initial temperatures depends more on the product, but in general it is less reliable than retort temperature extrapolations.

For broken-heating curves extrapolation to higher retort temperatures is acceptable, but not the reverse. The extrapolation from higher initial temperatures to lower gives conservative results, but not the reverse.

6.6 Simulation of Thermal Processing of Nonsymmetric and Irregular-Shaped Foods Vacuum Packed in Retort Pouches: A Numerical Example

The following simulation analysis has been summarized from the research work done by Morales-Blancas et al. (2005). The complete problem statement for a homogeneous, isotropic nonsymmetric irregular-shaped domain, with thermophysical properties independent of temperature and subject to constant boundary conditions is supported by the following equations:

Governing equation:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right) = \rho C_{\mathrm{p}} \frac{\partial T}{\partial t} \tag{6.28}$$

where for homogeneous and isotropic material:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{6.29}$$

Initial conditions at heating

$$T(x, y, z, 0) = T_0; \quad \forall x, y, z; \quad t = 0 \tag{6.30}$$

Initial conditions at cooling

$$T(x, y, z, t_g) = T_g(x, y, z, t_g); \quad \forall x, y, z; \quad t = t_g \tag{6.31}$$

For the cooling stage, initial temperature of each point of the domain (x, y, z) is temperature $T_g(x, y, z, t_g)$ reached at the end of heating stage (time t_g).

Boundary conditions at heating

$$k\frac{\partial T(x, y, z, t)}{\partial n} = U_1(T_{a_1} - T_S), \quad t \le t_g \tag{6.32}$$

Boundary conditions at cooling

$$k\frac{\partial T(x, y, z, t)}{\partial n} = U_2(T_{a_2} - T_S), \quad t > t_g \tag{6.33}$$

The global heat transfer coefficient (U) will be used, which involves all resistances from the external to the internal conditions.

$$\frac{1}{U} = \left[\frac{1}{h_i} + \frac{\delta_p}{k_p} + \frac{1}{h_e}\right] \tag{6.34}$$

where U: global heat-transfer coefficient; $h_{i,e}$: local heat-transfer coefficient (i: internal and e: external); δ_p: thickness of the packaging material; k_p: thermal conductivity of the packaging material.

Considering negligible the internal heat resistance, we obtain (see Fig. 6.7):

$$\frac{1}{U} = \left[\frac{\delta_p}{k_p} + \frac{1}{h_e}\right] \tag{6.35}$$

where Eqs. (6.34) and (6.35) have been derived from steady state conditions but also can be utilized in unsteady state conditions if the conductance of the packaging material is negligible in relation to the conductance of the food product. According to Zuritz and Sastry (1986) Eqs. (6.34) and (6.35) are valid if:

$$\delta \ll \frac{l(pC_p)_{\text{food}}}{2(pC_p)_{\text{package}}} \tag{6.36}$$

Fig. 6.7 Heat transfer resistances from ambient to food product

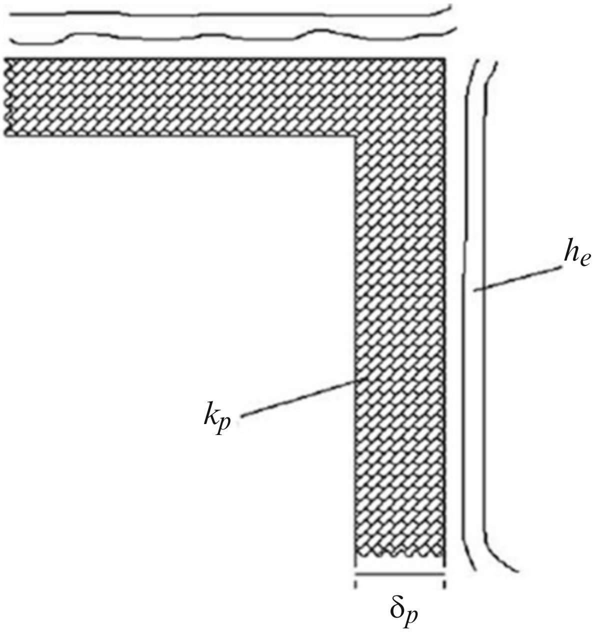
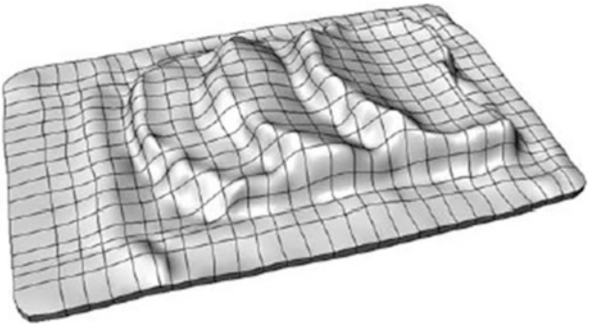


Fig. 6.8 Reconstruction of the three-dimensional surface and shape



6.6.1 *Reverse Engineering by 3D Digitizing*

Reconstruction of the three-dimensional surface and shape of the food products was carried out by using a precision mechanical 3D digitizer, accuracy of stylus tip 0.64 mm (Microscribe-3D™, Immersion Co., San José, CA) and a NURBS (Non-Uniform Rational B-spline) modeling software (Rhinoceros®, Robert McNeel & Associates, Seattle, WA). This technique recovers exact surface shape by capturing 3D points and building 3D surfaces directly from physical models (Fig. 6.8).

Fig. 6.9 Meshing of the 3D digitalized retort pouch

6.6.2 Simulation of Heat Conduction Processes

In order to reach an appropriate numerical convergence, simulations were carried out considering an average mesh size ranging from 2.0 to 3.0 mm (see Fig. 6.9), and a time step size ranging from 0.5 to 1 s.

6.6.3 Finite Element Analysis

The heat conduction model was solved using a Finite Element Analysis and Simulation software package (ALGOR®, ALGOR Inc., Pittsburgh, PA). FEA Models were obtained by solid meshing of the 3D digitized irregular-shaped geometry models. Bricks/tetrahedra elements were used in order to get the highest quality meshing and the lowest number of elements.

6.6.4 Experimental Validation

Results showed sufficiently good agreement between predicted and measured temperature profiles for the slowest heating/cooling point of each product (Fig. 6.10). The agreement between the experimental and predicted temperature profiles was evaluated by using the %RMSE (Percentage of Root Mean Square Error). In general, %RMSE calculated values were less than 8.0 %.

The proposed approach based on reverse engineering principles and CAD/CAE tools can be used to simulate and optimize thermal processes of odd-shaped foods.

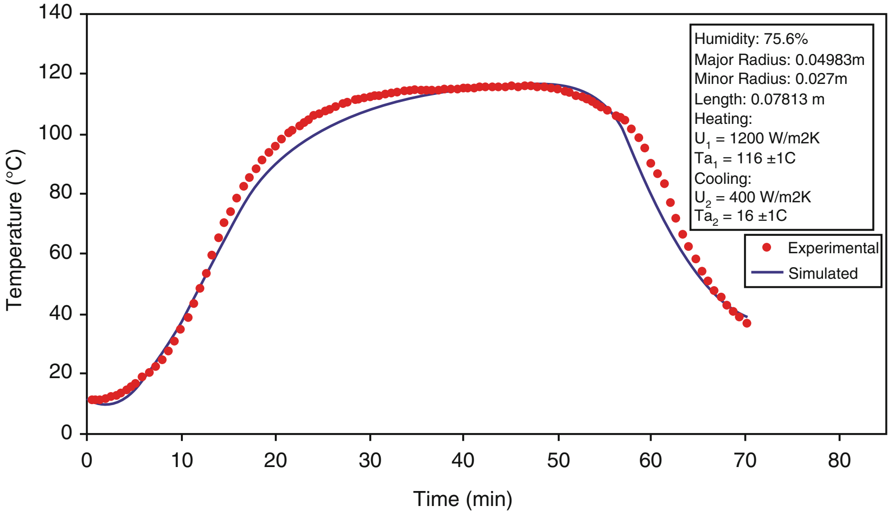


Fig. 6.10 Validation example: Jack Mackerel product

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Chapter 7
The General Method and Its Applications

7.1 Determination of F-Values: Process Safety

Process evaluation, also called process determination, is the science of determining the F-value for a given process time or the process time required for a given F-value. If the heat penetration curve has been determined, then the f_h- and j-values will be known and the appropriate methods can be used. The methods can also be used to determine the effect of altering the can size or the temperatures on the F-value. The importance of these methods for maintaining the safety of sterilized canned and packaged products cannot be overstated.

The methods of determining F-values fall into two classes: calculation methods and microbiological methods. In this section the calculation methods are discussed (see Chap. 4, Sect. 4.1.4 for the applicability and extension of Eqs. (7.1) and (7.2)).

The main equation to be solved is the basic integral equation for F_0

$$F_0 = \int_0^t 10^{(T-T_{\mathrm{ref}})/z} \mathrm{d}t, \tag{7.1}$$

or its Arrhenius kinetic form as discussed in Sect. 4.1.7. Equation (7.1) is often used in the exponential form

$$F_0 = \int_0^t e^{2.303(T-T_{\mathrm{ref}})/z} \mathrm{d}t, \tag{7.2}$$

The solution of this equation requires knowledge of the time–temperature history of the product at a specified point, usually the point of slowest heating. This may be obtained from the heat transfer equations given in Chap. 2, either by substitution in

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Eq. (7.1) or by calculating the temperature history and using one of the methods outlined below. The practical methods of determining the temperature history under processing conditions are discussed in Chap. 6.

7.2 The General Method

The simplest of all methods, known as the general method, is universally used in experimental work, precisely because of its simplicity. It was devised by Bigelow et al. (1920), and involves graphical or numerical integration of Eq. (7.1) when the temperature distribution is known, either from heat transfer equations or experimental data.

7.2.1 *Graphical Methods*

The method that prevailed for many years was to convert the time–temperature history graph into a lethal rate graph, using appropriate data, and then to determine the area under the curve (see Fig. 7.1). The area can be determined by counting

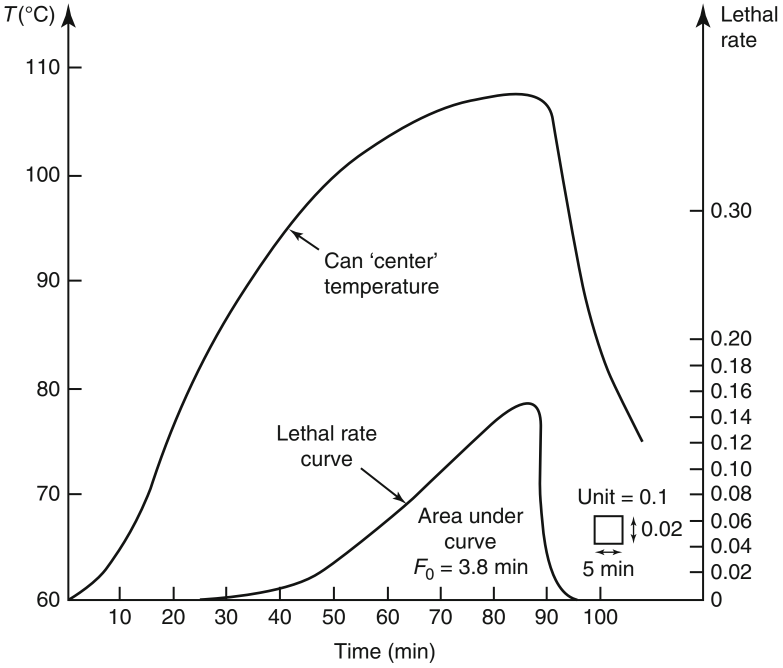

Fig. 7.1 Graphical method of determining F_0-value from lethal rate curve

squares or using a planimeter. While this mechanical method would no longer be used for routine purposes, it is a good method for training courses. It illustrates clearly the relative microbial killing power for different parts of the total process and, in particular, how the heating-up part of the curve contributes relatively little to the total lethality of the process until the retort temperature is approached, often in the last few minutes before cooling begins. The simple method was made more complex by the development of lethal rate paper, in which the ordinate axis is the lethal rate $L = 10^{(T-T_{\mathrm{ref}})/z}$ and the scale marked with the appropriate temperature (Schultz and Olson 1940). Other workers extended the use of the method for other z-values and extended processing temperatures (Cass 1947; Patashnik 1953; Hayakawa 1968, 1973; Leonhardt 1978).

7.2.2 Numerical Methods

There are various methods of determining the area F under the lethality curve by calculation rather than construction. Among them are the trapezoidal rule and Simpson's rule, which are used for finding the area of irregular geometric figures. Both make use of parallel chords, whose lengths are designated $y_0, y_1, y_2, \ldots, y_n$, spaced equally at a distance t (measured in minutes). Simpson's rule, generally the more accurate, requires an even number of areas, corresponding to an odd number of points, and is given by

$$F = \frac{1}{3}t(y_0 + 4y_1 + 2y_2 + 4y_3 + \cdots + 2y_{n-2} + 4y_{n-1} + y_n) \tag{7.3}$$

while the trapezoidal rule is expressed as

$$F = t\left(\frac{1}{2}(y_0 + y_n) + y_1 + y_2 + \cdots + y_{n-1}\right) \tag{7.4}$$

Patashnik (1953) used the latter equation, making the time interval $t = 1$ min, and selecting y_0 and y_n so that they were zero, to develop a very useful tabular method. In this method the temperatures are listed at equal time intervals, usually 1 min, the corresponding lethal rates are listed in an adjoining column (see Table 4.1), and the F-value obtained by simple addition. For equal time intervals, t, other than 1 min the general formula is given by the equation

$$F = \Delta t \sum_{1}^{n} (L_1 + L_2 + L_3 + \cdots + L_n). \tag{7.5}$$

An example of the use of this method is given in Table 7.1. It is interesting to note that with beans in tomato sauce in a conduction-heating pack, processed at

Table 7.1 Example of the use of Patashnik's method for process evaluation

Time (min)	Retort temperature (°C)	Center temperature (°C)	Lethal rate (min)	*L* (min)
0	44.3	26.8	–	–
1	92.1	26.8	–	–
2	103.1	26.8	–	–
3	108.3	26.9	–	–
4	110.3	27.2	–	–
5	112.2	27.6	–	–
6	116.6	28.1	–	–
7	119.9	28.9	–	–
8	120.6	29.9	–	–
9	120.7	31.1	–	–
10	120.7	32.6	–	–
11	120.7	34.3	–	–
12	120.7	36.2	–	–
13	120.7	38.3	–	–
14	120.7	40.5	–	–
15	120.7	42.8	–	–
16	120.7	45.2	–	–
17	120.7	47.7	–	–
18	120.7	50.3	–	–
19	120.7	52.8	–	–
20	120.7	55.3	–	–
21	120.7	57.8	–	–
22	120.7	60.2	–	–
23	120.7	62.6	–	–
24	120.7	64.9	–	–
25	120.7	67.4	–	–
26	120.7	69.5	–	–
27	120.7	71.6	–	–
28	120.7	73.7	–	–
29	120.7	75.7	–	–
30	120.7	77.8	–	–
31	120.7	79.5	–	–
32	120.7	81.4	0.0001	0.0001
33	120.7	83.1	0.0001	0.0002
34	120.7	84.7	0.0002	0.0004
35	120.7	86.5	0.0003	0.0007
36	120.7	87.9	0.0004	0.0011
37	120.7	89.4	0.0007	0.0018
38	120.7	90.9	0.0009	0.0027
39	120.7	92.1	0.0012	0.0039
40	120.7	93.5	0.0017	0.0056
41	120.7	94.7	0.0023	0.0079

(continued)

Table 7.1 (continued)

Time (min)	Retort temperature (°C)	Center temperature (°C)	Lethal rate (min)	*L* (min)
42	120.7	96.1	0.0032	0.0111
43	120.7	97.3	0.0042	0.0153
44	120.7	98.4	0.0053	0.0206
45	120.7	99.5	0.0070	0.0276
46	120.7	100.4	0.0090	0.0366
47	120.7	101.3	0.0104	0.0470
48	120.7	102.3	0.0130	0.0600
49	120.7	103.2	0.0162	0.0762
50	120.7	104.0	0.0194	0.0956
51	120.7	104.8	0.0234	0.1190
52	120.7	105.6	0.0281	0.1471
53	120.7	106.4	0.0339	0.1810
54	120.7	107.1	0.0400	0.2210
55	120.7	107.7	0.0457	0.2667
56	120.7	108.3	0.0534	0.3201
57	120.7	108.9	0.0602	0.3803
58	120.7	109.6	0.0708	0.4511
59	120.7	110.1	0.0790	0.5301
60	120.7	110.6	0.0890	0.6191
61	120.7	111.1	0.1000	0.7191
62	120.7	111.6	0.1120	0.8311
63	120.7	112.1	0.1258	0.9569
64	120.7	112.5	0.1380	1.0949
65	120.7	112.9	0.1513	1.2462
66	120.7	113.4	0.1698	1.4160
67	120.7	113.7	0.1820	1.5980
68	120.7	114.1	0.1995	1.7975
69	120.7	114.5	0.2187	2.0162
70	120.7	114.8	0.2340	2.2502
71	120.7	115.1	0.2511	2.5013
72 (Cool)	112.9	115.2	0.2570	2.7583
73	86.3	114.9	0.2398	2.9981
74	59.6	114.6	0.2238	3.2219
75	42.9	114.3	0.2089	3.4308
76	36.1	114.2	0.2041	3.6349
77	31.9	114.0	0.1949	3.8298
78	28.0	113.1	0.1584	3.9882
79	25.7	111.5	0.1100	4.0982
80	25.4	109.0	0.0616	4.1598
81	20.6	106.8	0.0371	4.1969
82	14.4	103.8	0.0190	4.2159
83	13.2	101.9	0.0120	4.2279

(continued)

Table 7.1 (continued)

Time (min)	Retort temperature (°C)	Center temperature (°C)	Lethal rate (min)	L (min)
84	12.0	100.1	0.0079	4.2358
85	11.9	96.7	0.0036	4.2394
86	11.8	94.2	0.0021	4.2415
87	11.8	92.7	0.0014	4.2429
88	11.9	90.5	0.0008	4.2437
89	11.8	88.7	0.0005	4.2442
90	11.7	86.2	0.0003	4.2445

Heat penetration data for UT can (73 × 115) of beans in tomato sauce processed under static conditions with saturated steam
Thus, $L = 4.24$ min and $F_0 = tL = 1 \times 4.24$ min

120.7 °C, it takes about 39 min to obtain a lethal rate of 0.001 min, and the heating phase only contributes 2.5 min to the total F_0-value of 4.22 min (about 60 %) after 1 h 12 min, whereas the cooling phase contributes 1.65 min (about 40 %) in 15 min. It is usual to take 0.001 min rather than 0.0001 min for the initiation of lethal rate build-up and decline. This fulfils the L_1 and L_n zero requirements with this method. The time increment t is equal to 1 min in this case.

Thus, $L = 4.24$ min and $F_0 = tL = 1 \times 4.24$ min.

Hayakawa (1968) developed a method using the Gaussian integration formula, which involved a template that could be used with the graphical method. The procedure is now available as a simple computer program with built-in statistical accuracy (Vinters et al. 1975; Pflug and Odlaugh 1978; Tung and Garland 1978), and can be used directly in conjunction with heat penetration equipment. Eszes and Rajkó (2004) have given a useful discussion of five different types of integral methods for obtaining the lethality of a given process from heat penetration data.

7.3 An Extension of the General Method: Revisited General Method (RGM)

Thermal processing is an important method of food preservation in the manufacture of shelf-stable canned foods and has been the cornerstone of the food processing industry for more than a century. Thermal processing calculations, in which processing times at specified retort temperatures are calculated to achieve safe levels of microbial inactivation (lethality), must be performed carefully to assure public health safety. However, over-processing must be avoided because thermal processes also have a detrimental effect on the quality (nutritional and sensorial factors) of foods. Therefore, the accuracy of the methods used for this purpose is important to food science and engineering professionals working in this field.

The first procedure to determine thermal processes was developed by W.D. Bigelow in the early part of the twentieth century and is usually known as the General Method (Bigelow et al. 1920). The General Method makes direct use of the time–temperature history at the coldest point to obtain the lethality value of a process.

Bigelow's procedure earned the name "General" method because it applies to any product/process situation. Because it relies solely on the measured cold spot temperature, it is blind to processing conditions, mode of heat transfer, product properties, and container size and shape. This "immunity" to product/process conditions has always been the strength of the General Method, in addition to its unquestioned accuracy. A detailed procedure was developed to allow practical application of the General Method proposed by Bigelow et al. (1920) so that it would include the following capabilities: (a) calculation of lethality (F_0 value) for a given set of heat penetration data, (b) calculation of processing time to achieve a specified lethality (F_r value) from a given set of heat penetration data, and (c) calculation of either processing time or lethality for alternative process conditions to the ones used during the original heat penetration tests (even if there is a slow come-up time) with no further experimental data.

In their work about Bigelow's General Method, Simpson et al. (2003) proposed at least three main capabilities of the method:

The first capability is a straightforward execution of the General Method with no involvement of heat transfer. The accumulated lethality is calculated by numerical integration of the lethal rate along the cold spot temperature profile measured in the heat penetration test (or provided by the simulation of a test).

The second capability requires execution of the first as a starting point. Integration must then be repeated with the cooling portion of the cold spot temperature profile, advanced or retarded on a trial and error basis until the desired lethality is achieved. The true profile of these cooling curves will be altered based on when the onset of cooling occurs, as the internal temperature distributions change continuously during heating. At best, these cooling temperature profiles are only crudely and conservatively estimated in the traditional use of the General Method. Herein lies one of the existing weaknesses that was addressed by integrating heat transfer concepts to more accurately predict the true alternate cooling temperature profiles.

The third capability has not been possible with traditional use of the General Method. This application requires accurate prediction of the entire cold spot temperature profile under wholly different retort and/or initial product temperature conditions, including retorts with unusually slow come-up times. These profiles can also be accurately predicted by integrating the heat transfer concepts developed here. Much of the significance of the work reported here stems from the heat transfer concepts developed in the following section.

The goal of this chapter is to reintroduce the General Method as a more accurate, powerful and easy-to-use method of thermal processing calculation. The specific objectives were as follows:

- Develop a procedure that would integrate lethality calculation by the General Method with principles of heat transfer theory,
- Demonstrate its ability to evaluate processes at different conditions from the ones used in heat penetration tests (e.g., retort temperature, initial temperature),

- Demonstrate its ability to account for slow come-up and cool down phases, and
- Demonstrate that through the use of software, the procedure performs with at least the same ease of use and reliability as the Formula Method but with better accuracy.

7.4 Theoretical Background of the General Method

Most mathematical models for the prediction of time–temperature histories in food products at a given point normally need to assume one of the basic modes of heat transfer. Two extreme cases have their own analytical solutions: (a) perfect mixing of a liquid (forced convection), and (b) homogeneous solids (pure conduction). Most foods are an intermediate case, and these extreme solutions provide a guideline for the usefulness of the temperature–time histories (profiles) developed here.

7.4.1 *Heat Transfer Model for Perfect Mixing*

For forced convection (agitated liquids), it is possible to assume that the temperature inside the can is uniformly distributed but time dependent. A transient energy balance, with the container as a system, gives

$$Q = \frac{\partial\left(M\underline{E}\right)_{\text{SYSTEM}}}{\partial t} \tag{7.6}$$

$$\text{UA}(\text{TRT} - T) = MC_{\text{p}}\frac{\partial T}{\partial t} \tag{7.7}$$

assuming constant ambient temperature (TRT) and provided that the can's inside temperature is uniformly distributed, then, T also denotes the cold spot temperature ($T = T_{\text{C.P.}}$). Using the initial condition as $T = \text{IT}$ at $t = 0$ and $T_{\text{C.P}}$ at time $t > 0$, the integration of Eq. (7.7) renders

$$\frac{\text{TRT} - T_{\text{C.P.}}}{\text{TRT} - \text{IT}} = \exp\left[-\frac{\text{UA}}{MC_{\text{p}}}t\right] \tag{7.8}$$

The dimensionless temperature ratio for forced convection (Eq. (7.8)) is dependent on geometry, thermal properties and time. Therefore, the dimensionless temperature ratio must be the same at different TRT and/or IT:

$$\frac{\text{TRT} - T_{\text{C.P.}}}{\text{TRT} - \text{IT}} = \frac{\text{TRT}' - T'_{\text{C.P.}}}{\text{TRT}' - \text{IT}'} = \text{Constant} \tag{7.9}$$

7.4.2 Heat Transfer Model for Pure Conduction

Heat transfer for pure conduction is based on Fourier's equation and can be written as

$$\rho C_{\mathrm{p}} \frac{\partial T}{\partial t} = \nabla k \nabla T \tag{7.10}$$

If thermal conductivity (k) is independent of temperature and the food material is assumed to be isotropic, as it is for most foods in the sterilization temperature range, then Eq. (7.1) becomes

$$\frac{\partial T}{\partial t} = \alpha \nabla^2 T \tag{7.11}$$

Although solutions for different geometries are not necessarily straightforward, in general, for any geometry, the dimensionless temperature ratio for constant retort temperature can be expressed as (Carslaw and Jaeger 1959)

$$\frac{\mathrm{TRT} - T_{\mathrm{C.P.}}}{\mathrm{TRT} - \mathrm{IT}} = f(\text{initial temperature distribution, geometry, thermal properties, time}) \tag{7.12}$$

Thus, if the initial temperature distribution, geometry, product (thermal properties) and time are held constant (changing only TRT and/or IT), then the dimensionless temperature ratio of the solid must be the same at different TRT and/or IT values according to Eq. (7.4).

A simplified analytical solution for homogeneous solids confined in a finite cylinder is presented in Eq. (7.13) (Merson et al. 1978). This simplified solution is only valid for long periods of time (after the initial lag period when Fourier number > 0.6), in addition to assuming a Biot number over 40 (meaning that the external heat resistance is negligible in comparison with the internal resistance).

$$\frac{\mathrm{TRT} - T_{\mathrm{C.P.}}}{\mathrm{TRT} - \mathrm{IT}} = 2.0396 \exp\left[-\left(\frac{(2.4048^2)}{R^2} + \frac{\pi^2}{l^2}\right)\frac{k}{\rho C_{\mathrm{p}}} t\right] \tag{7.13}$$

7.4.3 Heat Transfer Model: A General Approach

Although the heat transfer mechanisms are rather dissimilar, both models (pure conduction and forced convection), within certain limitations, can be described in a general way by Eqs. (7.8) and (7.13):

$$\frac{\mathrm{TRT} - T}{\mathrm{TRT} - \mathrm{IT}} = k_1 e^{-k_2 t} \tag{7.14}$$

where k_1 and k_2 are constants related to the sample geometry, dimension and physical-chemical properties and are obtained by fitting Eq. (7.14) to the cold spot data at long process time (could be considered after cold spot attained 100 °C) by nonlinear regression.

As shown by Datta (1990), the latter expression is valid for arbitrary shapes (e.g., rectangular, oval). The main limitations are that, for heat conducting foods, it is only valid for heating times beyond the initial lag period (when the Fourier number > 0.6).

An interesting, practical and general conclusion that can be drawn from the heat transfer theory presented here is that Eq. (7.9) remains independent of container geometry and heat transfer mode (conduction or forced convection), only requires a constant retort temperature and is also valid for the cooling phase (7.15):

$$\frac{T_{\mathrm{w}} - T_{\mathrm{C.P.}}}{T_{\mathrm{w}} - \mathrm{IT}} = \frac{T'_{\mathrm{w}} - T'_{\mathrm{C.P.}}}{T'_{\mathrm{w}} - \mathrm{IT}'} = \mathrm{Constant} \tag{7.15}$$

The importance and relevance is that we will be able to transform the raw data from heat penetration tests and use the General Method, not only to directly evaluate the raw data but also to evaluate processes at different conditions (retort temperatures, initial temperatures, longer or shorter process times) than those originally recorded. It is important to note that Eqs. (7.9) and (7.14) are valid for constant retort temperature (TRT), as is Eq. (7.15) for constant water temperature (T_{w}).

7.5 Methodology and Implementation of the General Method (Simpson et al. 2003)

7.5.1 Thermal Process Evaluation (Calculates Lethality)

The method must allow the calculation of the F value for a set of data obtained experimentally or by simulation. Given that the data are not continuous, the integration procedure should be performed numerically (e.g., Gauss, Simpson, trapezoidal), or alternatively, the data should be fit by an interpolation method (e.g., cubic spline) and the lethality integrated analytically.

7.5.2 Thermal Time Adjustment (Calculates Process Time)

To determine the processing time, so that the F value obtained (F_{p}) is greater or equal to than the required lethality (F_{r}), the F_{p} value has to first be determined from the original heat penetration data. This F_{p} value may be larger than, smaller than, or equal to F_{r}. Therefore, three situations arise: $F_{\mathrm{p}} > F_{\mathrm{r}}$, $F_{\mathrm{p}} = F_{\mathrm{r}}$, and $F_{\mathrm{p}} < F_{\mathrm{r}}$.

Table 7.2 Can dimensions and processing conditions for Figs. 7.2, 7.3 and 7.4

Figure	Can size (mm)	Can (Common name)	TRT[a] (°C)	P_t (min)	F_0 – Value[b] (min)
Figure 7.2	52 × 38	70 g tomato paste	116	50	9.8[c]
Figure 7.3	52 × 38	70 g tomato paste	116	28	3.1[d]
Figure 7.4	74 × 116	Nr 1 tall	130	40.1	6.0[e]

[a] TRT = Constant ($t >$ CUT)
[b] Calculated with General Method
[c] $F_p > F_r$
[d] $F_p < F_r$
[e] $F_r = 6$ (min)
CUT = 5 (min); Conduction heated product, $\alpha = 1.7 \times 10^{-7}$ (m^2/s); $T_w = 18$ (°C), IT = 70 (°C)

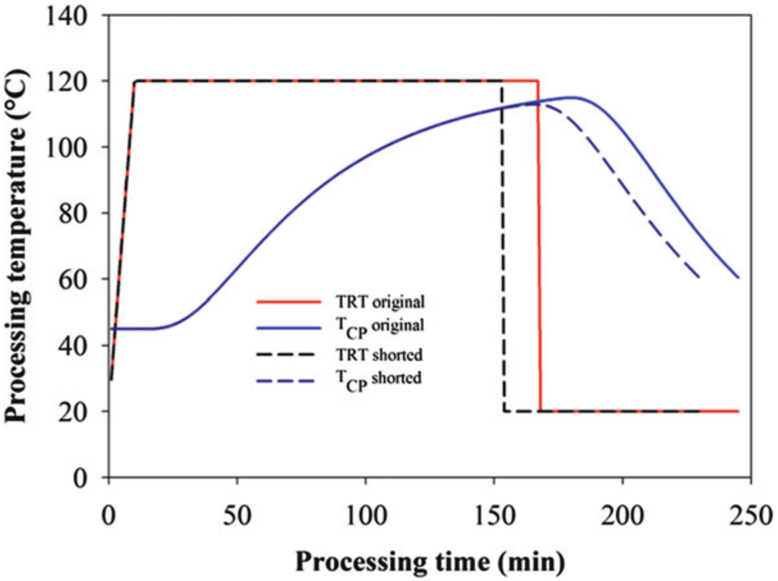

Fig. 7.2 Simulated Heat Penetration Data for analysis for **Case 1**

Situations such as $F_p > F_r$ and $F_p < F_r$ are of interest for further analysis and will be called **Case 1** ($F_p > F_r$) and **Case 2** ($F_p < F_r$) (specifications given in Table 7.2).

Case 1 ($F_p > F_r$) Here are all heat penetration tests in which the final lethality is greater than the required lethality, so the processing time must be shortened, i.e., to identify a new processing time that is shorter than the real processing time, so that $F_p \geq F_r$ and $F_p - F_r$ is minimized. A general situation is presented in Fig. 7.2 where the temperature at the coldest point (for the adjusted process) would be lower than the retort temperature, resulting in a nonuniform temperature distribution inside the can. In this situation, the temperature at the cold spot (referred to as the heating part) during the cooling phase will have inertia. To evaluate process lethality (for the adjusted process), it is necessary to generate data for the cooling phase. In this case, is possible to use Eq. (7.15) to generate data assuming that both cooling down temperature have the same inertia and considering IT′ as the temperature at the cold spot when the steam is turned off in the adjusted process. Although this representation is not completely accurate, the resulting error in predicted lethality arising from the adjusted cooling phase will be on the conservative (safe) side. Notice that the real inertia in the adjusted process is bigger than the one at the original process.

Case 2 ($F_p < F_r$) This case involves all heat penetration tests where the final lethality is lower than the required value, so the processing time has to be extended, i.e., to find a new processing time longer than the original processing time, so that $F_p \geq F_r$ and $F_p - F_r$ is minimized. In this case, the cooling phase temperature profile must be displaced to the right to extend the processing time. Figure 7.3 presents a general situation where it is first necessary to generate more data for the heating process to be able to extend the processing time utilizing Eq. (7.14). Due to a long processing time, the recorded data are well described by Eq. (7.14), and therefore, it is possible to obtain k_1 and k_2 by linear or nonlinear regression and thus obtain additional data for the heating phase, followed by the need to generate the new cooling temperature profile by Eq. (7.15). According to heat transfer theory, the recorded cooling temperature profile will have more pronounced inertia than the new cooling temperature profile, and therefore, in this situation (Fig. 7.3), the use of Eq. (7.15) would generate not only inaccurate but also unsafe data. To avoid this problem, Eq. (7.15) was applied considering only the data starting at point **A** (IT), as shown in Fig. 7.3 (**A** pinpoints the maximum temperature recorded in the process).

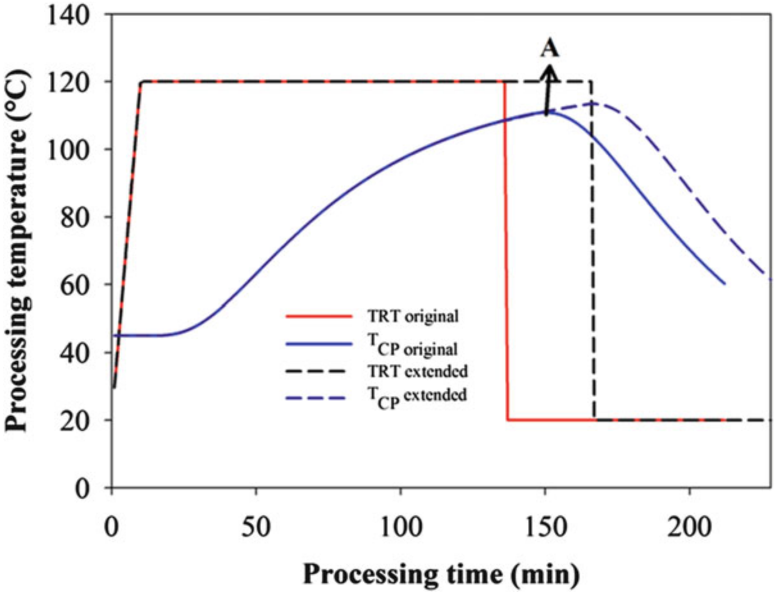

Fig. 7.3 Simulated Heat Penetration Data for analysis for **Case 2**

7.5.3 Thermal Process Evaluation at Conditions Other Than the Ones Experimentally Recorded (or Generated by Simulation)

Sometimes, it is useful to obtain a process evaluation at different conditions from the ones used for the original heat penetration test, avoiding or significantly reducing the number of new experiments. The new processing conditions could be as follows: initial food temperature (IT), retort temperature (TRT), and/or cooling temperature (T_w). The new time–temperature data should be predicted using adequate mathematical models (if the type of food allows it) or using the dimensionless temperature ratio concept developed in this study, which is applicable to any type of food. The dimensionless temperature ratio concept could be used for any type of geometry. However, in real processing situations, the TRT is not always constant (e.g., come-up time), which will impair the theoretical validity of the concept derived for dimensionless temperature ratio, as has been discussed in the literature (Schultz and Olson 1940). In this work, the retort temperature was divided into two parts, as follows: (a) processing temperature ($\mathrm{TRT} = Constant$) and (b) cooling temperature ($T_w = Constant$).

Equations (7.9) and (7.15) were used for the constant retort temperature (TRT) and cooling water temperature (T_w) conditions, respectively. In the case of Fig. 7.4, two aspects should be carefully considered when changing processing conditions (from TRT to TRT′ and/or *from* IT *to* IT′): (a) maintaining the same come-up time, and (b) deciding how to generate the new cooling temperature profile, specifically in the presence of different inertia. First, although it is a limitation, come-up time

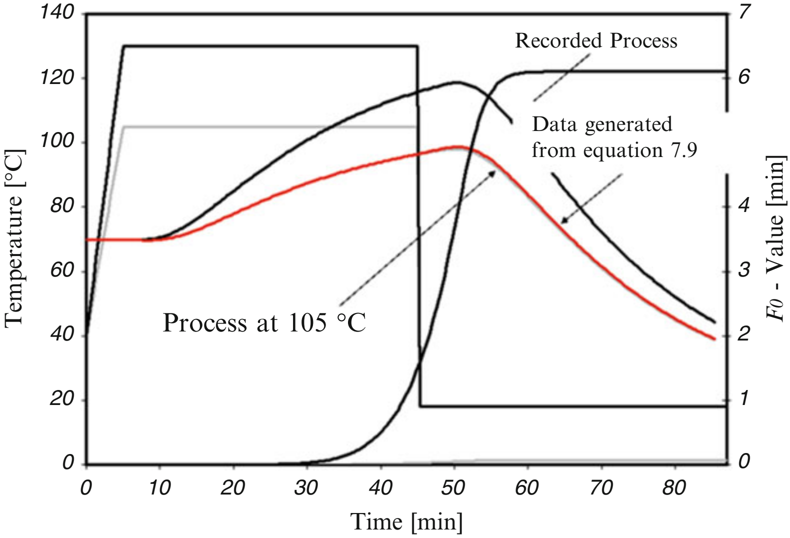

Fig. 7.4 Simulated Heat Penetration Data for analysis (changing processing conditions, TRT)

must be maintained. Second, the cool-down temperature data transformation could lead to a new cooling temperature profile with less inertia (e.g., the new retort temperature is lower than the original). In this case, the transformed data would overestimate the *F* value, which could result in an unsafe process. In this situation (very rare, see Fig. 7.3, where an extreme situation is presented), a safe procedure should be to follow the recommendation explained in **Case 2**. To manage the already transformed data (new processing conditions), it is necessary to follow the procedure explained in Sect. 7.5.2 to adjust the process.

7.6 Validation and Analysis of the New Methodology to Implement the General Method

7.6.1 Thermal Process Evaluation (Calculates Lethality) and Time Adjustment

To compare the results from the Revisited General Method (R.G.M.) revised in this text with the results from the Formula Method (F.M.), sets of computer-simulated data as well as experimental data were analyzed.

To analyze extreme situations, simulated heat penetration data (cold spot temperature profiles) were generated at different retort temperatures using a finite difference solution of the conduction heat transfer equation for a cylindrical can (Teixeira et al. 1969) and for a forced convection product utilizing Eqs. (7.10) and (7.8) respectively. The data set generated at 120 °C was then used as a starting point (reference process) to calculate process times to achieve a specified lethality by both methods. Calculations using the F.M. method were executed with the computer software P Evaluator. Calculations using the R.G.M. method (thermal processing evaluation at different conditions and adjustments) were executed according to the procedure described previously in Sect. 7.5.2.

Computer-supported experiments were developed to analyze extreme situations. Extreme cases were selected as follows: (a) pure conduction and forced convection, (b) extreme f_h values and (c) slow come-up time. Table 7.3 compares processing

Table 7.3 Comparison of operator processing time (P_t) required for the same lethality at alternative retort temperatures calculated by R.G.M. and F.M. with actual operator processing time in a data set generated by finite differences (F.D.) (conduction heated product) at each retort temperature

TRT (°C)	F.D. (min)	R.G.M. (min)	Error (%)	F.M. (min)	Error (%)
110	436	461	5.73	465	6.65
115	341	367	7.62	370	8.50
125	245	251	2.45	275	12.24
130	217	227	4.61	247	13.82

$F_r = 6$ (min); Conduction heated product, Can (603 × 910); $\alpha = 1.25 \times 10^{-7}$ (m^2/s); CUT = 30 (min); TRT = 120 (°C), IT = 50 (°C), $T_w = 20$ (°C); $f_h = 289.2$ (min); $j_{ch} = 1.8$

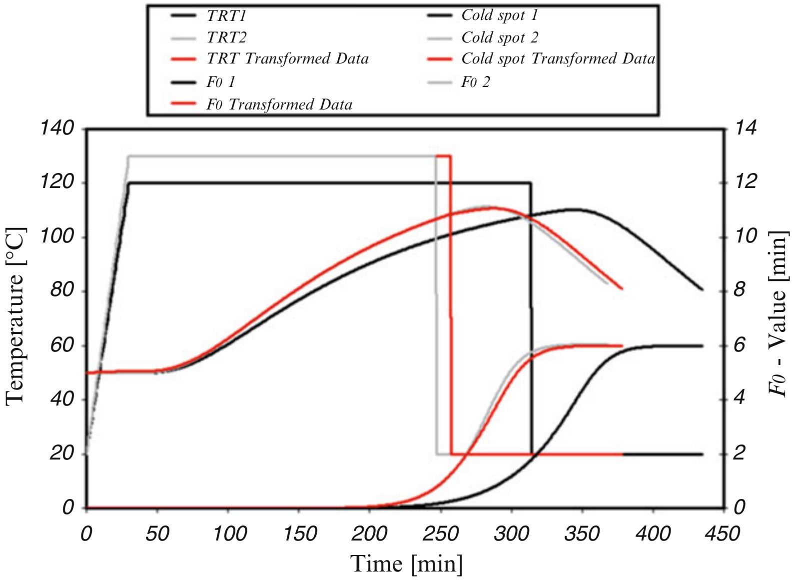

Fig. 7.5 Thermal process at 130 °C for a conduction heated product obtained from a reference process at 120 °C

times for four alternative processes (reference process was developed at 120 °C). Product (thermal diffusivity) and can dimensions were chosen to have a high f_h value (289.2 min). In addition, the reference process considered a very high come-up time (30 min). In all four computer-simulated experiments, the R.G.M. exhibited less error than the F.M. Note that the error in the R.G.M., in this example, was insensitive to retort temperature. In contrast, in the case of the F.M., the error was significantly higher as retort temperatures approached 130 °C, as others have shown (Holdsworth 1997; Smith and Tung 1982). Figures 7.5 and 7.6 show graphically how the R.G.M. was applied to generate and adjust the new process, starting with the reference process at TRT = 120 °C.

Figure 7.5 depicts the results of changing the retort temperature from 120 to 130 °C. For the period of constant retort temperature, Eq. (7.4) was utilized. Given that the reference process (TRT = 120 °C) had less inertia at the cooling phase than the new process at 130 °C, the dimensionless temperature ratio concept was directly applied to the entire cooling phase (Eq. (7.10)). Finally, the new process (TRT = 130 °C) was adjusted for a F_0 value of 6 min, according to the procedure described in the methodology.

Figure 7.6 depicts the results of changing the retort temperature from 120 to 110 °C. In this case, the data at 120 °C (reference process) were insufficient to achieve a F_0 value of 6 min at 110 °C. Then, utilizing Eq. (7.14), more heating data were generated at 120 °C before proceeding with the data transformation to 110 °C. To transform the thermal data from 120 to 110 °C, Eq. (7.9) was applied for the

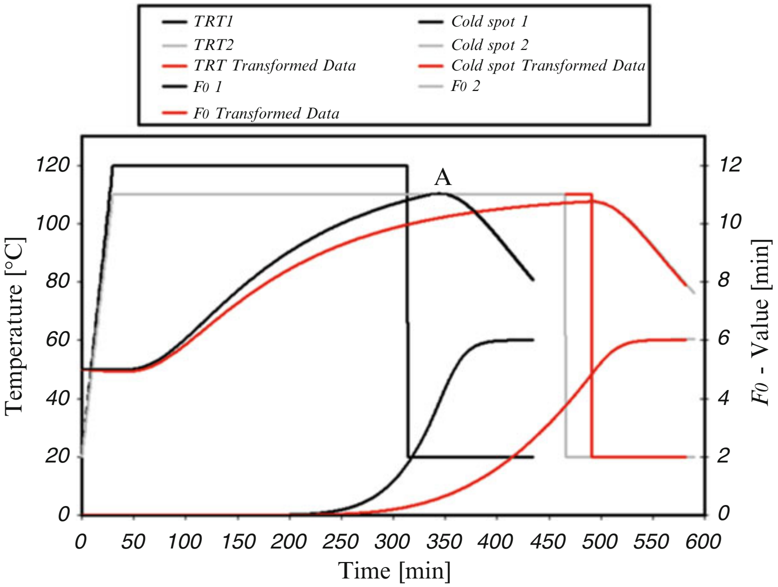

Fig. 7.6 Thermal process at 110 °C for a conduction heated product obtained from a reference process at 120 °C

Table 7.4 Comparison of operator process time (P_t) required for the same lethality at alternative retort temperatures calculated by R.G.M. and F.M. with actual operator process time in a data set generated by analytical solution (forced convection product) at each retort temperature

TRT (°C)	Analytical solution (min)	R.G.M. (min)	Error (%)	F.M. (min)	Error (%)
110	130.9	130.6	−0.23	127.1	−2.90
115	75.9	75.8	−0.13	72.5	−4.48
125	40.1	40.1	0.00	37.7	−5.99
130	32.0	32.0	0.00	30.1	−5.94

$F_r = 6$ (min); Convection heated product, Can dimensions 0.1 (m) diameter × 0.1 (m) height; U = 100 (W/m^2°C); TRT = 120 (°C), IT = 50 (°C), $T_w = 20$ (°C); CUT = 30 (min); $f_h = 45.3$ (min); $j_{ch} = 1.2$

holding time and finally Eq. (7.10) for the cooling phase, but starting from point A (Fig. 7.6) to avoid inertia and safely predict the cooling phase at 110 °C.

Table 7.4 compares the processing times for four alternative processes (reference process was developed at 120 °C). Given that Eq. (7.8) was derived for perfect mixing (linear temperature profile during come-up time), the dimensionless temperature ratio (Eq. (7.9)) could accurately transform the original time–temperature data (for $0 < t <$ CUT). Equation (7.9) was utilized for $t >$ CUT and Eq. (7.10) for the cooling-down phase. As seen in Table 7.3, the error attributed to the R.G.M. was approximately zero in all four cases, regardless of the new retort temperature. It is also important to note that, in these four examples, the F.M. predictions resulted in an error found on the risk side.

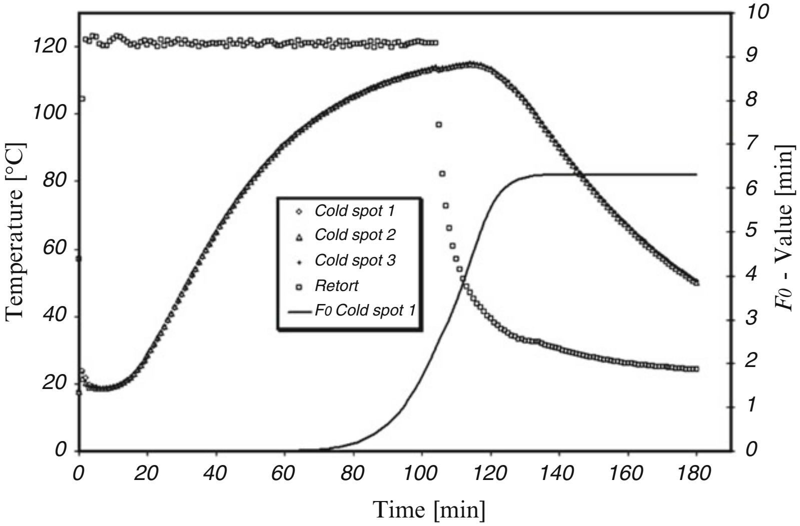

Fig. 7.7 Experimental data for a heat penetration test (taken from Teixeira et al. 1999)

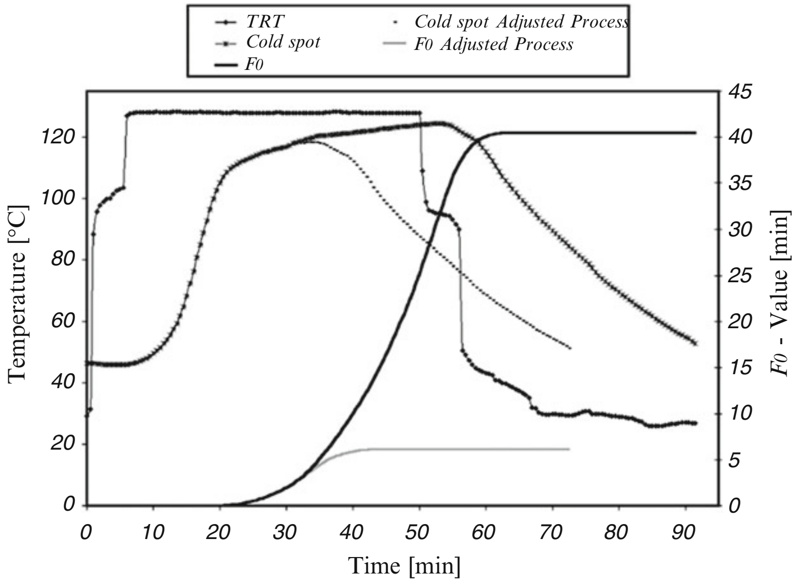

Fig. 7.8 Experimental data for a heat penetration test (broken heating curve). (Tucker 2002)

Figure 7.7 shows ***experimental data*** taken from Teixeira et al. (1999) for a thermal process that was evaluated using the R.G.M. as well as the traditional F.M. Figure 7.8 shows experimental data for a broken-heating curve (Tucker 2002). The results of process evaluations (Figs. 7.9 and 7.10) by both procedures as well as adjusted processes for a specified *F* value are depicted in Tables 7.5 and 7.6.

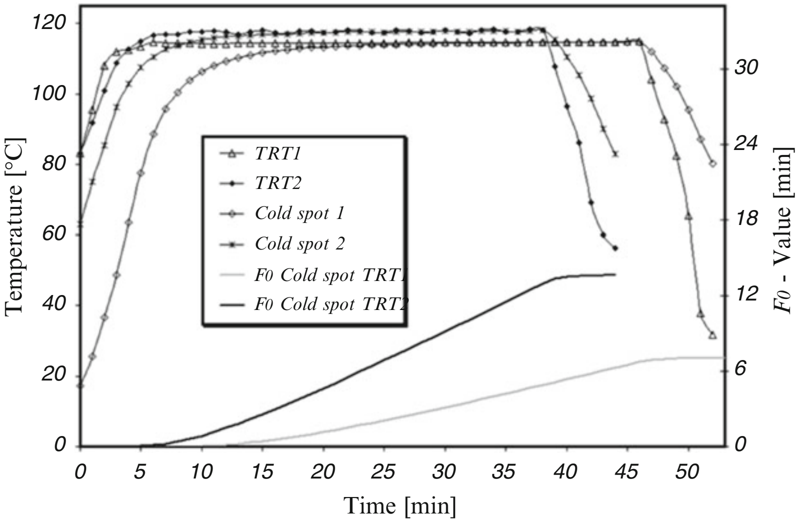

Fig. 7.9 Experimental data for a heat penetration test at two retort temperatures

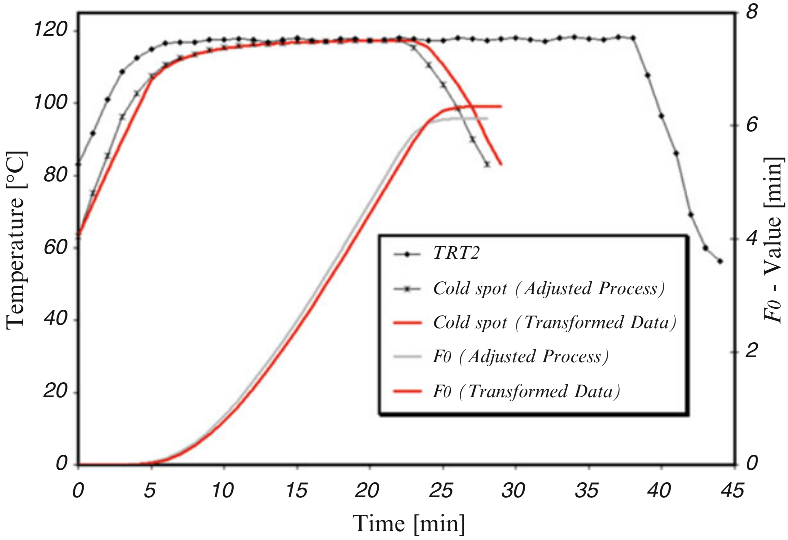

Fig. 7.10 Utilization of dimensionless temperature ratio concept to generate data at different retort temperature

First, in the case shown in Fig. 7.7, application of the Revisited General Method (R.G.M.) is no different from the original General Method because no data transformation was involved, and the data were directly evaluated. Table 7.4 shows the results from evaluating experimental data utilizing the R.G.M. and the Formula

Table 7.5 Process lethality and process time calculated from experimental data presented in Fig. 7.6 utilizing R.G.M. and F.M.

Evaluation technique	F_0 – Value[a] (min)	P_t[b] (min)
F.M.	3.59	111
R.G.M.	6.31	102

[a] F_0 value calculated from experimental data

[b] Calculated for $F_r = 6.3$ (min); 5 % Bentonite, 1 kg cans (98 × 110 mm); $j_h = 1.93$, $f_h = 71.73$ (min); IT = 17.8 (°C), TRT = 121 (°C), $T_r = 121$ (°C), $T_w = 24.2$ (°C)

Table 7.6 Process lethality and process time calculated from experimental data of a broken-heating curve presented in Fig. 7.8 utilizing R.G.M. and F.M.

Evaluation technique	F_0 – Value[a] (min)	P_t[b] (min)
F.M.	35	26
R.G.M.	40	25

[a] F_0 value calculated from experimental data

[b] Calculated for $F_r = 6.0$ (min); Product: Meat Chunks, UT can 73 × 115 (mm); $j_h = 5.65$, $f_h = 12.85$ (min), $f_{h2} = 47.96$ (min); IT = 46.5 (°C), TRT = 127.9 (°C), $T_r = 121$ (°C), $T_w = 25.9$ (°C)

Method (F.M.). The F.M. severely underestimated the F_0 value, while the R.G.M. produced a very close estimate. In this example, the F.M. overestimated the operator process time (P_t) by nearly 9 % compared to the R.G.M. This result is a reflection of the inherent weakness of the F.M. for the evaluation of lethality at the onset of the cooling phase (Merson et al. 1978; Spinak and Wiley 1982). This weakness is particularly significant in the situation shown in Fig. 7.5 because the accumulated lethality during the cooling phase is greater than during the heating phase.

Figure 7.8 represents experimental data for a broken heating curve. Again, the F.M. underestimated the accumulated lethality compared to the R.G.M. ($F_0 =$ 35 min compared to 40 min). When adjusting process time for a F_0 value of 6 min, the R.G.M. gave a slightly shorter operator process time ($P_t = 25$ min compared to 26 min).

7.6.2 Thermal Process Evaluation at Conditions Other Than Those That Were Experimentally Recorded (or Generated by Simulation)

Figure 7.9 represents experimental data collected in a seafood processing plant to test the developed procedure for changing retort temperature and/or initial temperature and then adjusting the process to a specified F_r value. Process specifications and calculations are given in Table 7.7.

The experimental data presented in Fig. 7.9 were selected as being normal thermal processing data. First, the come-up between both processes was similar but with slight differences. Second, the initial temperatures (IT) were different, and

Table 7.7 Can dimensions and processing conditions for experimental data shown in Fig. 7.9

Process	TRT (°C)	IT (°C)	F_0[a] (min) R.G.M.	F_0[a] (min) F.M.	P_t[b](min) R.G.M.	P_t[b](min) F.M.
1	114.5	17.3	7.0	6.0	36	40
2	117.6	63.1	13.6	9.9	16	23

[a] F_0 value calculated from experimental data

[b] Calculated for $F_r = 6$ (min); Product: Mussel (*Mytilus chilensis*) in brine, Can Format 100 × 22 (mm); $f_h = 9.11$ (min)[c]; $j_h = 1.21$[c]

[c] Obtained from the process at TRT = 114.5 (°C)

third, the retort temperature (TRT = 117.6 °C) was constant but with slight variations during the process. Thermal processing data were evaluated using both the R.G.M. and the F.M. (F_0 values are depicted in Table 7.6). In both cases, the F.M. underestimated the F_0 value in relation to the R.G.M., revealing once again that the higher the retort temperature, the lower the prediction capacity of the F.M.

Taking Process 1 (Table 7.6) as a reference process, thermal processing data were transformed from TRT = 114.5 °C to TRT = 117.6 °C according to the R.G.M. procedure and then used for process evaluation to compare with the results from the F.M. When comparing operator process time ($F_r = 6$ min), F.M. overestimated both processes by approximately 10 % and 44 %, respectively, compared with R.G.M. (TRT = 114.5 °C and TRT = 117.6 °C).

According to Fig. 7.10, the R.G.M. has very accurate prediction capacity, and the predicted F_0 value is on the safe side (F_0 value of 6.07 min compared to 6.14 min).

7.7 Summary

It was possible to develop a systematized procedure for the General Method to give it the same ease of use as Ball's Formula Method. The R.G.M. allows the same calculations as the Ball's Formula Method but with greater accuracy.

The proposed methodology was rather accurate when used for thermal process adjustment. The processing time was always estimated (overestimated) with an error less than 5 % (in all cases under study). For the Ball's Formula Method, it was common to find errors of 10–20 % or more. The new procedure safely predicted shorter processing times than the Ball's Formula Method. These shorter process times may have an important impact on product quality, energy consumption, plant production capacity, and adequate corrections for on-line control (process deviations). In contrast, the Ball's Formula Method predicted unsafe processes for the forced convection products analyzed in this study.

Further testing with experimental data must be performed on this developed procedure to check its performance, and then, it should be made available in a user-friendly software form. The developed procedure could be extended to pasteurization processes, UHT/HTST processes, and others. Future studies should consider the possibility of changing come-up time, the nonlinear temperature profile during come-up time, and the ability to evaluate broken heating curves at different conditions from the originally recorded temperature (TRT and/or IT).

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Chapter 8
Formula Methods and Analytical techniques

8.1 Some Formula Methods

8.1.1 Introduction

It is easy today to dismiss the methods developed in the past as no longer relevant. Modern computers can now be used to calculate processes without any knowledge of the background for the calculations. However, it is instructive to see how the methods developed and the problems associated with calculating processes. For this purpose two methods have been selected for more detailed treatment: the Ball methods, because of their ingenuity and widespread use; and the Gillespy method, widely used in the UK canning industry. A number of other methods are mentioned, but in less detail.

The formula methods have their origin in the use of the simple F_0 integral Eq. (7.1) and substitution of an empirical model of the temperature distribution from heat penetration experiments. Each worker has used different representations for the modeling of the heating and cooling curves. The Ball methods (Ball 1923; Ball and Olson 1957) involved f_h and j parameters for straight-line heating and a hyperbolic function to model the onset of cooling. The method was further developed by a number of workers, in particular, Jakobsen (1954), Hayakawa (1970), and Stumbo (1973). Gillespy (1953), Hicks (1951), and Flambert and Deltour (1972a) used theoretically derived equations based on conduction heat transfer into cylindrical containers.

Among the reviews of the methods which are useful background reading are Holdsworth and Overington (1975), Merson et al. (1978) and, especially, Hayakawa (1977, 1978, 1982).

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8.2 Ball's Methods

8.2.1 *Development of the Methods*

The pioneering work of C.O. Ball (1923) is the starting point for thermal process calculations, and it is useful and instructive to discuss the methods and their development in order to provide some background on the subject. The methods that he developed (Ball 1923, 1928) and subsequently modified (Ball and Olson 1957) are still very widely used in industry. Here we will use the accepted nomenclature, together with Fahrenheit units.

The method makes use of the straight-line heating section of the semilogarithmic heat penetration curve discussed in Chap. 6. The following equation is used to model the temperature distribution during heating:

$$\log(T_1 - T) = (-t/f_\mathrm{h}) + \log[j(T_1 - T_0)], \tag{8.1}$$

where T is the required temperature distribution, T_1 is the processing (retort) temperature, T_0 is the initial temperature of the can contents, t is the time and f_h and j are the heat penetration parameters. The value of $T_1 - T$ at the end of heating is referred to as g, and log g is given by the equation

$$\log g = (-t_\mathrm{B}/f_\mathrm{h}) + \log[j(T_1 - T_0)], \tag{8.2}$$

where t_B is referred to as the process time. Substituting Eq. (8.2) in the lethality Eq. (7.1) and integrating (see Ball and Olson 1957) gives

$$F = \frac{f_\mathrm{h} e^{g/z}}{t}[Ei(-80/z) - Ei(-g/z)], \tag{8.3}$$

where $-Ei(-x)$ is the exponential integral also denoted by $E_1(x)$ and defined in Sect. 8.3.4, and the interval of 80 °F was chosen because it was safe to assume that any temperature more than 80 °C lower than the processing temperature has a negligible lethal rate compared with that of the whole process. Using another hyperbolic expression for the cooling part of the curve, Ball (1923) obtained his classical equation for the whole heating and cooling process in which the total lethality of the process is given by

$$\begin{aligned} A = (f_\mathrm{he}/t)\Big\{ & e^{g/z_\mathrm{e}}[Ei(-80/z_\mathrm{e}) - Ei(-g/z_\mathrm{e})] \\ & + \left[0.33172 e^{-0.343m/z_\mathrm{e}} + 0.5833(z_\mathrm{e}/m)e^{0.300m/z_\mathrm{e}} E\right], \\ & + e^{-m/z_\mathrm{e}}\left[Ei(0.657m/z_\mathrm{e}) - Ei\frac{m+g-80}{z_\mathrm{e}}\right]\Big\} \end{aligned} \tag{8.4}$$

where

$$\begin{aligned} f_{\mathrm{he}} &= f_{\mathrm{h}}/\ln 10 = f_{\mathrm{h}}/2.303 \\ z_{\mathrm{e}} &= z/2.303 \\ E &= \int_{u_2}^{u_1} e^{-u}\left[u^2 - (0.3m/z_{\mathrm{e}})^2\right]^{1/2} \mathrm{d}u \end{aligned},$$

with $u_1 = 0.643\, m/z_{\mathrm{e}}$ and $u_2 = 0.3\, m/z_{\mathrm{e}}$, and m is the difference in temperature between the maximum temperature attained in the product at the end of heating, T_{g}, and the cooling water temperature. Ball denoted by C the term in the curly brackets, and he derived tables of C as a function of g, m and z. Although the formula given in Ball and Olson (1957) has an incorrect negative sign, due to the use of $Ei(-x)$ instead of $-Ei(-x)$, the tables presented there are the same as the ones in the original publication (Ball 1923), based on the correct $Ei(x)$. For a discussion of this problem see Flambert et al. (1977), Larkin (1989), Merson et al. (1978), Steele and Board (1979), Steele et al. (1979), and Storofos (1991). Olson and Stevens (1939) derived a series of nomographs based on the above equation for process determination.

The method developed so far allows the determination of the F-value for a process, conversion for various can sizes, based on f_{h} and j, and new processes can be evaluated for differing temperatures T_1 and T_0. However, to permit the calculation of process time for a given F-value, the C-equation was modified as follows. Equation (8.4) can be represented more simply in the form

$$F = fL_1 e^{-2.303g/z} C \tag{8.5}$$

or

$$fL_1/F = e^{+2.303g/z}/C;$$

if we then write $F_1 = 1/L_1$ and $U = FF_1$, then

$$f/U = e^{2.303g/z}/C. \tag{8.6}$$

F_1 is equivalent to the thermal death time at the retort temperature for an organism whose F-value is unity; U is equivalent to the thermal death time at 250 °F for an organism whose thermal death time is F min. Extensive tables for f/U versus g are given in Ball and Olson (1957) for various z-values and differing values of $m + g$. For the purpose of illustrating the use of the method a table of f/U versus log g is given in Table 8.3 for $z = 18$ °F. For tables in degrees Celsius and examples of application to determine F-values, see Hayakawa and Downes (1981).

Various modifications to the Ball method have been presented in the literature; these include the new formula method (Ball and Olson 1957) and Pflug's (1968) method, which uses Hicks' (1958) tables.

The process time, t_p, for a commercial operation is measured from the time when the retort reaches processing temperature, T_1, to the time when the steam is turned off and the cooling water applied. However, there is a significant time for the retort to reach processing temperature, which makes a contribution to the total lethal effect; this is known as the “come-up time” or CUT (t_c). Ball (1923) determined a value of $0.42t_c$ for the contribution to the lethal effect, so that the effective process time, t_B, was given by

$$t_B = t_p + 0.42t_c. \tag{8.7}$$

The figure of 42 % is generally regarded as a conservative estimate and is really only applicable to batch retorts with a linear heating profile. While the lethal effects of CUT at the product center of a container are small for most cans, with thin profile plastic packages the effect of CUT could be more significant. Spinak and Wiley (1982) that found that CUT effectiveness varied from 35 to 77 % and Ramaswamy and Tung (1986) found that the effectiveness factor of 42 % was very conservative for thin profile packages. Ramaswamy (1993) again using thin profile retort packages, and two retort temperature profiles, one linear and the other logarithmic, showed that the traditional 42 % CUT was appropriate for the former, but for the latter the values were twice as large. Apart from package thickness, other factors had only a small influence on the CUT. For other types of retort, initial conditions and venting procedures, the reader should consult Alstrand and Benjamin (1949), Berry (1983), Ikegami (1974a, b), Succar and Hayakawa (1982), and Uno and Hayakawa (1981).

8.2.2 *Correction Factor for Come Up Time Under Critical Scrutiny*

As stated by Dr. Olin Ball in his original work and later confirmed by several other authors, there is no doubt that the CUT length and shape effectively contribute to the lethal effect. In addition, as reported by different authors, the contributions will vary with package geometry, size, and other factors (Ramaswamy 1993; Spinak and Wiley (1982). However, the real question is to understand whether this effect is considered in Ball’s Formula Method. The hypothesis proposed by Simpson et al. (2012) was that Ball’s Formula Method, like the General Method, accounts for the effect of the CUT in its calculations, regardless of where the zero time line is placed within the come-up time (see Fig. 8.1).

Supporting this argument is the fact that Ball’s Formula Method requires the experimental data to be fit to a curve. Thus, the linear regression of the heat penetration data always fits the same experimental data, independently of the location of time zero. Thus, when calculating the heating lethality (F_{Heating}), the CUT effect is always considered. Possibly a real concern should be the “quality” of the accuracy of Eq. (7.14) in terms of “goodness of fit” during the heating stage,

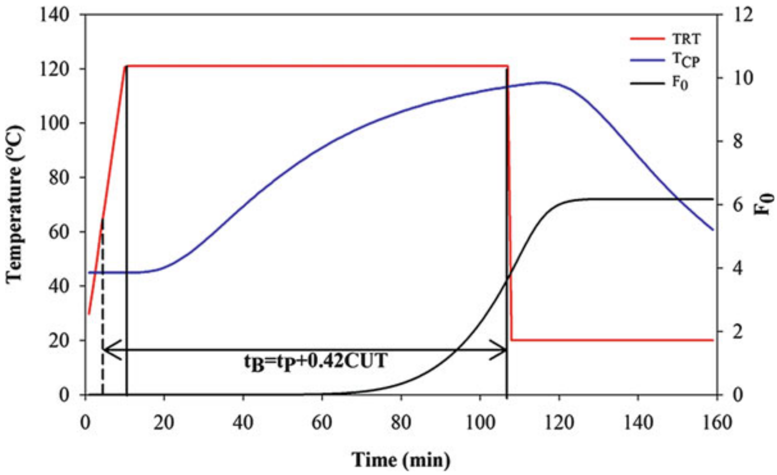

Fig. 8.1 Graphical representation of the correction factor in Ball's procedure

depending on the CUT shape and length and the value of f_h. Although substantial empirical evidence has shown a high correlation when fitting the straight-line portion of the temperature–time profile to experimental data, this evidence was tested using several computer-based experiments. Simpson et al. 2012 concluded that the prediction of operator process time (t_p) by Ball's Formula Method was the same regardless of where time zero was placed within the come-up time (or the CUT contribution). This result is due to the linear regression of the heat penetration data along the straight-line portion of the semilog heat penetration curve, which produces a mathematical expression (heating stage) that predicts the same time–temperature history independently of the location of time zero. In addition, given that high correlations were obtained in all cases, the calculation of the F-value from the regressed data (Ball's procedure) was essentially identical to the F-value calculated by the General Method, which is based directly on the experimental data points.

8.2.3 Application of the Method: Straight-Line Heating

The examples here and in Sect. 8.2.4 show how the process lethality can be calculated for four different cases.

Example 1 *Calculation of* F_0 *Value for a Straight-Line Heating Profile*. To use this method, the values of f_h and j must either be known from heat penetration experiments or assumed for the given can size and contents. In this example we have $f_h = 50$ min and $j = 1.48$; in addition, we are given a retort temperature $T_1 = 245$ °F, an initial temperature $T_0 = 162$ °F, a process time $t_B = 85$ min, and we will take the microbial inactivation factor z to be 18 °F with T_{ref} 250°F and $m + g = 180$ °F. The lethal rate L for the processing temperature T_1 is obtained from

$$L = 10^{(T-250)/18} = 10^{-5/18} = 0.53$$

We then calculate the difference between the retort and initial temperatures

$$T_1 - T_0 = 83°\mathrm{F},$$

multiply this difference by j

$$j(T_1 - T_0) = 1.48 \times 83 = 122.84,$$

and take logs

$$\log[j(T_1 - T_0)] = 2.089.$$

We can calculate log g from

$$\begin{aligned}\log g &= \log[j(T_1 - T_0)] - t_{\mathrm{B}}/f_{\mathrm{h}}\\ &= 2.089 - 85/50 = 0.389,\end{aligned}$$

which, using Table 8.1 and interpolation, gives

$$f_{\mathrm{h}}/U = 2.32.$$

We can now calculate F_0 from Eqs. (8.2) and (8.3) in the form

$$\begin{aligned}F_0 &= (f_{\mathrm{h}} \times L)/f_{\mathrm{h}}/U\\ &= (50 \times 0.53)/2.32 = 11.42\,\mathrm{min}\end{aligned}$$

Example 2 *Calculation of Process Time* t_{B} *for a Straight-Line Heating Profile.* In this example we are given the required value of F_0 (10 min) and wish to calculate the processing time to achieve it. We now have $f_{\mathrm{h}} = 52$ min and $j = 1.78$; in addition, we are given a retort temperature $T_1 = 245$ °F, an initial temperature $T_0 = 100$ °F, and we will take the microbial inactivation factor z to be 18 °F and $m + g = 180$ °F as before.

The lethal rate L for the processing temperature T_1 is obtained, as in Example 1, from

$$L = 10^{(T-250)/18} = 10^{-5/18} = 0.53.$$

The difference between the retort and initial temperatures is

$$T_1 - T_0 = 145\,°\mathrm{F},$$

Table 8.1 Values of f_h/U for given log $g (z = 18\ °F)$, based on Ball (1928)

Log g	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
−2.00	0.369	0.368	0.366	0.365	0.364	0.362	0.361	0.360	0.358	0.357
−1.90	0.383	0.382	0.380	0.379	0.377	0.376	0.375	0.373	0.372	0.370
−1.80	0.398	0.397	0.395	0.394	0.392	0.391	0.389	0.388	0.386	0.385
−1.70	0.415	0.413	0.412	0.410	0.408	0.407	0.405	0.403	0.402	0.400
−1.60	0.433	0.431	0.429	0.427	0.426	0.424	0.422	0.420	0.418	0.417
−1.50	0.452	0.450	0.448	0.446	0.444	0.442	0.441	0.439	0.437	0.435
−1.40	0.474	0.472	0.469	0.467	0.465	0.463	0.461	0.459	0.457	0.455
−1.30	0.498	0.495	0.493	0.490	0.488	0.485	0.483	0.481	0.478	0.476
−1.20	0.524	0.521	0.518	0.515	0.513	0.510	0.508	0.505	0.503	0.500
−1.10	0.552	0.549	0.546	0.543	0.541	0.538	0.535	0.532	0.529	0.526
−1.00	0.585	0.581	0.578	0.575	0.571	0.568	0.565	0.562	0.559	0.556
−0.90	0.623	0.618	0.614	0.609	0.604	0.599	0.599	0.595	0.592	0.588
−0.80	0.670	0.665	0.660	0.656	0.651	0.647	0.642	0.637	0.633	0.628
−0.70	0.717	0.712	0.708	0.703	0.698	0.693	0.689	0.684	0.679	0.674
−0.60	0.769	0.763	0.758	0.753	0.747	0.742	0.737	0.732	0.727	0.722
−0.50	0.827	0.820	0.814	0.808	0.802	0.797	0.791	0.785	0.780	0.774
−0.40	0.894	0.887	0.880	0.873	0.866	0.859	0.852	0.846	0.839	0.833
−0.30	0.974	0.966	0.957	0.949	0.940	0.932	0.924	0.917	0.909	0.901
−0.20	1.071	1.060	1.050	1.040	1.030	1.020	1.011	1.001	0.992	0.983
−0.10	1.187	1.175	1.162	1.150	1.138	1.126	1.115	1.103	1.092	1.081
−0.00		1.314	1.299	1.284	1.269	1.255	1.241	1.227	1.214	1.200
0.00	1.330	1.346	1.362	1.379	1.396	1.413	1.431	1.449	1.468	1.487
0.10	1.506	1.526	1.546	1.567	1.588	1.610	1.632	1.654	1.678	1.701
0.20	1.726	1.751	1.776	1.803	1.829	1.857	1.885	1.914	1.944	1.974
0.30	2.005	2.037	2.070	2.104	2.139	2.174	2.211	2.248	2.287	2.327

(continued)

Table 8.1 (continued)

Log *g*	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.40	2.368	2.410	2.454	2.498	2.544	2.592	2.640	2.691	2.743	2.796
0.50	2.852	2.909	2.968	3.029	3.092	3.157	3.224	3.294	3.366	3.441
0.60	3.519	3.599	3.682	3.768	3.858	3.951	4.048	4.148	4.252	4.361
0.70	4.474	4.591	4.714	4.842	4.975	5.113	5.258	5.410	5.568	5.733
0.80	5.906	6.087	6.276	8.74	6.682	6.901	7.130	7.370	7.623	7.889
0.90	8.168	8.463	8.773	9.100	9.445	9.809	10.194	10.600	11.031	11.486
1.00	11.969	12.481	13.024	13.601	14.213	14.865	15.560	16.299	17.088	17.929
1.10	18.828	19.789	20.817	21.919	23.100	24.367	25.729	27.192	28.767	30.465
1.20	32.295	34.271	38.07	38.718	41.221	43.935	46.881	50.083	53.568	57.364
1.30	61.505	66.028	70.974	76.389	82.326	88.843	96.008	103.895	112.589	122.187
1.40	132.8	144.5	157.6	172.0	188.1	206.0	226.0	248.4	273.4	301.4
1.50	332.9	368.3	408.2	453.3	504.3	562.0	626.6	702.2	787.1	884.2

which we again multiply by j

$$j(T_1 - T_0) = 1.78 \times 145 = 258.1;$$

taking logs gives

$$\log[j(T_1 - T_0)] = 2.41.$$

We now rearrange the equation for F_0 as used in Example 1, to give

$$\begin{aligned} f_h/U &= (f_h \times L)/F_0 \\ &= (52 \times 0.53)/10 = 2.756 \end{aligned};$$

using Table 8.1 and interpolation, we obtain

$$\log g = 0.483.$$

Finally, we calculate t_B from the expression

$$\begin{aligned} t_B &= f_h \log\{[j(T_1 - T_0)] - \log g\} \\ &= 52(2.41 - 0.483) = 100.2\,\text{min}. \end{aligned}$$

8.2.4 Products Exhibiting Broken-Heating Curves

Some packs heat quickly during the initial stages and then, because of the thickening of the constituents, the process slows down. The heating curve, plotted on a semilogarithmic basis, for such products often shows two lines of differing slope, known as a broken-heating curve (see Fig. 8.2). In order to calculate processes for these cases, it is necessary to know: the j-value; the f-value for the first part of the heating curve, f_h; the f-value for the second part of the heating curve, f_2; and the time at the intersection of the two lines, x_{bh}, taking into account the zero corrected for come-up time allowance. The method for process evaluation of the broken-heating curve pack given here is an extension of the Ball's method as developed by the American Can Co (1950).

The equations required for calculating the F_0-value are as follows:

$$\log g_{bh} = \log[j(T_1 - T_0)] - x_{bh}/f_h \tag{8.8}$$

$$\log g_{h2} = (f_h \log[j(T_1 - T_0)] + (f_2 - f_h)\log g_{bh} - t_B)/f_2 \tag{8.9}$$

$$F_0 = \frac{f_2 L}{(f_h/U_{h2})} - \frac{r_{bh} L(f_2 - f_h)}{(f_h/U_{bh})}. \tag{8.10}$$

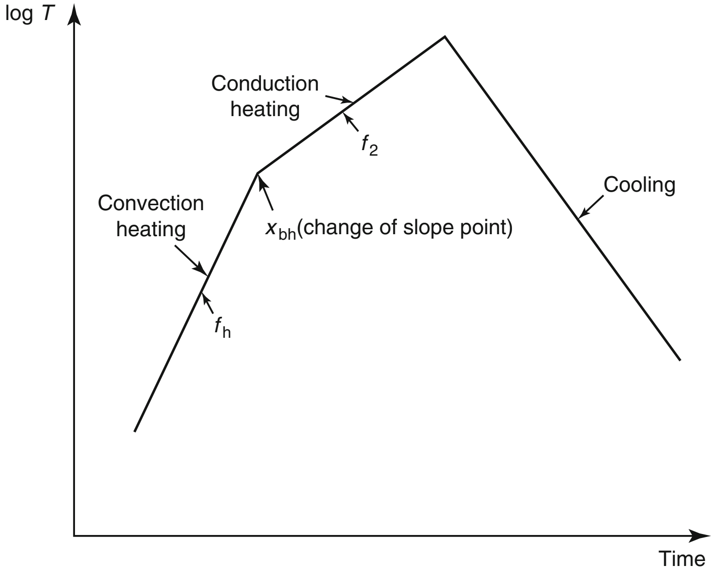

Fig. 8.2 Semilogarithmic curve representing broken heating conditions

In Eq. (8.8) all the values required to calculate log g_{bh} are known from the heat penetration data, f_h, j and x_{bh}, along with the retort temperature, T_1, and the initial temperature of the can contents, T_0. The value of g_{bh} represents the number of degrees below retort temperature the can "center" point is at the intersection of the lines and, using the value f_h/U_{bh}, can be obtained from Table 8.1, for use in Eq. (8.10). The value of g_{h2} is calculated using Eq. (8.9) and represents the number of degrees the can "center" point is below the processing temperature at the end of the process. The value of f_h/U_{h2} is obtained from Table 8.1, for use in Eq. (8.10). The value of r_{bh} is obtained from Table 8.2.

The equation for log g_{h2} is based on the condition that $f_c = f_2$; if, however, $f_c = f_h$, then it is necessary to correct the value of log g_{h2} by adding the term $0.071(1 - f_c/f_2)$

The equations required for calculating the process time, t_B, are as follows:

$$\log g_{bh} = \log[j(T_1 - T_0)] - x_{bh}/f_h \qquad \text{(Eq. (8.8)) see above}$$

$$f_h/U_{h2} = f_2/[F_0/L + r_{bh}(f_2 - f_h)/(f_h/U_{bh})] \tag{8.11}$$

$$t_B = f_h\log[j(T_1 - T_0)] + (f_2 - f_h)\log g_{bh} - f_2\log g_{h2}. \tag{8.12}$$

The value of log g_{bh} is calculated as before using Eq. (8.9), which then allows the values of f_h/U_{bh} and r_{bh} to be found from Tables 8.3 and 8.4. The value of log g_{h2} is then found from the value of f_h/U_{h2} calculated in Eq. (8.11). All the factors are then known for calculating t_B using Eq. (8.12).

Table 8.2 Values of r_{bh} and log g for broken heating curve calculations

log g	r_{bh}	log g	r_{bh}
−1.0	0.947	1.05	0.710
−0.9	0.944	1.10	0.692
−0.8	0.941	1.15	0.675
−0.7	0.939	1.20	0.655
−0.6	0.934	1.25	0.635
−0.5	0.930	1.30	0.610
−0.4	0.927	1.35	0.590
−0.3	0.920	1.40	0.565
−0.2	0.915	1.45	0.540
−0.1	0.910	1.50	0.510
0.0	0.900	1.55	0.480
0.1	0.891	1.60	0.450
0.2	0.880	1.65	0.423
0.3	0.870	1.70	0.400
0.4	0.855	1.75	0.380
0.5	0.840	1.80	0.350
0.6	0.822	1.85	0.330
0.7	0.800	1.90	0.300
0.8	0.780	1.95	0.265
0.9	0.750	2.00	0.240
1.0	0.725		

If $f_c = f_2$, then the value of log g_{h2} is obtained directly from the value of f_h/U_{h2}; if $f_c = f_h$, then the correction factor discussed above, $0.071(1 - f_c/f_2)$, must be subtracted from the value of log g_{h2}.

The examples in Sect. 8.2.4 illustrate the application of these equations.

The method has been computerized and FORTRAN programs published by Griffin et al. (1969). A method of establishing thermal processes for products with broken-heating curves from data taken at other retort temperatures and initial temperatures has been developed by Berry and Bush (1987).

8.2.5 Application to Broken-Heating Curves

Example 3 *Calculation of F_0 Value for a Broken-Heating Curve Process*. In this example we have $f_h = 14$ min and $j = 1.5$; other heat penetration factors are $f_2 = 68$ and $x_{bh} = 15$ min. In addition, we are given a retort temperature $T_1 = 240$ °F, an initial temperature $T_0 = 162$ °F, a process time $t_B = 52$ min; and we will again take the microbial inactivation factor z to be 18 °F and $m + g = 180$ °F.

We begin by calculating the difference between the retort and initial temperatures

Table 8.3 Values of u for v ranging from -0.2 to 3.49 (Gillespy's method)

v	0.00	0.02	0.04	0.06	0.08
−0.2	0.003	0.003	0.004	0.005	0.005
−0.1	0.006	0.008	0.009	0.010	0.012
0.0	0.014	0.016	0.019	0.021	0.024
0.1	0.027	0.030	0.034	0.038	0.042
0.2	0.047	0.051	0.057	0.062	0.068
0.3	0.074	0.080	0.087	0.094	0.102
0.4	0.110	0.118	0.126	0.135	0.144
0.5	0.154	0.164	0.174	0.184	0.195
0.6	0.206	0.218	0.229	0.241	0.253
0.7	0.266	0.279	0.292	0.305	0.318
0.8	0.332	0.346	0.360	0.375	0.390
0.9	0.404	0.419	0.435	0.450	0.466
1.0	0.482	0.498	0.514	0.530	0.546
1.1	0.563	0.580	0.597	0.614	0.631
1.2	0.648	0.665	0.683	0.700	0.718
1.3	0.736	0.754	0.772	0.790	0.808
1.4	0.826	0.844	0.863	0.881	0.900
1.5	0.918	0.937	0.955	0.974	0.993
1.6	1.012	1.031	1.050	1.069	1.088
1.7	1.126	1.126	1.145	1.164	1.184
1.8	1.203	1.222	1.241	1.261	1.280
1.9	1.300	1.319	1.339	1.358	1.378
2.0	1.397	1.417	1.436	1.456	1.475
2.1	1.495	1.515	1.534	1.554	1.574
2.2	1.593	1.613	1.633	1.653	1.672
2.3	1.692	1.712	1.732	1.751	1.771
2.4	1.791	1.811	1.831	1.851	1.870
2.5	1.890	1.910	1.930	1.950	1.970
2.6	1.990	2.009	2.029	2.049	2.069
2.7	2.089	2.109	2.129	2.149	2.169
2.8	2.189	2.209	2.229	2.248	2.268
2.9	2.288	2.308	2.328	2.348	2.368
3.0	2.388	2.408	2.428	2.448	2.468
3.1	2.488	2.508	2.528	2.548	2.568
3.2	2.588	2.608	2.628	2.648	2.668
3.3	2.688	2.708	2.728	2.748	2.768
3.4	2.788	2.807	2.827	2.847	2.867

$$T_1 - T_0 = 78\,^{\circ}\mathrm{F},$$

and multiply this difference by j

$$j(T_1 - T_0) = 1.5 \times 78 = 117,$$

Table 8.4 Comparison of F-values for cooling phase for static processing (from Board et al. 1960)

		F_c-Value for cooling phase		
Product	Can size	General method	Ball method	Gillespy method
Spaghetti bolognaise	301 × 411	1.47	0.63	2.29
Baked beans	603 × 700	1.50	1.20	4.02
Vegetable soup	301 × 411	0.323	0.106	0.305
Cream style corn	401 × 411	1.89	0.62	1.79
Meat loaf	401 × 411	1.46	0.51	1.54
Tomato pulp	401 × 411	1.11	0.60	1.63

and take logs

$$\log[j(T_1 - T_0)] = 2.068.$$

We now calculate log g_{bh} from Eq. (8.8),

$$\begin{aligned}\log g_{\mathrm{bh}} &= \log[j(T_1 - T_0)] - x_{\mathrm{bh}}/f_{\mathrm{h}} \\ &= 2.06889 - 15/14 = 0.996\end{aligned}.$$

Based on this value of log g_{bh}, we can use Table 8.1 and interpolation to derive an estimate for $f_{\mathrm{h}}/U_{\mathrm{bh}}$ of 11.6; and we can use Table 8.2 and interpolation to estimate r_{bh} at 0.73.

We now calculate log g_{h2} using Eq. (8.9), adding a correction factor, to give

$$\begin{aligned}\log g_{\mathrm{h2}} &= \{f_{\mathrm{h}}\log[j(T_1 - T_0)] + (f_2 - f_{\mathrm{h}})\log g_{\mathrm{bh}} - t_{\mathrm{B}}\}/f_2 + 0.071(1 - f_{\mathrm{h}}/f_2) \\ &= 0.487\end{aligned},$$

and use Table 8.3 to estimate $f_{\mathrm{h}}/U_{\mathrm{h2}}$ at 2.78.

The lethal rate L for the processing temperature T_1 is obtained from

$$L = 10^{(T-250)/18} = 10^{-10/18} = 0.278.$$

This gives us the last piece of information we need. We can now calculate F_0 by substitution into Eq. (8.10):

$$F_0 = 5.86\,\mathrm{min}.$$

Example 4 *Calculation of Process Time t_B for a Broken-Heating Curve Process.* In this example we are given $F_0 = 7$ min, and wish to calculate the processing time to achieve it. We now have $f_{\mathrm{h}} = 12.5$ min and $f_2 = 70$; other factors are $j = 1.5$ and $x_{\mathrm{bh}} = 15$ min as in Example 3. In addition, we are given a retort temperature $T_1 = 235$ °F, an initial temperature $T_0 = 180$ °F, and we will again take the microbial inactivation factor z to be 18 °F and $m + g = 180$ °F.

We begin by proceeding exactly as in Example 3. Thus,

$$\begin{aligned} T_1 - T_0 &= 55°\text{F} \\ j(T_1 - T_0) &= 1.5 \times 55 = 82.5 \\ \log[j(T_1 - T_0)] &= 1.92 \\ \log g_{\text{bh}} &= \log[j(T_1 - T_0)] - x_{\text{bh}}/f_{\text{h}} \\ &= 1.92 - 15/12.5 = 0.72, \end{aligned}$$

using the last value to estimate $f_{\text{h}}/U_{\text{bh}} = 4.714$ using Table 8.1 and $r_{\text{bh}} = 0.796$ using Table 8.2.

The lethal rate L for the processing temperature T_1 is obtained exactly as in Example 3 and gives the value, $L = 0.1468$. We now use Eq. (8.11) to calculate $f_{\text{h}}/U_{\text{h2}} = 1.843$. Then we calculate log g_{h2} using and interpolating from Table 8.1, subtracting a correction factor, to give log $g_{\text{h2}} = 0.245 - 0.0583 = 0.18668$. Finally, we substitute these values into Eq. (8.12) to give

$$t_{\text{B}} = 52.3\,\text{min}$$

8.2.6 *Comments on Ball's Methods*

Despite the widespread use of the Ball (1923) procedures, it is important to note the following points:

1. The method applies to a j_{c}-value of 1.41.
2. The curvilinear portion of the cooling curve stops at $t_{\text{c}} = 0.141\,f_{\text{c}}$.
3. The method overestimates the F-value when $j_{\text{c}} < 1.41$ and, conversely, underestimates the F-value when $j_{\text{c}} > 1.41$.
4. The cooling phase treatment is less satisfactory than some of those developed by other workers.

These points should be taken into account, especially when processes with long come-up times are being considered, e.g., flexible pouches and rectangular-shaped plastic containers of food. In these cases it is important to use one of the general methods to determine the process lethality for the heating and cooling phases. The Ball method tends to underestimate the F_{total}-value.

8.3 Gillespy's Method

8.3.1 *Standard Heating and Cooling Conditions*

In his two classical papers, Gillespy (1951, 1953) published methods of determining process lethality for standard and complex heating profiles. The standard method (Gillespy 1951) has been in use for many years in the UK canning industry and is well established in industrial training programs. The simplified methodology with its computer algorithms did not appear until published by Board and Steel (1978).

The method is based on Ball's asymptotic approximation of the heating, which uses a dimensionless time t equal to the process time divided by the f_h-value:

$$T_R - T = j(T_R - T_0)10^{-t}. \tag{8.13}$$

The F-value for the process is obtained from $F = LU$, where L is the lethal rate at processing temperature and U is value of the process in terms of time at retort temperature. In Gillespy's notation the classical U/f is denoted by u and is obtained from the equation

$$u_H = (w - s) - \mu\gamma + \log\mu + \sum_{n=1}^{\infty} \frac{(-\mu)^{-(n-1)} 10^{-n(w-s)}}{n \cdot n!} \tag{8.14}$$

where w is the processing time corrected for "come up" divided by f_h, and s is the time, in units for f, for the temperature on the asymptote to the heating curve to rise from T_A to T_S, where $T_S = T_R - z$, and $s = (T_R - T_A)/z = \log[(T_R - T_0)/z] + \log j$, $\mu = \log_{10}e = 0.4343$, and $\gamma = 0.5772$ (Euler's constant). Equation (8.14) is equivalent to the exponential integral form for heating given in Eq. (8.42). The term $w - s$, also written as υ, can be obtained from Table 8.5. For estimating the cooling contribution it was assumed that $f_h = f_c$. Board et al. (1960) showed that Gillespy's method often overestimated the contribution of the cooling phase. This was especially for the case of conduction-heating packs, which cooled slower than Gillespy anticipated. In the simplified version, the factor for estimating the cooling phase was replaced by a single constant 0.08, and Gillespy's equation became

$$\upsilon = B/f_h - \log[j(T_R - T_0)/z] + 0.08;$$

for a z-value of 18 °F (i.e., $\log_{10}z = 1.255$), this equation is often written

$$\upsilon = B/f_h - \log[j(T_R - T_0)/z] + 1.335. \tag{8.15}$$

The process time B can be estimated from

$$B = f_h\{\upsilon + \log[j(T_R - T_0)] + 1.335\}. \tag{8.16}$$

8.3.2 Examples of the Use of Gillespie's Simple Method

Example 5 *Determination of the F-Valuefor a process*. In this example we have an initial temperature $T_0 = 140$ °F and a process temperature $T_R = 240$ °F; the heat

Table 8.5 Comparison of lethalities calculated by the general method and formula methods

Product	Size	General method	Ball (1923) method	Gillespy (1951) method	Hayakawa (1970) method	Ball and Olson (1957)	Pflug (1968) method	Griffin (1971) method	Jakobsen (1954) method	Reference
			Cooling only							
Spaghetti bolognaise	301 × 411	1.47	0.63	2.29						Board et al. (1960)
Baked beans	603 × 700	1.50	1.20	4.02						
Vegetable soup	301 × 411	0.32	0.11	0.30						
Cream style corn	401 × 411	1.89	0.62	1.79						
Meat loaf	401 × 411	1.46	0.51	1.54						
Tomato pulp	401 × 411	1.11	0.60 heating and cooling	1.63						
Chicken chop suey	Rectangular	9.60	7.00	6.68						Unpublished experimental data
Vegetable curry	Rectangular	9.00	10.70	5.60						
Sweet and sour pork	Rectangular	9.3	9.85 heating only	10.30						
Chicken chop suey	Rectangular	7.00	4.80	4.90						Unpublished experimental data
Vegetable curry	Rectangular	7.20	8.60	8.60						
Sweet and sour pork	Rectangular	7.50	8.20 heating only	8.50						
Meat and cereal	3 kg	6.10	–	4.30						Board and Steel (1978)
Ham	1 kg	0.80	–	0.30						
Meat and cereal	0.3 kg	11.72	–	10.35						

(continued)

Table 8.5 (continued)

Product	Size	General method	Ball (1923) method	Gillespy (1951) method	Hayakawa (1970) method	Ball and Olson (1957)	Pflug (1968) method	Griffin (1971) method	Jakobsen (1954) method	Reference
Small abalone	0.5 kg	3.70	–	3.70						
Cream	0.2 kg	1.20	–	1.10						
			Cooling only							
Potato soup	211 × 400	0.9	–	–	1.1	3.1	3.0			Hayakawa (1970)
Shrimp soup	211 × 400	1.5	–	–	1.4	4.4	3.9			
Vegetable/beef soup	211 × 400	0.5	–	–	0.7	4.1	3.7			
			Heating and cooling							
Potato soup	211 × 400	10.5	–	–	10.7	13.6	11.7			Hayakawa (1970)
Shrimp soup	211 × 400	8.4	–	–	8.4	11.3	9.9			
Vegetable/beef soup	211 × 400	6.5	–	–	7.0	10.2	10.0			
			Cooling only							
Theoretical (Hicks 1951)	11.6 × 10 cm	2.44	0.89	–	1.38	–	–	0.94	1.18	Skinner and Jowitt (1975)
Not specified TP1 (simple heating)		1.15	0.78	–	0.83	–	–	0.62	1.04	
Not specified TP2 (broken heating)		0.16	0.19	–	0.17	–	–	0.13	0.25	

penetration factors are $f_h = 53$ min and $j = 1.30$; and the processing time corrected for come-up is $B = 84$ min.

We begin by calculating υ from Eq. (8.15):

$$\begin{aligned}\upsilon &= B/f_{\mathrm{h}} - \log[j(T_{\mathrm{R}} - T_0)/z] + 1.335 \\ &= 84/53 - \log(1.3 \times 100) + 1.335 \\ &= 0.805(\text{heating and cooling})\end{aligned}\quad .$$

Table 8.3 (and interpolation) converts this υ-value into a u-value of 0.332. F_0 is then calculated from

$$F_0 = uf_{\mathrm{h}}L_{\mathrm{TR}} = 0.332 \times 53 \times 10^{(240-250)/18} = 4.72 \text{ min}.$$

For heating only, the value of 1.335 in the equation for υ should be replaced by 1.255; then we would obtain $\upsilon = 0.725$ and $u = 0.283$, and hence $F_0 = 4.17$ min.

Note that for unknown j, a value of 1 should be assumed for a convection pack and 2 for a conduction pack; two-thirds of the come-up time of the retort from 212 °F to the retort temperature should be counted as part of the process time B.

Note also that for z-values other than 18 °F, it is necessary to substitute log $z + 0.08$ as the final term in Eq. (8.15).

Example 6 *Determination of ProcessTimeB for a Given F_0-Value*. Using the same initial temperature $T_0 = 140$ °F, process temperature $T_R = 240$ °F, heat penetration factors $f_h = 53$ min and $j = 1.30$ as in Example 5, we now wish to find the processing time for an F_0-value of 5.

We must first determine u:

$$u = F_0/f_{\mathrm{h}}L = 5/(53 \times 0.278) = 0.339.$$

Table 8.3 (and interpolation) converts this to a υ-value of 0.810. We can now use Eq. (8.16) to calculate the process time:

$$B = 53(0.810 + 2.114 - 1.335) = 84.2 \text{ min}.$$

Note that if a j-value has been assumed, the come-up time correction must be deducted to obtain the operational time.

8.3.3 Some Comparisons with Other Methods

Board et al. (1960) made an extensive analysis of several methods of process determination, including the general method, Ball's formula method and Gillespy's method for a variety of products. Whereas all methods gave similar results for the heating phase, the cooling lethalities were considerably different. Ball's method gave figures which were much lower than the general method and significantly lower than Gillespy's, for example (see Table 8.4).

Gillespy's method generally agrees with the general method when cooling is by pure conduction. However, in products which cool more rapidly due to a combination of conductive cooling and convective cooling, Gillespy's method tends to overestimate the cooling contribution to the lethality. Using a computerized version of Gillespy's method, Board and Steel (1978) showed that *F*-values for the total process were generally lower than those obtained by the general method. It was concluded that the mechanism of internal cooling in the can was mainly responsible for the discrepancies. Bown (1989) showed that Gillespy's (1951) method gave very close results to a numerical finite-difference model, which was developed for process sensitivity studies.

8.3.4 Complex Heating Profiles

Gillespy (1953) developed a method of process determination for cases where the heating profile was time-dependent, e.g., linear or exponential. Relatively little use has been made of this method, although it was used to determine processes in the heating and cooling legs of hydrostatic cookers at a time when it was believed that the temperature gradients in the legs were linear functions of time. It has subsequently been shown that the conditions are somewhat different. The method is applicable to packs which have a slow "come up," e.g., conduction-heating products in flexible pouches or plastic containers.

The method used the usual step rise in temperature and Duhamel's theorem to determine the response to a time-dependent heating profile. Using the new temperature distribution, the *F*-value was calculated at the point of slowest heating. The temperature at the center of the can being processed was given by

$$T = T_{\mathrm{R}} - \Phi(t)(T_{\mathrm{ref}} - T_0) \tag{8.17}$$

and the variation of T_{R} with time t by

$$T_{\mathrm{R}} = T_0 - \Theta(t)(T_{\mathrm{ref}} - T_0). \tag{8.18}$$

Using Duhamel's theorem, the temperature response to the new conditions is given by

$$T = T_R - (T_{\mathrm{ref}} - T_0)\int \Phi(t-\lambda)\Theta'(\lambda)\mathrm{d}\lambda. \tag{8.19}$$

In the Gillespy notation a jump in temperature is designated $J(t)$, and a break $B(t)$. The heating and cooling profile can then be formulated in terms of a series of jumps, breaks or holds. The method can be illustrated by reference to determining the fraction of the come-up time, which is equivalent in lethal effect to time at process temperature, for a slab of material being heated in a water retort with a slowly rising linear gradient temperature. The temperature history is as follows:

1. For $t < 0$, retort temperature $T_R = T_0$, the slab initial temperature.
2. At $t = 0$, the retort temperature rises instantaneously to T_W, the water temperature at the start, a jump of $(T_W - T_0)$.
3. For $0 < t < t_c$, the retort temperature rises linearly from T_W to processing temperature T_R, a break of $(T_R - T_W)/t_c$.
4. For $t > t_c$, the retort temperature is T_R, a break of $-(T_R - T_W)/t_c$.

The pack center temperature is then given, for $0 \le t \le t_c$, by

$$T = T_W + t(T_R - T_W)/t_c - J(t)(T_W - T_0) - B(t)(T_R - T_W), \tag{8.20}$$

$$\begin{aligned} T = T_R - J(t)(T_W - T_0) - B(t)(T_R - T_W)/t_c \\ + B(t - t_c)(T_R - T_W)/t_c \end{aligned} \tag{8.21}$$

For a slab,

$$J(t) = \frac{4}{\pi}\left(e^{-\pi^2 x} - \frac{1}{3}e^{-9\pi^2 x} + \frac{1}{5}e^{-25\pi^2 x} - \cdots\right), \tag{8.22}$$

$$\begin{aligned} B(t) &= \int_0^z J(z)\mathrm{d}z \\ &= \frac{4L^2}{\alpha\pi^3}\left(\frac{\pi^3}{32} - e^{-\pi^2 x} + \frac{1}{27}e^{-9\pi^2 x} - \frac{1}{125}e^{-25\pi^2 x} + \cdots\right) \end{aligned} \tag{8.23}$$

Values of $J(t)$ and $B(t)$ can readily be evaluated, knowing the thermal diffusivity, α, and slab thickness, L, for various times t, where $x = t/L^2$. Thus the time–temperature history may be calculated and the F-value determined by a numerical technique (Patashnik 1953). To determine the process time necessary to achieve a desired F-value with no come-up time, i.e., at $t = 0$, note that the retort temperature rises instantaneously from T_0 to T_R. Thus if a particular process of 10 min come-up time +20 min at T_R gives an F_0-value of 4, and it is calculated that 27 min at the same T_R are required to deliver the same F_0-value without come-up time, then 7 min of come-up time is equivalent to time at the same T_R, i.e., 70 %.

Hayakawa (1974) developed a method of estimating temperature histories for products undergoing time-variable processing temperatures. He made a comparative study of his method with Gillespy's without much success, and suggested that there might be errors in Gillespy's tables, without identifying them. He considered that Gillespy's method underestimates food temperatures in the heating phase when $j < 2.04$ and, conversely, overestimates temperatures when $j > 2.04$.

More recently, Noronha et al. (1995) have produced a semiempirical method for determining the effect of time-variable boundary conditions on process values and compared this with other methods, using eight different processes. Most of the methods compared reasonably well, except for one or two anomalies.

8.4 Hayakawa's Method

Hayakawa (1970, 1971) developed an important method of process determination by producing a series of empirical equations to represent the various parts of the heating and cooling curves. The formulae were further modified (Hayakawa 1983c) and presented as follows:

1. Curvilinear portion of the heating curve:
    (a) for $0.001 \leq j \leq 0.4$,

$$T_1 - T = (T_1 - T_0)10^{-t/Bn}, \tag{8.24}$$

where

$$n = (t/f - \log j)(t_1/f) \tag{8.25}$$

$$B = t_1(t_1/f - \log j)^{-n}; \tag{8.26}$$

    (b) for $0.4 \leq j < 1$,

$$T_1 - T = (T_1 - T_0)\cot\left[Bt + \pi/4\right] \qquad 0 \leq t \leq t_1 \tag{8.27}$$

where

$$\begin{aligned} B &= \frac{1}{t_1}\left\{\arctan\left[\frac{\log(T_1 - T_0)}{\log[j(T_1 - T_0)] - t_1/f}\right] - \frac{\pi}{4}\right\} \\ t_1 &= 0.9f(1 - j); \end{aligned} \tag{8.28}$$

    (c) for $j > 1$

$$T_1 - T = (T_1 - T_0)\cos Bt \tag{8.29}$$

$$B = \frac{1}{t_1}\left\{\arccos\left[\frac{\log[j(T_1 - T_0)] - t_1/f}{\log(T_1 - T_0)}\right]\right\}. \tag{8.30}$$

2. Linear portion of heating:

$$T_1 - T = j(T_1 - T_0)10^{-t/f} \qquad \text{for } t_1 \leq t. \tag{8.31}$$

3. Curvilinear portion of the cooling curve: Use $f = f_c$, $j = j_c$, $T_1 - T = T - T_W$, $T_1 - T_0 = T_g - T_W$, and $t = t_c$ in the heating equations.
4. Linear portion of the cooling curve: Use the same substitutions in the linear heating curve Eq. (8.31).

The method involves the use of universal tables of U/f versus g/K_s, which can be used for converting from one z-value to another, since $K_s = z_b/z_a$. The general procedure is similar to that of the Ball method but enables a much better evaluation of the cooling contribution. The method is considered one of the best available for covering both the heating and the cooling ranges. Some comparative data are given in Table 8.5.

8.5 Other Formulae Methods

Table 8.6 gives a wide range of formula methods which have been proposed; however, many of these have not so far been adopted by industry and are mainly of research and teaching interest. Table 8.6 gives some comparative data on different methods; however, very few of these comparisons cover a wide range of processing parameter. Each method should be judged on its own merits. Smith and Tung (1982) studied the percentage errors in process lethality for five formula methods, applied to conduction-heating packs. The degree of error in descending order was: Ball and Olson (1957) > Ball (1923) > Steele and Board (1979) > Hayakawa (1970) > Stumbo (1973). It was found that the error was a function of the H/D ratio of the can for all the methods, with a maximum value at $H/D = 1$. The error also increased with increasing values of g, the temperature difference between the center of the can and the retort temperature at the end of cooking; thus greater errors were experienced with higher retorting temperatures (140 °C) than with more conventional temperatures (120 °C). Stumbo's method was found to be the one with least errors; however, it was found to be more sensitive to slight variations in f_h and j_c. Pham (1987) showed that his method was as good as the best of the above (Stumbo's method), and extended it to cover the cases where f_h and f_c were not the same (Pham 1990), with similar success. Since all the methods showed underestimates of the process lethality, the calculated process times would be larger than necessary and hence introduce a margin of safety. However, since the errors were dependent on the processing conditions, the extra safety margins would be variable.

The above applies to conduction-heating packs, where the value of g can be quite high at the end of a process. For convection-heating packs, where temperatures are more uniform, especially in agitated packs, process calculations do not involve such high errors.

Much of the earlier work was concerned with metallic cans; however, with the development of sterilizable plastic pouches and plastic trays with thin rectangular profiles, it is necessary to examine process calculation methods. This is partly because of the profile but also because of the processing methods, which involve

Table 8.6 Some formula methods of process lethality determination

Method	Reference	Comment
Formula methods (a) Empirical	Ball (1923)	First formula method published and the basis for most developments in process determination used f_h- and j-values for heating and cooling, and a hyperbola for representing the curvilinear parts of the heat penetration curve. Applicable for $j_c = 1.41$ and cooling time $t_c = 1.41 f_c$
	Ball and Olson (1957)	Simplified Ball's (1923) method using P_h and P_c factors for determining the process lethality. Applicable for $j_c = 1.41$ and cooling time $t_c = 1.41\ f_c$ and for $f_h \neq f_c$. Broken-heating curve method developed
	Gillespy (1951)	Used Ball's (1923) asymptotic approximation for heating and developed an approximate method for cooling
	Jakobsen (1954)	Hyperbolic sine function used to represent temperature history; $j_c = 2.04$. This was modified by Shiga (1970)
	Hicks (1958)	Revision of P_h and P_c tables of Ball and Olson (1957)
	Herndon et al. (1968)	Computer-derived tables based on Ball (1923)
	Griffin et al. (1969)	Computer-derived tables for broken-heating curves
	Griffin et al. (1971)	Computer-derived tables for cooling curves
	Stumbo and Longley (1966)	Lethality parameters determined by hand-drawn curves and areas measured with a planimeter. Applicable to variable j_c and for $f_h \simeq f_c$
	Hayakawa (1970)	Curvilinear parts of heating and cooling curve represented by exponential cotangent and cosine functions. Applicable for $f_h \neq f_c$ and to broken-heating curves. One of the best methods in this group
	Skinner and Urwin (1971)	Computer program for Stumbo and Longley (1966) method, including algorithm for f/U and g
	Vinters et al. (1975)	Computer algorithm developed for Ball's (1923) tables
	Shiga (1970, 1976)	B_h and B_c functions developed from Ball and Olson's (1957) P_h, and P_c functions. Linear relation between F_h (heating lethality) and t_h^2 (heating process time)
	Skinner and Jowitt (1975)	Review and comparison of Formula methods: Ball (1923); Jakobsen (1954); Griffin et al. (1969); Hayakawa (1970)
	Hayakawa (1977, 1978, 1983a)	Reviews of formula method models

(continued)

Table 8.6 (continued)

Method	Reference	Comment
	Downes and Hayakawa (1977)	°C tables developed
	Hayakawa and Downes (1981)	New parameters for process determination based on °C
	Tung and Garland (1978)	Computer method for process determination based on Stumbo (1973)
	Steele and Board (1979)	Concept of dimensionless sterilizing ratios (S) developed which are independent of temperature scale used.
	Kao et al. (1981)	$S=(T_{\mathrm{retort}}-T_{\mathrm{centre}})/z$. Uses cooling treatment developed by Griffin et al. (1971) Computer programs for process determination, which handle different z- and j_{c}-values. Applicable for $j_{\mathrm{c}}=0.4$–23 and z-values 10–26 °F
	Hayakawa (1983b)	Parametric tables of U/f against g, for $z=10$ °C, $T_0=70$ °C and $j=1.0$. Uses notation of Hayakawa (1970)
	Smith and Tung (1982)	Comparison of formula methods: Ball (1923); Stumbo and Longley (1966); Hayakawa (1970); Steele and Board (1979)
	Spinak and Wiley (1982)	Comparison of General and Ball's (1923) formula method for retort pouches
	Pham (1987)	Algebraic formulae developed for determining tables of U/f against g. Uses Smith and Tung (1982) methodology
	Pham (1990)	Extension of Pham (1987) to $f_{\mathrm{h}}\neq f_{\mathrm{c}}$
	Sablani and Shayya (2001)	Replace Stumbo's 57 tables by two neural network programs, viz., ANNG for the g-parameter and ANNF for the $\mathfrak{f}_{\mathrm{h}}/U$ parameter
	Larkin and Berry (1991)	Modified Ball's original method using a modified hyperbolic function for the cooling curve
	Teixeira et al. (1992)	Time-shift method
	Wiese and Wiese (1992)	Comparison of techniques
	Chiheb et al. (1994)	A finite Nth-order linear model, with variable retort temperatures.
	Denys et al. (1996)	Semiempirical model for broken-heating curves.
	Noronha et al. (1995)	Semiempirical method for time-variable boundary conditions
(b) Theoretical temperature distributions	Riedel (1947)	Analytical method for dealing with complex heating and cooling profiles
	Gillespy (1953)	Extension of the Reidel method; deals with linear and exponential heating profiles. Uses Duhamel's theorem for dealing with time-variable boundary conditions

(continued)

Table 8.6 (continued)

Method	Reference	Comment
	Hicks (1951)	Analytical equations for heating and cooling. Heating phase results agree with, and cooling treatment is better than, Ball (1923)
	Teixeira et al. (1969)	Numerical solution of equations
	Flambert and Deltour (1972b)	Analytical equations for heating and cooling
	Lenz and Lund (1977)	Dimensionless treatment of microbial destruction kinetics and Arrhenius equation
	Hayakawa (1977)	Numerical integration of analytical equations
	Naveh et al. (1983a, b; c)	Numerical solution of heat transfer equation. Application to transient cooling of conduction heating products
	Bhowmik and Tandon (1987)	Finite-difference equations and numerical solution
	Ghazala et al. (1991)	Finite-difference equations, analysis of errors, and application to thin packages
	Tucker (1991, 2002)	CTemp includes facilities for studying process deviations and can handle various shapes of package. Thermal diffusivities derived from f_h-values
	Teixeira et al. (1992)	Time-shift model
	Hayakawa et al. (1996)	Statistical distribution free equation applicable when cooling phase lethality is small

the use of pressurized steam or hot water. These introduce further lags to the heat transfer in the system and result in relatively slow come-up times. Spinak and Wiley (1982) compared the general and the Ball formula methods and showed general satisfaction with the Ball method. Ghazala et al. (1991) examined a number of methods for estimating the lethality, including Ball (1923), Stumbo (1973), Steele et al. (1979), Pham (1987), and the authors' computerized model, including sensitivity tests for various processing parameters. Although the Pham and Stumbo methods had the lowest percentage of overall errors, the difference between these and the other methods was not particularly great—probably because the j_c-value for these packs was nearer to the assumed values in the models.

In conclusion, while many developments are taking place in computer technology that enable easy solutions to the problems, it is nonetheless important for the student to study the methods that have been developed to understand the background of process calculations. It is also important to check new methods for accuracy, sensitivity, and applicability to the process required. With the development of newer types of processes, especially those with slow come-up times, it is essential to make sure that the asymptotic approximation, which underlies many of the methods of process calculation, is justified. Whichever method is used, it is always necessary to bear in mind the consequences of an inadequate process and the potential danger to the public. Food safety is paramount, and everyone applying these methods has a responsibility for recommending processes which are inherently safe. The ultimate responsibility rests with the correct operational procedures being applied, which is a major engineering problem.

8.6 Analytical Techniques

8.6.1 Introduction

The analytical approach is instructive, first, because it demonstrates the problems encountered in this type of work, and second, because the results are useful in other methods of analysis. The method essentially substitutes the equation for the temperature distribution T (t, r, x, y, z) obtained from the analytical heat transfer equations of Chap. 2 in the F_0 Eq. (7.1) to give

$$F_0 = \int_0^t 10^{\left(T(t,r,x,y,z) - T_{\text{re f}}\right)/z} \mathrm{d}t. \tag{8.32}$$

Some examples of different temperature profiles show how complex the situation can become.

For heating of canned foods, initially at a temperature T_0 and in a retort at temperature T_{R}, the general equation is

$$T = T_{\mathrm{R}} - (T_{\mathrm{R}} - T_0)F(t)$$

where $F(t)$ is the analytical solution for the temperature at the center point for the given geometrical shape (see Chap. 2). Substituting this in Eq. (8.32) gives

$$F_0 = \int_0^t 10^{[T_{\mathrm{R}} - (T_{\mathrm{R}} - T_0)F(t) - T_{\text{re f}}]/z} \mathrm{d}t. \tag{8.33}$$

For heating and cooling, the equation for $F(t)$ is

$$F(t) = T_{\mathrm{R}} - (T_{\mathrm{R}} - T_0)F(t) + (T_{\mathrm{C}} - T_{\mathrm{R}})[1 - F(t - t_{\mathrm{h}})], \tag{8.34}$$

where t is the total time for the whole process and t_{h} is the time for the heating part; when this is used in calculating the F_0, the total equation is the addition of the two parts for heating and cooling F_{h} and F_{c} respectively. This leads to the equation

$$F_0 = \int_0^{t_{\mathrm{h}}} 10^{[T_{\mathrm{R}} - (T_{\mathrm{R}} - T_0)F(t) - T_{\text{re f}}]/z} \mathrm{d}t + \int_{t_{\mathrm{h}}}^{t} 10^{[T_{\mathrm{R}} - (T_{\mathrm{R}} - T_0)F(t) + (T_{\mathrm{C}} - T_{\mathrm{R}})(1 - F(t - t_{\mathrm{h}})) - T_{\text{re f}}]/z} \mathrm{d}t \tag{8.35}$$

Hicks (1951) and Hurwicz and Tischer (1952) have discussed the solution of this equation for the case of cylindrical cans, using the first-term approximation. Whether the approximation is valid for the cooling period, where the value of t is small, is debatable.

8.6.2 Special Cases

8.6.2.1 Constant Temperature with Time

For $T_t = T$, at time t, e.g., during the holding time in a retort sequence or during passage through a heat exchanger, the equation reduces to

$$F_0 = 10^{(T - T_{\mathrm{ref}})/z} t. \tag{8.36}$$

8.6.2.2 Linear Temperature Gradient

For $T = T_0 + at$, where a is the slope of the profile $(T_2 - T_1)/(t_2 - t_1)$, for temperatures T_1 and T_2 corresponding to times t_1 and t_2,

$$F_0 = (z/a \ln 10)\left[10^{(T_2 - T_{\mathrm{ref}})/z} - 10^{(T_1 - T_{\mathrm{ref}})/z}\right]. \tag{8.37}$$

8.6.2.3 Exponential Temperature Rise

This is a general case where the temperature is given by $T = Ae^{-Bt}$, in which A and B are the heat transfer parameters, for example j and f_{h}. This represents the first term of many of the series solutions to the heat transfer equation and will only apply in practice when the heating time is long and the second and subsequent terms in the series become negligible. The temperature in this case is the reduced temperature $(T - T_{\mathrm{H}})/(T_0 - T_{\mathrm{H}})$, where T_{H} is the heating or retort temperature and T_0 is the initial temperature, and the basic temperature distribution equation becomes

$$T = T_{\mathrm{H}} - (T_0 - T_{\mathrm{H}})Ae^{-Bt}$$

The solution is given by the equation

$$F_0 = \int_0^t 10^{(T_{\mathrm{H}} - (T_{\mathrm{H}} - T_0)Ae^{-Bt} - T_{\mathrm{ref}})/z} \mathrm{d}t, \tag{8.38}$$

which becomes

$$F_0 = L\int_0^t 10^{-(T_{\mathrm{H}} - T_0)A\mathrm{e}^{-Bt/z}} \mathrm{d}t, \tag{8.39}$$

where the lethal rate at temperature T_{H} is $L = 10^{(T_{\mathrm{H}} - T_{\mathrm{ref}})/z}$. If $A' = A\,\ln 10^{(T_{\mathrm{H}} - T_0)/z}$, then the equation can be solved using the exponential integral

$$E_1(x) = \int_x^{\infty} e^{-x}/x\,\mathrm{d}x \tag{8.40}$$

and

$$F_0 = (L/B)\left[E_1\left(A'e^{-bt}\right) - E_1(A')\right]. \tag{8.41}$$

Since the second term is generally negligible, the equation becomes

$$F_0 = (L/B)E_1\left(A'e^{-bt}\right). \tag{8.42}$$

8.6.3 The Exponential Integral

The solution of many of the F_0 equations involves integrals of the type

$$\int_0^x e^{-e^{-x}}\mathrm{d}x \text{ and } \int_0^x 10^{-10^{-x}}\mathrm{d}x,$$

which are types of exponential integral. Tables are available for solving such integrals (National Bureau of Standards 1940; Pagurova 1961). Newman and Holdsworth (1989) produced a computer program, based on the algorithm

$$E_1(x) = -\gamma - \ln(x) + \sum_{n=1}^{\infty} (-1)^{n+1} x^n (n.n), \tag{8.43}$$

where γ is Euler's constant (0.577 215 665).

The exponential integral $E_1(x)$, as defined in Eq. (8.40), was originally used by Ball (see Ball and Olson 1957) in the e^x form and by Gillespy (1951) in the 10^x form. Throughout the literature there are examples of incorrect exponential integrals being used (see Ball and Olson 1957; Flambert et al. 1977). Great care needs to be taken in defining and using this function.

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Chapter 9
Some Factors Affecting *F*-Values and Mass-Average Sterilizing Values

9.1 Some Factors Affecting *F*-Values

9.1.1 Introduction

The main factors that affect the magnitude of the *F*-value of a process and that are contained in the equations for determining *F*-values may be listed as follows:

1. Process-Related Factors.
   - (a) Retort temperature history, heating, holding, and cooling temperatures and times: The accuracy of temperature measurements has a direct effect on lethality values, and temperature-measuring devices need to be calibrated to a traceable standard.
   - (b) Heat transfer coefficients: For processes heated by steam and vigorously agitated in boiling water, these are usually so high that no effect is observed; however, with other methods of heating, which have much lower values, it is important to estimate the effective values as accurately as possible.
2. Product-Related Factors.
   - (a) Initial temperature of can contents: The uniformity of the initial filling temperature should be carefully controlled. The higher the initial temperature the shorter the required process time.
   - (b) Pre-retorting delay temperature and time: This is related to the filling temperatures and results from malfunctioning of the process, and delays affect the initial temperature of the can contents.
   - (c) Thermal diffusivity of product: Most models are very sensitive to changes in the value of this property.
   - (d) z- and D-value of the target microbial species.

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3. Container-Related Factors.
   (a) Container materials: Apart from tin-plate and other metallic containers, all other materials, e.g., plastics and glass, impede the heat transfer into the container.
   (b) Container shape: The most rapidly heating containers have the largest surface area and the thinnest cross section.
   (c) Container thickness: The thicker the container wall, the slower the heating rate.
   (d) Headspace: This is of particular importance to agitated and rotary processes. The headspace and the rate of rotation need to be carefully controlled.
   (e) Container stacking: The position of the containers inside the retort and the type of stacking also affect the heat transfer to individual containers.

9.1.2 Statistical Variability of F*-Values*

From a consideration of all the factors that affect the F-value delivered to an individual can of food, it can be seen that there is likely to be a distribution in the F-values. Variations in heat penetration data were discussed in Chap. 6; however, here the effects of various parameters on lethality are discussed.

One of the earliest F_0 distributions was published by Fagerson et al. (1951), who made a study of convection-heating products. It was found that the distribution was nonsymmetrical rather than normal. Powers et al. (1962), for similarly heating products, found non-normal distributions, and these varied according to the product and the length of processing time. Positively skewed distributions were obtained for short processing times (less than 50 min) and negatively skewed distributions for longer times, using over 700 experimental values. Extreme-value analysis was used to determine, for a range of F_0-values, the proportion of F_0-values outside a certain confidence level. While most of the variation was due to processing time, the filled weight of product also affected the F_c-values, but not the F_h- or F_0-values. The coefficient of variation (CV), the standard deviation divided by the mean, for the results varied in the range of 16.3–57.4 %. The extreme-value method of analysis was recommended for determining the safety margins for canned foods. A Monte Carlo procedure was used by Lenz and Lund (1977) to study the effect of thermal diffusivity and energy of activation for thermal inactivation of microorganisms. An 8–15 % CV was observed in process lethality, and with increase of heating time there was a reduction in CV. These workers also studied the effect of cooling water temperature from 5.5 to 10 °C on variation of F-value but found no significant effect. Lund (1978) also reviewed the available literature and the uncertainties underlying process calculations. For home canning, Thompson et al. (1979) found that the CV values for nine different foods ranged from 43 % to 82 %, with all but one less than 60 %. Pflug and Odlaugh (1978) and Thompson et al. (1979) showed that an error in retort temperature measurement of ±0.55 °C could cause an error of 12 % in the mean F_0-value.

Naveh et al. (1983) studied the effect of f_h on the process lethality and produced a graphical method of analysis. Robertson and Miller (1984) used a 90-min process at 121 °C to study seven replicate cans of 55 bentonite over eight runs. The results showed that the process lethality values for the heating phase, F_h, varied from 3.4 to 7.1 min or 13 to 26 % around the mean value. Increasing the headspace in the cans significantly increased the f_h-value. Hayakawa et al. (1988) used a computerized method of determining the statistical variability of thermal process lethality, for a conduction-heating product, spaghetti in tomato sauce. Experimental CV values for two can sizes, 211 × 300 and 307 × 409, were, respectively, 67.0 % and 28.5 %, which agreed with the computer predictions. The F-value distributions were heavily skewed in favor of the higher values. Predictive equations were also developed and compared with regression equations (Wang et al. 1991; Hayakawa et al. 1994). These workers showed that variations in the process temperature had the greatest effect on the F-value, and that high-temperature processes required greater control of process parameters than more conventional processes. Bown (1989), using a computer simulation technique, studied the effect of five variables on lethality calculations. These were ranked in order of greatest influence as thermal diffusivity; z-value; initial temperature; temperature of pre-retorting delay; and duration of pre-retorting delay. The results are interesting and shown in Fig. 9.1. Akterian et al. (1990) also reported on a sensitivity analysis for a range of convection-heating packs. Other work on lethality distribution has been reported by Campbell and Ramaswamy (1992a, b), Smout et al. (2000a, b), and Varga et al. (2000a, b) who have shown that the statistical distribution of lethalities approximated to a gamma-distribution skewed.

Turning to microbiological parameters variations in D- and z-values are among the most variable and difficult to quantify (Hicks 1961). While laboratory

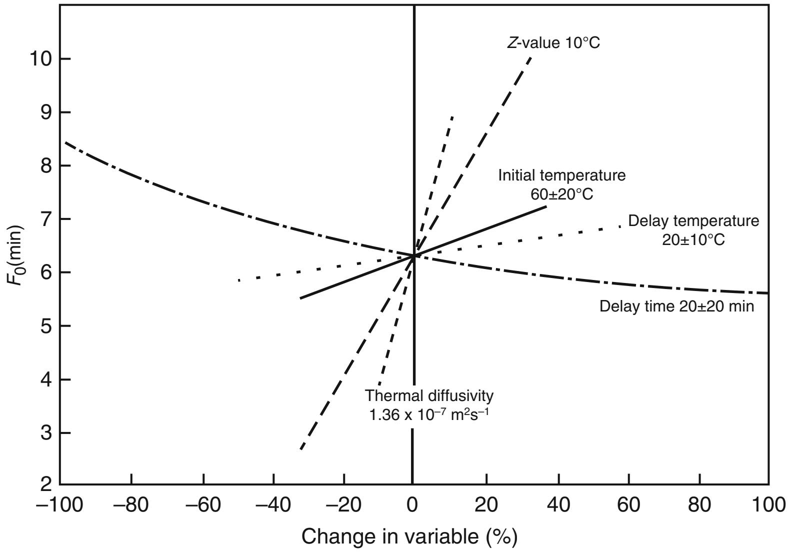

Fig. 9.1 Sensitivity of F_0 to various factors (Bown 1989)

experiments can be used to estimate these quantities (Chap. 3), the circumstances are highly idealized compared with the commercial canning environment. For z-values Hicks (1961) reported CVs of 2–9 % and found that the effect of errors in z-values was less when g was small. Patino and Heil (1985) estimated that the standard deviation (SD) for D-values was 3–6 %, and for z-values between 0.5 and 1.0 °F. These were lower than the results obtained by Lenz and Lund (1977): SDs for D-values of 10 % and for z-values of 2.0 °F. Perkins et al. (1975) made a study of the influence of the z-value for *Clostridium botulinum* on the accuracy of process calculations and concluded that a more realistic estimate of the potential hazard in cans of product underprocessed by a few degrees or minutes may be made by assuming that any contaminating anaerobes may have a z-value of 14 °F or 7.78 °C. Pflug and Odlaugh (1978) reviewed the existing z- and F-value data and their variability, concluding that the minimum *botulinum* cook of $F_0 = 3$ min, using $z = 18$ °F and $T_{\mathrm{ref}} = 250$ °F, represented a safe process for low-acid foods. Patino and Heil (1985) showed that the effect of z-value variation on F-values varied between $F/z = 0.12$ and 0.81. A useful method of converting F-values based on a z_1-value to one based on a z_2-value was presented by Pflug and Christensen (1980). The method involved the use of Ball's (1923) method and Stumbo's (1973) tabulated data, together with an f_h-value, assumed or known. The statistical modeling of lethality distribution in canned foods has been reviewed by Hall (1997).

The effect of container stacking patterns on the delivery of target F_0-values during the thermal processing of 2.7 kg cans (134 × 102 × 215.5 mm) of corned beef was studied by Warne and Moffit (1985). They compared the F-values obtained for specifically positioned cans in retort baskets with standard commercial packing and with tight packing, with an extra 21 cans per basket. For the former the F_0-values ranged from 9.8 to 11.7 min, but for the latter, where the cans were located in the center, the values ranged from 2.3 to 5.4 min.

9.2 Mass-Average Sterilization Value (F_s-Value)

The concept of a total integrated or mass-average sterilization value, F_s, for the entire contents of a container was introduced in Sect. 4.1.5. This was primarily to compensate for any problems which might arise if the critical point was not the point of slowest heating. This would mean that the point at which the temperature history was measured might not give the lowest F-value in the container. In Chap. 5 the evidence for this was reviewed, and it is generally concluded that for the domestic sizes of cans there is no problem, but for large cans the point of slowest heating could be displaced into a toroidal ring some distance from the axis of the can. This was because at the end of heating and the start of cooling the center temperature continues to rise for some time before the effect of the cooling water is felt. To deal with these circumstances the concept of integrating the lethal effects through the whole can volume was developed. It has been widely applied by Stumbo (1953), who introduced the method, after thoroughly reconsidering the bacteriological basis for process calculations. At the time this provoked a flurry of activity and discussion on the basis of process calculations and the need to introduce new methods (Ball 1949; Hicks 1952). Stumbo's methods are detailed in his excellent text (Stumbo 1973). His method involves the use of 57 tables, and these have been replaced by two tables using a neural network analysis (Sablani and Shayya 2001). Stumbo's method has also computerized for determining F_0-values by Germer et al. (1992).

An excellent review and critical analysis of the methods of process evaluation of processes has been presented by Storofos et al. (1997). Their work covers much of the material presented in this text, but in more detail.

A comparison of methods for treating broken heating curves has been presented by Wiese and Wiese (1992). Denys et al. (1996) have made a study of broken heating using a 3–5 % cereal starch suspension starch with end-over rotation of 73 × 109.5 mm cans and 81 × 172 mm glass jars in a Barriquand Steriflow process simulator. A semiempirical method was developed for predicting the breakpoint in the heating curve. The method was also applicable to the study of process deviations.

Two outstanding papers (Gillespy 1951; Hicks 1951) produced two other methods of calculating F_s-values. Gillespy was always critical about the need for F_s-values in terms of commercial canning operations, since his method showed that F_c was always the minimum value in the whole pack. Holdsworth and Overington (1975) considered that this was due to the form of the equation for the volume integral, which did not permit Stumbo's conclusion. Other workers have also considered this approach, and Table 9.1 lists some of these.

Table 9.1 Some methods of calculation of mass-average sterilization values

1. *Analytical solutions:*	
Gillespy (1951)	Uses first-term approximation for determining heating profile. Derives F_s-value in terms of F_c-value. See Eq. (4.19)
Stumbo (1953)	Uses Ball (1923) for lethality calculation. Derives F_s-value in terms of F_c-value, see Eq. (4.17)
Ball and Olson (1957)	Used P_h- and P_c-values to calculate local concentrations of heat-vulnerable components in each of the 11 isothermal regions
Hayakawa (1969)	Dimensionless number method. Solution of heat distribution equations included all non-negligible terms
Jen et al. (1971)	Extension of Stumbo's (1953) method
Newman and Holdsworth (1989)	Revised Jen et al. (1971) figures and extended the concept to other geometrical shapes. Includes extensive computer programs in Basic
2. *Numerical methods:*	
Teixeira et al. (1969)	Finite-difference equations. Applicable to variable heating and cooling medium temperatures
Flambert and Deltour (1972)	Numerical solution. Location of slowest heating point discussed
Manson et al. (1970)	Application to brick-shaped containers
Manson et al. (1974)	Application to pear-shaped containers
Tucker and Holdsworth (1991)	Numerical model for brick-shaped containers, with finite surface heat transfer coefficients

With the development of interest in the thermal inactivation of heat-vulnerable components during the sterilization operation, these methods, using appropriate *z*-values, have been widely applied to optimizing processes. This is because the heat-vulnerable components are distributed throughout the volume of the food product and the concept of determining the effects of heating at the critical point only is inappropriate compared with microbial inactivation. This subject is dealt with in more detail in Chap. 19.

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Chapter 10
Microbial Methods

10.1 Introduction

The F_s-value was defined in Eq. (4.18),

$$F_s = D_r \log(n_0/n_t),$$

where D_r is the D-value for the organism under consideration at the reference temperature 121.1 °C or 250 °F, n_0 is the initial microbial spore loading, and n_t is the spore loading after time t. This can be used to obtain an independent estimate of the total integrated F-value for the whole container.

A similar study was reported by Sumer and Esin (1992), who studied the effect of the arrangement of cans on the slowest heating point for a can filled with water, peas in brine, and 28 % tomato paste. For the water the point was 10–15 % of the height of the can from the bottom, for the peas 20–25 %, and for the tomato paste the point was around the geometric center. A finite element model was developed for the distribution of temperature in the stacking patterns.

If the microorganisms can be encapsulated in a bead, glass sphere, or a synthetic particle, then this can be placed at the point of slowest heating and the F-value determined at that point. Thus provided that it is possible to determine the number of microbial species, usually spores, at the start and at the conclusion of the trial it should be possible to determine the safety of the process.

10.2 Inoculated Pack Method

The inoculated pack method, also known as the count reduction technique, is the simplest method and involves inoculating the food product with organisms of known heat resistance, preferably with a high D-value, 12–16 min at 115.5 °C in

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phosphate buffer (Hersom and Hulland 1980). The extent of survival of the spores is determined by culture or incubation tests. The spores should be of appropriate heat resistance for the particular type of product being dealt with. For low-acid canned foods heat-resistant spores of PA 3679 are generally used, rather than spores of *Clostridium botulinum*, which require special facilities for handling them. The level of inoculum is usually between 10^3 and 10^5 spores per can. The heat resistance and amount of inoculum should be judged so that the process being considered should provide a low level of spoilage.

The method of inoculation depends on the nature of the product. If the product is liquid, then mixing will ensure uniform dispersion; if the product is a solid–liquid mixture then a pipette can be used to disperse the inoculum into the covering liquid; and in the case of more solid materials a syringe can be used to deliver the inoculum as near to the center of the food mass as possible.

The inoculated cans are then treated in a series of different processes, such that at the lowest level of sterilization a 100 % spoilage should be achieved and at the highest level 0 %. In the case of gas-producing spoilage it is possible to estimate the degree of spoilage from the number of blown cans.

10.3 Encapsulated Spore Method

The simplest form of this is to use a capillary tube filled with the inoculum. Alternatively, small bulbs of approximately 5 mm outside diameter that hold 0.05 ml can be used. These are filled by means of an accurate syringe. The advantage of using bulbs is that they can be located at the point of slowest heating or in particles of food or synthetic material. The time required for the bulb and contents to reach the temperature of the surroundings, up to 121.1 °C, is about 15 s, and the contribution of the come-up time to the total process time is about 6 s at the operating temperature—thus 9 s is subtracted from the contact time to give the time of exposure (Hersom and Hulland 1980). The bulbs may be located at the appropriate point in the can by using a Tufnol rod 6 mm wide and 3 mm deep, cut to an appropriate length to fit the can diagonally from top to bottom. The stem of the capillary is inserted through a small hole in the rod and the bulb secured by a short collar of silicon elastomer. Each bulb contains approximately 10^6 spores of, for example, the highly heat-resistant *Bacillus stearothermophilus* suspended in citrate buffer. The process lethality can then be determined from the initial number of spores and the number of survivors. The heat resistance can be obtained by using replicate bulbs, processed under the same conditions. For full details of these techniques the reader should consult standard texts, such as Townsend et al. (1954), Ball and Olson (1957), Stumbo (1973), Yawger (1978), and Pflug (1987).

10.4 Biological and Chemical Indicators

We now turn to the development of some other methods of determining process lethality, i.e., time–temperature indicators.

We have already discussed the use of encapsulated spores in relation to simple devices. The development of these for aseptic processing of particulates has been discussed by Holdsworth (1992). The use of the spores in spheres and tubes has been extended by the development of biological indicator units (BIUs) by Pflug et al. (1980a, b) and Pflug (1982). In this technique a sample tube is filled with spores, such that when a BIU rod is inserted into a can the spores are at the slowest point of heating. The tubes are made of plastic and a large batch is prepared, from which a representative sample is calibrated by being submitted to a known thermal process and an F-value determined from heat penetration. The technique was developed further by Rodriguez and Teixeira (1988) by using aluminum instead of plastic as the containment material. This improves the heat transfer and removes a lag involved in the use of plastic materials. If the spores do not have a z-value of 10 °C, then the F-value may be determined at the z-value using the method of conversion previously described (Pflug and Christensen 1980). Two procedures have been suggested by Odlaugh et al. (1981) for converting the biological F-values into F_0 values: one involves converting F^z (biological) into F_0 (biological), $z = 10$ °C, and comparing with F_0 (heat penetration); the other involves calculating F^z from heat penetration data and the BIU z-value and comparing with F^z (biological).

Pflug et al. (1980b) showed good agreement between F_0-values from heat penetration compared with F-values (BIU). In general the biological values tended to be slightly lower than the F_0 from heat penetration measurements. Many workers (see Table 10.1) have developed chemical indicators as time–temperature indicators. These are based on, for example, the inactivation of enzymes, color destruction, vitamin degradation, sugar inversion, and other chemical reactions. Hendrickx et al. (1992) has developed a time–temperature indicator based on the inactivation of the heat-stable fraction of peroxidase immobilized on porous glass beads in dodecane, which has a z-value of 10 °C. The results from using this unit were in excellent agreement with thermocouple results.

Rönner (2002) has described a commercial system, developed at SIK in Sweden, which uses heat-resistant spores of *B. stearothermophilus* and *B. stearothermophilus* immobilized in an 8 mm diameter porous polymer bead, i.e., a modified polyacrylamide gel (PAG). These can be used for validating sterilization processes either in containers or in continuous sterilization processes. A similar system using ascospores has been developed for pasteurization processes.

The performance of a range of commercial indicators has been discussed by Lee et al. (1979). The calibration of a biomedical steam sterilizing indicator, Thermalog S, in F_0 units was carried out by Bunn and Sykes (1981). There is a continuous search for systems that can be used in practice. The commercial units should always be tested in order to find out what their limits of performance are and

Table 10.1 Some biological and chemical indicators used for determining sterilization values

System	Comments	Reference
(a) General:		
Bioindicators	Review of principles	Myers and Chrai (1980)
Bioindicators	*F*-values for different *z*-values	Odlaugh et al. (1981)
Chemical markers	Kinetic theory and principles	Ross (1993)
Biological/chemical indicators	Review of applications	Van Loey et al. (1996), Hendrickx et al. (1994, 1995)
Biological/chemical indicators	Comprehensive list of potential indicators	Van Loey et al. (2004)
Multicomponent indicators	Theoretical considerations	Maesmans et al. (1993)
Heat process indicators	Review of validation techniques	Tucker (2001b, 2004)
(b) Biological indicators:		
B. stearothermophilus	Contained in plastic tube	Pflug et al. (1980a, b)
B. stearothermophilus	In microporous beads 90 % water	Rönner (2002)
B. subtilis	In microporous beads 90 % water	Rönner (2002)
Bioindicators	Conversion of *F*-values for different *z*-values	Pflug (1982)
Biological indicators	Improved heat transfer using aluminum tubes	Rodriguez and Teixeira (1988)
(c) Chemical/biochemical indicators:		
Anthocyanins	Chemical kinetics and application	Tanchev (1985)
Thiamin	Chemical kinetics and application	Berry (1989), Mulley et al. (1975)
Sucrose inversion	Chemical kinetics and application	Adams et al. (1984)
Sucrose inversion	Kinetics and application to F_0 determination	Siriwattanayotin et al. (2006)
Methylmethionine sulfonium	Chemical kinetics and application	Berry (1989), Berry et al. (1990)
α-Amylase	Kinetics and application to pasteurization	Van Loey (1996), Van Loey et al. (1997b, c)
α-Amylase	Kinetics and application	Guiavarc'h (2002), Guiavarc'h et al. (2002)
α-Amylase, stabilized by polyols	Kinetics and application	De Cordt et al. (1994a)
α-Amylase, reduced water content	Kinetics and application	Haentjens et al. (1998)
α-Amylase, *B. amyloliquefaciens*	Kinetics and pasteurization	Tucker (2001a)
α-Amylase, *B. licheniformis*	Kinetics and pasteurization	De Cordt et al. (1992), Maesmans et al. (1994b)
α-Amylase	Kinetics and pasteurization	Tucker (1999)

(continued)

Table 10.1 (continued)

System	Comments	Reference
Marker M-1	Biochemical indicator factors	Kim and Taub (1993)
Marker M-2	Biochemical indicator—kinetic factors	Lau et al. (2003)
Marker M-3	Biochemical indicator—kinetic factors	Lau et al. (2003)
Nitrophenyl glucoside hydrolysis	$z = 21.7$ °C and $D = 10$ min	Adams and Langley (1998)
Nitrophenyl glucoside hydrolysis	$z = 23$ °C applied to C_0-values	Williams and Adams (1997)
Protein-based indicators	Kinetics and application	De Cordt et al. (1994b)
Peroxidase (horseradish)	Kinetics and application to sterilization	Van Loey et al. (1997a)
Lactulose (in milk)	Kinetics and application to milk processing	Andrews (1984), Andrews and Morant (1987)
(d) Commercial systems: Various	Comparative performance	Lee et al. (1979)
	Performance tests on indicator strip	Bunn and Sykes (1981)

whether they are suitable for the desired purpose. Some indicators are relatively simple and only give an indication that the cans have received a process; others are more complex and are intended to give qualitative information.

The validity of the principles underlying the operation of BUIs and other types of time–temperature indicator have been discussed by Hendrickx et al. (1992), in particular the use of indicators with z-values other than 10 °C. It would appear that provided both the thermocouple and the BIU go through the same process, which they should if they are correctly located, then there should be no problem. This assumes that there is no variation in the z-value with temperature. Elaborate mathematical analysis would appear to support a contrary view that the z-values for the indicators should be the same as the z-value of the target organism. While this may be ideal in theory, it is difficult in practice. Berry and Bradshaw (1986) also make the important point that the reaction kinetics should be of the same order and character. These workers considered that the thermal inactivation of *B. stearothermophilus* does not follow first-order kinetics over the entire heating period. It is, in fact, necessary to correct for the initial period when considering the equivalent process for a BIU. Moreover, the time lag before first-order kinetic behavior is established depends on the product factors. This means that it is necessary carefully to compare the kinetic characteristics of the marker organism and the analogue if satisfactory results are to be obtained. Chemical indicators have also been used to determine heat transfer coefficients between food particles and liquids (Maesmans et al. 1993, 1994a; Weng et al. 1992; Van Loey et al. 1995).

Tucker (1999) has described a method of validating pasteurization processes using a *Bacillus amyloliquefaciens* alpha-amilase time–temperature indicator. This was fabricated by injecting a silicone particle with the indicator, and was used for yog-fruit (strawberries, pineapple, and apricot pieces) pasteurizations. The z-value was 9.7 ± 0.3 °C and the pasteurizing temperatures were from 70 to 90 °C.

Proteins and glucose, e.g., whey proteins, in food products will interact under heating conditions to produce a range of compounds that may be used to determine the degree of heating applied. Three compounds that are formed have been used as chemical markers, viz. **M-1**, 2,3-dihydro-3,5-dihydroxy-6-methyl-(4H-pyran-4-one) (Kim and Taub 1993; Kim et al. 1996a, b; Ramaswamy et al. 1996; Wang et al. 2004), **M-2**,.4-hydroxy-5-methyl-3(2H)-furanone (Prakash et al. 1997; Lau 2000; Lau et al. 2003), and **M-3**, 5-hydroxymethylfurfural (Lau et al. 2003). For M-2 Lau et al. (2003) found that the kinetic parameters were $E_A = 64.2–122.7$ kJ/mol and $k_{121.1°C} = 0.94–0.166\ \mathrm{min}^{-1}$.

10.5 Summary

Microbiological methods are essentially very time consuming and expensive. They do, however, fulfil a useful purpose for independently verifying processes. They are particularly useful for products which show considerable variation in f_h-values—e.g., spinach and leafy packs, as well as celery and artichoke hearts. The use of chemically based time–temperature indicators is important for practical control of canning operations. These should be carefully tested before using.

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Chapter 11
Software for Thermal Food Processing Evaluation and Optimization

11.1 Introduction

As we can see in the previous chapter, the application of computer simulation and sophisticated optimization algorithms based on mathematical modeling of the heating process has played an important role in the field of thermal food processing by making it possible to answer the question “what if” in a rapid and low-cost manner. This ability has established the basis for developing computer-aided technologies, which are an interesting alternative to handbook calculation and physical prototypes (Chen and Ramaswamy 2007).

The development of thermal food processing software has been focused on two main aspects: optimization and process analysis. Regarding optimization, Texeira et al. (1969) developed the first computer program that, through computer modeling, allowed optimization of the nutrient retention during thermal processing by the conduction mechanism based on finite differences. Texeira et al. (1975) developed a software that makes it possible to show the advantage of using variable retort temperature instead of constant retort temperature. Abakarov and Nuñez (2013) developed OPT-PROx (http://tomakechoice.com/optprox/download.html), a thermal processing software program that made it possible to simulate and optimize the process based on an adaptive random search algorithm coupled with a penalty function approach and the finite element difference method with cubic spline approximation under specific conditions related to can size and shape and food conductivity. In addition, software has also been developed in the process analysis area. One program is called PEvaluator (Holdsworth and Simpson 2007) and uses Ball’s method to determine from the heating penetration curve the Ball processing time and lethality (F_0) reached during the process.

Some commercial software packages designed for the evaluation of thermal food processing have been developed, such as CALSoft™ (https://tcal.com/calsoft-software, Technical, USA) and the WINCalc™-Thermal processing software (http://thermalprocesstech.net/wincalc).

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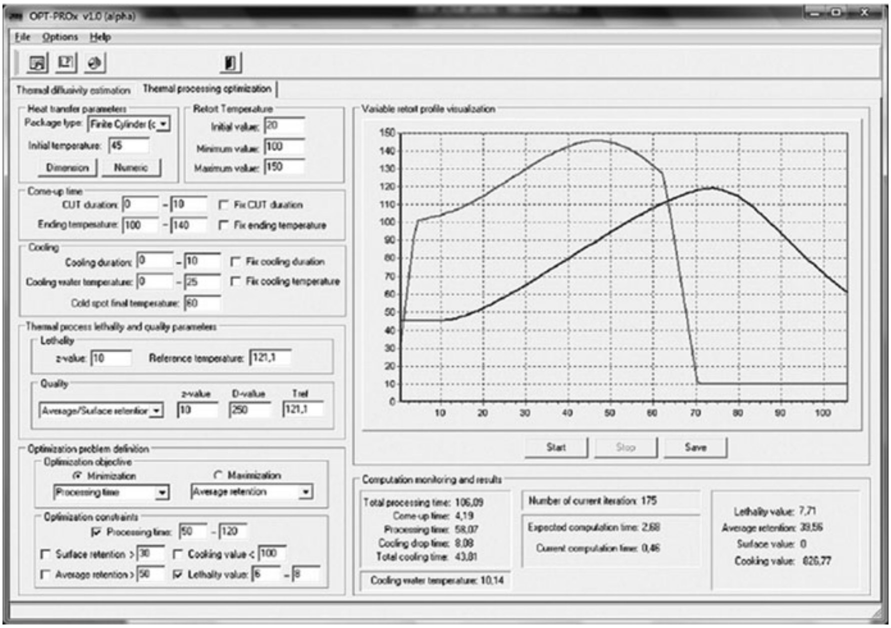
In this chapter, we introduce a new software package to estimate process time and lethality based on Bigelow's method (Chap. 7), which also has the capability to estimate processing time under other retort temperatures and under any *F*-value requested. Additionally, this software presents certain advantages in terms of processing time prediction compared with software based on Ball's formula method, which will be discussed later.

11.2 Thermal Food Processing Software: Process Optimization

In thermal food processing, the most important objective that must be attained is safety, which implies that the food must remain above 100 °C for a certain time to reach a requested *F*-value. However, the second objective is to maintain the quality of canned food; in other words, the texture and taste should be maintained in an acceptable range, and therefore over-processing must be avoided. Additionally, total processing time and total and transient energy consumption must be considered during process optimization.

Abakarov and Nuñez (2013) developed the OPT-PROx software for thermal processing optimization (Fig. 11.1). The mean square error minimization principle



Heat transfer parameters
Package type: Finite Cylinder (c
Initial temperature: 45

Retort Temperature
Initial value: 20
Minimum value: 100
Maximum value: 150

Come-up time
CUT duration: 0 - 10 ☐ Fix CUT duration
Ending temperature: 100 - 140 ☐ Fix ending temperature

Cooling
Cooling duration: 0 - 10 ☐ Fix cooling duration
Cooling water temperature: 0 - 25 ☐ Fix cooling temperature
Cold spot final temperature: 60

Thermal process lethality and quality parameters
Lethality
z-value: 10 Reference temperature: 121,1
Quality
Average/Surface retention z-value 10 D-value 250 Tref 121,1

Optimization problem definition
Optimization objective
● Minimization Processing time
○ Maximization Average retention
Optimization constraints
☑ Processing time: 50 - 120
☐ Surface retention > 30 ☐ Cooking value < 100
☐ Average retention > 50 ☑ Lethality value: 6 - 8

Computation monitoring and results
Total processing time: 106,09
Come-up time: 4,19
Processing time: 58,07
Cooling drop time: 8,08
Total cooling time: 43,81
Cooling water temperature: 10,14
Number of current iteration: 175
Expected computation time: 2,68
Current computation time: 0,46
Lethality value: 7,71
Average retention: 39,56
Surface value: 0
Cooking value: 626,77

Fig. 11.1 Thermal food processing optimization (from Abakarov and Nuñez 2013, Journal of Food Engineering) was used to estimate the heat transfer coefficient of food to be processed under optimal conditions. The adaptive random search algorithm with penalty function approach and finite difference method with cubic spline interpolation are the fundamentals tools of the simulation and optimization of thermal food processing.

The OPT-PROx software was developed under the following possible objective functions: minimization of total processing time, minimization of cooking value, maximization of surface quality retention, and maximization of average quality retention, based on thiamine lethality parameters, considering optimization constraints for surface quality retention, average quality retention, cook value, thermal lethality value, and total thermal processing time. The geometries supported by the software are related to packaging format: cylinder (can), rectangle (pouch), and sphere.

One of the important capabilities of this software is to generate iso-lethal processes at a targeted F_0 using different retort temperatures. Each point n this curve defines a constant retort temperature and a processing time to obtain a targeted F_0. Additionally, it is possible to achieve quality retention at each constant retort temperature. Both curves can help to determine the optimal processing time at which maximal quality is retained (Fig. 11.2).

In this example presented in Abakarov and Nuñez (2013), it can be observed that the maximal quality retention is close to 48 % at processing temperatures ranging between 118 and 122 °C with processing times of approximately 120–100 min, respectively. At other retort temperatures, quality retention is lower because higher temperatures can destroy the nutrients by thermal denaturation, while at lower temperatures, higher processing times are required to reach a targeted F_0. For example, if the process is performed at 110 °C, the processing time required is

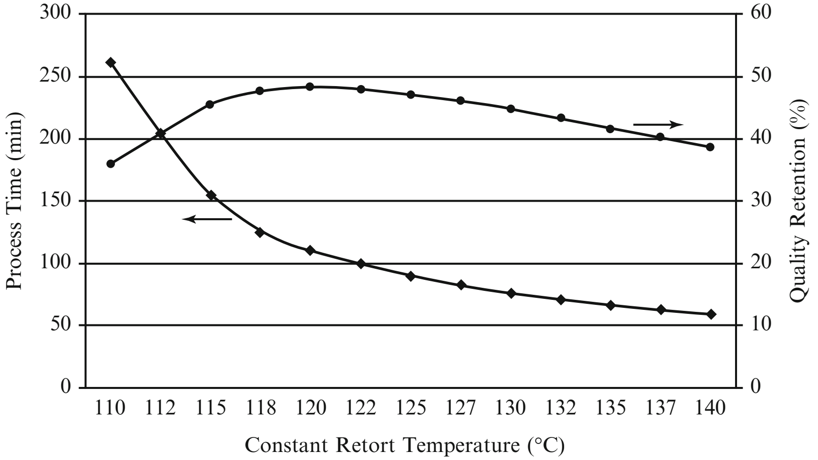
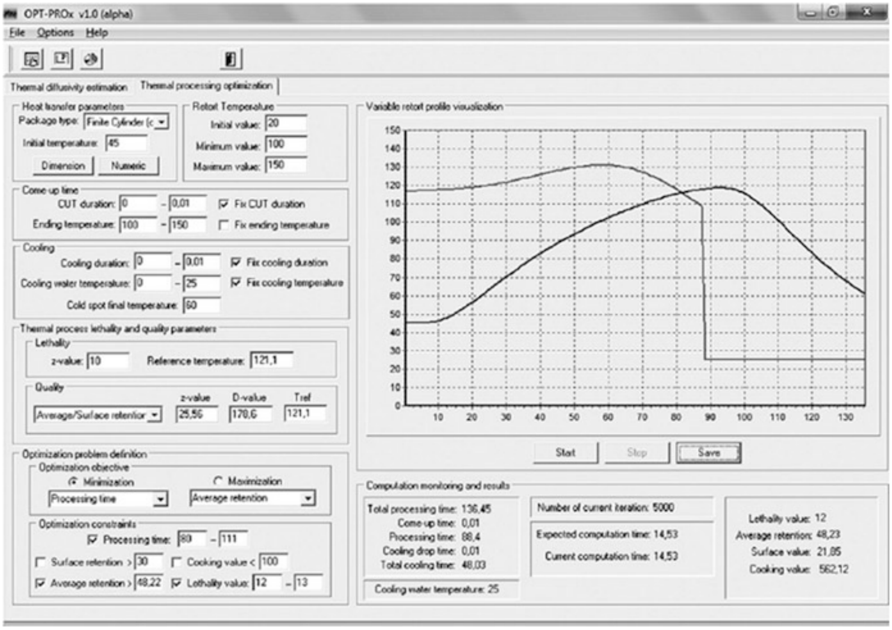


Fig. 11.2 Iso-lethality curve obtained for a requested lethality $F_0 = 12$ min and thiamine retention curve, both as functions of constant retort temperature processes (from Abakarov and Nuñez 2013, Journal of Food Engineering)



Heat transfer parameters
Package type: Finite Cylinder (c
Initial temperature: 45

Retort Temperature
Initial value: 20
Minimum value: 100
Maximum value: 150

Come up time
CUT duration: 0 - 0,01 ☑ Fix CUT duration
Ending temperature: 100 - 150 ☐ Fix ending temperature

Cooling
Cooling duration: 0 - 0,01 ☑ Fix cooling duration
Cooling water temperature: 0 - 25 ☑ Fix cooling temperature
Cold spot final temperature: 60

Thermal process lethality and quality parameters
Lethality
z-value: 10 Reference temperature: 121,1
Quality
Average/Surface retention z-value: 25,56 D-value: 170,6 Tref: 121,1

Optimization problem definition
Optimization objective
● Minimization: Processing time
○ Maximization: Average retention
Optimization constraints
☑ Processing time: 80 - 111
☐ Surface retention > 30 ☐ Cooking value < 100
☑ Average retention > 48,22 ☑ Lethality value: 12 - 13

Computation monitoring and results
Total processing time: 136,45
Come-up time: 0,01
Processing time: 88,4
Cooling drop time: 0,01
Total cooling time: 48,03
Cooling water temperature: 25

Number of current iteration: 5000
Expected computation time: 14,53
Current computation time: 14,53

Lethality value: 12
Average retention: 48,23
Surface value: 21,85
Cooking value: 562,12

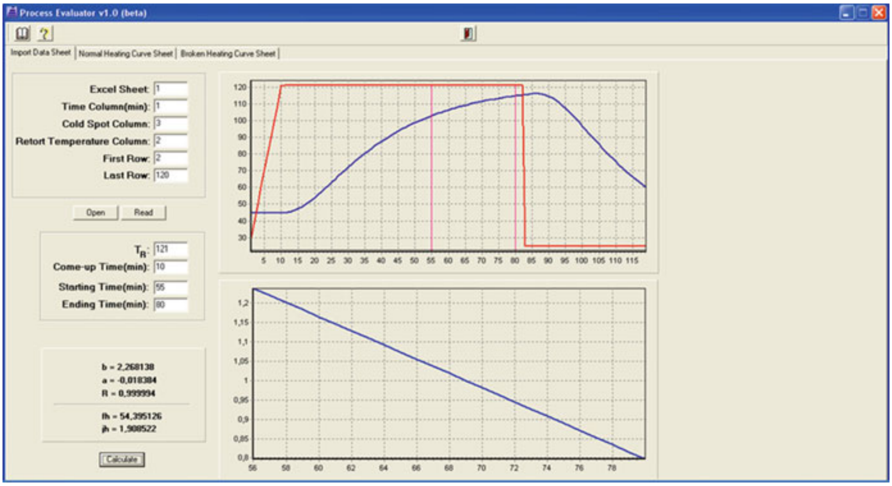
Fig. 11.3 Optimum variable retort temperature profile to minimize processing time by random search algorithm and cubic spline (from Abakarov and Nuñez 2013, Journal of Food Engineering)

260 min, which is more than double the time required at 120 °C, and the quality retention is approximately 35 %.

Moreover, OPT-PROx allows optimization of the thermal processing (minimizing processing time or maximizing quality retention) by generating variable retort temperature (VRT) profiles (Fig. 11.3).

11.3 Software for Thermal Processing Analysis: Ball's Method

An interesting software package called PEvaluator was developed by Simpson, Abakarov, and Almonacid at the Universidad Técnica Federico Santa María (Holdsworth and Simpson 2007). Through this software, it is possible to analyze the heating curve obtained during any thermal process for any food and from any geometry based on Ball's formula method. From this analysis, it is possible to obtain Ball's parameters, f_h and j_h (Fig. 11.4). For example, when a thermal curve is analyzed by the PEvaluator software, the first step is to determine the best segment that represents a lineal zone during the heating process to estimate the Ball's parameters f_h and j_h. As depicted in Fig. 11.4, the values obtained for f_h and j_h were 54.4 and 1.91, respectively.



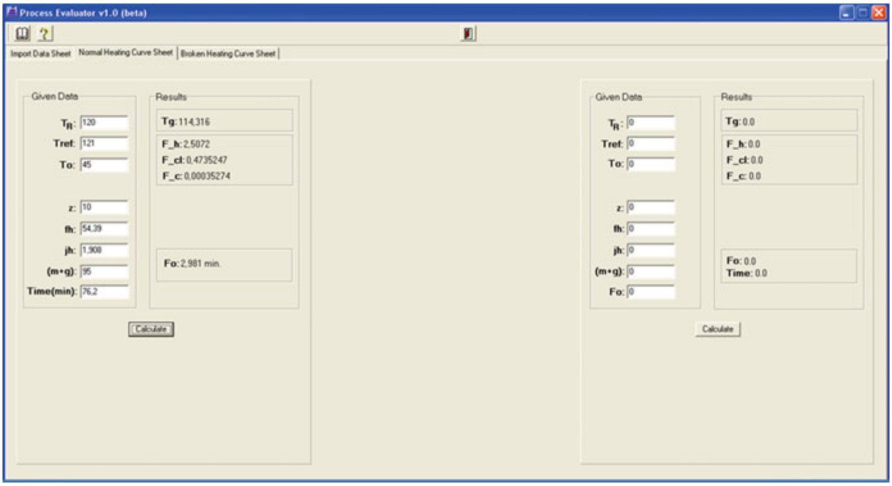
Excel Sheet: 1
Time Column(min): 1
Cold Spot Column: 3
Retort Temperature Column: 2
First Row: 2
Last Row: 120

T_R: 121
Come-up Time(min): 10
Starting Time(min): 55
Ending Time(min): 80

b = 2,268138
a = -0,018384
R = 0,999994

fh = 54,395126
jh = 1,908522

Fig. 11.4 Analysis of heating curve to determine Ball's parameters f_h and j_h by PEvaluator software



T_R: 120
Tref: 121
To: 45
z: 10
fh: 54.39
jh: 1.908
(m+g): 95
Time(min): 76.2

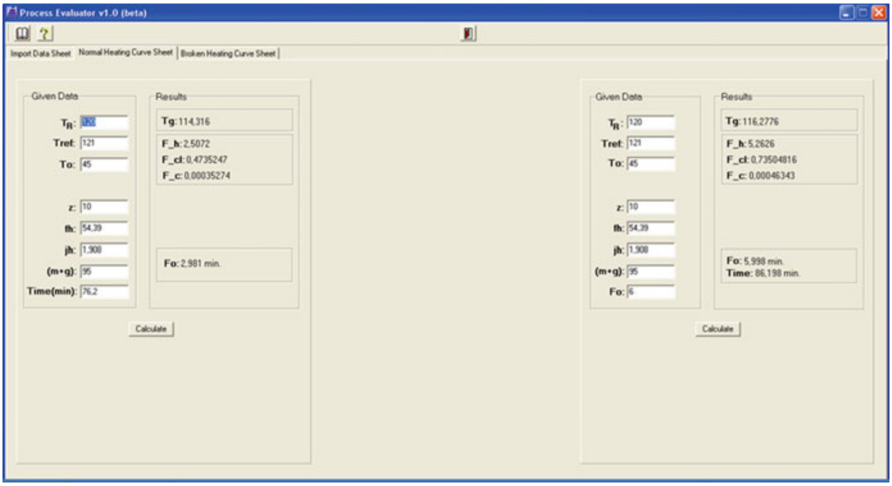
Tg: 114.316
F_h: 2.5072
F_cl: 0.4735247
F_c: 0.00035274
Fo: 2.981 min.

T_R: 0
Tref: 0
To: 0
z: 0
fh: 0
jh: 0
(m+g): 0
Fo: 0

Tg: 0.0
F_h: 0.0
F_cl: 0.0
F_c: 0.0
Fo: 0.0
Time: 0.0

Fig. 11.5 Estimation of lethality value (F_0) reached during Ball's processing time (t_B) by PEvaluator software

The parameters f_h and j_h are required to determine the processing time (Ball's time, t_B) and the F_0 value for a determined thermal process (Fig. 11.5). According to the software analysis, the processing time t_B was 76.4 min (where $t_B = t_P + 0.42$ (CUT)), and the lethality value F_0 attained during this thermal process was 2.98 min, where the largest contribution was provided by the heating stage ($F_{heating} = 2.52$ min), while the cooling phase contributed little ($F_{cooling} = 0.47$ min).



Given Data

T_R: 120
Tref: 121
To: 45
z: 10
fh: 54.39
jh: 1.908
(m+g): 95
Time(min): 76.2

Results

Tg: 114.316
F_h: 2.5072
F_cl: 0.4735247
F_c: 0.00035274
Fo: 2.981 min.

Given Data

T_R: 120
Tref: 121
To: 45
z: 10
fh: 54.39
jh: 1.908
(m+g): 95
Fo: 6

Results

Tg: 116.2776
F_h: 5.2626
F_cl: 0.73504816
F_c: 0.00046343
Fo: 5.998 min.
Time: 86.198 min.

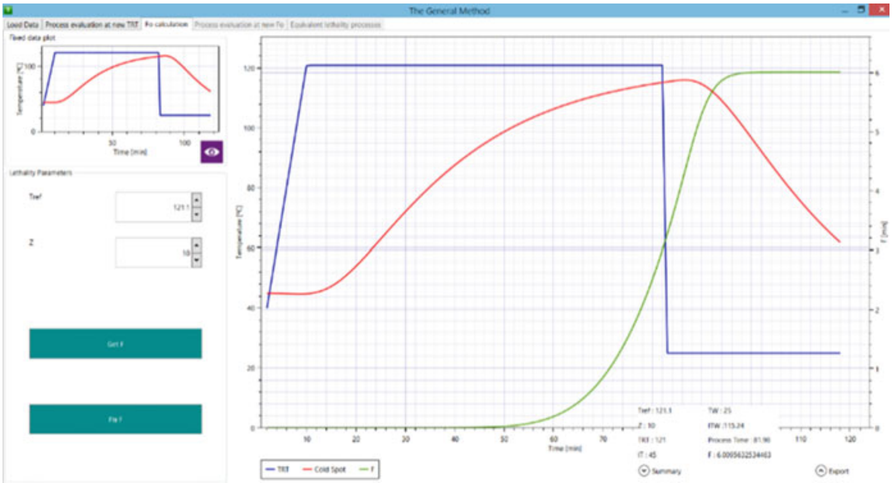
Fig. 11.6 Estimation of Ball's processing time (t_B) for a requested lethality value (F_0) through application of PEvaluator software

Additionally, the software can determine the Ball's processing time (t_B) for a required F_0 as shown in Fig. 11.6. In this example, the question is to find the processing time required to obtain $F_0 = 6$ min. The software estimates a Ball's processing time of 86.20 min, and it is also possible to conclude from the data reported for the software that the major contribution to F_0 is during the heating phase, at 5.26 min, while the cooling phase only provides 0.74 min, which can certainly be discussed considering the effect of thermal inertia during cooling phase.

The usefulness of this software based on Ball's formula method is undisputed; however, it has some limitations in the estimation of lethality during the cooling phase, leading to underestimation of lethality values, which ultimately translates to extended processing time and is thus detrimental to the quality of the canned food.

11.4 Software for Thermal Processing Analysis: General Method

A new software package is being developed at Universidad Tecnica Federico Santa María by Simpson, Ramírez, and Almonacid to analyze thermal processing based on the General Method and determine the lethality (F_0) of the process (Simpson et al. 2003). The fundamentals of the software are based on the General Method proposed by Bigelow in 1920 to allow the straightforward determination of lethality by numerical integration of the lethal rate along the cold spot temperature profile



Tref : 121.1

z : 10

Tref : 121.1

z : 10

TRT : 121

IT : 45

TW : 25

ITW : 115.24

Process Time : 81.98

Fig. 11.7 Screenshot of Bigelow's software for the determination of lethality value F_0

measured in the heat penetration test. The main advantage of this software is to allow better F_0 prediction due to an accurate estimation of the F value during the cooling phase. Therefore, the processing time estimation is more accurate than for the Ball's formula method. Additionally, with this software, it is possible to shorten or extend the processing time based on the F_0 value required for the product using only one heating penetration curve obtained from the food's cold spot.

As an example, the same process that was analyzed by PEvaluator will be studied by the new software based on Bigelow's General Method. Figure 11.7 shows a screenshot in which the software delivers a summary of main results obtained during the analysis, for example, the initial cooling temperature (IT_w), processing time (t_P), and lethality (F_0). The retort temperature and temperature measured at the food cold spot are represented graphically in blue and red, respectively, while the green color represents the lethality curve, which was obtained by numerical integration. Clearly, as of 50 min, the lethality begins to accumulate and continues until 6 min past 100 min of the process. Another interesting aspect is that the cooling phase contributes importantly to the final F_0, which is not accurately predicted by Ball's formula method. As depicted in Fig. 11.7, approximately 3 min of F-value is accumulated during the cooling phase due, mainly, to thermal inertia inside the food product. Therefore, the processing time predicted by the Bigelow's General Method software to reach $F_0 = 6$ min was 82 min (CUT = 10 min, $t_P = 72$ min), while PEvaluator predicted 92 min (CUT = 10 min, $t_P = 82$ min), in other words, 10 min more than Bigelow's General Methods. Meaning that de Bigelow's General Method software will generate products with higher quality and, in addition, the thermal process will require less energy and with higher productivity.

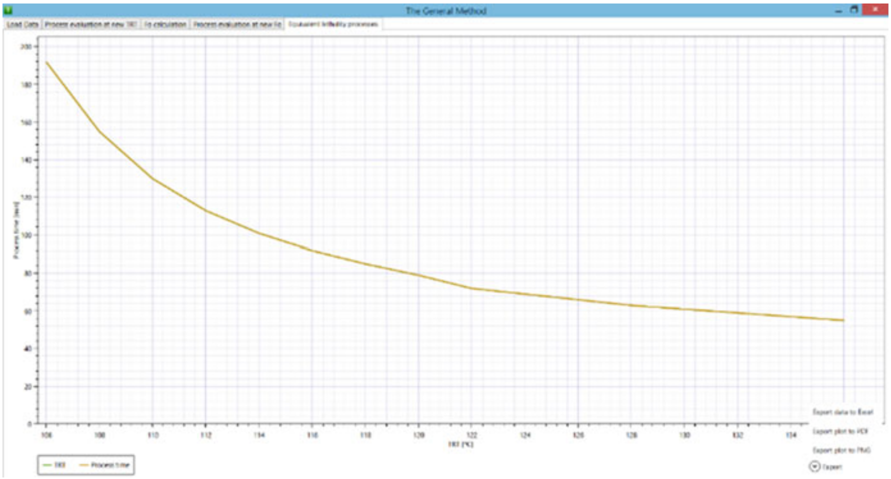


Fig. 11.8 Screenshot of Bigelow's software for the determination of iso-lethality curve for $F_0 = 6$ min

This software is also able to estimate the iso-lethality curve from one experimental or simulated heating curve. For example, Fig. 11.8 presents the iso-lethality curve obtained for the process presented in Fig. 11.7.

11.5 Summary

The development of software and computational tools has allowed the design and optimization of thermal processing and simultaneously helped to understand the behavior of the phenomena that occur inside the product during thermal processing. Additionally, with an optimization software, it is possible to perform a simultaneous sterilization (Chap. 14) with different can sizes or different products (thermal diffusivity) and to quickly estimate the heating curve and processing time. Similarly, using thermal processing analysis software allows estimation of the lethality (F-value) for any process, simulated or experimentally conducted, and determination of the processing conditions needed to obtain the required F-value to guarantee consumer safety as well as the nutritional and organoleptic characteristics of the food and, thus, determination of whether it is necessary to modify the thermal conditions of the process.

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Part III

Engineering Aspects of Thermal Food Processing

Chapter 12
Pressures in Containers

12.1 Development of Internal Pressures

When a hermetically sealed container of food is heated the internal pressure rises due to increasing vapor pressure of the liquid portion; air and other gases in the headspace expanding; and expansion of the food mass. The rise is partially counterbalanced, in the case of a can, by expansion of the can and the outward movement of the can ends, which are designed with expansion rings. The situation is different with semirigid packaging materials that have only a limited elastic expansion, which can damage the material or the seams.

The headspace is also very important, not only in the case of agitated packs but also in all types of rigid container. The headspace has the function of allowing for the liquid and gaseous expansion.

The filling temperature also has an effect on the pressure: the higher the filling temperature the lower the pressure developed internally. This also produces a lower vacuum in the can when it is cooled. It is important to eliminate the air after filling. This was formerly done by clinching the lid on the can and "exhausting" the can by heating and then seaming. It is now done by blowing steam across the can before seaming, in a process known as steam flow closing. The removal of air from the headspace also reduces the amount of oxygen in the can and reduces the likelihood of product–container interactions.

12.2 Internal Pressure Calculation

A general equation for calculating the pressure developed in a container is

$$P_{\mathrm{T}} = P_{\mathrm{a}} + P_{\mathrm{w}} + C_1 + C_2, \tag{12.1}$$

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where P_T is the total pressure, P_a is the partial pressure of the air in the headspace, P_w is the saturated vapor pressure of water (or oil) at the temperature of the food surface, C_1 is a correction factor for the expansion or shrinkage of the package, and C_2 is a correction factor for the thermal expansion of the food.

The partial pressure of the air depends on both the temperature and the volume of air, and is calculated using Charles's law:

$$(P_i V_i)/T_i = (P_f V_f)/T_f, \tag{12.2}$$

where P is the pressure, V is the volume, and T is the temperature; the subscripts i and f refer to the initial and final conditions.

The strain pressure P developed is given by

$$P = P_a + P_w - P_{ext}, \tag{12.3}$$

where the pressures of air and water vapor are the final pressures at the processing temperature and P_{ext} is the external pressure of steam (and air). Strain pressures in cans vary in the range of 1–2 bar, with ambient external pressure and $\frac{1}{2} - 1$ bar under processing conditions.

The pressure of water vapor may be estimated from the equation

$$P_w = e^{(16.0-4967/T)}. \tag{12.4}$$

A more complex relation has been derived for plastic containers of liquid, where the effects of expelled non-condensable gases are taken into account (Beck 1985). The pressure–volume relationship for flexible pouches has been derived for flexible packaging materials (Davis et al. 1960). The pressure developed during the processing of pouches of food has been examined by Yamano (1983) for steam–air processing. The internal pressure profile has been examined by Patel et al. (1991) for the processing of semirigid food packages in steam–air mixtures.

An empirical model used to estimate the water vapor pressure was developed by Wagner and Pruss (1987). This empirical model predicts the vapor pressure as a function of temperature (T) using reduced temperatures (T_R) and critical pressure (P_c):

$$\ln\left(\frac{P_v}{P_c}\right) = \frac{1}{T_R}\Big[a_1(1-T_R) + a_2(1-T_R)^{1.5} - a_3(1-T_R)^3 + a_4(1-T_R)^{3.5} - a_5(1-T_R)^4 + a_6(1-T_R)^{7.5}\Big] \tag{12.5}$$

where P_c is 22.064 MPa, T_c is 647.096 K, and reduced temperature is expressed as $T_R = T/T_c$. Parameter a_i with i from 1 to 6 is presented in Table 12.1.

Table 12.1 Parameter a_i with $i = 1, 2, \ldots, 6$ used in the Wagner and Pruss equation

Parameters	Value
a_1	−7.8595
a_2	1.8441
a_3	11.7866
a_4	22.6807
a_5	15.9617
a_6	1.8012

Table 12.2 Parameter q_i used for the Shibue's equations

Parameter	Value
q_1	8.78054E+01
q_2	2.42541E+03
q_3	−6.07790E+03
q_4	1.17033E+06
q_5	9.00404E+02
q_6	−2.92542E+04
q_7	1.39806E+06
q_8	−2.80756E+07
q_9	2.41637E+08
q_{10}	−7.18726E+08

12.2.1 *Vapor Pressure Model for Aqueous Solutions with Nonvolatile Solutes*

Shibue (2003) published an expression to calculate the vapor pressure in aqueous solutions containing NaCl and $CaCl_2$, based on the Wagner and Pruss equation but incorporating a term that corrects the critical temperature and pressure including the molar fraction of the salts:

$$T_c\ [\mathrm{K}] = 647{,}096 + q_1 \cdot x^{0,5} + q_2 \cdot x + q_3 \cdot x^2 + q_4 \cdot x^4 \tag{12.6}$$

$$P_c\ [\mathrm{MPa}] = 22{,}064 + q_5 \cdot x + q_6 \cdot x^2 + q_7 \cdot x^3 + q_8 \cdot x^4 + q_9 \cdot x^5 + q_{10} \cdot x^6 \tag{12.7}$$

The values for parameter q_i with i from 1 to 10 are presented in Table 12.2.

The complete equation is expressed as

$$\ln\left(\frac{P_v}{P_c}\right) = \frac{1}{T_R}\Big[a_1(1-T_R) + a_2(1-T_R)^{1.5} - a_3(1-T_R)^3 + a_4(1-T_R)^{3.5} - a_5(1-T_R)^4 + a_6(1-T_R)^{7.5}\Big] + h(X) \tag{12.8}$$

Table 12.3 Parameters a_i, b_i, and u used in the modified Wagner and Pruss equation

Concentration	Molar fraction
Diluted solutions	$0 \leq X \leq 0.024$
a_1	1.28746×10^{-1}
a_2	-7.31097×10^{-1}
a_3	-3.15058×10^{2}
Concentrated solution	$0.024 \leq X \leq 0.117$
b_1	3.92767×10^{2}
b_2	-2.46440×10^{3}
u	0.024

where the parameter $h(X)$ is the empirical correction term for the effect of the dissolved salt.

The study expressed $h(X)$ at the dilute region $(0 \leq X \leq 0.024)$ is as follows:

$$h(X) = \frac{a_2 \cdot X}{X + a_1^2} + a_3 \cdot X^2 \tag{12.9}$$

where a_1, a_2, and a_3 are the regression coefficients. At the concentrated region $(0.024 < X < 0.117)$, the function $h(X)$ was considered as follows:

$$\begin{aligned} h(X) = {} & \left(\frac{a_1^2 \cdot a_2}{\left(u + a_1^2\right)^2} + 2a_3 u - b_1 u - b_2 u^2 \right)(X - u) + b_1 (X - u) X \\ & + b_2 (X - u) X^2 + \frac{a_2 u}{u + a_1^2} + a_3 u^2 \end{aligned} \tag{12.10}$$

where a_i, b_i, and u depend on solution concentration according to Table 12.3.

12.3 Models to Determine Internal Headspace Pressure

12.3.1 *Patel's Model (1991)*

This model was developed by Patel et al. (1991) and is presented below:

$$\left[\frac{P}{P_V}\right] = \alpha \left[\frac{\left({}^{P_i}\!/_{T_i}\right)}{\left({}^{P_V}\!/_{T}\right)}\right]^a \left[\frac{H}{V}\right]^b \tag{12.11}$$

where T_i is initial product temperature (°F); T is the product temperature (°F); H is the headspace volume; V is the total inside volume of the package; P_i is the internal pressure in package (psia), absolute; P_V is the vapor pressure of product temperature (psia), absolute; a and b are the exponents of dimensionless group to be determined experimentally; and α is the coefficient for dimensionless correlation to be determined experimentally.

According to Patel et al. (1991), the values obtained experimentally for α, a, and b were 1.679, 0.515, and 0.206, respectively. However, these values are valid only for the experimental condition that was performed (H/V ranged from 015 to 0.3 and $(P_i/T_i)/(P_V/T)$ ranged from 0.76 to 1.7) and for similar product with 3 % of starch solution.

12.3.2 Awuah's Model (2003)

This model was proposed by Awuah (2003) and is presented below:

$$\frac{P_{\max}}{P_V} = k\left[\frac{P_i}{P_V}\right]^a \left[\frac{T_{pf}}{T_{pi}}\right]^b \left[\frac{H}{V}\right]^c \tag{12.12}$$

where ($P_{\max}$) is the maximum container pressure at retort temperature, (P_i) is the container initial pressure (both determined from the time-pressure profile recorded by the remote pressure sensor), (T_{pi}) is the average product initial temperature before retorting, (T_{pf}) is the average product temperature after the product temperature had been stabilized at a given retort temperature (both were determined from gathered heat penetration data from the two containers), and H and V are the headspace and container height, respectively. The exponents a, b, and c, and coefficient of correlation k, are constants to be determined from experimental data. The vapor pressure of water (P_V) was estimated using the empirical correlation (Beck 1985):

$$P_V = \exp\left[16 - \frac{4967}{\theta}\right] \tag{12.13}$$

where θ corresponds to product temperature (K).

The constants k, a, b, and c were 1.415, 0.490, 0.101, and −0.274, respectively, which are valid for $P_{\max}/P_V$, between 1.83 and 3.24, P_i/P_V, between 0.55 and 1.24, H/V between 0.10 and 0.21, and T_{pf}/T_{pi} between 1.80 and 5.87.

12.3.3 Ghai's Model (2011)

This model was proposed by Ghai et al. (2011) and considered that for isentropic process that was taking place inside the strong rigid container; the relationship between pressure and temperature measured at two different conditions can be represented by Eq. (12.14):

$$\frac{P_1^{\gamma-1}}{T_1^{\gamma}} = \frac{P_2^{\gamma-1}}{T_2^{\gamma}} \tag{12.14}$$

where γ is the heat capacity ratio or adiabatic index or isentropic expansion factor. Since the majority of the headspace is filled with water vapor due to vacuum withdrawal, γ takes the value for water vapor (1.324). Therefore, the expression to calculate the final pressure exerted by gaseous phase as function of initial pressure and initial temperature is defined as

$$P_2 = P_1 \left(\frac{T_2}{T_1}\right)^{4.09} \tag{12.15}$$

The result of this model to estimate the internal pressure was variable and dependent on the complexity of the food system. For example, for simple foods like water, sucrose (10 %, w/v), and salt (5 %, w/v) solutions the internal pressure predicted by the model had good agreement with the experimental data. Due to the internal pressure profiles for green beans and sweet peas were determined based on model for pure water; the results obtained were affected by the food water content. For example, green beans have high water content, and thus the internal pressure prediction was in close agreement with experimental data. However, when the food is more complex (low water content, presence of starches and soluble sugar) the prediction of internal pressure varied considerably from the experimental data with a 13 % of error (Ghai et al. 2011).

12.4 Processing Requirements

As previously mentioned, the internal pressure in rigid containers is counterbalanced to a certain extent by the pressure of the steam or hot water in the heating stage. However, at the end of the heating stage, if the pressure on the can is suddenly released while still hot, there is a danger of can distortion, known as peaking, which may weaken the seam or cause the can to jam in a valve or a subsequent process, such as labeling. The effect is more serious with the larger diameter cans, and it is usual to prevent such distortion by superimposing a pressure during the cooling cycle, for sufficient time for the can to have cooled and the internal pressure to have reduced to a comfortable level. The situation is more complicated in continuous reel-and-spiral pressure cookers, where pressure must be maintained in the transfer valve during the transfer of cans from the cooker to the cooler. These valves require careful design in order to prevent can distortion and jamming. From the design point of view it is necessary to know the mechanical characteristics of the cans being processed, as well as the pressure–temperature relationship in the can/container for the processing conditions. Can manufacturers supply tables of strain pressures that the cans and seams can withstand to enable the determination of safe working pressures.

An important part of the technology of can handling concerns the bacteriological status of cooling water. For the purposes of this book, it should be mentioned that the seams of a can are vulnerable to ingress of spoilage microorganisms at the cooling stage, when a vacuum is developing in the headspace of the can. It is, therefore, necessary to chlorinate cooling water so that it has a residual of 1 ppm free chlorine before it is used. This topic is dealt with in standard canning technology books. See also Thorpe and Gillespy (1968) and Campden BRI (1985, 1997).

12.5 Semirigid Containers and Retort Pouches

The development of semirigid containers and sterilizable flexible packaging materials resulted in the need for overpressure processing.

This has been achieved using steam–air mixtures and air-pressurized water. For a half-litre semirigid pack, containing 100 cm^3 of air, the pressure in the container, originally about 1 bar, is increased to about 3.2 bar at 121.1 °C. This includes the effect of the air and the water vapor present in the pack, and gives an estimate of the overpressure required to prevent seam and container damage.

The retort profiles for this type of package vary depending on the type of package and its construction. A typical come-up profile is a linear ramp from 70 to 121 °C in 15 min and a cooling period from 121 to 40 °C in the same time.

Campbell and Ramaswamy (1992) have studied the heating rate, lethality, and cold-spot location in air entrapped in retort pouches. Massaguer et al. (1994) have discussed the selection of heat-transfer media, including air/steam, mixtures, and pressurized hot water.

Pape (2008) has discussed the design of rigid cans which will withstand the pressures experienced in various types of canning retorts, so that panelling of the can bodies and peaking/buckling of the ends are avoided. Examples given are the processing of (a) solid-pack pet food in hydrostatic sterilizers batch over-pressure retorts, (b) vacuum-packed sweet corn in a four-shell reel-and-spiral pressure cooker and a six-stage Hunister overpressure hydrostatic cooker, (c) mushrooms in brine in a two-shell reel-and-spiral pressure cooker, (d) a soup in a two-shell reel-and-spiral pressure cooker, and (e) vegetables in brine in a five-shell reel-and-spiral pressure cooker.

Retort pouches are a flexible laminate that can be thermally processed under the same conditions as a typical can, with the main advantage that the thin cross section allows rapid heat penetration to the coldest point during thermal processing, and therefore minimal surface overcooking occurs (Ali et al. 2005; Mohan et al. 2006). For example, Mohan et al. (2006) studied the effect of cans or pouches on the thermal processing time of shrimp, and its results showed that processing time was reduced from 52.53 min for a can to 33.79 min for a pouch under the same processing conditions. Moreover, less energy is required for thermal processing, and resulting in a product with higher quality (i.e., color, texture, flavor). Because pouches weigh less than cans, storage and transportation space and distribution cost can be reduced (Lyon and Klose 1981; Lebowitz and Bhowmik 1990).

However, there is an important processing disadvantage of pouches during thermal processing compared with traditional cans, which is related to the capacity to support internal pressure. During thermal processing of this type of packages, the internal pressure may be greater than the saturation pressure of the steam used to heat the product (Campbell and Ramaswamy 1992). This increase in internal pressure, according to Davis et al. (1960), is due to the effect of temperature on the water vapor pressure in the food, gas pressure in the headspace, release of occluded gas from the internal food structure, and the thermal expansion of the product. All of these contributions to the pressure can cause serious deformation of the container. Additionally, the gas entrapped in the packages substantially affects the heating rate of the contents, as shown by Campbell and Ramaswamy (1992) who reported that a package containing 40 mL of air presented a similar trend to a package without air during the early heating period (f_h approximately 9–10 min), but a broken heating behavior was presented thereafter by the package with 40 mL of air, with a lower heating rate (f_h approximately 21 min). This result implies that lethality can be influenced by the entrapped air. Interestingly, the results presented by Campbell and Ramaswamy (1992) showed that overpressure from 60 to 100 kPa (65 % and 74 % steam, respectively) increased the lethality in packages that contain entrapped air volumes $\geq$20 mL. The overall heat transfer can be affected by the heat transfer coefficient between the medium and the package, the level of overpressure, and the temperature. Furthermore, during the heating process, the entrapped gas tends to collect between the top surface of the food and the pouch material, and therefore the cold spot is shifted toward the top surface (Campbell and Ramaswamy 1992).

For this reason, an appropriate counterbalance of external pressure must be applied during thermal processing of this type of container, especially at the beginning of the cooling phase, because ΔP reaches its maximum value when the steam pressure is cut off, and therefore the retort pressure begins to fall more rapidly than the internal pressure of the pouch. Thus, it is highly necessary to try to maintain the overriding pressure during cooling until the pressure inside the pouch is reduced to maintain seal integrity. Therefore, the estimation of internal pressure in flexible packages is critical for product integrity and process development (Amézquita and Almonacid 2009). Thus, higher temperatures induce greater expansion, while higher overpressures have the opposite effect (Campbell and Ramaswamy 1992). In this sense, air overpressure is used to minimize the expansion of entrapped gases in the thermal processing of this type of package.

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Chapter 13
Mechanical Agitation and Rotation of Cans

13.1 Introduction

Thermal food processing under agitation conditions is an attractive method for food processors due to increased heat transfer and more uniform heat distribution inside the can produced by product mixing. Forced convection obtained through agitation of cans during thermal processing has been applied to provide rapid heating conditions, especially in convection-heated products (Singh et al. 2015). Ultimately, this approach results in higher quality and lower processing time because lethality is reached in less time than with a static retort (Garrote et al. 2008; Dwivedi and Ramaswamy 2010; Ates et al. 2014). For example, Ates et al. (2014) compared the bacterial inactivation between an agitation retort and a static retort for a fish soup inoculated with *Listeria innocua* at a concentration of 10^8 cell/ml, and the result showed clearly that agitation retort processing could deliver similar lethality to the model microorganism (*Listeria innocua*) within a significantly shorter processing time than for static processing. According to the authors, no colonies were observed after 11.5-, 6.8-, and 5.5-min processing in agitation mode compared to 77-, 67-, and 52-min processing in static mode at 62, 65, and 68 °C, respectively. Simpson et al. (2008) studied by mathematical modeling the effect of end-over-end rotation in retorting canned peas in brine on global and surface heat transfer coefficients and quality factors. The results indicate that the slowest heating rates were obtained for maximal rotation speed and higher headspace, which was consistent with expectations based on knowledge of convective heat transfer. Additionally, they showed that comparing the results for processing time and quality retention obtained from processing performed at 5 rpm, 120 °C, 4 mm headspace and 15 rpm, 120 °C, 12 mm headspace revealed that the heat transfer at the surface induced by higher rotation speed and larger headspace allowed processing time to be shortened by 11 % (from 13.9 to

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12.3 min), and the average quality was approximately 87 % and surface quality was 81 % for both processing conditions. Interestingly, at 130 °C, the average quality retention was 93 and 87 % for the surface, which are higher than were obtained at lower temperature. This result is because maximal quality retention is achieved with the shortest possible processing time and reaches the same level in all cases.

Two types of agitation are commonly used: end-over-end and axial agitation. However, in this chapter, we also describe other types of retort agitation, such as the *Steritort and Orbitort Processes* and the *Zinetec Shaka™ Retort Process*.

13.2 End-Over-End Agitation

This type of motion creates a stirring of the contents in the can and improved heat transfer. The result of this type of motion is to enable processes to be shortened, with the accompanying attributes of improved quality characteristics. More recently Tucker (2004) has considered all the factors that are involved in the effectiveness of rotation in improving heat transfer to and in containers of food.

As shown in Table 13.1, the types of product which benefit from this kind of motion are convection packs containing solids or particulates. During the rotation the headspace bubble moves through the food mixture, causing a continuous stirring action; the degree of mixing depends on the speed of rotation and the size of the headspace. It is necessary, in using this type of technique, to ensure that both these factors are carefully and correctly controlled.

The time for the contents of the can to reach processing temperature was found to decrease with increasing speed of rotation. There is, however, a limiting speed, the optimum speed of rotation, beyond which no further reduction is observed. This is due to centrifugal force, which induces a static condition of the food in the can. The agitation of the can's contents will cease when the gravitational force equals the centrifugal force, i.e., when the maximum speed of rotation, $N_{\max} = 0.498/R_{\mathrm{r}}^{1/2}$, where R_{r} is the radius of rotation of the can. For a retort of 66 cm, this means that $N_{\max}$ should be less than 36.8 rpm. The factors affecting the heat penetration have been studied in detail by Anantheswaran and Rao (1985a, b), who showed that the rate of heat transfer was independent of the size of can for headspace volume 3–9 % and a radius of rotation up to 15 cm. Heat transfer correlations for both Newtonian and non-Newtonian foods were discussed in Chap. 2.

An extensive review of heat transfer in rotary processing of particle/liquid mixtures in cans has been given by Dwivedi and Ramaswamy (2009). The experimental work that made use of a Stock retort, a Steritort simulator for an FMC-Sterilmatic cooker, and a Shaka™ Retort (see Sect. 13.4) has studied both the visualization of particle/liquid movements in high-viscous fluids and heat transfer in canned bob-Newtonian fluids containing particles (Meng and Ramaswamy 2007a, b; Dwivedi and Ramaswamy 2009).

Table 13.1 Some heat transfer studies with canned foods processed in agitating cookers

Type of motion/ retort system	Rotation speed (rpm)	Can size	Products	Heat transfer factors	References
(a) End-over-end	0–50	307 × 409	Cut green beans, peas, diced beets and carrots, corn kernels, lima beans, and mixed vegetables	f_h	Roberts and Sognefast (1947)
	0–200	Wide range	Water, peas, carrots, beets, asparagus, cabbage, mushroom soup, evaporated milk	cut	Clifcorn et al. (1950)
	10, 20, and 30	300 × 208; 300 × 401	Water, suet, pea purée	f_h	Niinivaara et al. (1968)
	15–90	307 × 409	Water, tomato purée, corn kernels, peas, and orange concentrate	hpc	Conley et al. (1951)
	27–144	303 × 700	5 % bentonite	hpc	Parchomchuk (1977)
	20–40	Special cans	Water, organic liquids, sugar solution, salt solution	htc	Duquenoy (1980)
	20–120	Special cans	84° brix glucose syrup	htc	Naveh and Kopelman (1980)
	40–140	74 × 80 mm	5–6 % carboxymethylcellulose	hpc	Hotani and Mihori (1983)
	0–37	Special can	Water and sucrose, glycerine and guar gum solutions	htc	Anantheswaran and Rao (1985a, b)
	0–100	300 × 306; 307 × 408	Six oils of different viscosity	f_h	Javier et al. (1985)
	0–20	307 × 409	Plastic particles	htc	Sablani and Ramaswamy (1993, 1996, 1997), Sablani et al. (1997), Ramaswamy et al. (1993, 1997)
	0–20	[307 × 407]	Nylon spheres/guar gum	f_h	Krishnamurthy et al. (2001)
	10–15	73 × 109.5 mm	3.5 % cereal starch	f_h	Denys et al. (1996a)
		cans			

(continued)

Table 13.1 (continued)

Type of motion/ retort system	Rotation speed (rpm)	Can size	Products	Heat transfer factors	References
	10–15	81 × 172 mm glass jars	3.5 % cereal starch	f_h	Denys et al. (1996a)
	10–50	cans	Colflo 67 starch	f_h : rpm	Emond and Tucker (2001)
	0–5	303 × 406	Guar gum 0.4 %, 0.5 %, 0.75 %	Htc	Price and Bhomik (1994)
	10	307 × 409	Ny; pn spheres/CMC	htc;F_0	Meng and Ramaswamy (2005)
(b) Axial	0–50	307 × 409	Cut green beans, peas, diced beets and carrots, corn kernels, lima beans, and mixed vegetables	f_h	Roberts and Sognefast (1947)
	0–250	401 × 411	Peaches	hpc	Van Blaricom (1955)
	20–120	Special cans	84° brix glucose syrup	htc	Naveh and Kopelman (1980)
	40–140	74 × 80 mm	5–6 % carboxymethylcellulose	hpc	Hotani and Mihori (1983)
	0–100	300 × 306; 307 × 408	Six oils of different viscosity	f_h	Javier et al. (1985)
	0–150	Range	Water and silicone oils	htc	Soule and Merson (1985)
(c) Spin	0–400	Various	Orange and citrus juice products	f_h	Casimir (1961)
	0–400	202 × 214	Fruits and fruit juice products; tomato juice, paste, and soup	cut	Pruthi et al. (1962)
	0–500	603 × 700	Papaya purée and passion fruit juice	hpc	Wang and Ross (1965)
	0–420	Various	Sucrose solution, CMC, tropical fruit juices, and nectars	htc	Quast and Siozawa (1974)
(d) FMC Steritort	0–8	303 × 406; 608 × 700	Water/sucrose solutions; spheres/water, spheres/sucrose solution	htc	Lenz and Lund (1978)
	5–11	303 × 406	Cream style corn formulations	f_h	Berry et al. (1979)
	3–10	Various	Cream of celery soup	F_0	Berry and Bradshaw (1980)

	1–15	Various	Whole kernel corn in brine, and vacuum-packed corn	f_h	Berry and Dickerson (1981)
	0–9	Various	Mushrooms, sliced	f_h	Berry and Bradshaw (1982)
	3–11	Various	Milk-based products	f_h	Berry and Kohnhorst (1985)
	2–8	303 × 406; 603 × 700	Water and glycerine, sugar and guar gum solutions	htc	Rao et al. (1985)
	2–6	303 × 406	Snap beans	htc	Fernandez et al. (1988)
	1–10	Various	White beans in brine	F_0	Deniston et al. (1991)
	0–10	221 × 300	Tomato concentrate	htc	Deniston et al. (1992)
	0–10	603 × 700	Tomato concentrate	htc	Deniston et al. (1992)
(e) FMC Orbitort	25–42	Various	Cream of celery soup	F_0	Berry and Bradshaw (1980)
	10–642	Various	Whole kernel corn in brine, and vacuum-packed corn	f_h	Berry and Dickerson (1981)
(f) Water Cascade Retort	0 and 10	Glass jars	Green and white beans	f_h	Ávila et al. (1999, 2006) and Smout et al. (2000)
	0–25	Glass jars 600 ml	White beans (*Phaseolus vulgaris*)	f_h	Denys et al. (1996b)
	0	Trilaminate pouch	Silicon rubber bricks	f_h	Campbell and Ramaswamy (1992a)
	0–20	Glass jars 370 ml	White beans	htc	Van Loey et al. (1994)

cut come-up time, *hpc* heat penetration curve, *htc* heat transfer coefficient

13.3 Axial Rotation and Spin Cooking

Axial rotation in cans has been studied up to 500 rpm (for the higher range above 180 rpm the process is usually described as spin processing). The degree of mixing depends on the size of the headspace, and this and the speed of rotation have to be controlled. Most interest in this type of cooking has been shown in the processing of tropical fruit juices with delicate flavors. The high-speed processes have been shown to give better flavor retention and overall quality. Table 13.1b and c gives brief details of some of the products that have been studied.

13.4 Steritort and Orbitort Processes

The Steritort is a pilot model of the FMC Sterilmatic continuous reel-and-spiral pressure cooker–cooler, and is used to determine suitable rotational speeds and heat penetration for establishing processes for the full-scale model. Speeds of operation are usually in the range 10–42 rpm, and the cooker can be used for a wide range of products that benefit from axial rotation. Some experimental work with this type of system is indicated in Table 13.1d.

The Orbitort, unlike the Sterilmatic cooker, does not allow cans to roll during processing. The usual speed of rotation is 35 rpm. Experimental work has shown that, for a product such as whole kernel corn, the size of the headspace bubble volume and the filled weight are important in obtaining a consistent and satisfactory process. Rao and Anantheswaran (1988) have given a full review of the heat transfer aspects of agitated and rotary cooking processes.

13.5 Zinetec Shaka™ Retort Process

In this batch retort system the cans and jars are vigorously agitated (shaken) at a frequency of 100–200 cycles per minute. The shaking of the food product is achieved through a strong horizontal movement of the baskets, which creates a substantial increase of heat transfer rate, and a greatly reduced processing time compared to standard retort systems. Homogeneous conduction-heating products containing small particles, in 153 × 178 mm cans, gave processing times of 10 min $F_0 = 8\text{–}10$, compared with 3–4 h in a static retort. Containers made of plastic materials with lower thermal conductivities than metals showed a longer processing time (Walden 2008).

Reduction of process time has a high positive impact on quality of end product (color, taste, vitamin retention, etc.) compared to quality retention obtained with standard retorts. One of the main advantages of this fairly new system (SHAKA™ technology) is that it can be used with all types of packages from rigid cans, glass jars, and trays to flexible packaging such as retortable pouches. Products such as sauces, soups, baby food, vegetables, or pet food have been tested and shown to have superior organoleptic properties.

In addition, a significant reduction in process time greatly improves the utilization of the sterilization equipment (production capacity). In general, manufacturers claim that 4–5 sterilization cycles per hour can be performed on the SHAKA™ system. A full description of this system has been given by Walden (2008) (see also Chap. 17).

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Chapter 14
Simultaneous Sterilization

14.1 Introduction

According to Simpson et al. (2003) the Revisited General Method (RGM) has the capability to generate the isolethal processes from a single heat penetration test. As described in Simpson et al. (2003) when the isolethal processes have been generated, then utilizing the cubic spline interpolation procedure, it is possible to attain a continuous function. Natural cubic splines are used for creating a model that can fill in the holes between data, in effect, approximating a trend. They are, therefore, useful for making observations and inferences about a pattern existing in the data (Atkinson 1985). A piecewise technique which is very popular. Recall that the philosophy in splining is to use low-order polynomials to interpolate from grid point to grid point. This is ideally suited when one has control of the grid locations and the values of the data being interpolated (i.e., you have a way to produce them at any location as in thermal processing). The purpose of this proposed methodology is to explore and analyze the potential application of the RGM method to generate isolethal processes at different TRT and F_0 values and implement simultaneous sterilization of different product lots in the same retort.

14.2 Simultaneous Sterilization of Different Product Lots in the Same Retort

Simultaneous sterilization applies, mainly, to small canneries with few retorts that are frequently required to process small lots of different products in various container sizes that normally require different process times and retort temperatures. In these situations, retorts often operate with only partial loads because of the small lot sizes, and are underutilized. The proposed approach to this optimization problem is to take advantage of the fact that, for any given product and container

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size, there exists any number of alternative combinations of retort temperature (above the lethal range) and corresponding process time that will deliver the same lethality (F_0 value). These can be called isolethal processes. They were first described by Teixeira et al. (1969) to find optimum isolethal process conditions that would maximize nutrient retention (thiamine) for a given canned food product, and later confirmed by others (Lund 1977; Ohlsson 1980). Barreiro et al. (1984) used a similar approach to find optimum isolethal process conditions that would minimize energy consumption.

Important to this analysis is the fact that the differences found in the absolute level of quality retention are relatively small over a practical range of isolethal process conditions. This relative insensitivity of quality over a range of different isolethal process conditions opens the door to maximizing output from a fixed number of retorts for different products and container sizes. Isolethal processes can be identified for each of the various products, from which a common set of processes and conditions can be chosen for simultaneous sterilization of different product lots in the same retort.

14.3 Simultaneous Sterilization Characterization

In terms of analysis, a range of isolethal processes for selected products and container sizes should be obtained from experimental work. Heat penetration tests should be conducted on each product in order to establish process time at a reference retort temperature to achieve target lethality (F_0 values). A computer program can be utilized to obtain the equivalent lethality processes according to the following specifications:

- Two F_0 values should be considered for each product ($F_{0\min}$ and $F_{0\max}$). The referred values are product related, but in general, $F_{0\min}$ is chosen according to a safety criterion and $F_{0\max}$ according to a quality criterion.
- For each F_0 value ($F_{0\min\,j}$ and $F_{0\max\,j}$) isolethal processes at retort temperatures of TRT_1, TRT_2, TRT_3, . . ., TRT_N should be obtained for each product.
- The discrete values that define each process per product at different temperatures will be transformed as a continuous function through the cubic spline procedure (for both $F_{0\min}$ and $F_{0\max}$, per product), obtaining a set of two continuous curves per product (Fig. 14.1).

In addition, the following criteria should be established for choosing the optimum set of process conditions for simultaneous sterilization of more than one product:

- The total lethality achieved for each product must be equal or greater than the preestablished $F_{0\min}$ value for that specific product.
- The total lethality for each product must not exceed a preestablished maximum value ($F_{0\max}$) to avoid excessive over-processing.

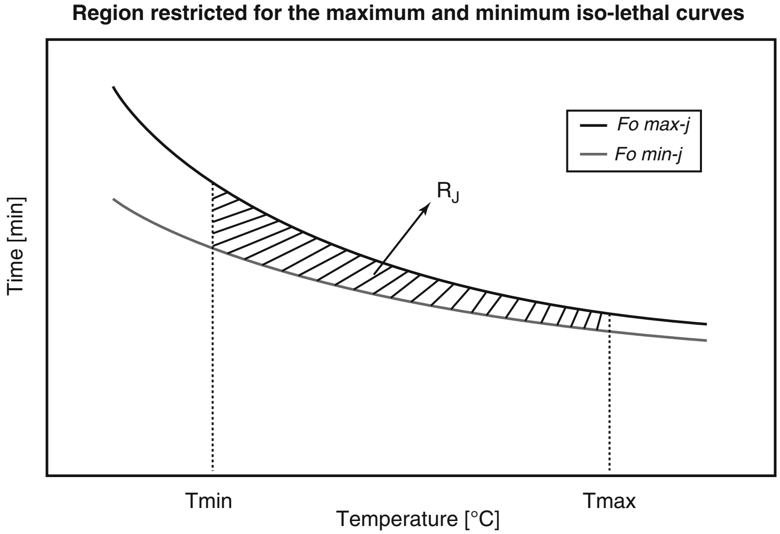

Fig. 14.1 Region restricted for the maximum and minimum isolethal curves ($F_{0\min-j}$ and $F_{0\max-j}$) for the *j*-*n*th product

14.4 Mathematical Formulation for Simultaneous Sterilization

Let us assume that we have $n \geq 2$ products, say $P_1, \ldots, P_n$, which are processed at the plant location. Let us consider the index set

$$X = \{1, 2, \ldots, n\} \ , \tag{14.1}$$

Considering the temperature interval [$T_{\min}$, $T_{\max}$], which denotes the temperature capabilities of the process.

Each product P_j, for $j \in X$, has attached two strictly decreasing continuous functions, say

$$m_j, M_j : [T_{\min}, T_{\max}] \to (0, +\infty) \tag{14.2}$$

where $m_j(T) \leq M_j(T)$, for each $T \in [T_{\min}, T_{\max}]$. The meaning of $m_j(T)$ (respectively, $M_j(T)$) is the minimum time (respectively, maximum time) needed to process the product P_j at temperature T.

Defining the region R_j:

$$R_j = \left\{(T, t) : T_{\min} \leq T \leq T_{\max}, \ \ m_j(T) \leq t \leq M_j(T)\right\} \tag{14.3}$$

The interpretation of R_j is that the product P_j can be processed at temperature T with time t if and only if $(T, t) \in R_j$ (Fig. 14.1).

It is clear that a sub-collection of products will be

$$P_{j_1}, \ldots, P_{j_r} \tag{14.4}$$

where

$$1 \leq j_1 \leq j_2 \leq \cdots \leq j_r \leq n$$

can be simultaneously processed at temperature T and time t if and only if

$$(T, t) \in R_{j_1} \cap R_{j_2} \cap \cdots \cap R_{j_r}$$

It follows that to obtain all possible sub-collection of products that can be simultaneously processed is equivalent to finding all possible subsets

$$\begin{aligned} &Q = \{j_1, \ldots, j_r\} \subset X \\ &r > 0, \\ &1 \leq j_1 \leq j_2 \leq \cdots \leq j_r \leq n, \end{aligned}$$

for which it holds that

$$I_Q = R_{j_1} \cap R_{j_2} \cap \cdots \cap R_{j_r} \neq \varnothing$$

14.5 Computational Procedure

In the practical sense, we have the products $P_1, \ldots, P_n$ and the temperature interval $[T_{\min}, T_{\max}]$.

1. We choose a positive integer $k \in \{1, 2, 3, \ldots\}$ and a partition $P = \{T_0 = T_{\min}, T_1, \ldots, T_k = T_{\max}\}$
   where $T_m < T_{m+1}$ for $m = 0, \ldots, k-1$.
2. For each product P_j we compute the values $m_j(T_m)$, $M_j(T_m)$, $m = 0, 1, \ldots, k$.
3. For each $m \in \{0, 1, \ldots, k\}$, we define the values $m_p(T_m) = \text{Maximum}\{m_p(T_m): j \in P\}$; $M_p(T_m) = \text{Minimum}\{M_p(T_m): j \in P\}$.
4. If for some $m \in \{0, 1, \ldots, k\}$ we have that $m_p\,(T_m) \leq M_p\,(T_m)$, then we observe that products $P_1, \ldots, P_n$ can be simultaneously processed at temperature T_m with time $t \in [m_p(T_m), M_p(T_m)]$.

14.6 Experimental Validation

The experimental procedure was divided into four steps, as follows:

1. Can sizes for each of the selected products were chosen according to N.F.P.A. (1982). The can sizes chosen for each product are depicted in Table 14.1.

Table 14.1 Canned vegetable products showing combinations of product and can sizes selected for study

Product	Can size 211 × 400	300 × 407	307 × 113	307 × 409	401 × 411
Peas	√			√	√
Corn	√	√		√	√
Green beans	√	√		√	√
Asparagus	√	√		√	√
Asparagus tips			√		

2. Each canned product was processed at a retort temperature of 117 °C and product initial temperature of 40 °C.
3. Each experimental process was carried out to achieve a F_0 value between 6 and 10 min. Thereafter, each process was adjusted to a F_0 of 6, 8, and 10 min.
4. Equivalent lethality processes (6 per product) were obtained by a computer program for retort temperatures in the range of 110–125 °C. Data management, to adjust each new process to a F_0 of 6, 8, and 10 min, was carried out according to the procedure developed by Simpson et al (2003).

14.6.1 Heat Penetration Tests for Products Under Study

Heat penetration experiments at TRT of 117 °C and different processing times were conducted to examine the nature of the heat penetration curves (center temperature histories). Experiments were carried out in triplicate, and thermocouples were located at the slowest heating point. In all cases under study, the center of the can was a representative location of the slowest heating point. The retort heating profile used consisted of an initial equilibrium phase at 20 °C, followed by a linear coming-up time (C.U.T.) of 7–9 min to accomplish venting, and holding phase at 117 °C over the calculated process time required to achieve the target lethality for the specific product under thermal processing.

14.7 Experimental Results

Figure 14.2 shows three isolethal curves for peas (211 × 400) at F_0 values of 6, 8, and 10 min. Isolethal processes were obtained with RGM procedure for six different retort temperatures and fitted with cubic spline interpolation method. Those curves, at three F_0 levels (6, 8, and 10 min), were obtained for all 16 products under study. The information given in those curves is the basis to analyze and implement simultaneous sterilization at any given retort temperature in the range of 110–125 °C.

Figures 14.3, 14.4, and 14.5 show process time per each product at different F_0 values (6, 8, and 10 min) at TRT = 110, 117, and 125 °C, respectively. Similar

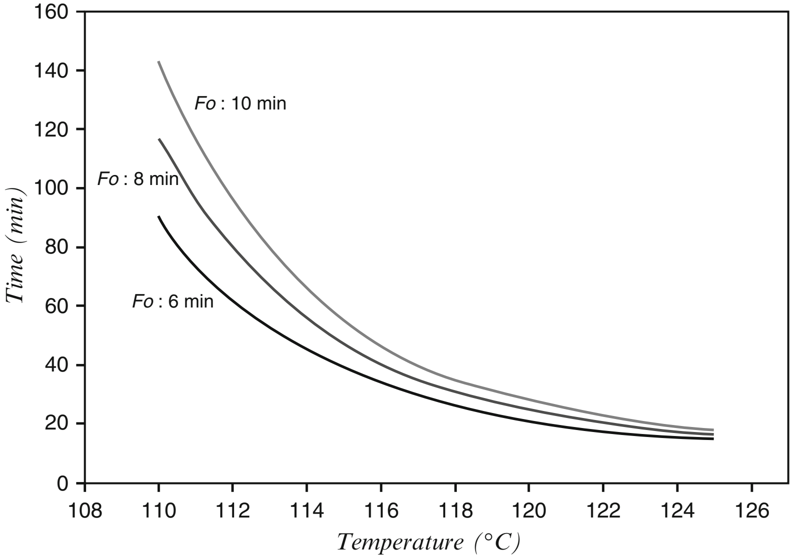

Fig. 14.2 Three isolethal curves for peas (211 × 400) at F_0 values of 6, 8, and 10 min obtained with RGM procedure and fitted with cubic spline interpolation method

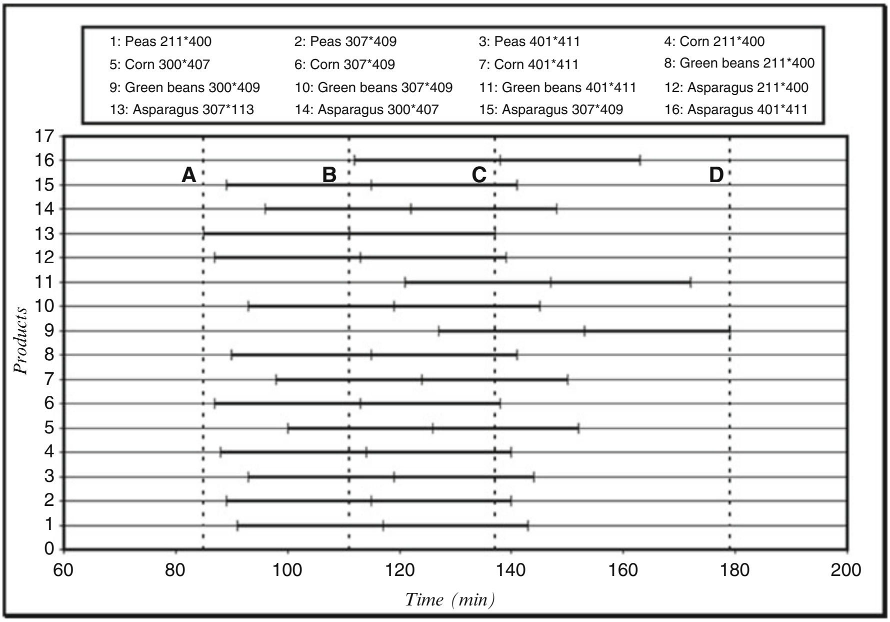

Fig. 14.3 Process time per each product at different F_0 values (6, 8, and 10 min) at TRT = 110 °C obtained with RGM procedure

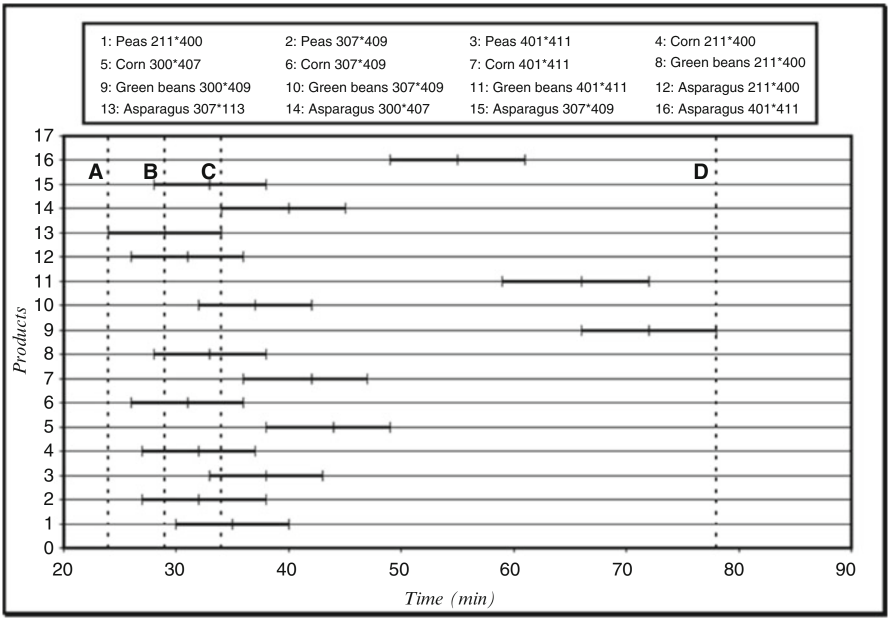

Fig. 14.4 Process time per each product at different F_0 values (6, 8, and 10 min) at TRT = 117 °C obtained with RGM procedure

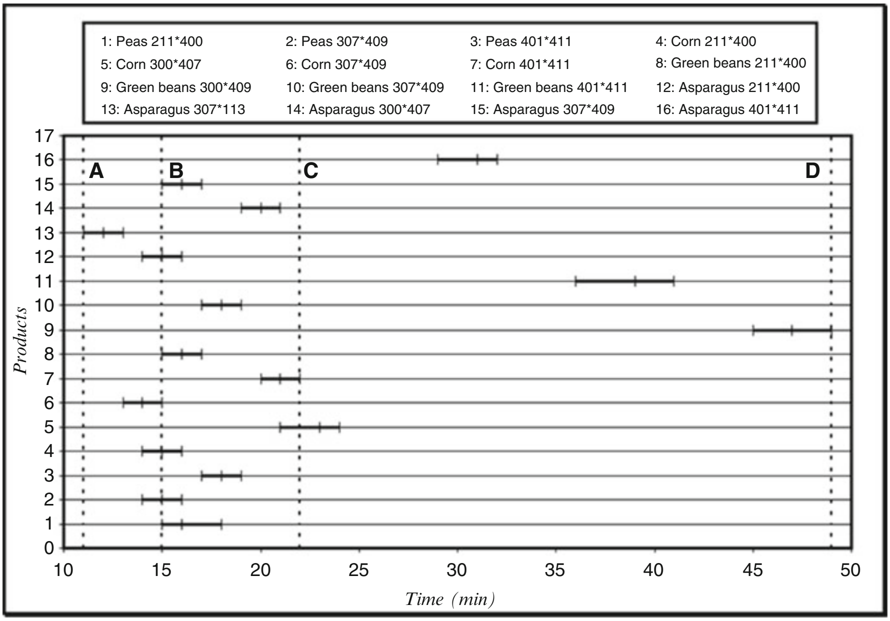

Fig. 14.5 Process time per each product at different F_0 values (6, 8, and 10 min) at TRT = 125 °C obtained with RGM procedure

information can be obtained at any given temperature from 110 through 125 °C. Due to the continuous data attained with the cubic spline method, simultaneous sterilization could be analyzed at any given retort temperature. Clearly, the possibility to implement simultaneous sterilization is higher if retort temperature is lower (Figs. 14.3, 14.4, and 14.5). In terms of further analysis, two retort temperatures (110 and 117 °C) were chosen.

Figure 14.3 shows the wide range of opportunities to implement simultaneous sterilization at 110 °C. Independent of the maximum selected F_0 value (8 or 10 on this study) almost all products, under study, can be simultaneously processed at the same time. On the other hand, at retort temperature of 117 °C, although several choices are available, it is hardly possible to attain simultaneous sterilization for all or most of the products at the same time.

As was described in Sect. 14.5, to obtain all possible simultaneous sterilization combinations (sub-sets) at any given temperature, first it is necessary to get the minimum and maximum process time at the referred retort temperature (dotted lines A and D in Figs. 14.3 and 14.4). As shown in those figures (14.3 and 14.4) dotted lines B and C represent two of the multiple alternatives for simultaneous sterilization at those retort temperatures.

Table 14.2 shows some of the opportunities available at two widely different retort temperatures (110 and 117 °C) with each column representing a different process time at that temperature. Therefore, all the cells in one column experience the same retort process. Although the F_0 value received by each product will differ,

Table 14.2 Feasibility matrix for simultaneous sterilization of canned vegetable products for $F_{0\min} = 6$ min and $F_{0\max} = 8$ min

Product	Retort temperature (°C)				
	110			117	
	Time (min)			Time (min)	
	91	100	111	26	29
Peas 211 × 400	1	1	1	0	0
Peas 307 × 409	1	1	1	0	1
Peas 401 × 411	0	1	1	0	0
Corn 211 × 400	1	1	1	0	1
Corn 300 × 407	0	1	1	0	0
Corn 307 × 409	1	1	1	1	1
Corn 401 × 411	0	1	1	0	0
Green beans 211 × 400	1	1	1	0	1
Green beans 300 × 409	0	0	0	0	0
Green beans 307 × 409	0	1	1	0	0
Green beans 401 × 411	0	0	0	0	0
Asparagus 211 × 400	1	1	1	1	1
Asparagus 307 × 113	1	1	1	1	1
Asparagus 300 × 407	0	1	1	0	0
Asparagus 307 × 409	1	1	1	0	1
Asparagus 401 × 411	0	0	0	0	0

1 indicates that products are feasible for simultaneous sterilization

Table 14.3 Feasibility matrix for simultaneous sterilization of canned vegetable products for $F_{0\min} = 6$ min and $F_{0\max} = 10$ min

Product	Retort temperature (°C)					
	110		117			
	Time (min)		Time (min)			
	93	137	28	34	40	68
Peas 211 × 400	1	1	0	1	1	0
Peas 307 × 409	1	1	1	1	0	0
Peas 401 × 411	1	1	0	1	1	0
Corn 211 × 400	1	1	1	1	0	0
Corn 300 × 407	0	1	0	0	1	0
Corn 307 × 409	1	1	1	1	0	0
Corn 401 × 411	0	1	0	0	1	0
Green beans 211 × 400	1	1	1	1	0	0
Green beans 300 × 409	0	1	0	0	0	1
Green beans 307 × 409	1	1	0	1	1	0
Green beans 401 × 411	0	1	0	0	0	1
Asparagus 211 × 400	1	1	1	1	0	0
Asparagus 307 × 113	1	1	1	1	0	0
Asparagus 300 × 407	0	1	0	1	1	0
Asparagus 307 × 409	1	1	1	1	0	0
Asparagus 401 × 411	0	1	0	0	0	0

1 indicates that products are feasible for simultaneous sterilization

it will lie in the acceptable range (between 6 and 8 min) if the cell is marked with the numeral 1, which indicates that the process is feasible for that product. When a zero appears in a cell, it means that the F_0 value received by the product under that process falls outside the acceptable range, and the process is not feasible for that product. From this table it is possible to infer that the lower the process temperature the higher the possibility to attain simultaneous sterilization for more products. For most of the products considered in this study, it was possible to sterilize simultaneously at a retort temperature of 110 °C (13 out of 16 for a range of F_0 values from 6 to 8 min and 16 out of 16 when the range of F_0 values was from 6 through 10 min). A computer software program was developed to generate all combinations of practical isolethal processes at any process temperature. As an example, according to Table 14.3 at 117 °C the plant manager will be able to utilize different alternative process times for simultaneous sterilization. To generate all the potential combinations at a given temperature it is necessary to follow the computational procedure previously described strictly.

Although in this research study all products have been analyzed for F_0 values in the range from 6 through 8 min and in addition from 6 to 10 min, in a real situation, each product will have its own specific range for F_0 values, depending on specific quality attributes. In addition, in this research the initial temperature was 40 °C for every product. In a real plant, in order to increase the opportunities to apply simultaneous sterilization each product can have its own initial temperature.

The opportunity to carry out simultaneous sterilization and the possibility of employing alternative processes (same F value) provide flexibility to optimize retort utilization. Within a preestablished range of F values, it was possible to obtain all the combinations for simultaneous sterilization. This procedure is of special relevance for small companies that normally work with many different products at the same time. Practical implementation of this flexibility will require close attention to batch record-keeping requirements of the FDA Low Acid Canned Food regulations, and the need to file with the FDA each of the alternative processes as an acceptable scheduled process for each product.

14.8 Expected Advantages of the Implementation of Simultaneous Sterilization

The opportunity to carry out simultaneous sterilization and the possibility of employing alternative processes (same F value) provide flexibility to optimize retort utilization. Within a preestablished range of F values, it was possible to obtain all the combinations for simultaneous sterilization. This procedure is of special relevance for small companies that normally work with many different products at the same time. Practical implementation of this flexibility will require close attention to batch record-keeping requirements of the FDA Low Acid Canned Food regulations, and the need to file with the FDA each of the alternative processes as an acceptable scheduled process for each product.

According to Simpson (2005) an important finding indicates that the lower the process temperature the higher the possibility to attain simultaneous sterilization for more products at the same time. Independent of the selected process temperature, several combinations of simultaneous sterilization can be attained.

Simultaneous sterilization provides flexibility to optimize retort utilization. This procedure is of special relevance for companies that normally work with many different products at the same time.

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Chapter 15
Total and Transient Energy Consumption in Batch Retort Processing

15.1 Introduction

Among problems confronted by canned food plants with batch retort operations are peak energy/labor demand, underutilization of plant capacity, and underutilization of individual retorts (Simpson et al. 2003). In batch retort operations, maximum energy demand occurs only during the first few minutes of the process cycle to accommodate the venting step, while very little is needed thereafter in maintaining process temperature. In order to minimize peak energy demand it is customary to operate the retorts in a staggered schedule, so that no more than one retort is venting at any one time. Similar rationale applies to labor demand, so that no more than one retort is being loaded or unloaded at any one time.

A limited number of research studies have addressed and analyzed energy consumption in retort processing (Barreiro et al. 1984; Bhowmik et al. 1985; Singh 1977). Most of these have attempted to quantify total energy consumption but not transient energy consumption. Furthermore, these studies were applied to processes used for traditional cylindrical cans, and their findings are not necessarily applicable to processes used for flexible or semirigid trays, bowls, or retort pouches. Almonacid-Merino et al. (1993) developed a transient energy balance equation for a still-cook retort, but the model only simulated the holding time and did not include come-up time. Transient energy consumption should be an important factor in deciding retort scheduling, as well as determining optimum variable temperature profiles to achieve specified objectives (e.g., minimize energy consumption, maximize nutrient retention, or minimize process time) (Almonacid-Merino et al. 1993).

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15.2 Total and Transient Energy Consumption in Batch Retort Processing

A detailed description will be given according to the work done by Simpson et al. (2006). The transient energy balance for a system defined as the retort including cans without their contents, and the steam and condensate in the retort, requires no work term. The heat transfer terms—between the system and its environment—include radiation and convection to the plant cook room environment and heat transfer to the food within the cans. Equations should be solved simultaneously and the heat transfer equation for the food material can be solved numerically using, e.g., an explicit finite difference technique. Correlations valid in the range of interest (100–140 °C) should be used to estimate the thermodynamic properties of steam, condensate, and food material. The thermal process is divided into three steps: (a) venting period, (b) period after venting to reach process temperature, and (c) holding time. Cooling step is not analyzed because no steam is required. First, the mathematical model for the food material is presented and then a full development of the energy model for the complete thermal process.

Nomenclature	**Subscripts**
A: Area (m^2)	a: Air
Cp: Specific heat (J/kg K)	b: Bleeder
E: Energy (J)	amb: Ambient
g_c: Universal conversion factor; 1 (kg m/N s^2)	c: Convection
$\underline{H}$: Enthalpy (J/kg)	cv: Condensed vapor
h: Heat-convection coefficient (W/m^2 K)	cr: Critical value
$\dot{m}$: Mass flow rate (kg/s)	cw: Cooling water
M: Mass (kg)	e: Metal container
P: Pressure (Pa)	in: Insulation
P_m: Molecular weight (kg/kmol)	p: Food product
$\dot{Q}$: Thermal energy flow (W)	r: Radiation
R: Ideal gas constant 8.315 (Pa m^3/kmol K); (J/kmol K)	rt: Retort
t: Time (s)	s: Steam
t^*: Time required to eliminate air from retort	sl: Saturated liquid
T: Temperature (K)	sv: Saturated vapor
T_0: Initial temperature	rs: Retort surface
$\bar{T}$: Average product temperature (K)	t: Time
v: Velocity (m/s)	v: Vapor
V: Volume (m^3)	w: Condensed water
Greek symbols	
ρ: Density (kg/m^3)	
ε: Surface emissivity of retort shell at an average of emitting and receiving temperatures (dimensionless)	
γ: Ratio of specific heat at constant pressure to specific heat at constant volume (dimensionless)	
σ: Stefan-Boltzmann constant, 5.676×10^{-8} (W/m^2 K^4)	

15.3 Mathematical Model for Food Material

The food material is assumed to be homogeneous, isotropic, and contained in a cylindrical format; therefore, the heat conduction equation for the case of a finite cylinder could be expressed as (other geometries can be considered)

$$\frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial r^2} + \frac{\partial^2 T}{\partial z^2} = \frac{1}{\alpha}\frac{\partial T}{\partial t} \tag{15.1}$$

where T is a function of the position (r, z) and time (t). The respective boundary and initial conditions are as follows: $T(\text{food material}, 0) = T_0$, where T_0 is a known and uniform value through the food material at time 0.

To estimate the temperature at food surface at any time t, a finite energy balance is developed at the surface:

$$-kA\frac{\partial T}{\partial r} + hA\partial T = MC\mathrm{p}\frac{\partial T}{\partial t} \tag{15.2}$$

In most practical cases, it can be assumed that the Biot number is well over 40, meaning that the temperature of the surface of the food material could be equalized, at any time, with retort temperature (Teixeira et al. 1969; Datta et al. 1986; Simpson et al. 1989, 1993; Almonacid-Merino et al. 1993). The aforementioned statement is not necessarily applicable for processing retortable pouch or semirigid trays and bowls (Simpson et al. 2003). The model (Eq. 15.2) considers the possibility of a Biot number less than 40, but is also suitable for a Biot number equal to or larger than 40.

15.4 Mass and Energy Balance During Venting

Before expressing the energy balance, it is necessary to define the system to be analyzed: Steam–air inside the retort—at any time t ($0 \le t \le t^*$), during venting—is considered as the system (Fig. 17.1).

Global mass balance:

$$\dot{m}_\mathrm{s} - \dot{m}_\mathrm{sv} - \dot{m}_\mathrm{a} = \frac{dM}{dt} \tag{15.3}$$

Mass balance by components:

$$\text{Air}: \quad -\dot{m}_\mathrm{a} = \frac{dM_\mathrm{a}}{dt} \tag{15.4}$$

$$\text{Vapor}: \ \dot{m}_\mathrm{s} - \dot{m}_\mathrm{sv} - \dot{m}_\mathrm{w} = \frac{dM_\mathrm{sv}}{dt} \tag{15.5}$$

$$\text{Condensed water : } \dot{m}_{\mathrm{w}} = \frac{dM_{\mathrm{w}}}{dt} \tag{15.6}$$

where

$$M = M_{\mathrm{a}} + M_{\mathrm{sv}} + M_{\mathrm{w}}; \quad \dot{m} = \dot{m}_{\mathrm{sv}} + \dot{m}_{\mathrm{a}} \tag{15.7}$$

General energy balance:

$$\left[\underline{H}_{\mathrm{s}}\dot{m}_{\mathrm{s}}\right]_{\mathrm{IN}} - \left[\underline{H}_{\mathrm{sv}}\dot{m}_{\mathrm{sv}} + \underline{H}_{\mathrm{a}}\dot{m}_{\mathrm{a}}\right]_{\mathrm{OUT}} + \delta\dot{Q} - \delta\dot{W} = \frac{dE_{\mathrm{system}}}{dt} \tag{15.8}$$

where

$$\delta\dot{Q} = \delta\dot{Q}_{\mathrm{c}} + \delta\dot{Q}_{\mathrm{r}} + \delta\dot{Q}_{\mathrm{p}} + \delta\dot{Q}_{\mathrm{e}} + \delta\dot{Q}_{\mathrm{rt}} + \delta\dot{Q}_{\mathrm{in}} \tag{15.9}$$

and

$$\delta\dot{W} = 0 \tag{15.10}$$

Replacing the respective terms into Eq. (15.9), the term δQ in Eq. (15.8) can be quantified as

$$\begin{aligned}\delta\dot{Q} = {} & hA(T_{\mathrm{in}} - T_{\mathrm{amb}}) + \sigma\varepsilon A\left(T_{\mathrm{in}}^4 - T_{\mathrm{amb}}^4\right) + M_{\mathrm{p}}\mathrm{Cp}_{\mathrm{p}}\frac{d\bar{T}_{\mathrm{p}}}{dt} + M_{\mathrm{rt}}\mathrm{Cp}_{\mathrm{rt}}\frac{d\bar{T}_{\mathrm{rt}}}{dt} \\ & + M_{\mathrm{e}}\mathrm{Cp}_{\mathrm{e}}\frac{d\bar{T}_{\mathrm{e}}}{dt} + M_{\mathrm{in}}\mathrm{Cp}_{\mathrm{in}}\frac{d\bar{T}_{\mathrm{in}}}{dt}\end{aligned} \tag{15.11}$$

The following expression shows how the cumulative term of Eq. (15.8) was calculated. Because of the system definition, changes in potential energy as well as kinetic energy were considered negligible:

$$\begin{aligned}\frac{dE_{\mathrm{system}}}{dt} = {} & M_{\mathrm{sv}}\frac{d\underline{H}_{\mathrm{sv}}}{dt} + \underline{H}_{\mathrm{sv}}\frac{dM_{\mathrm{sv}}}{dt} - P_{\mathrm{sv}}\frac{dV_{\mathrm{sv}}}{dt} - V_{\mathrm{sv}}\frac{dP_{\mathrm{sv}}}{dt} + M_{\mathrm{a}}\frac{d\underline{H}_{\mathrm{a}}}{dt} \\ & + \underline{H}_{\mathrm{a}}\frac{dM_{\mathrm{a}}}{dt} - P_{\mathrm{a}}\frac{dV_{\mathrm{a}}}{dt} - V_{\mathrm{a}}\frac{dP_{\mathrm{a}}}{dt} + M_{\mathrm{w}}\frac{d\underline{H}_{\mathrm{w}}}{dt} + \underline{H}_{\mathrm{w}}\frac{dM_{\mathrm{w}}}{dt} \\ & - P_{\mathrm{w}}\frac{dV_{\mathrm{w}}}{dt} - V_{\mathrm{w}}\frac{dP_{\mathrm{w}}}{dt}\end{aligned} \tag{15.12}$$

The mass flow of condensate was estimated from the energy balance as

$$\begin{aligned}\dot{m}_{\mathrm{w}}\left(\underline{H}_{\mathrm{sv}} - \underline{H}_{\mathrm{sl}}\right) = \delta\dot{Q} = {} & hA(T_{\mathrm{in}} - T_{\mathrm{amb}}) + \sigma\varepsilon A\left(T_{\mathrm{in}}^4 - T_{\mathrm{amb}}^4\right) \\ & + M_{\mathrm{p}}\mathrm{Cp}_{\mathrm{p}}\frac{d\bar{T}_{\mathrm{p}}}{dt} + M_{\mathrm{rt}}\mathrm{Cp}_{\mathrm{rt}}\frac{d\bar{T}_{\mathrm{rt}}}{dt} + M_{\mathrm{e}}\mathrm{Cp}_{\mathrm{e}}\frac{d\bar{T}_{\mathrm{e}}}{dt} + M_{\mathrm{in}}\mathrm{Cp}_{\mathrm{in}}\frac{d\bar{T}_{\mathrm{in}}}{dt}\end{aligned} \tag{15.13}$$

Therefore:

$$\dot{m}_{\mathrm{w}} = \frac{hA(T_{\mathrm{in}} - T_{\mathrm{amb}}) + \sigma\varepsilon A\left(T_{\mathrm{in}}^4 - T_{\mathrm{amb}}^4\right) + M_{\mathrm{p}}\mathrm{C\,p}_{\mathrm{p}}\frac{d\bar{T}_{\mathrm{p}}}{dt} + M_{\mathrm{rt}}\mathrm{C\,p}_{\mathrm{rt}}\frac{d\bar{T}_{\mathrm{rt}}}{dt} + M_{\mathrm{e}}\mathrm{C\,p}_{\mathrm{e}}\frac{d\bar{T}_{\mathrm{e}}}{dt} + M_{\mathrm{in}}\mathrm{C\,p}_{\mathrm{in}}\frac{d\bar{T}_{\mathrm{in}}}{dt}}{\left(\underline{H}_{\mathrm{sv}} - \underline{H}_{\mathrm{sl}}\right)} \tag{15.14}$$

Therefore the steam mass flow demand during venting should be obtained replacing Eqs. (15.5), (15.6), (15.7), (15.11), (15.12), and (15.14) into Eq. (15.8).

15.5 Mass and Energy Consumption Between Venting and Holding Time (to Reach Process Temperature)

As was mentioned before, first, it is necessary to define the system to be analyzed: Steam and condensed water inside the retort were considered as the system (Fig. 17.1):

$$\text{Global mass balance}: \ \dot{m}_{\mathrm{s}} - \dot{m}_{\mathrm{b}} = \frac{dM}{dt} \tag{15.15}$$

$$\text{Vapor}: \ \dot{m}_{\mathrm{s}} - \dot{m}_{\mathrm{b}} - \dot{m}_{\mathrm{w}} = \frac{dM_{\mathrm{sv}}}{dt} \tag{15.16}$$

$$\text{Condensed water}: \ \dot{m}_{\mathrm{w}} = \frac{dM_{\mathrm{w}}}{dt} \tag{15.17}$$

Energy balance on the bleeder: system, steam flow through the bleeder, considering an adiabatic steam flow:

$$\left[\underline{H}_{\mathrm{sv}}\dot{m}_{\mathrm{b}}\right]_{\mathrm{IN}} - \left[\left(\underline{H}_{\mathrm{b}} + \frac{v^2}{2g_{\mathrm{c}}}\right)\dot{m}_{\mathrm{b}}\right]_{\mathrm{OUT}} = 0 \tag{15.18}$$

Where the bleeder is assumed to be operating in steady-state condition, with no heat, no work, and negligible potential energy effects, the energy balance around the bleeder reduces to (Balzhizer et al. 1972)

$$\left(\underline{H}_{\mathrm{b}} - \underline{H}_{\mathrm{sv}}\right) + \frac{v_{\mathrm{b}}^2 - v_{\mathrm{sv}}^2}{2g_{\mathrm{c}}} = 0. \tag{15.19}$$

For a gas that obeys the ideal gas law (and has a Cp independent of T)

$$\left(\underline{H}_{\mathrm{sv}} - \underline{H}_{\mathrm{b}}\right) = \mathrm{C\,p}(T_{\mathrm{sv}} - T_{\mathrm{b}}) \tag{15.20}$$

Neglecting v_{sv}^2 in relation to v_{b}^2, and replacing Eq. (15.18) into Eq. (15.17), it reduces to

$$v_{\mathrm{b}}^2 = -2g_{\mathrm{c}}\mathrm{C}\,\mathrm{p}T_{\mathrm{sv}}\left(\frac{T_{\mathrm{b}}}{T_{\mathrm{sv}}} - 1\right). \tag{15.21}$$

Considering an isentropic steam flow in the bleeder which obeys the ideal gas law, Eq. (15.19) could be rewritten as

$$v_{\mathrm{b}}^2 = \frac{-2g_{\mathrm{c}}P_{\mathrm{sv}}}{p_{\mathrm{sv}}}\left(\frac{\gamma}{\gamma\ -\ 1}\right)\ \left(\left(\frac{P_{\mathrm{b}}}{P_{\mathrm{vs}}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)} - 1\right) \tag{15.22}$$

where the continuity equation is

$$\dot{m}_{\mathrm{b}} = pv_{\mathrm{b}}A. \tag{15.23}$$

Therefore, combining Eq. (15.22) and Eq. (15.23)

$$\dot{m}_{\mathrm{b}} = \frac{P_{\mathrm{s}}A_{\mathrm{b}}}{\sqrt{\frac{RT_{\mathrm{s}}}{\gamma}}}\left(\frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}}\right)\sqrt{\left(\frac{2}{\gamma - 1}\right)\left(1 - \left(\frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right)}. \tag{15.24}$$

The maximum velocity of an ideal gas in the throat of a simple converging nozzle is identical to the speed of sound at the throat conditions. The critical pressure is P_{c} (Balzhizer et al. 1972):

$$P_{\mathrm{c}} = P_{\mathrm{amb}}\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \tag{15.25}$$

Then Eq. (15.24) will be valid for P_{s} in the following range:

$$\left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}} \leq \frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}} < 1. \tag{15.26}$$

If P_{s} is bigger than P_{c}, substituting Eq. (15.25) into Eq. (15.26), the expression for the mass flow is as follows:

$$\dot{m}_{\mathrm{b}} = \frac{P_{\mathrm{s}}A_{\mathrm{b}}}{\sqrt{\frac{RT_{\mathrm{s}}}{\gamma}}}\left(\frac{2}{\gamma\ +\ 1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}; \quad \text{for } \frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}} < \left(\frac{2}{\gamma + 1}\right)^{\frac{\gamma}{\gamma-1}}. \tag{15.27}$$

15.6 Mass and Energy Balance During Holding Time

System: steam inside the retort (Fig. 17.1):

$$\text{Global mass balance}: \quad \dot{m}_{\mathrm{s}} - \dot{m}_{\mathrm{b}} = \frac{dM}{dt} \tag{15.28}$$

$$\text{Vapor}: \quad \dot{m}_{\mathrm{s}} - \dot{m}_{\mathrm{b}} - \dot{m}_{\mathrm{w}} = \frac{dM_{\mathrm{sv}}}{dt} \tag{15.29}$$

$$\text{Condensed water}: \quad \dot{m}_{\mathrm{w}} = \frac{dM_{\mathrm{w}}}{dt} \tag{15.30}$$

Energy balance on the bleeder: The steam flow through the bleeder was estimated as previously mentioned; therefore:

$$\dot{m}_{\mathrm{b}} = \frac{P_{\mathrm{s}} A_{\mathrm{b}}}{\sqrt{\frac{RT_{\mathrm{s}}}{\gamma}}} \left(\frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}}\right) \sqrt{\left(\frac{2}{\gamma-1}\right)\left(1-\left(\frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}}\right)^{\left(\frac{\gamma-1}{\gamma}\right)}\right)}; \quad \text{if} \quad \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}} \leq \frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}} < 1$$

$$\dot{m}_{\mathrm{b}} = \frac{P_{\mathrm{s}} A_{\mathrm{b}}}{\sqrt{\frac{RT_{\mathrm{s}}}{\gamma}}} \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{2(\gamma-1)}}; \quad \text{if} \quad \frac{P_{\mathrm{amb}}}{P_{\mathrm{s}}} < \left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}$$

$$\dot{m}_{\mathrm{w}} = \frac{hA(T_{\mathrm{in}} - T_{\mathrm{amb}}) + \sigma\varepsilon A\left(T_{\mathrm{in}}^4 - T_{\mathrm{amb}}^4\right) + M_{\mathrm{p}} \mathrm{Cp}_{\mathrm{p}} \frac{dT_{\mathrm{p}}}{dt} + M_{\mathrm{rt}} \mathrm{Cp}_{\mathrm{rt}} \frac{dT_{\mathrm{rt}}}{dt} + M_{\mathrm{e}} \mathrm{Cp}_{\mathrm{e}} \frac{dT_{\mathrm{e}}}{dt} + M_{\mathrm{in}} \mathrm{Cp}_{\mathrm{in}} \frac{dT_{\mathrm{in}}}{dt}}{\left(\underline{H}_{\mathrm{sv}} - \underline{H}_{\mathrm{sl}}\right)}$$

Therefore the steam mass flow was estimated as

$$\dot{m}_{\mathrm{s}} = \dot{m}_{\mathrm{w}} + \dot{m}_{\mathrm{b}} \tag{15.31}$$

15.7 Validation

The developed model was tested using bibliographic data (Barreiro et al. 1984), as a preliminary means of validation. The following data were utilized for the following calculations:

Retort: m_{rt}: 163.6 [kg], c_{rt}: 500 [J/kg °C], A_{b}: 7.94×10^{-6} [m^2], A_{rt}: 2.97 [m^2], V_{rt}: 0.356 [m^3].
Containers: Can dimensions: 307 × 409, number of cans inside the retort: 180, m_{e}: 0.06 [kg], c_{e}: 500 [J/kg °C].
Product: Pea puree with a thermal diffusivity of 1.70×10^{-7} [m^2/s].

Table 15.1 Comparison between data obtained from Barreiro et al. (1984) and calculations from the developed procedure in this study

Temperature (°C)	Process time (min)	Energy (MJ) (Barreiro et al. 1984)	Energy (MJ) (This research study)
104.4	196	118.0	114.6
110.0	113	100.8	103.6
115.6	85	97.0	103.0
121.1	66	93.1	106.7
126.7	56	95.0	109.4
132.2	50	100.4	114.8

Processing conditions: The time–temperature requirements were calculated for the thermal sterilization of the pea puree in 307 × 409 cans reaching an integrated lethal value F_c of 2.52 [min] for *Clostridium botulinum* at 121.1 [°C] (Barreiro et al. 1984). T_{po}: 37.8 [°C], T_{cw}: 26.7 [°C].
Surface heat transfer coefficient and emissivity: h: 5.77 [w/m^2 °C], ε: 0.94.

Table 15.1 shows a comparison between calculations (total energy consumption) obtained from Barreiro et al. (1984) and the ones obtained with the model developed in this study. Although estimations are in the same range and compare well, values obtained with the model developed in this research study are higher except at TRT 104 [°C]. One potential explanation lies in the fact that the procedure developed by Barreiro et al. (1984) clearly underestimates the steam mass flow during venting. One of the main contributions of this research study was to develop a complete transient energy model, but also to approach the critical behavior of energy demand during venting.

15.8 Potential Applications

To analyze the impact of different process variables in total and transient energy consumption the following variables could be analyzed: retort insulation, CUT, initial food temperature, retort size, etc.

As an example, Fig. 15.1 compares the total and transient steam consumption for two different initial food temperatures (37.8 and 75 °C). Figure 15.1 shows that for the high temperature, the maximum peak and the total steam consumption could be reduced as much as 30 % and 29 %, respectively. This example shows that initial temperature of food material is an important variable to reduce the peak of energy consumption.

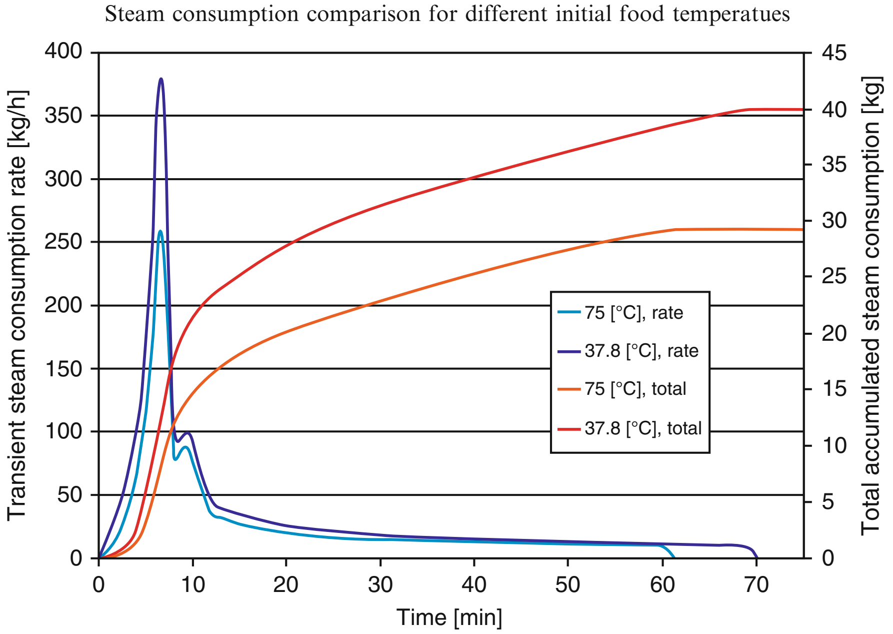

Fig. 15.1 Total and transient steam consumption for two different initial food temperatures (37.8 and 75 [°C])

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Chapter 16
Batch Processing, Retort Scheduling, and Optimizing Plant Production

16.1 Introduction

Batch processing has been widely practiced but little analyzed in the context of canned food plants. Although high-speed processing with continuous rotary or hydrostatic retort systems can be found in very large canning factories, such systems are not economically feasible in the majority of small- to medium-sized canneries (Simpson et al. 2003).

Batch processing will be analyzed in a retrospective and a prospective view. Firstly, batch processing problem structure will be defined in relation to canned food plants. Then, batch processing in canned food plants will be discussed. To bridge the gap between thermal processing and industrial engineering in optimizing design and operation of food canning plants we will discuss and present specifics procedures, e.g., retort scheduling.

Finally, we will try to discuss and analyze this large and diverse field, in which there should be plenty of room for surprises, particularly for those who take time to look closely enough with an open and speculative mind.

16.2 Batch Processing Problem Structure in Canned Foods

Batch processing with a battery of individual retorts is a common mode of operation in many food canning plants (canneries). Although high-speed processing with continuous rotary or hydrostatic retort systems can be found in very large canning factories (where they are cost-justified by high-volume throughput), such systems are not economically feasible in the majority of small- to medium-sized canneries (Norback and Rattunde 1991). In such smaller canneries, retort operations are carried out as batch processes in a cook room in which the battery of retorts is located. Although the unloading and reloading operations for each retort are labor

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intensive, a well-designed and managed cook room can operate with surprising efficiency if it has the optimum number of retorts and the optimum schedule of retort operation.

This type of optimization in the use of scheduling to maximize efficiency of batch processing plants has become well known, and is commonly practiced in many process industries. Several models, methods, and implementation issues related to this topic have been published in the process engineering literature (Rippin 1993; Kondili et al. 1993; Reklaitis 1996; Barbosa and Macchietto 1993; Lee and Reklaitis 1995a, b). However, specific application to retort batteries in food canning plants has not been addressed in the food process engineering literature. Food canneries with batch retort operations are somewhat unique in that the cannery process line as a whole is usually a continuous process in that unit operations both upstream and downstream from the retort cook room are normally continuous (product preparation, filling, closing, labeling, case packing, etc.). Although retorting is carried out as a batch process within the cook room, unprocessed cans enter and processed cans exit the cook room continuously at the same rate (see Fig. 16.1). Since the entire process line operates continuously, food canneries are often overlooked as batch process industries. The focus of this work was to apply these batch process optimization techniques only to the retort operations within the cook room, and not the entire process line of the cannery.

Food processing, and thermal processing in particular, are industries confronted with strong global competition. Continuous innovation and improvement of processing procedures and facilities are needed. Although the literature in food science and thermal processing is very extensive, most of the references deal with

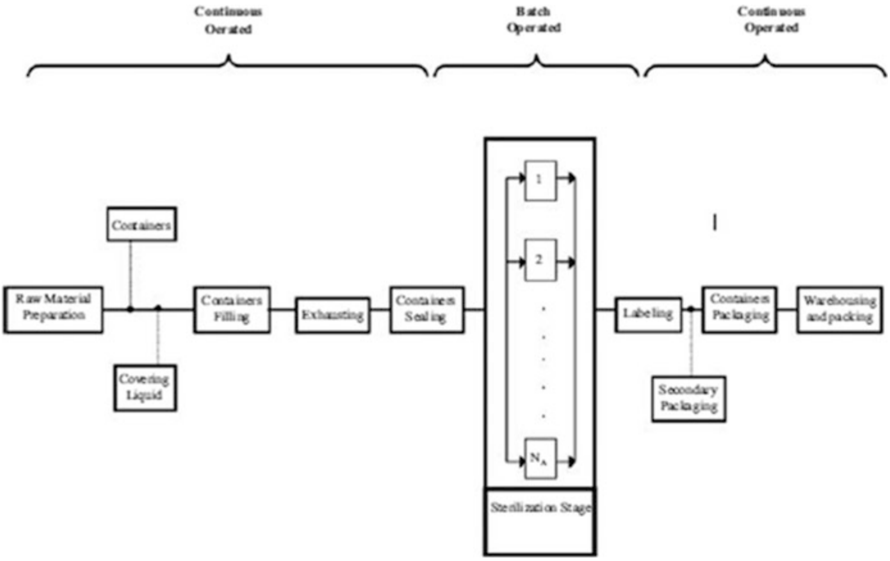


Fig. 16.1 General simplified flow diagram for a canning plant

the microbiological and biochemical aspects of the process or with engineering analysis of a single-unit process operation, and rarely analyze the processing operations in the context of manufacturing efficiency. The early stages of a project usually involve studies of alternative processes, plant configurations, and types of equipment. Among problems confronted by canned food, plants with batch retort operations are peak energy/labor demand, underutilization of plant capacity, and underutilization of individual retorts.

16.3 Batch Processing in Canned Food Plants

In batch retort operations, maximum energy demand occurs only during the first few minutes of the process cycle to accommodate the venting step, while very little is needed thereafter in maintaining process temperature. Likewise, peak labor demand occurs only during loading and unloading operations, and is not required during the holding time at processing temperature. In order to minimize peak energy demand it is customary to operate the retorts in a staggered schedule, so that no more than one retort is venting at any one time. Similar rationale applies to labor demand, so that no more than one retort is being loaded or unloaded at any one time. Too few retorts in a battery can leave labor unutilized, while too many will leave retorts unutilized. The optimum number will maximize utilization of labor and equipment, thus minimizing ongoing processing costs. Alternatively, the optimum number of retorts may be based upon maximizing the economic rate of return on the capital investment in the project measured in terms of net present value (NPV), which takes many additional factors beyond processing costs into account. In the case of maximizing output from a fixed number of retorts for different products and container sizes, iso-lethal processes can be identified for each of the various products (alternative combinations of retort temperature and process time that deliver the same lethality), from which a common set of process conditions can be chosen for simultaneous processing of different product lots in the same retort (see Chap. 14).

16.4 The Hierarchical Approach

The hierarchical approach consists of successive refinements, and the design procedure is similar to the hierarchical planning strategy discussed in the artificial intelligence (AI) literature (Douglas 1988).

In contrast to normal true batch processes, canned food plants are operated with just one-stage functioning in a batch mode. During normal operation of the sterilization stage (Fig. 16.1), the various retort units are filled with cans, perform the retorting process for a specified period, and then shut down, and the cycle is repeated. As previously mentioned, in canned food plants, all units, with the exception of retorts, operate continuously. The distinction between batch and continuous processes is sometimes somewhat “fuzzy” (Douglas 1988). According to the literature, when a plant has one or two batch operations with large production rates that otherwise operate continuously, they are normally referred to as a continuous process. Although most of the food science and food engineering literature refers to a canning plant as a batch plant, when the sterilization stage is operated in batch mode, and the hierarchical approach is applied, it is assumed that it is better to classify it as a continuous process.

The design effort will be to decide whether a concept is sufficiently promising from an economic point of view so that a more detailed study could be justified. In our specific case the flow scheme of the process is presented in Fig. 16.1. Although some exceptions to this flow scheme could be justified, the following analysis will consider it as a general flow scheme for canned food plants. The main target in the following sections will be to decide the optimum number of retorts that can be allocated in a canned food plant. The approach will be to identify a general procedure that can be applied to canned food plants.

Finally, to decide and optimize canned food plant design and operation the NPV (or net present worth) profitability evaluation method should be utilized.

16.5 Retort Scheduling

Batch processing in food canneries consists of loading and unloading individual batch retorts with baskets or crates of food containers that have been filled and sealed just prior to the retorting operation. Each retort process cycle begins with purging of all the atmospheric air from the retort (venting) with inflow of steam at maximum flow rate, and then bringing the retort up to operating pressure/temperature, at which time the flow rate of steam falls off dramatically to the relatively low level required to maintain process temperature. The retort is then held at the process temperature for the length of time calculated to achieve the target lethality (F_0 value) specified for the product. At the end of this process time, steam to the retort is shut off, and cooling water is introduced to accomplish the cooldown process, after which the retort can be opened and unloaded.

One of the factors that should be considered to decide retort scheduling is the energy demand profile during sterilization processing (Almonacid et al. 1993). In batch retort operations, maximum energy demand occurs only during the first few minutes of the process cycle to accomplish the high steam flow venting step. Very little steam is needed thereafter to compensate for the bleeder (and convection and radiation losses) in maintaining process temperature (Bhowmik et al. 1985; Barreiro et al. 1984). A typical representation of the energy demand profile during one cycle of a retort sterilization process is shown in Fig. 16.2. As shown, at the initial stage of the process a high peak of energy consumption occurs (venting before reaching the retort temperature), later decreasing dramatically, and finally reaching a low and constant value (convection, radiation, and bleeder). Thus, the

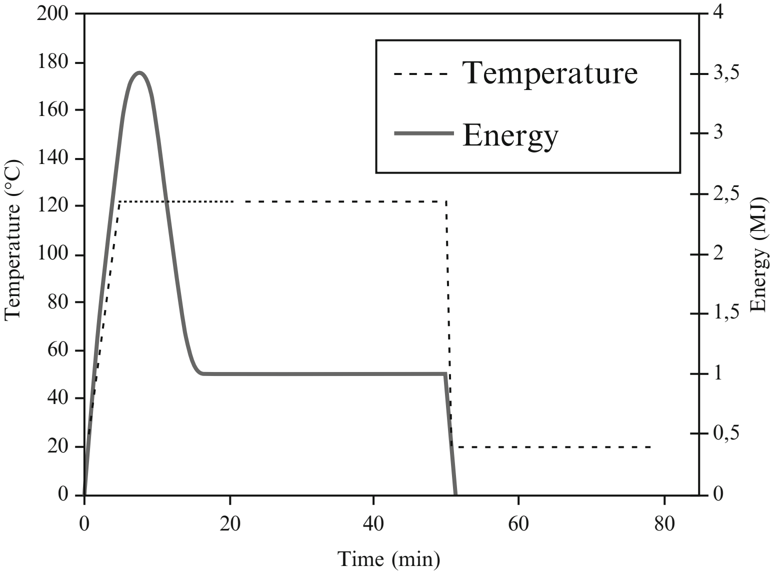


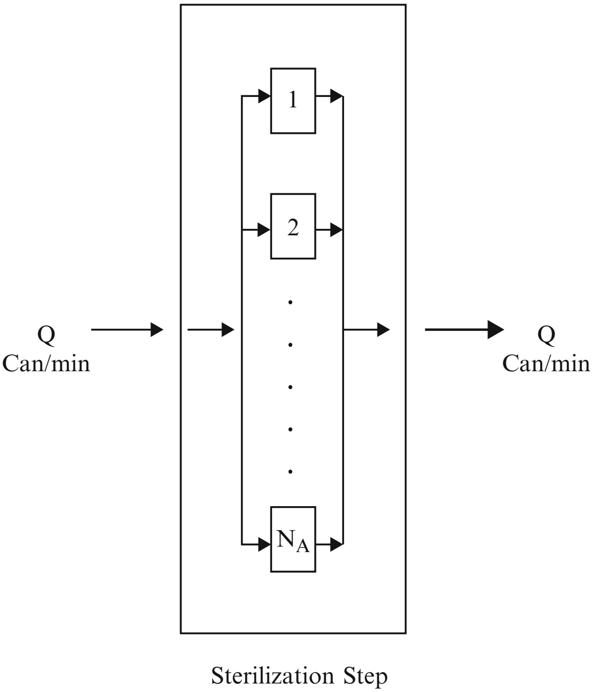
Fig. 16.2 Energy consumption in a batch cycle

energy demand for the whole plant will be conditioned upon this acute venting demand in the sterilization process of each retort operating cycle. To minimize the boiler capacity and maximize energy utilization, it is necessary to determine adequate scheduling for each individual retort.

Likewise, peak labor demand occurs only during loading and unloading operations, and is not required during the holding time at processing temperature. Therefore, a labor demand profile would have a similar pattern to the energy demand profile. In order to minimize the peak energy and labor demands, the retort must operate in a staggered schedule so that no more than one retort is venting at any one time, nor being loaded or unloaded at any one time. When a battery consists of the optimum number of retorts for one labor crew, the workers will be constantly loading and unloading a retort throughout the workday, and each retort will be venting in turn, one at a time. Under these optimum circumstances, unprocessed product will flow into and processed product will flow out of the retort battery system as though it were a continuous system as shown in Fig. 16.3 while the energy profile will appear as in Fig. 16.4.

The optimum number of retorts in the battery will maximize utilization of labor and equipment, thus minimizing unit processing costs. Too few retorts in a battery can leave labor unutilized, while too many will leave retorts unutilized. A Gantt chart showing the temporal programming schedule of the battery retort system (see Fig. 16.3) can be used as a first step in determining the optimum number of retorts. Optimum operation of the retort battery can be achieved if the loading step of the last retort starts at the same time as the first retort finishes its cycle and is ready for unloading. This means that the loading time multiplied by the number of retorts

Fig. 16.3 Diagram for operation of a battery with optimum number (N_A) of retorts such that the cook room system operates with continuous inflow and outflow of product



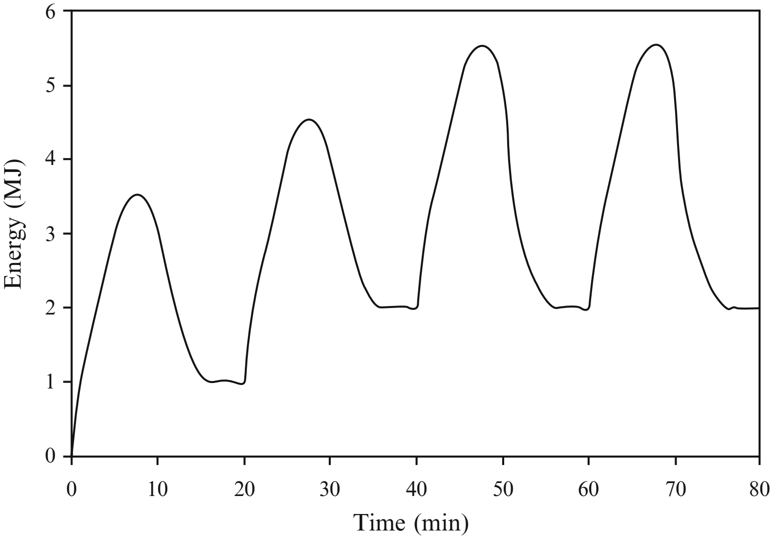


Fig. 16.4 Energy demand profile from retort battery operating with optimum number of retorts and venting scheduling

must fit within the total time to load, process, and unload one retort. This relationship can be expressed mathematically:

$$t_{\mathrm{c}} + t_{\mathrm{p}} + t_{\mathrm{d}} = t_{\mathrm{c}} N_{\mathrm{A}}$$

where N_{A} is the number of retorts and t_{c}, t_{p}, and t_{d} are the loading, process, and unloading times, respectively. Considering that loading and unloading times are equal ($t_c = t_d$), we get

$$N_{\mathrm{A}} = 2 + \frac{t_{\mathrm{p}}}{t_{\mathrm{c}}} \tag{16.1}$$

Therefore

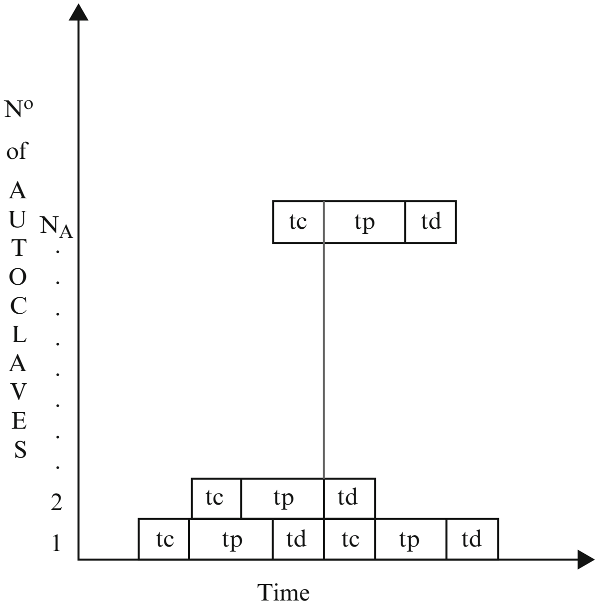
$$3 \leq N_{\mathrm{A}} \leq \infty,$$

and the minimum number of retorts for optimum operation under this criterion is 3. The number of retorts for any given situation will depend upon the ratio of process time to loading/unloading time.

Moreover, according to the operation scheme presented in Fig. 16.5, the following mathematical relationships can relate the plant production capacity (Q) to loading time and retort size:

$$Qt_{\mathrm{c}} = KV \tag{16.2}$$

Fig. 16.5 Gantt chart showing temporal programming schedule of the battery retort system operation



Rearranging Eq. (16.2) and replacing t_c from Eq. (16.1) it is possible to obtain an expression for production capacity (Q) as a function of processing time (t_p) and retort number (N_A) as follows:

$$Q = \frac{KV(N_A - 2)}{t_p}. \tag{16.3}$$

From Eq. (16.3) it is possible to infer that production capacity is directly influenced by process temperature because the higher the process temperature, the shorter the process time and the higher the production capacity (more batches per day).

16.6 Application of Mixed-Integer Linear Programing for Scheduling Optimization

Over the last few years, many papers have been published in which mixed-integer linear programing (MILP) has been successfully applied to optimize scheduling. Examples of sequential MILP short-term scheduling models can be found in Méndez and Cerda (2000, 2002), Harjunkoski and Grossmann (2002), and Castro and Grossmann (2006). In the following research papers, sequence-based MILP models for multi-product batch plants have been presented: Jung et al. (1994), Moon et al. (1996), Castro and Grossmann (2006), Floudas and Lin (2004), Gupta and Karimi (2003), Maravelias (2006), Mendez et al. (2001, 2006), Ha et al. (2006), and Liu and Karimi (2008). An interesting application of MILP planning for a petrochemical plant has been described in Hui and Natori (1996). Erdirik-Dogan and Grossmann (2007) presented a multi-period MILP model for the simultaneous planning and scheduling of single-stage multi-product continuous plants with parallel units. It is well known that in MILP problems, it is necessary to restrict the decision variables of linear programming models to integers or binary values. Usually, MILP problems are much harder to solve than pure linear programming problems because the feasible region of MILP problems does not allow the application of the well-known Simplex Algorithm. An exception to this case is to combine the Simplex Algorithm (to solve the linear relaxation of the MILP problem, which is also called a subproblem) with other algorithms, for example, branch-and-bound techniques to compute the optimal solution of the initial problem by LP relaxation implementation. This scheduling optimization method coupled with simultaneous sterilization was studied by Simpson and Abakarov (2009). For example, in the case of non-simultaneous sterilization, the plant operation time was 332.5 min, while simultaneous operation with MILP implementation reduced this plant operation time to 249.05 min for the same production. The MILP model proposed by Simpson and Abakarov (2009) always gives lower or equal plant operation times compared with non-simultaneous sterilization, and the difference between the two times will depend on the given data: the possibility of simultaneous sterilization, the amounts of product taken, and the autoclave capacity.

Therefore, the results show that the proposed MILP model based on the possibility of simultaneous sterilization provides flexibility to optimize battery retort utilization, with a plant operation time reduction close to 25 %. This procedure is of special relevance for small- and medium-sized canneries that normally work with many different products at the same time. Furthermore, depending on the practical situation, the proposed methodology for developing the MILP model allows addressing other types of optimization problems: for example, the MILP model proposed can easily be modified to maximize the number of products sterilized for a given plant operation time. Therefore, according to Simpson and Abakarov (2013), adequate design of MILP makes it possible to resolve two problems: plant operation time minimization and maximization of the amount of sterilized product.

16.7 Searching for the Optimum Number of Retorts

A criterion to optimize plant design and operation is to determine the number of retorts that will maximize the NPV of the invested capital for the new process line. This can be approached on the basis of microeconomics.

Equation (16.4) is the expression for NPV:

$$\text{N.P.V.} = -I + \sum_{j=1}^{n} \frac{\beta_j}{(1+i)^j} \tag{16.4}$$

where two main terms can be distinguished, total investment ($-I$) and annual benefits (β_j). The total investment for the project will be expressed as the cost requirement in retorts, fittings, boiler, general equipment, construction and engineering, working capital, etc. Expressing the total investment mathematically

$$I = I_{\mathrm{N}} + I_{\mathrm{F}} + I_{\mathrm{B}} + I_{\mathrm{X}} \tag{16.5}$$

According to Guthrie (1969) the cost of equipment (retorts, etc.) could be expressed as being in proportion to its capacity. Therefore, in the specific case of retorts, a mathematical expression is

$$C_{\mathrm{R}} = k_{\mathrm{R}} V^a, \quad 0 < a < 1 \tag{16.6}$$

Therefore the required investment in N_{A} retorts could be expressed as

$$I_{\mathrm{N}} = N_{\mathrm{A}}(k_{\mathrm{R}} V^a) \tag{16.7}$$

According to the scheme presented in Figs. 16.3 and 16.4 and utilizing Eq. (16.3), it is possible to obtain a mathematical relation between the retort size (V) and the number of retorts (N_{A}):

$$V = Q\frac{t_{\mathrm{P}}}{(N_{\mathrm{A}} - 2)K} \tag{16.8}$$

Replacing Eq. (16.8) in Eq. (16.7) an expression for retort investment as a function of retort number is obtained:

$$I_{\mathrm{N}} = N_{\mathrm{A}}\left[k_{\mathrm{R}}\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}} - 2)K}\right)^{a}\right] \tag{16.9}$$

The fittings investment (I_{F}) will be considered as directly related to the retort investment. Therefore from Eq. (16.9)

$$I_{\mathrm{F}} = \varphi N_{\mathrm{A}}\left[k_{\mathrm{R}}\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}} - 2)K}\right)^{a}\right]; \quad 0 < \varphi < 1 \tag{16.10}$$

The boiler size is related to the size of each retort but also to retort scheduling (total magnitude of peak energy consumption). In this analysis the retort scheduling was adopted from the Gantt chart presented in Fig. 16.5. Each retort has a time delay equivalent to the loading time (t_{c}) resulting in a boiler size mainly dependent on the retort size; then

$$B \alpha V \tag{16.11}$$

$$B = k_{\mathrm{B}}V \tag{16.12}$$

$$C_{\mathrm{B}} = k_1[B]^b = k_1[k_{\mathrm{B}}V]^b = k_2[V]^b; \quad 0 < b < 1 \tag{16.13}$$

Arranging Eq. (16.13), the boiler investment (I_{B}) could be expressed as

$$I_{\mathrm{B}} = k_2(V)^b = k_2\left(\tfrac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)K}\right)^b; \quad 0 < b < 1 \tag{16.14}$$

Replacing Eqs. (16.9), (16.10) and (16.14) into Eq. (16.5), the total investment could be expressed as

$$I = (1 + \varphi)N_{\mathrm{A}}\left[k_{\mathrm{R}}\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}} - 2)K}\right)^{a}\right] + k_2\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}} - 2)K}\right)^{b} + I_{\mathrm{X}} \tag{16.15}$$

As is shown in Eq. (16.15), investment (I) is a function of retort number (N_{A}) and process time (t_{p}):

$$I = I\left(N_{\mathrm{A}}, t_{\mathrm{p}}\right)$$

Annual incomes:

Analyzing the second term of Eq. (16.4), annual benefits (or debits) could be expressed as

$$\sum_{j=1}^{n}\frac{\beta_j}{(1+i)^j} \qquad \text{where} \qquad \beta_j = Q{*}(P_u - C_u); \qquad \text{and } Q{*} = QT \tag{16.16}$$

$$\beta_j = QT_yP_u - QT_yC_u \tag{16.17}$$

Replacing Eq. (16.3) into Eq. (16.17)

$$\beta_j = \frac{KV(N_\mathrm{A}-2)}{t_\mathrm{p}}T_y(P_u - C_u) \tag{16.18}$$

From Eq. (16.18) it is possible to infer

$$\beta_1 = \beta_2 = \cdots = \beta_n = \beta = \frac{KV(N_\mathrm{A}-2)}{t_\mathrm{p}}T_y(P_u - C_u) \tag{16.19}$$

Expressing the annual benefits as a present value, the second term of Eq. (16.4) could be reduced to

$$B_\mathrm{E} = \sum_{j=1}^{n}\frac{\beta_j}{(1+i)^j} = K'\frac{KV(N_\mathrm{A}-2)}{t_\mathrm{p}}T_y(P_u - C_u) \tag{16.20}$$

where $K' = \frac{([1+i]^n-1)}{i(1+i)^n}$

And then, $B_\mathrm{E} = B_\mathrm{E}\left(N_\mathrm{A}, t_\mathrm{p}\right)$

Replacing Eqs. (16.16) and (16.20) into Eq. (16.4)

$$\text{N.P.V.} = -(1+\varphi)N_\mathrm{A}\left[k_\mathrm{R}\left(\frac{Qt_\mathrm{p}}{(N_\mathrm{A}-2)K}\right)^a\right] - k_2\left(\frac{Qt_\mathrm{p}}{(N_\mathrm{A}-2)K}\right)^b - I_\mathrm{X} + K'\frac{KV(N_\mathrm{A}-2)}{t_\mathrm{p}}T_y(P_u - C_u) \tag{16.21}$$

where

$$\text{N.P.V.} = f\left(N_\mathrm{A}, t_\mathrm{p}\right) \tag{16.22}$$

Therefore NPV is a function of process time and number of retorts. To maximize NPV it is necessary to get the partial derivatives of Eq. (16.21) and find the critical values for N_A and t_p.

By inspection, and analyzing Eq. (16.3), it can be demonstrated that (see Eq. 16.3)

$$\left(\frac{\partial(V(N_{\mathrm{A}}-2))}{\partial N_{\mathrm{A}}}\right)t_{\mathrm{p}}=0 \tag{16.23}$$

Also the NPV function (Eq. 16.21) increases indefinitely as process time decreases (with corresponding increasing process temperature). Therefore, in terms of maximizing NPV, the process temperature must be as high as possible. The upper limit on process temperature will be restricted by adverse effects on product quality and upper operating limits of the retort. To find the critical value for number of retorts (N_{A} for maximum NPV), Eq. (16.21) will be treated as an independent variable function (N_{A}); then

$$\text{N.P.V.}=-I(N_{\mathrm{A}})+B_{\mathrm{E}}(N_{\mathrm{A}}) \tag{16.24}$$

Taking derivatives

$$\frac{d(\text{N.P.V.})}{dN_{\mathrm{A}}}=-\frac{dI(N_{\mathrm{A}})}{dN_{\mathrm{A}}}+\frac{dB_{\mathrm{E}}(N_{\mathrm{A}})}{dN_{\mathrm{A}}} \tag{16.25}$$

But, according to Eq. (16.23)

$$\frac{dB_{\mathrm{E}}(N_{\mathrm{A}})}{dN_{\mathrm{A}}}=0 \tag{16.26}$$

Therefore

$$\frac{d(\text{N.P.V.})}{dN_{\mathrm{A}}}=-\frac{dI(N_{\mathrm{A}})}{dN_{\mathrm{A}}} \tag{16.27}$$

According to Eq. (16.27) the maximization of NPV corresponds to the minimization of investment ($I(N_{\mathrm{A}})$).

Study cases: As a starting point, a simplified situation will be analyzed in which the investment for a specified plant size is affected by the number of retorts (N_{A}). The investment on fittings and boiler (I_{F} and I_{B}) would be independently considered to N_{A}. Therefore Eq. (16.21) can be rewritten for this simplified case as

$$\begin{aligned}\text{N.P.V.}=&-N_{\mathrm{A}}\left[k_{\mathrm{R}}\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)K}\right)^{a}\right]+I_{\mathrm{B}}+I_{\mathrm{F}}+I_{\mathrm{X}}\\&+K'\frac{KV(N_{\mathrm{A}}-2)}{t_{\mathrm{p}}}t_{y}(P_{u}-C_{u})\end{aligned} \tag{16.28}$$

To maximize NPV it is necessary to take the derivative of Eq. (16.29), equalize it to zero, and find the critical value for N_{A}. If the second derivative is less than zero then the critical value for N_{A} will represent a maximum value for NPV. Taking the derivative from Eq. (16.28), considering Eq. (16.23), and equalizing to zero

$$\begin{aligned}\frac{d(\text{N.P.V.})}{dN_{\mathrm{A}}} &= -k_{\mathrm{R}}\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)K}\right)^{a} \\ &\quad + k_{\mathrm{R}} a N_{\mathrm{A}}\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)^2 K}\right)\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)K}\right)^{a-1} \\ &= 0 \end{aligned} \tag{16.29}$$

Rearranging Eq. (16.29) the critical value for N_{A} is

$$N_{\mathrm{A}}^{*} = \frac{2}{1-a} \tag{16.30}$$

Given that the second derivative of Eq. (16.29) is less than zero, N_{A}^{*} represents a maximum for NPV. According to Guthrie (1969) the exponent $\boldsymbol{a}$ has a value of 0.6 for horizontal retorts and 0.65 for vertical retorts. Therefore

$$N_{\mathrm{A_H}}^{*} = \frac{2}{1-0.6} = 5 \tag{16.31}$$

$$N_{\mathrm{A_V}}^{*} = \frac{2}{1-0.65} \cong 6 \tag{16.32}$$

A general approach should analyze and consider, as a basic starting point, Eq. (16.21). Following the same procedure, it is necessary to find the first and second derivatives of Eq. (16.21) to identify the critical value for N_{A} and to see if it represents a maximum or minimum for NPV. Therefore, taking derivatives of Eq. (16.21)

$$\begin{aligned}\frac{d(\text{N.P.V.})}{dN_{\mathrm{A}}} &= (1+\varphi)N_{\mathrm{A}}k_{\mathrm{R}}a\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)K}\right)^{a-1}\frac{Qt_{\mathrm{p}}}{K(N_{\mathrm{A}}-2)^2} \\ &\quad - (1+\varphi)k_{\mathrm{R}}\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)K}\right)^{a} \\ &\quad + k_2 b\left(\frac{Qt_{\mathrm{p}}}{(N_{\mathrm{A}}-2)K}\right)^{b-1}\frac{Qt_{\mathrm{p}}}{K(N_{\mathrm{A}}-2)^2} \\ &= 0 \end{aligned} \tag{16.33}$$

Arranging and simplifying Eq. (16.33)

$$\begin{aligned}&\frac{(1+\varphi)N_A k_R a}{(N_A-2)}\left(\frac{Qt_p}{(N_A-2)K}\right)^a-(1+\varphi)k_R\left(\frac{Qt_p}{(N_A-2)K}\right)^a\\&+\frac{k_2 b}{(N_A-2)}\left(\frac{Qt_p}{(N_A-2)K}\right)^b\\&=0\end{aligned}\tag{16.34}$$

Equation (16.34) should be solved numerically by using a procedure like Newton–Raphson and regula falsi. If the exponents ***a*** and ***b*** are similar ($\boldsymbol{a} \cong \boldsymbol{b}$), Eq. (16.34) has an analytical and interesting solution (Eq. 16.35). Reported values for ***a*** and ***b*** exponents are in the range of 0.6–0.65 for ***a*** and 0.55–0.65 for ***b*** (Guthrie 1969; Peters and Timmerhaus 1991; Vilbrandt and Dryden 1959):

$$N_{\mathrm{A}}^{*}=\frac{k_2 a+2k_{\mathrm{R}}(1+\varphi)}{k_{\mathrm{R}}(1-a)\,(1+\varphi)}\tag{16.35}$$

Rearranging

$$N_{\mathrm{A}}^{*}=\frac{k_2 a}{k_{\mathrm{R}}(1-a)\,(1+\varphi)}+\frac{2}{1-a}\tag{16.36}$$

As was stated before, the exponent ***a*** could be 0.6 or 0.65 depending on retort type (horizontal or vertical), and then for horizontal retorts, Eq. (16.36) could be expressed as

$$N_{\mathrm{A}}^{*}=\frac{1.5k_2}{k_{\mathrm{R}}(1+\varphi)}+5\tag{16.37}$$

To evaluate N_{A} it is necessary to quantify k_2, k_{R}, and φ. Values for these constants can be found in the literature (Guthrie 1969; Peters and Timmerhaus 1991; Vilbrandt and Dryden 1959) or directly from the manufacturers of equipment (retorts and boilers). It is interesting to note that independent of its respective values (k_2, k_{R}, and φ) in this general analysis the optimum number of retorts is always larger than 5 for horizontal retorts and larger than 6 for vertical retorts.

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Chapter 17
Thermal Food Processing Equipment

17.1 Introduction

The design, operation, and choice of sterilizing and pasteurization systems, known as retorts, cookers, or autoclaves, for packaged foods depend on a number of factors.

Product characteristics are the first factors to be considered. Acid products with pH less than 4.5 usually require only a mild treatment, and this can be achieved with steam at atmospheric pressure or boiling water. Consequently, the equipment required is much simpler than for low-acid products with greater than pH 4.5. For pasteurization of acid food products, temperatures of the order of 120–130 °C are necessary, and pressure vessels will be required to contain the pressure of the steam or maintain the condition of the hot water or other heating medium. In factories that process a wide range of products, pressurized retorts are often used for acidic food products. It is more usual to find atmospheric equipment operating in factories where fruit products are processed in large volumes and where it is possible to have dedicated systems for retorting.

Many products have high-viscosity components, e.g., meat and vegetable stews, cream-style corn, beans in tomato sauce, macaroni cheese, puddings, sauces with thickening agents, and a variety of cream soups, and the processing of cans of these products is enhanced by using agitating processes. These can involve axial or end-over-end motion, and special retorts or modified retorts are used. Apart from the product aspects, many large sizes of cans of food for the catering food processing industry benefit enormously from agitating processes. The rate of heat penetration is increased, and the problems of the overcooking of the outside layers of the canned product are reduced. In order to ensure adequate sterilization of products undergoing an agitating process, it is necessary to control the headspace in the can carefully, as well as the solid–liquid ratio, consistency and speed of rotation, and other factors such as process temperature, time, pressure, and operating cycle.

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Food Engineering Series, DOI 10.1007/978-3-319-24904-9_17

The nature and form of the packaging material make up the second factor to take into account. It is essential that the conditions applied in the processing operation maintain the integrity of the packaging material. Hermetically sealed containers should not be distorted, and the seams, end(s), and body should not be affected by the process. For all types of sealed container the vapor pressure of the liquid portion of the components increases with increasing temperature, so that as the can is heated externally the internal pressure rises. In the case of pressurized steam there is some counterbalancing between the internal and external pressures, usually, in the case of rigid containers, sufficient to prevent permanent distortion. With larger sizes of can, however, when the process is completed, the can has a residual internal pressure, and this must be counterbalanced during cooling; otherwise there will be a tendency to distort the seams by peaking the ends. There is also a possibility of vacuum formation if the cooling is too rapid, and paneling of the bodies will result. This means that normal steam-operated retorts require a compressed air supply to counterbalance the internal pressure during cooling. While this applies to rigid containers, many of the newer types of plastic containers have seams that are unable to withstand the differential pressures imposed by steam heating. Consequently, it is necessary to use an additional pressure during heating. This can be achieved by the use of steam–air mixtures or pressurized hot water processing. Many new retorts have been devised that can be used with these heating media. The third factor is production throughout. While batch retorts are flexible in relation to container size and process conditions, they have a relatively slow production rate and are labor and energy intensive. Consequently, most factories operate high-speed lines with continuous rotary or hydrostatic cookers. Large-volume production is necessary to achieve marketing objectives.

The choice of a retorting system is, therefore, quite complex and requires special care. There are, of course, a large number of other factors of a general engineering nature that also have to be considered. These include site location, available floor area and factory layout, as well as many other financial, personnel, and marketing aspects, all of which are outside the scope of this text but are dealt with elsewhere (see, for example, Downing 1996).

During the last two centuries, a large variety of devices have been manufactured and used. In the following discussion only the major types of equipment in current use are mentioned. The reader seeking historical information should consult Bitting (1916) and Thorne (1986), together with patents and articles in the trade journals, although much of the detail, unfortunately, is not directly available. It would be a useful exercise in mechanical engineering design to document the achievements of individual designers and how they overcame many of the problems involved in continuous cooker design and can handling. Some of the major types of retorting systems currently in use are listed in Table 17.1; they are classified according to the mode of operation and the heat transfer media commonly used. The discussion in this text is confined to the factors which concern the delivery of a safe process, and many aspects of the technology of canning and heat processing are not dealt with here. The excellent recent texts of Rees and Bettison (1991) and Footitt and Lewis (1995), together with the encyclopedic three-volume work of Downing (1996),

Table 17.1 Some commercial retorting systems

System	Heat-transfer medium	Condensing saturated steam	Steam–air mixtures	Hot water	Flame
1(a)	Batch—static	Conventional vertical and horizontal retorts	Horizontal retorts: – Lubeca – Lagarde Steristeam – Barriquand	Steriflow – Barriquand [raining water]	–
1(b)	Batch—rotary	Horizontal—Millwall (internal rotation of cans fixed in a cage) –FMC Orbitort –Zinetec Shaka Vibration of horizontally arranged containers	Horizontal retort: – Lagarde	Konservomat – Atmos (Alfa Laval Gruppe) Rotomat—Stock Lubeca	–
2(a)	Continuous—static	Hydrostatic cookers:— Hydroflex—FMC Hydromatic – Stork – Carvallo	–	–	–
		Hydrostat—M&P Hydron – Mitchell Webster – Hunister			
		Horizontal hydrostatic cooker: Hydrolock—LST Storklave—Stork Universal cooker – FMC	–	–	–
	Semicontinuous	Crateless retorts – Malo/Odenberg – FMC			
2(b)	Continuous—rotary	Hydrostatic cookers with rotating carrier bars – FMC – Stork	–	Rotary cooker/coolers – FMC – Stork Hydroflow	Steriflam – ACB Hydroflam
		Rotary cooker-coolers: reel-and-spiral Sterilmatic—FMC Steristork—Stork	–	–	–

Manufacturers: ACB, Ateliers et Chantiers de Bretagne, Nantes, France; Atmos-Lebensmitteltechnik, Hamburg, Germany; Barriquand SA, Paris, France; ATM Carvallo, Drancy, France; FMC Machinery Europe NV, Sint-Niklaas, Belgium; Hunister, Komplex Hungarian Trading Company, Budapest, Hungary; LST, La Sterilization Thermique, Paris, France; Lubeca Maschinen und Anlagen GmbH, Lübeck, Germany; M&P, Mather and Platt, Bolton, UK (no longer manufactured); Mitchell-Webster, Chisholm-Ryder, USA; Millwall, John Fraser & Sons Ltd., Newcastle-upon-Tyne, UK; Odenberg Engineering Ltd, Dublin, Ireland; Stock, Hermann Stock GmbH, Neumünster, Germany; Stork Amsterdam, Amsterdam, Netherlands, Zinetec Ltd. Faringdon, Oxford, UK adequately cover many of the technological aspects. More details of the mechanical and technical aspects of the design of retorts are given by Brown (1972), Richardson and Selman (1991), May (2001), and Holland (2008).

17.2 Batch Retorts

17.2.1 Conventional Static Retorts

The conventional batch canning retort is either circular or rectangular in cross section and arranged either vertically or horizontally. Several retorts are usually arranged in banks, and a sequence of filling, closing, retorting, and emptying is operated to give a supply of cans sufficient to maintain continuous labeling and packing. The cans are arranged in baskets, appropriate to the geometry of the retort, either randomly packed or arranged in layers on plastic divider plates. Vertical retorts are usually sunk into the flooring so as to give easy access to the hinged lid at the top. The services to the retort, and indeed any similar type of retort, consist of a steam distribution system with a spreader, cooling water supply, a compressed air supply for pressurized cooling, valves for venting and draining the retort, petcocks for bleeding air from the retort, and an instrument pocket arranged on the side, so as not to interfere with the loading and unloading of the crates of cans. The services and valves are shown in Fig. 17.1. The steam and air supplies should not exceed the

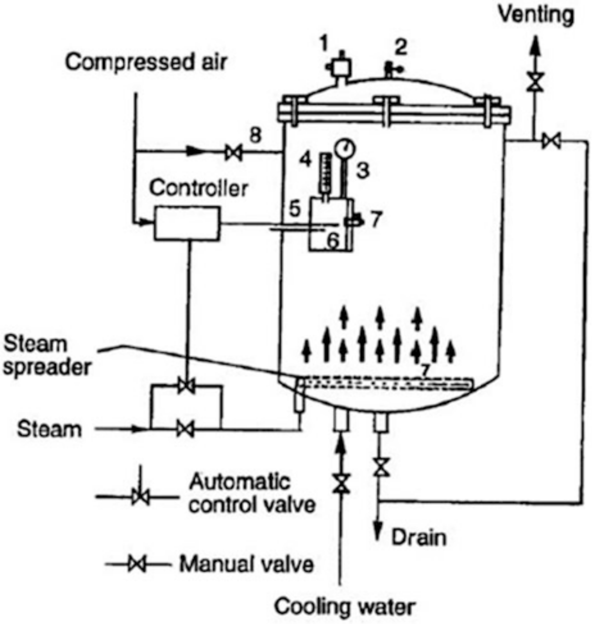


Fig. 17.1 A vertical batch retort: (*1*) safety valve; (*2*) petcocks to maintain a steam bleed from retort during processing; (*3*) pressure gauge; (*4*) thermometer; (*5*) sensing element for controller; (*6*) thermo-box; (*7*) steam spreader; (*8*) air inlet for pressure cooling

safe-working pressure of the retort, and should be sufficient to carry out the operations adequately. Batch retorts are operated according to the following general principles estimated for UK practice (Department of Health 1994; Thorpe et al. 1975).

1. Baskets of cans are placed in the retort and the lid closed.
2. With the vent, drain, and the bypass to the controller valves open, the venting sequence to remove the air from in between the cans and baskets is started by introducing steam until the temperature in the retort is about 100 °C. The drain is then closed.
3. Venting continues for the prescribed time, and the vent valve is then closed.
4. The temperature is brought up to about 5 °C below the required processing temperature, and the steam bypass valve closed.
5. The retort is allowed to attain the scheduled temperature using the controller.
6. When the time for processing is complete, the steam valve is closed and the cooling cycle started.
7. Compressed air is introduced to balance the pressure inside the can.
8. While continuing to counterbalance the pressure, water is allowed to run through the overflow/vent valve until cooling is completed, i.e., until the cans have reached a temperature of about 40 °C.
9. When the pressure is atmospheric the lid, which should be fitted with a safety bolt, is opened and the baskets removed.

The importance of removing air by venting and using petcocks during processing is paramount to maintaining the correct temperature. Small quantities of air in the steam reduce the temperature significantly, especially at the surface of the cans where condensation is taking place. The venting cycle is established, for all types of retort, by placing thermocouples at strategic points in the crates of cans, and steam is introduced for a period sufficient to make all the thermocouples read the same. It is important to note that the arrangement of cans in the baskets, whether layered or scrambled, affects the heat penetration into the cans, and it is necessary to carry out tests under the conditions that are to be used in production. Sumer and Esin (1992) have attempted to establish a mathematical model based on a model for predicting the come-up time (see Chap. 6, Sect. 6.2.4 for more details). Kannan and Gourisankar Sandaka (2008) have presented an analysis of heat transfer in a batch retort.

A protocol has been published by the Institute for Thermal Processing Specialists determining the temperature distribution for steam heating in batch retorts, which excludes crateless retorts (IFTPS 1992, 2014).

The above description is specific to UK operations; other countries use slightly differing procedures. A minimum time is often quoted for the temperature to rise above 100 °C for a specific type of retort pipework layout and services; for example the vent value shall be open for x min until a temperature of at least T is achieved, after which it is closed and the retort brought up to temperature (Downing 1996; NFPA 1982).

17.2.2 Other Batch Retorts

While steam retorting is convenient for many types of container, several types of plastic container and pouch require overpressure to maintain the integrity of the packaging material. This may be achieved using steam–air mixtures or recirculating pressurized hot water. Hot water is often used for glass jar sterilization. Some typical examples of batch retort are given in Table 17.1. The Lagarde system, developed in 1972, is very versatile and uses steam–air mixtures for heating and water for cooling. The system is illustrated in Fig. 17.2. It consists of cans. Rotating mixer blades are used to circulate the steam and to ensure that the mixture is kept uniform; this is particularly important in order to maintain a uniform temperature during processing. The Barriquand system (Steriflow) uses a raining water system to heat the food containers. This uses about 400 l of water, recycled every 9 s at a flow rate of 160 m^3 h^{-1}, in a typical four-crate system. The water is heated indirectly with steam using a heat exchanger. The cooling water is separate from the heating system, and may be cooled and recirculated if necessary. The pressure of the system is regulated by using compressed air and is controlled to suit the mechanical requirements of the container. Ramaswamy et al. (1993) have evaluated a Lagarde steam/air retort operating in end-over-end mode. A starch suspension (2–4 %) was used with 307 × 409 cans at temperatures from 110 to 130 °C and 10 to 20 rpm.

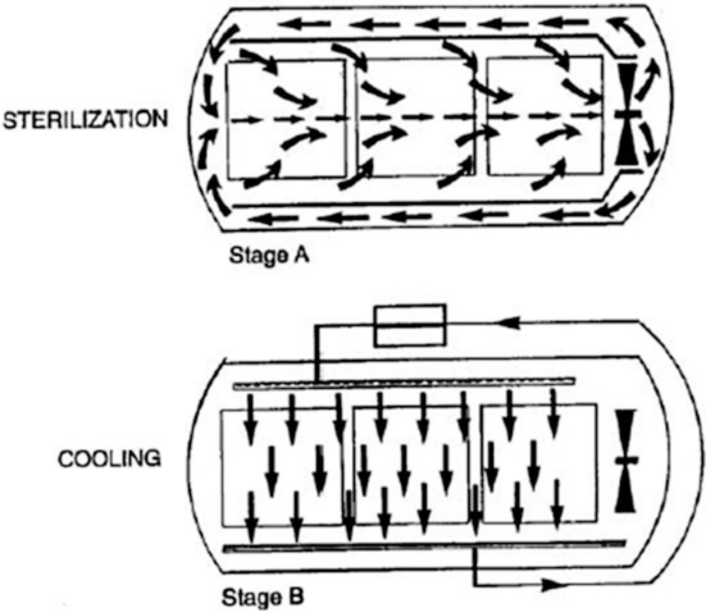


Fig. 17.2 The Lagarde system. *Stage A*: The sterilizing process uses forced steam circulation. *Stage B*: The rapid cooling is achieved by spraying of recycled cold water

Mention must also be made of the crateless retort, of which one or two are commercially available. These retorts have top and bottom opening facilities, and the cans are placed directly in the retort, which is filled with water. Steam is introduced when the filling is completed and the water displaced. This is followed by a venting cycle. When the process is finished the cans are cooled from the bottom for the requisite time before being discharged onto a moving belt underwater. The system is of a semicontinuous nature and has the advantages of the flexibility of a batch system and also the high production rate of a continuous cooker. Several retorts, or pots as they are called, are used in a battery system.

A high-speed reel-type sterilizer, known as the Orbitort sterilizer, is used for viscous packs, e.g., cream-style corn and meat and vegetable stews, packed in large-sized catering cans such as 603 × 600 and 603 × 700. The cans rotate around the periphery of a long cylindrical pressure vessel at a speed of 36.7 rpm, such that the headspace bubble is kept continuously moving inside the cans and imparting mixing and agitation to the can contents (Fig. 17.3). The inside motion of the cans from the inlet to the outlet is developed by a rotating reel-and-spiral device, which has flights that hold the cans in place and prevent contact during processing. The cans are loaded automatically and are counted until the correct number is in place. The unit is then sealed and steam introduced, followed by venting, processing, and cooling.

17.2.3 Batch Rotary Systems

The advantages of using agitation of the headspace to increase heat transfer in cans were recognized during the nineteenth century, and many attempts to use the

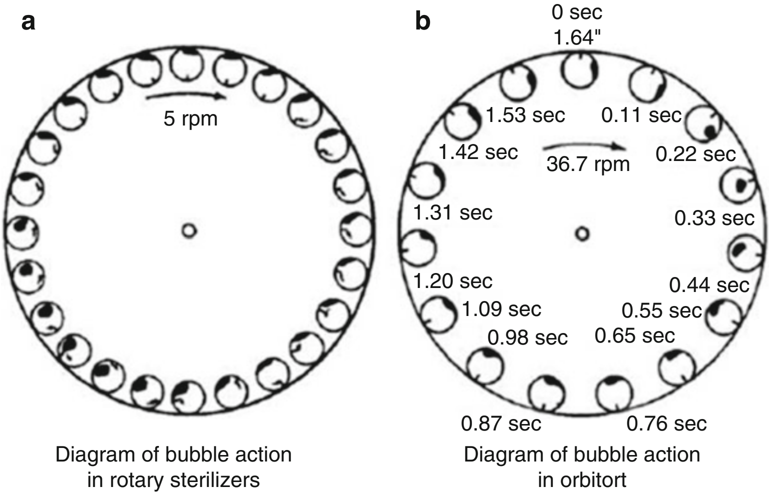


Fig. 17.3 Typical motion of the headspace bubble in cans being rotated in two different types of rotary cooker: (**a**) bubble action in rotary sterilizer; (**b**) bubble action in Orbitort (courtesy FMC Corp, St Jose, USA)

principle were investigated. Agitation may be imparted by either an end-over-end action, e.g., a retort rotating about a central horizontal axis, or an axial rotation of cans in a horizontal plane. While retorts of the former type are occasionally found today, most retorts use the second type of principle. The Millwall retort, for example, has baskets of A10 cans that slide into the system via a pressure lock and fit into an internally rotating cage. The system is ideally suited to catering pack sizes, since these benefit most from having the contents mixed during processing.

The Rotomat, developed by Hermann Stock of Neumünster, Germany, in 1952, is widely used in industry. The Rotomat uses recirculating pressurized hot water, and the temperature pressure differential between the water in the reservoir and the processing vessel provides the necessary overpressure required for plastic and other containers. Retorts of this type are usually operated at about 6–8 rpm; during heating and cooling, however, a faster speed of about 15 rpm is used for the come-up period. Heat transfer depends on the water contacting all the cans in the baskets as well as on the rotational motion. It is necessary to take the nature of the divider plates in the baskets between the cans into account in ensuring that there is adequate distribution of the hot water during the process. A full discussion of these overpressure rotary cookers with regard to determination of temperature distribution and also heat penetration has been presented by Hendrickx (1997).

17.2.4 Vibration Retort

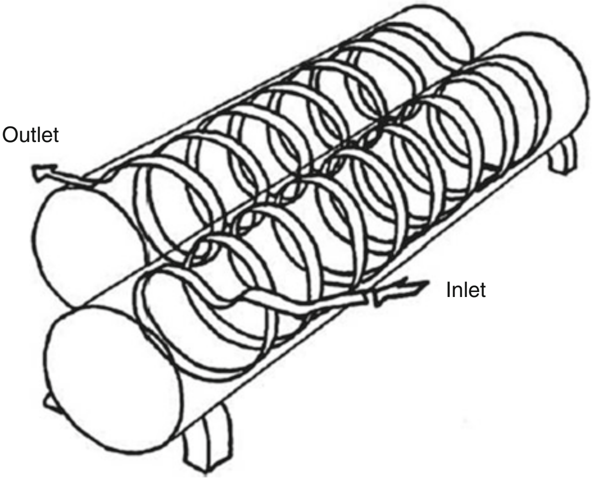
The Zintec Shaka ™ as previously discussed in § 13.5 is a batch retort using steam as the heating medium. It is a very robust system as it uses vibrations of a frequency of 100–200 cycles per minute. Process times of a tenth of the time taken for a conventional static process may be achieved. The time for processing a 5 % starch solution in a 73 × 110 mm can is only 4.2 min for a 125 mm stroke and 120 rpm, compared with a static retort process (Walden 2008). The very short processing times are particularly important for improving quality in a range of products which do not require long cooking times to soften the product, e.g., vegetables in thick sauces.

17.3 Continuous Cookers

17.3.1 Reel and Spiral Cookers

This type of cooker was originally developed at the end of the nineteenth century; the pressure valve to allow the passage of cans into and out of the various pressurized chambers was developed in 1919 (Ball and Olson 1957). The cooker derives its name from an internal reel-and-spiral arrangement that permits cans to

Fig. 17.4 Path of cans through a reel-and-spiral cooker-cooler



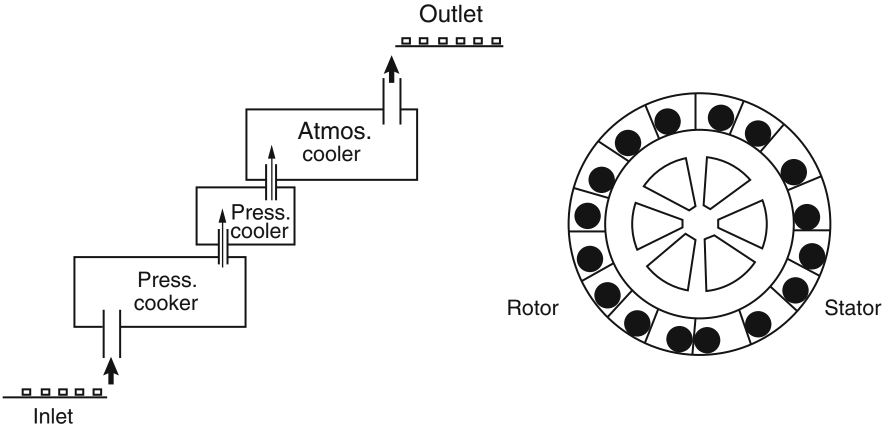


Fig. 17.5 Arrangement of heating and cooling shells in a typical reel-and-spiral cooker-cooler

progress along the internal periphery of a cylindrical vessel, allowing them to rotate while keeping them apart. The cylindrical pressure vessels are known as shells, and a typical arrangement consists of preheating, sterilizing, and cooling shells, although other arrangements for preheating and cooling are also possible. The cookers are predominantly steam-heated, although it is necessary to avoid condensate flooding the lower part of the sterilizer. The cookers are very flexible inasmuch as the resistance time of the cans, the speed of rotation, and the temperature can be adjusted to desired levels (see Figs. 17.4 and 17.5).

The most important initial application of the cooker was for sterilizing canned evaporated milk. The first machines, known as AB cookers after the company that first developed them (Anderson and Barngrover, which eventually became a division of the FMC Corporation), were installed at Nestlé Milk Products in the USA for this purpose in 1924. Subsequently various manufacturers made cookers for use with a variety of canned products. If the valves are well maintained and regularly inspected the cookers behave relatively well, although production difficulties have been reported with valves jamming. Much of the success of this type of cooker depends on the ability to control the pressure inside the valve carefully when the cans are transferred from the heating to the cooling shell. Distorted cans are also a cause of valve jamming.

The CTemp commercial computer program has been used to evaluate the effect of process deviations on the performance of reel-and-spiral cookers (Dobie et al. 1994). Process control methods in this type of cooker have been developed by Bratt et al. (1989), and Campden (1997a).

17.3.2 Hydrostatic Cookers

These were first developed for commercial use by Pierre Carvallo in 1948, and subsequently by other manufacturers, e.g., Mitchell-Webster, FMC, Mather and Platt, and Stork. The essential principle was the use of hydrostatic legs of water of sufficient height, about 30 m, to counterbalance the pressure of the steam used in rotary sterilizers. They also required relatively little floor space, being vertically orientated. A typical hydrostatic cooker (Fig. 17.6) consists of a preheating leg, a steam sterilizing chamber, and one or more cooling legs. The cans or bottles are transported on long horizontal carrier bars (which may or may not impart rotary motion) chained together. The carrier bars enter the preheat leg at the top and progress down until they reach the steam chamber, where they make at least one double pass before emerging upwards through the cooling leg. There are many different arrangements of the legs, depending on the nature of the product being sterilized. There are also canned fruit and fruit juice sterilizers which operate at or near atmospheric pressure.

The Hunister hydrostatic sterilizer has a large number of legs, each operated at a different temperature and pressure, forming a multistage process. This arrangement significantly lowers the height to approximately 6 m and can easily be accommodated under normal factory conditions. It can process glass jars and cans at temperatures up to 135 °C.

The Hydrolock retort system is a horizontal cooker using the carrier bar system with a complex rotary pressure-sealing valve of undisclosed design. The carrier bars make multiple passes through the pressure chamber before passing through water at the base of the pressure vessel and discharging to a trough of water below the cooker.

Best et al. (1994a, b) have presented a steady-state and a dynamic sterilization of the processing of cans in a Hydrolock sterilizer using zone modeling and a computer program: “Flowpack” (ICI, UK).

An important guide for the control of hydrostatic cookers has been produced by Campden BRI (1981).

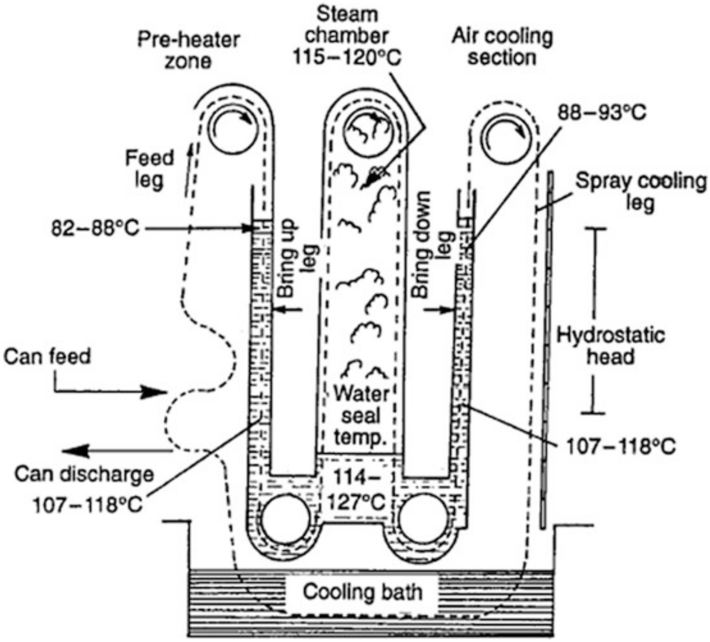


Fig. 17.6 Hydrostatic cooker-cooler sterilizer

17.4 Commercial Pasteurizers

Pasteurization temperatures are usually of the order of 90–100 °C, and hot water or sprayed water is the usual heating medium. While the process may be carried out in normal canning retorts, it is more usual to use tunnel pasteurizers with moving belts operating at atmospheric pressure, and zones of sprayed water at different temperatures. For a detailed treatment of the pasteurization of food products see Buckenhskes et al. (1988).

A typical industrial pasteurizer for glass jars of an acidic product would be of the order of 12 m in length and would have (1) a preheating section at 70 °C, 5 min; (2) a pasteurization section at 90 °C, 30 min; (3) a cooling section 70 °C, 12 min; (4) a cooling section at 50 °C, 7 min; and (5) a cooling section at 20 °C, 7 min. The conveyor belt would move the jars at 0.003 m/s. Each zone would be thermostatically controlled and include heat recovery systems.

For packs that benefit from agitation, rotary atmospheric cooker-coolers may be used. Using the system with various heating and cooling zones, it is possible to employ gentle thermal treatment of glass bottles and jars and other packaging systems that may be damaged with thermal shock.

Plazl et al. (2006) have modeled the 3-D temperature distributions in glass jars of a tomato product being sterilized in a five-stage pasteurizer using a finite difference technique.

Horn et al. (1997) have modeled an industrial tunnel pasteurizer for bottled beer (0.33 l Vichy botttle DIN 6075). Temperature measurements were made inside the bottle in two positions: one in the bottom zone and the other in the body of the fluid. The model showed good agreement with the experimentally determined results.

Guerrei (1993) developed a simulation model involving heat transfer and fluid dynamics for an eight-stage continuous pasteurizer; the first four sections had hot water temperatures of 25, 36, 47, and 67 °C, respectively, followed by four cooling sections. A comparison was made with a commercial plant involving 20 and 100 cl bottles, filled with water; the improved simulation gave PUs which agreed with the achieved values. The model also examined the effect of altering the shape and dimensions of the bottles.

17.5 Heat Transfer Media

17.5.1 Introduction

Condensing saturated steam has the important property of a very high surface heat-transfer coefficient and thus a negligible resistance to heating the surface of the can. The surface of the can is therefore immediately at the temperature of the condensing steam. Given the correct venting conditions, already outlined for batch retorts in Sect. 8.1.2, then there is no problem with saturated steam. Vigorously boiling water has a similar heat-transfer coefficient to condensing steam. With the requirements for other types of packaging material, steam–air mixtures and pressurized water systems are now commonly in use. These and other heat transfer media do not have the properties of condensing steam and require extra controls to safeguard the process. The heat-transfer coefficients are much lower (see Table 17.2); consequently, there is an appreciable resistance to heat transfer at the surface of the container. This resistance must be taken into account in determining the process requirements (see Chap. 2). In particular, the heat-transfer coefficient is dependent on the velocity of the fluid flow over the surface; consequently, this factor must be controlled by adequate pumping and consistent can orientation and layout in the retorting system. The same applies to cooling water and air, which have low heat-transfer coefficients.

The literature on external heat-transfer coefficients has been reviewed by Holdsworth (1976) in relation to the processing of packages in steam–air mixtures, hot water, and fluidized beds.

The relative energy usage for various different types of retorts and cookers is given in Table 17.3 (Holdsworth 1992).

Table 17.2 Some heat-transfer coefficients for heating and cooling media

Heat-transfer media	Process conditions (°C)	Container/product	External heat-transfer coefficient (Wm^{-2} K^{-1})	Overall heat-transfer coefficient (Wm^{-2} K^{-1})	Reference
(a) Steam—saturated	105.0	Lead cylinder dia. 95 mm	3527	–	Merrill (1948)
	115.5	Lead cylinder dia. 95 mm	4508	–	Merrill (1948)
	121.1	Lead cylinder dia. 95 mm	4995	–	Merrill (1948)
	121.1	No. 2 can/water	–	1417	Merrill (1948)
	–	No. 3 can/water	–	1474	Merrill (1948)
	–	No. 2 can/1 % bentonite	–	1321	Merrill (1948)
	–	No. 3 can/1 % bentonite	–	1321	Merrill (1948)
	74	Quart jars/water	–	147	Pflug and Nicholas (1961)
	82	Quart jars/water	–	153	Pflug and Nicholas (1961)
	90.5	Quart jars/water	–	158	Pflug and Nicholas (1961)
	99	Quart jars/water	–	158	Pflug and Nicholas (1961)
	107	Quart jars/water	–	170	Pflug and Nicholas (1961)
	74	Pint jars/5 % bentonite	–	71	Pflug and Nicholas (1961)
	82	Pint jars/5 % bentonite	–	68	Pflug and Nicholas (1961)
	90.5	Pint jars/5 % bentonite	–	65	Pflug and Nicholas (1961)
	74	Quart jars/5 % bentonite	–	23	Pflug and Nicholas (1961)

(continued)

Table 17.2 (continued)

Heat-transfer media	Process conditions (°C)	Container/product	External heat-transfer coefficient (Wm^{-2} K^{-1})	Overall heat-transfer coefficient (Wm^{-2} K^{-1})	Reference
	82	Quart jars/5 % bentonite	–	23	Pflug and Nicholas (1961)
	90.5	Quart jars/5 % bentonite	–	25	Pflug and Nicholas (1961)
	Up to 115.5	No. $2\frac{1}{2}$, No. 1 tall and lb squat cans/15 % bentonite including effect of headspace	– ■	40–60	Evans and Board (1954)
	115.5	Metallic cylinder	5053	–	Pflug (1964)
		303 × 406 can/water	–	1093	Pflug (1964)
(b) Steam–air mixtures 75 %	74–107	Quart jars/water	–	123–154	Pflug and Nicholas (1961)
	74–90.5	Pint jar/5 % bentonite	–	57–65	Pflug and Nicholas (1961)
	74–90.5	Quart jars/5 % bentonite	–	25.5	Pflug and Nicholas (1961)
	74–90.5	Solid cylinder	318–812	–	Schmidt and Pflug (1965)
36 % 0.45 m/s	74	Solid cylinder	193	–	Pflug (1964)
1.14 m/s	74	Solid cylinder	250	–	Pflug (1964)
1.78 m/s	74	Solid cylinder	255	–	Pflug (1964)
51 % 0.45 m/s	82	Solid cylinder	415	–	Pflug (1964)
1.14 m/s	82	Solid cylinder	425	–	Pflug (1964)
1.78 m/s	82	Solid cylinder	442	—	Pflug (1964)
70.5 % 0.45 m/s	90.5	Solid cylinder	732	–	Pflug (1964)
1.14 m/s	90.5	Solid cylinder	823	–	Pflug (1964)
1.78 m/s	90.5	Solid cylinder	875	–	Pflug (1964)

75 %	115.5	Solid cylinder	851	–	Pflug (1964)
90 %	115.5	Solid cylinder	1306	–	Pflug (1964)
75 %	115.5	303 × 406 can/water	–	823	Pflug (1964)
90 %	115.5	303 × 406 can/water	–	948	Pflug (1964)
90 %	121.1	303 × 406 can/water	–	965	Pflug (1964)
55 % steam	120	13.5 × 13.5 × 2 cm pouch/40 % bentonite	–	410–420	Yamano (1983)
65.9 % steam	120	13.5 × 13.5 × 2 cm pouch/40 % bentonite	–	360–400	Yamano (1983)
10–50 % air	105–125	Retort pouch laminate	–	850–2500	Kisaalita et al. (1985)
Positive flow retort: 0 % air	105–125	Silicone rubber/nylon	–	10,310	Tung and Ramaswamy (1986)
15 % air	105–125	12.1 × 17.8 × 1.9 cm	–	5480	Ramaswamy and Tung (1988)
35 % air	105–125	12.1 × 17.8 × 1.9 cm	–	2360	Tung et al. (1989)
50 % air	105–125	12.1 × 17.8 × 1.9 cm	–	1260	Tung et al. (1989)
Lagarde retort: 0 % air	105–125	12.1 × 17.8 × 1.9 cm	–	6360	Tung et al. (1989)
15 % air	105–125	12.1 × 17.8 × 1.9 cm	–	5220	Tung et al. (1989)
35 % air	105–125	12.1 × 17.8 × 1.9 cm	–	4010	Tung et al. (1989)
50 % air	105–125	12.1 × 17.8 × 1.9 cm	–	–	Tung et al. (1989)
Lagarde Retort: 0–40 % air	122	Retort pouches	–	9,69–2500	Britt (2004)
(c) Water—heating	115.5	303 × 406 can/water	–	908	Pflug (1964)
	121.1	303 × 406 can/water	830	877	Pflug (1964)
	65.5	Lead cylinder	977	–	Merrill (1948)
	87.8	Lead cylinder	1079	–	Merrill (1948)
	104.5	Lead cylinder	1175	–	Merrill (1948)

(continued)

Table 17.2 (continued)

Heat-transfer media	Process conditions (°C)	Container/product	External heat-transfer coefficient ($Wm^{-2} K^{-1}$)	Overall heat-transfer coefficient ($Wm^{-2} K^{-1}$)	Reference
	121.1	Lead cylinder	–	–	Merrill (1948)
	121.1	307 × 409 can/water	–	931	Merrill (1948)
	121.1	404 × 414 can/water	–	1079	Merrill (1948)
	121.1	307 × 409 can/1 % bentonite	–	636–1079	Merrill (1948)
	121.1	404 × 414 can/1 % bentonite	–	880	Merrill (1948)
	82.2	300 × 408 can/water	–	1250–1703	Blaisdell (1963)
	26.7	307 × 409 can/citrus juice	–	1022	Heid and Scott (1937)
	26.7	307 × 409 can/citrus segments	–	176	Heid and Scott (1937)
Flow: in 1/s: 0.63	121.1	30.4 × 45 × 2.5 pouches/10 % bentonite	–	187	Peterson and Adams (1983)
1.07	121.1	30.4 × 45 × 2.5 pouches/10 % bentonite	–	210	Peterson and Adams (1983)
1.82	121.1	30.4 × 45 × 2.5 pouches/10 % bentonite	–	250	Peterson and Adams (1983)
3.09	121.1	30.4 × 45 × 2.5 pouches/10 % bentonite	–	238	Peterson and Adams (1983)
4.44	121.1	30.4 × 45 × 2.5 pouches/10 % bentonite	–	227	Peterson and Adams (1983)
5.67	121.1	30.4 × 45 × 2.5 pouches/10 % bentonite	–	278	Peterson and Adams (1983)
6.93	121.1	30.4 × 45 × 2.5 pouches/10 % bentonite	–	272	Peterson and Adams (1983)
	120	Institutional size pouches/8 % bentonite	–	186 ± 54	Lebowitz and Bhowmik (1990)

	10–123	13.0 × 18.0 × 2.5 cm pouch/10 % bentonite	–	1100–2400	McGinnis (1986)
	120	20.3 × 30.5 × 2.5 cm pouch/8 % bentonite	–	178–186	Lebowitz and Bhowmik (1990)
(d) Water—cooling	10	305 × 404 can/fish	–	136	Okada (1940a, b)
	10	215 × 404 can/fish	–	57	Okada (1940a, b)
	10	305 × 109 can/fish	–	40	Okada (1940a, b)
	10	303 × 209 × 100 can/fish	–	148	Okada (1940a, b)
	10	215 × 201 × 104 can/fish	–	136	Okada (1940a, b)
	10	412 × 112 × 104 can/fish	–	120	Okada (1940a, b)
	10	401 × 112 × 104 can/fish	–	136	Okada (1940a, b)
86 rpm	26.7	307 × 409 can/citrus segments	–	205	Heid and Scott (1937)
0 rpm	26.7	307 × 409 can/citrus juice	–	216–255	Heid and Scott (1937)
70 rpm	26.7	307 × 409 can/citrus juice	–	500	Heid and Scott (1937)
100 rpm	26.7	307 × 409 can/citrus juice		1618	Heid and Scott (1937)
261 rpm	26.7	307 × 409 can/citrus juice	–	823	Heid and Scott (1937)
555 rpm	26.7	307 × 409 can/citrus juice	–	1675	Heid and Scott (1937)
(e) Air heating:	145	211 × 400 can/vegetables in brine	–	83	Gillespy (1958)
	145	300 × 410 can/vegetables in brine	–	57	Gillespy (1958)
	145	211 × 400 can/beans in tomato sauce	–	77	Gillespy (1958)
	145	300 × 410 can/beans in tomato sauce	–	51	Gillespy (1958)
	145	300 × 410 fruit/syrup	–	57	Gillespy (1958)
Flow: 4 m/s	145	211 × 400 can/vegetables in brine	–	196	Gillespy (1962)

(continued)

Table 17.2 (continued)

Heat-transfer media	Process conditions (°C)	Container/product	External heat-transfer coefficient ($Wm^{-2}\ K^{-1}$)	Overall heat-transfer coefficient ($Wm^{-2}\ K^{-1}$)	Reference
9 m/s	145	211 × 400 can/vegetables in brine	–	116	Gillespy (1962)
15 m/s	145	211 × 400 can/vegetables in brine	–	159	Gillespy (1962)
Flow: 4 m/s	145	307 × 408 can/vegetables in brine	–	37	Gillespy (1962)
9 m/s	145	307 × 408 can/vegetables in brine	–	54	Gillespy (1962)
15 m/s	145	307 × 408 can/vegetables in brine	–	74	Gillespy (1962)
(f) Air cooling:	10	305 × 404 can/fish	–	10.2	Okada (1940a, b)
	10	215 × 404 can/fish	–	7.9	Okada (1940a, b)
	10	305 × 109 can/fish	–	7.9	Okada (1940a, b)
	10	303 × 207 × 100 can/fish	–	10.2	Okada (1940a, b)
	10	215 × 201 × 104 can/fish	–	10.2	Okada (1940a, b)
	10	412 × 115 × 104 can/fish	–	10.2	Okada (1940a, b)
	10	401 × 112 × 104 can/fish	–	10.2	Okada (1940a, b)
(g) Flame/radiation heating:					
Gas flame	Approx. 1600	211 × 400 can/water	–	1000	Casimir (1975)
Can surface rotation 10–100	Approx. 170	303 × 406 can/silicon fluid	44–47	380–1264	Peralta Rodriguez and Merson (1983)

Table 17.3 Relative energy usage for various sterilizers (Holdsworth 1992)

Retort system	Casimir (1971)	Savage (1984)	Jowitt and Thorne (1971)	Ferrua and Col (1975)	Holdsworth (1989)
Batch retort	100	100	100	100	100
Crateless	–	50	–	–	–
Hydrostatic cooker	21.3	25	56	–	56–96
Fluidized bed	–	–	38	–	–
Microwave sterilizer	1230	–	–	–	–
Continuous rotary cooker	–	–	–	46	45
Continuous atmospheric	–	–	–	64	–
Flame sterilizer (batch)	266	–	–	–	–
Flame sterilizer (continuous)	90	–	–	88	–
Hydrolock cooker	–	–	–	–	54

Table 17.4 Properties of dry saturated steam

Processing temperature		Absolute pressure (bar)	Latent heat of condensation (kJ kg^{-1})	Specific heat (kJ kg^{-1})	Total heat (kJ kg^{-1})
(°C)	(°F)				
115.5	(240)	1.72	2216	483	2699
121.1	(250)	2.06	2196	510	2706
126.7	(260)	2.43	2188	532	2720
132.2	(270)	2.90	2166	556	2722
137.8	(280)	3.50	2142	582	2724

17.5.2 Saturated Steam

The properties of dry saturated steam are given in Table 17.4 for a range of temperatures including typical thermal sterilization values. The figures are useful for determining the amount of heat required, including steam supply, for processing operations.

It is important to note that any throttling or incorrectly working valves should be avoided, as they might induce superheating. Superheated steam does not have the latent heat of saturated steam; therefore, superheated steam heats less effectively until the superheat is lost.

In using saturated steam the principle outlined in Sect. 17.2 for venting and bleeding the retort must be observed.

Altitude affects the temperature and pressure of saturated steam, and this needs to be kept in mind when canneries are located at high altitudes. The volumes of steam that can flow through orifices of differing sizes are given in Lopez (1987);

Table 17.5 Steam requirements for various retorts (Lopez 1987)

Retort type	Steam inlet size (mm)	Maximum demand (kg h^{-1})	Operating demand (kg h^{-1})	Average steam used per case (kg)
Batch	25.4	1134	45–68	2.35
	31.75	1587	45–68	2.35
	38.1	2041	45–68	2.35
	50.8	2721	45–68	2.35
Continuous pressure cooker	50.8	2721	453–680	1.36–1.60

these are of importance to the steam supply designer. The typical steam demands for some retorts are shown in Table 17.5. With batch retorts, the main steam demand is during the venting, and this falls off progressively after about 10 min to a relatively constant value for the rest of the process. For a vegetable canning operation an overall steam consumption of about 0.8 kg per kg of product is required; for a longer process, such as meat canning, the figure rises to about 1 kg per kg of product (Holdsworth et al. 1988; Holdsworth 1992). Genta et al. (2001) reported that for canning 20,000 t of vegetables, the steam consumption was 7 t/h.

Several models have been proposed for the estimation of energy in retort operations (see Bhowmik and Hayakawa 1983, 1988; Bhowmik et al. 1985). An interesting optimization study by Guariguata et al. (1984) showed that for a series of processes at different temperatures, corresponding to $F_0 = 2.52$ min, the amount of energy consumed for pea purée in 307 × 409 cans was a minimum of 34.5 kg for a processing temperature of 121.1 °C and processing time 66 min. Bhowmik and Hayakawa (1983) showed that for conduction-heating packs the energy required for sterilization increased with the size of the can, but for convection-heating packs the energy was independent of the can size. In general, steam consumption depends on the method of process operation and the energy-saving measures which are used.

17.5.3 Steam–Air Mixtures

Of the various methods of heat-transfer media, less is known about the properties of steam–air mixtures than about any of the others. Although experimental work was carried out as early as the 1930s, nonuniform heat penetration results led to a limited commercial acceptance of the system. In particular, the concept of air in steam, especially with regard to the stringent venting required for batch retorts, was not recommended. However with more extensive investigations and careful retort design, successful sterilizing systems are available (see Table 17.1) which use carefully controlled steam–air mixtures. Table 17.6 gives some equivalent temperatures for different proportions of air mixed with steam. For more extensive information see Wasmund (1976). The commercial systems use fans to mix the steam and air, and baffles running the length of the retort to direct the mixture

Table 17.6 Variation of temperature of steam–air mixtures with pressure (Holdsworth 1976)

	Temperature (°C) steam pressure:			
% air by volume	1 bar	1.07 bar	1.38 bar	2.06 bar
0	100.0	115.0	126.1	134.4
5	98.3	113.9	124.4	132.8
10	97.2	112.2	122.8	131.1
20	93.9	108.3	118.9	127.2
30	90.6	104.4	115.0	122.8
40	86.1	100.0	110.0	117.8
50	81.7	95.0	105.0	112.2
60	76.1	89.4	98.3	105.6
70	69.4	81.7	90.6	97.2
80	60.6	72.2	80.6	86.7
90	46.1	56.7	63.9	70.0

through the baskets holding the cans or packages. The main factors that must be considered to obtain uniform heating are the flow rate, the ratio of steam to air, the direction in which the mixture flows across the surface, and the nature of the circulation system. It is necessary to determine suitable values for these and to control them in an appropriate manner. Failure to do this could lead to understerilization or uneven product quality.

Parcell (1930) was one of the first to publish details of steam–air heating of glass containers, where the overpressure was required to retain the metal caps on the glass jars. It was reported that steam–air mixtures heated more slowly and less uniformly than saturated steam at the same temperature. This was directly attributed to a stagnant film of air that was displaced during condensation and formed near the surface of the container. It was found that initially during the coming-up period the temperature distribution within the retort baskets was very wide; however, this disappeared during the heating period. Advantages were also gained by mixing the steam and air prior to entry into the retort.

With the development of sterilizable plastic pouches in the 1960s many workers (see Table 17.2b) investigated the behavior of steam–air mixtures. Extensive studies by Pflug and Nicholas (1961), Pflug and Blaisdell (1961), and Schmidt and Pflug (1965) showed that the f_h values decreased with increasing velocity and temperature of the mixture. It was also shown that the effect of steam–air mixtures was far greater with convection than with conduction-heating packs.

From Table 8.6 it can be seen that for a given pressure the temperature decreases with increasing quantities of air in the steam. Similarly, the heat-transfer coefficient decreases. The standard method of determining the external heat-transfer coefficient for condensing steam–air mixtures has been to use aluminum blocks or cylinders. These have the advantage that, because aluminum is a rapid heat conductor, the main resistance to heat transfer is the external coefficient, and this can be found without recourse to the internal heat-transfer coefficient. Ramaswamy and Tung (1983) derived an empirical equation, based on the formal heat transfer equations (see Chap. 2), for determining heat-transfer coefficients, h, in the temperature range of 105–125 °C for various percentages of steam, s, in steam–air mixtures:

$$h = 135e^{0.0483s}. \tag{17.1}$$

Tung et al. (1984) studied the effect of flow rate of steam–air mixtures on the heat-transfer coefficient for rectangular metal blocks, using two types of retort—a vertical positive flow retort and a Lagarde horizontal forced-circulation retort. In general, the values of h increased with increasing flow rate, due to increasing turbulence. The effect of brick orientation also had an effect on the surface heat-transfer coefficient. The mechanism of heat transfer from a steam–air mixture to a retort pouch laminate has been studied in detail by Kisaalita et al. (1985).

Tung et al. (1990) have outlined the historical development of the processing of retort pouches and the use of retorts made by Lagarde and Truxon, which have a forced convection heating system and facilities for rotary processing.

17.5.4 Hot Water

The alternative method of processing pouches or plastic containers is to use hot water, which has an overpressure of air. In many retorts (see Table 17.2c) the water is agitated to improve heat transfer, either by recirculation or by bubbling air through the water. The velocity of the water and the way it impacts the containers both affect the heat transfer. As with steam–air processing, it is necessary to place the pouches or semirigid plastic containers in a strict geometrical arrangement, normally by using a rigid support system. It is essential that all the containers receive the same treatment, and the insert to support the containers should be designed accordingly. Only by paying strict attention to these design features can the required process be adequately implemented; otherwise there is a danger of nonuniform heating and understerilized packs. Water processing is also used for glass containers, where the excess pressure prevents the metal lids from being damaged. Unlike steam, the total heat content is much lower at a given temperature since the latent heat of condensation is not available. However, more recently a very flexible processing system has been developed that uses steam with hot water spray. The FMC Steam Water Spray™ is a horizontal processing vessel with external heat exchangers to control the water temperature. Heating is achieved by a combination of water sprays using nozzles and direct steam injection. Excellent temperature distribution, efficient heat transfer, and good overpressure control are claimed (Vandenberghe 2004).

Some typical values of the heat-transfer coefficients for water processing are given in Table 17.2c.

Peterson and Adams (1983) studied the effect of water velocity of heat penetration into institutional sized pouches, and showed that, using water at 121.1 °C, the required process time decreases from 28.5 min for a water velocity of 38 $\mathrm{l\ min^{-1}}$ to 25.7 min for 400 $\mathrm{l\ min^{-1}}$. This illustrates the need for careful process control to obtain uniform heat penetration. Bhowmik and Tandon (1987) developed a heat transfer correlation,

$$h = kaA^{1/2}\tan A^{1/2}, \tag{17.2}$$

where k is the thermal conductivity, $A = 2.303/\alpha f_h$, α is the thermal diffusivity, f_h is the slope index of the heat penetration curve, and a is the half-thickness of the retort pouch. Lebowitz and Bhowmik (1989) used an elegant computer optimization technique to determine heat-transfer coefficients for retortable pouches heated by circulating hot water. The work emphasized the importance of having and maintaining the correct flow patterns during heat processing.

Batch retorts using pressurized hot water cascading retorts, e.g., Barriquand–Steriflow, are an important class of newer retorting systems. Akterian et al. (1998) have studied the effect of temperature nonuniformity in batch water cascading retorts with four baskets, using a theoretical model and comparing the results with the sterilization of canned pea purée in 300 × 405 cans. The results showed that the effect of temperature nonuniformity was greater on the F-value than on the thiamin retention.

Similar experimental work has been carried out on overpressure rotary retorts. Adams and Hardt-English 1990; Campbell and Ramaswamy 1992a, b; Lanoiseuille et al. 1995; Park et al. 1990; Smout et al. 1997, 1998, 2000a, b, 2001; Smout and May (1997); and Varga et al. 2000a, b have produced an important set of guidelines for the correct operation of overpressure retort systems.

Richardson et al. (1997) have studied the distribution of temperature and lethality in a full water immersion system with four retort baskets using PTFE blocks and cans containing water and 5 % starch solution.

Varga and Oliveira (2000) have determined the heat-transfer coefficients between bulk medium and packed containers using a Barriquand steriflow retort and cascading water. The containers were filled with 10 % bentonite suspension and were arranged in two differing stacking patterns. The calculated heat-transfer coefficients varied from 162 to 203 $\mathrm{W\ m^{-2}\,{}^{\circ}C^{-1}}$ for heating and 75–-142 $\mathrm{W\ m^{-2}\,{}^{\circ}C^{-1}}$ for cooling in the middle of the stack of packs. The values were lower for the top of the packs compared with the bottom.

Ramaswamy et al. (1991) made a study of the temperature distribution in a single-crate water cascade retort to establish the uniformity of the process.

Guidelines for the use of a range of batch retort systems have been produced by Campden BRI (1997b). These include full water immersion and raining spray water types of retort.

17.5.5 Water Cooling

The cooling of cans and packages is important in reducing the temperature to a level so that thermophilic organisms do not germinate and cause spoilage. The process is generally rather slow because of the low heat-transfer coefficients, especially in static water. In continuous cookers, e.g., hydrostatic cookers, it is often necessary to have several cooling legs to achieve adequate cooling within the cooker. While heat transfer in the steam chamber is highly effective, it is necessary to remember that the hot bars also have to cool, and they themselves shield the cans from the water to some extent. Other types of continuous cooker, e.g., reel-and-spiral pressure cookers, have their own cooling shell, and the cans are rapidly cooled. Relatively little work has been done on the engineering aspects of cooling, and few data are available in the literature on heat-transfer coefficients.

17.5.6 Air Heating

For some years there was interest in dry processing methods to conserve water and possibly reduce leaker spoilage problems. Ekelund (1961) described a rotating hot air sterilizer which used air at temperatures of 140–165.5 °C and velocities of 7–10 m s^{-1}. The method was shown to have application to the high-temperature short-time in-pack sterilization of convection-heating products. The rate of heating is controlled almost entirely by the rate of external heat transfer to the can. Ekelund (1961) obtained heat-transfer coefficients of the order of 70 W m^{-2} K^{-1} for the above-quoted velocities. Gillespy (1958, 1962) published extensive details of trials using a prototype cooker, with small sizes of can, which would withstand the internal pressure generated, in the absence of a superimposed pressure. The method does not appear to have been developed for commercial use.

17.5.7 Fluidized Bed

Piggot (1963a, b) described experimental work on the application of fluidized beds to the heating of cans and obtained high heat-transfer rates. For example, for the heating of a 307 × 201 can of salmon at 117 °C, a center temperature of 115 °C was observed after 36-min processing. This shows that fluidized bed heating could be as effective as steam heating. Like hot air processing, the method, being unpressurized, could only be used for small containers. The method was extensively investigated by Jowitt and Thorne (1972), who showed that for conduction-heating packs, processing times were almost the same as for steam heating, but for convection-heating packs processing times were longer under comparative conditions to achieve the same F-value. Using a theoretical heat-transfer model, it was shown that heat-transfer coefficients were in excess of 600 W m^{-2} K^{-1} (Thorne and Jowitt 1972; Jowitt and Mynott 1974). The method has not so far been developed for commercial use.

17.5.8 Flame Sterilization

The commercial success of the flame sterilizer was due to Max Beauvais, in France, who developed the process in the 1950s (Beauvais et al. 1961). This continuous process involved rolling the cans over a series of gas flames and subsequently cooling the cans in water. The main problem was to prevent the can lids from peaking due to the unrestrained pressure inside the cans. This was subsequently overcome by making stronger ends for the containers. The development of the process has been well documented by Richardson (1987), who discussed the problems of temperature measurement in the container during flame sterilization, heat transfer, container requirements, product quality, and economics of using flame sterilizers. Most of the work on heat transfer uses the complex models for radiation heat transfer outlined in Chap. 2 (Peralta Rodriguez and Merson 1982, 1983). Teixeira Neto (1982) discussed the rate of heat transfer to convection-heating liquid packs and determined the effect of headspace, rotational speed, and viscosity. He showed that nearly 90 % of the resistance to heat transfer was due the external heat-transfer coefficient. Cummings and Wright (1984) developed a thermocouple system that had a special rotating adaptor and support, and Paulus and Ojo (1974) have reported on the internal and external temperature distribution during flame processing. The main advantages of this method of high-temperature short-time process were ones of economy and improved product quality (Casimir 1971, 1975; Leonard et al. 1975a, b, 1976, 1977, 1984a, b; Noh et al. 1986).

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Part IV
Mathematical Modeling, Simulation, Optimization, Control and Automation

Chapter 18
Computational Fluid Dynamics in Thermal Food Processing

18.1 Introduction

Computational fluid dynamics (CFD) is a simulation tool used to analyze fluid flow and heat-transfer problems (Scott and Richardson 1997). In food processing, CFD has been applied to simulate drying, mixing, refrigeration, and sterilization conditions (Xia and Sun 2002). Basically, the method involves the solving of Navier-Stokes transportequations (Norton et al. 2013), describing the conservation of mass (Eq. 18.1), momentum (Eq. 18.2), and energy (Eq. 18.3), which are numerically resolved to predict, for example, velocity, temperature, shear, and pressure profiles inside a studied system that can adopt any geometry (Scott and Richardson 1997):

$$\frac{\partial \rho}{\partial t} + \rho \nabla \cdot \vec{v} = 0 \qquad \text{Conservation mass equation} \qquad (18.1)$$

$$\rho \frac{\partial}{\partial t}(\vec{v}) + \rho \vec{v} \cdot \nabla \vec{v} = -\nabla p + \mu \nabla^2 \vec{v} + S_\mathrm{m} \qquad \text{Momentum equation} \qquad (18.2)$$
$$S_\mathrm{m} = -\rho_\mathrm{ref} \beta (T - T_\mathrm{ref}) g$$

$$\frac{\partial T}{\partial t} + \vec{v} \nabla \cdot (T) = \frac{1}{\rho C_\mathrm{p}} \nabla \cdot (k \nabla T) \qquad \text{Energy equation} \qquad (18.3)$$

where $\vec{v}$ is the velocity vector, ρ is the density, a is the acceleration, p is the pressure, μ is the dynamic viscosity, S_m is the Boussinesq approximation, β is the thermal dilatation coefficient, ρ_ref is the density at the boundary wall condition, T_ref is the temperature at the boundary wall condition, g is the gravitational force, k is the thermal conductivity, C_p is the specific heat capacity, and T is the temperature (Augusto and Cristianini 2012; Padmavati and Anadharamakrishnan 2013).

The advantages of this simulation method are related to the recent advances in modern computing. CFD can now be used to accurately solve heat-transfer problems in many types of food processing by reducing the amount of experiments

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(Norton and Sun 2006). On the other hand, accurate measurement of temperatures inside the can undergoing thermal treatment is difficult because probes may disturb the temperature-velocity fields, and the slowest heating zone is not fixed in one location (Kannan and Sandaka 2008). Additionally, it is possible to evaluate different types of packaging geometries with less time and cost compared with laboratory analysis (Xia and Sun 2002). Considering these factors, the application of mathematical simulation tools allows a comprehensive understanding of how heating is conducted inside the can.

18.2 Application of CFD in Food Sterilization

Food sterilization is among the food processes in which CFD has been widely applied to perform studies on solid and liquid canned food (Dhayal et al. 2013; Padmavati and Anadharamakrishnan 2013), related to natural heating convection (Kannan and Sandaka 2008), microbiological and vitamin reduction (Ghani et al. 1999), solid-liquid food mixtures (Ghani and Farid 2006), sterilization time (Farid and Ghani 2004), effect of can position (Varma and Kannan 2005; Augusto et al. 2010), effect of can rotation (Ghani et al. 2003), and type of package (Ghani et al. 2001; Augusto and Cristianini 2012).

Certainly, the physical nature of a food product (size, shape, composition, and viscosity) and the heating mode (hot water or steam) determine the amount of heat that must be delivered during sterilization process (Dhayal et al. 2013). However, the processing temperature and time must be controlled during the thermal processing of food material to avoid loss of nutritional quality. For example, Dhayal et al. (2013) studied the heat transfer of canned milk using CFD simulation. Canned milk is a heat-sensitive food because it has various thermolabile nutrients (e.g., thiamine, alpha-lactoalbumin, and beta-lactoglobulin), and therefore a good estimation of processing time is required (Dhayal et al. 2013). The estimation of this time could be not precise due to temperature gradients within the liquid induced by density differences, which facilitate the natural convection and therefore the movement of the slowest heating zone (cold spot for solid materials) toward the bottom of the can.

CFD can predict the temperature distribution inside the can along with the position of the slowest heating zone at various time stages of thermal processing. The results indicate that the slowest heating zone is found at the bottom of the can during stationary heating, whereas its location shifts to the right-side bottom of the can when turned. Therefore, the can in the horizontal position required less processing time than in the vertical position. According to Anadharamakrishnan (2013), this result can be explained because in the thermal sterilization of canned liquid foods, initially, the food near the wall is at rest due to the application of no-slip boundary conditions. Later, as the steam comes in contact with the outer walls of the can, the liquid close to the wall heats up until it reaches the wall temperature by conduction, but the liquid away from the wall remains at its initial temperature. Because of the gravity and density variations in the can, buoyancy forces are developed. These forces act in opposition to the liquid viscosity forces, and this difference determines the velocity of convective currents during heating. As the heating progresses, the viscosity is decreased, and the heating velocity increases. When the temperature inside the can becomes uniform, the buoyancy forces diminish, producing a significant reduction in heating velocity and lowering of recirculation.

CFD has also been applied to liquid-solid canned food. Padmavati and Anadharamakrishnan (2013) applied CFD modeling to the thermal processing of canned pineapple slices and titbits, where one of the objectives was to study the temperature profiles considering temperature-dependent thermophysical properties and to validate the simulation by CFD prediction with experimental results and slowest heating zone location during the thermal processing of canned pineapple slices and titbits. Comparing the predictions with experimental data reveals a close prediction of temperatures with an error of 0.703 for the sugar solution (20%, w/w) and 0.097 % for the pineapple slices (Fig. 18.1).

With respect to the location of the slowest heating zone, the results obtained by Padmavati and Anadharamakrishnan (2013) indicate that the slowest heating zone location changed due to buoyancy effects that produced a movement of sugar solution within the can. Due to natural convection, the temperature gradients create a density difference, and the hot solution begins to flow upwards. This recirculation phenomena was observed until the fluid was uniformly heated. This result implies that solid pineapple slices were heated by both conduction and natural convection in a conjugate manner, which in turn suggests that if the effect of natural convection is ignored, the heating times can be much longer than needed, thus yielding overprocessed food. For example, if natural convection is considered in the heating process of pineapples, at 2400 s of processing time, the pineapple slices are heated at 10 K higher than when only considering conduction. CFD analysis provides insight into the natural convective process occurring during the sterilization of solid-liquid mixtures of canned food (Kannan and Sandaka 2008). According to the

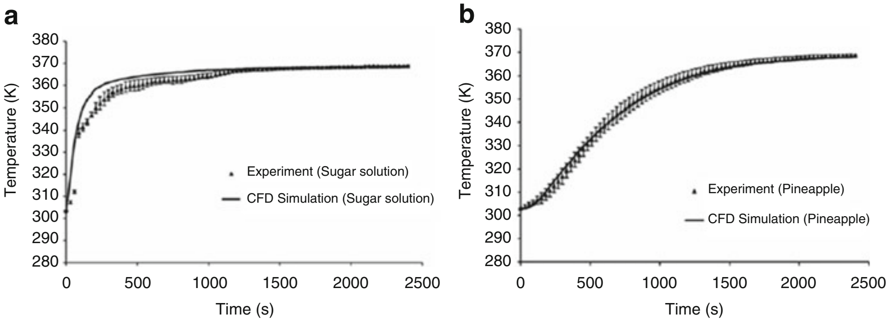


Fig. 18.1 Comparison of CFD simulation results with the experimental measurement of temperature (average of three trials with standard deviation) for (**a**) 20 % (w/w) sugar solution and (**b**) pineapple slices (Padmavati and Anadharamakrishnan 2013)

authors, an appreciable agreement between the simulation predictions and the experimental temperature measurements was obtained. Ghani and Farid (2006) performed a study using a simulated heating process based on CFD to analyze the thermal sterilization of solid-liquid (pineapple slices in pineapple juice) food mixtures by solving the governing equation for continuity, momentum, and energy conservation, using the finite volume method of solution. Basically, they propose solving the governing equation and boundary condition for the pineapple juice (free liquid) and pineapple slices (solid), considering the latter as either an impermeable or porous solid. They also studied the effect of solid in contact with the bottom of the can or slightly separated from the bottom. This difference can also be observed in the thermal profiles presented in Figs. 18.2 and 18.3. In the first, the pineapple slice is separated from the can bottom, and it is observed that at later stages of

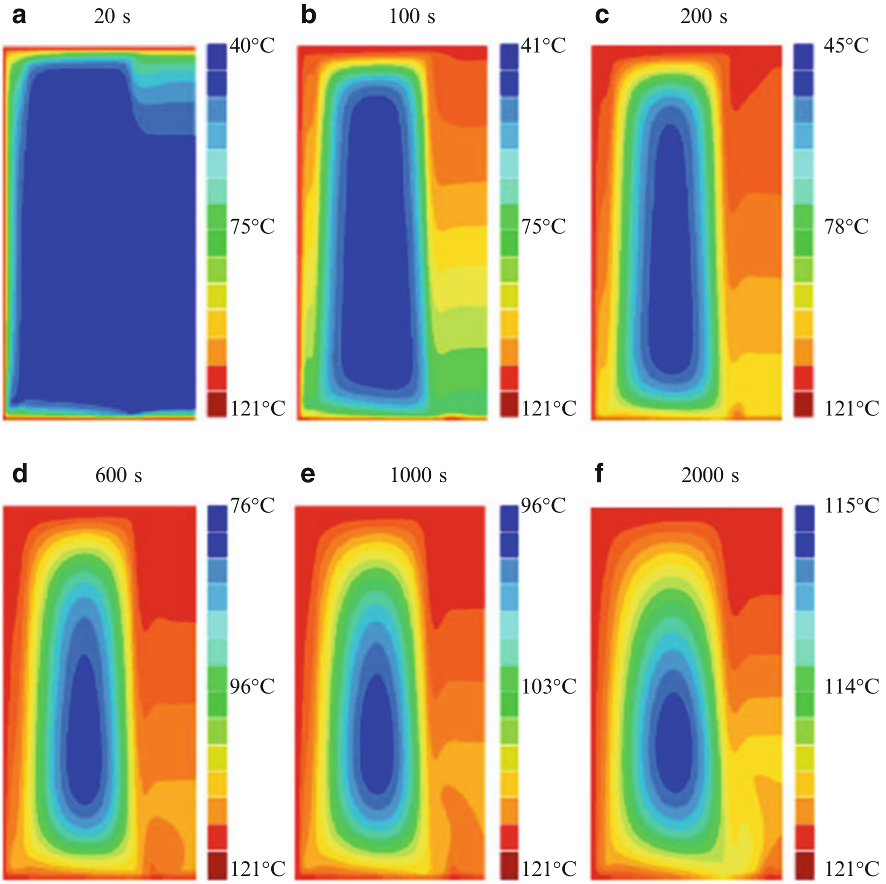


Fig. 18.2 Temperature contours of solid–liquid food mixture (pineapple with its liquid) in a cylindrical can heated by condensing steam with liquid flow beneath the bottom pineapple slices, for the periods of (**a**) 20 s; (**b**) 100 s; (**c**) 200 s; (**d**) 600 s; (**e**) 1000 s; and (**f**) 2000 s. The right-hand side of each figure is the center line (Ghani and Farid 2006)

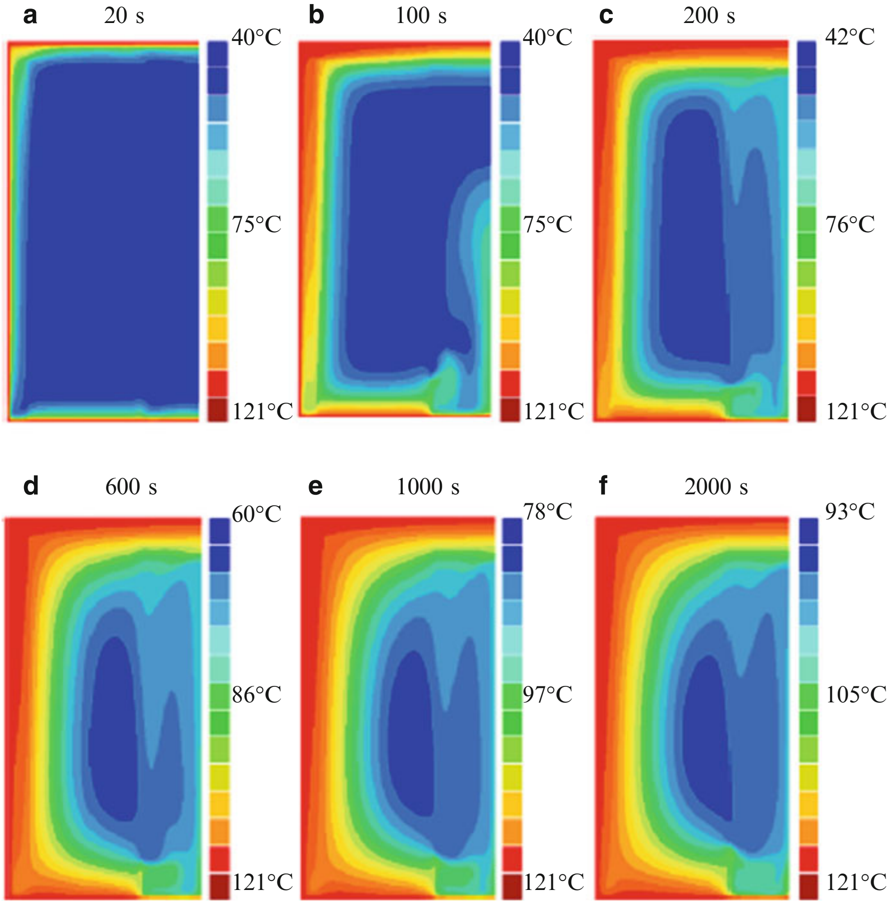


Fig. 18.3 Temperature contours of solid-liquid food mixture (pineapple with its liquid) in a cylindrical can heated by condensing steam with pineapple slices seated at the bottom of the can, for the periods of (**a**) 20 s; (**b**) 100 s; (**c**) 200 s; (**d**) 600 s; (**e**) 1000 s; and (**f**) 2000 s. The right-hand side of each figure is the center line (Ghani and Farid 2006)

heating, the flow of the hot liquid food from the side walls of the can will move the slowest heating zone from the geometric center toward the bottom of the can, as shown in Fig. 18.2d, e, and g. Therefore, the slowest heating zone is moving during heating but remains close to the bottom (30–35 % of the can height from the bottom). In the case of a pineapple slice settling to the bottom, the isotherm simulated by CFD (Fig. 18.3) clearly shows lower heating compared with Fig. 18.1 because of reduced fluid recirculation into the can, which causes a loss of heating transfer by natural convection due to the presence of a solid bottom. Furthermore, it is possible to observe that the slowest heating zone moves toward the geometric center of the can. According to the simulation, the temperatures attained at the slowest heating zone were different according to the location of the pineapple slices, varying from 105 °C for floating slices to 93 °C for bottom-sitting slices. They conclude through simulations that buoyancy forces favor the heating of solids by natural convection and that the configuration of the solid inside the can significantly influences the heating rate, being faster in case of solids separated from the bottom due to the effect of natural convection, which increases the heating rate.

Additionally, the effect of can rotation during the sterilization of liquid food has been studied by CFD (Ghani et al. 2003). In this case, the CFD simulation is useful because the experimental incorporation of thermocouples to record the data during the heating process at different locations in the can could affect the flow patterns, and therefore the temperature distribution inside the can could include some errors. The work performed by Ghani et al. (2003) proposed to evaluate the effect of natural convection coupled with forced convection provided by rotation at 10 rpm on the temperature distribution and slowest heating zone location in a can filled with viscous liquid food heated to 121 °C using CFD simulation. The results showed, through isotherms obtained for the plane *R*–*Z* (Fig. 18.4), that during the first seconds, the heating behavior is similar to the results obtained by pure conduction heating; however as heating continues, the isotherms begin to be influenced by convection.

However, the slowest heating zone remains in the lower half of the can, with a distorted elliptical shape. These results are certainly different from the stationary can heating process, mainly because the slowest heating zone keeps moving during heating and at the end tends to remain in a region that is close to 20–25 % of the can height and covers all the length of the can base, as was shown by Ghani et al (2002) in Fig. 18.5.

In the case of a rotating can, the temperature profiles for plane *R*–*θ* must be analyzed. Figure 18.6 clearly shows the combined effect of natural convection produced by buoyancy forces and forced convection produced by can rotation. The first observation of note is that the slowest heating zone is split into two regions with a temperature of 109 °C.

According to Ghani et al. 2002, in the case of a stationary can, the slowest heating zone remains in a single location at the bottom of the can, reaching a maximal temperature of 105 °C. Second, the size of the slowest heating zone is clearly smaller in the case of rotation because of the mixing effect caused by rotation. Finally, the variation of temperature in the slowest heating zone allows the conclusion that mild rotation at 10 rpm produces an improvement in the heating process with an increase of 4 °C compared to the stationary process.

In the same way, Augusto and Cristianini (2012) evaluated the liquid thermal process in a brick-shaped package through CFD simulation. As seen before, many simulations have been conducted on the typical cylindrical can. If the liquid flow patterns inside the packaging are considered as a function of geometry, however, any change could produce alterations in the heating behavior (Augusto and Cristianini 2012). Considering that many liquid foods with different viscosities are packaged in brick-shaped packaging, it is relevant to evaluate how thermal processing is performed in this type of package, in addition to the influence of

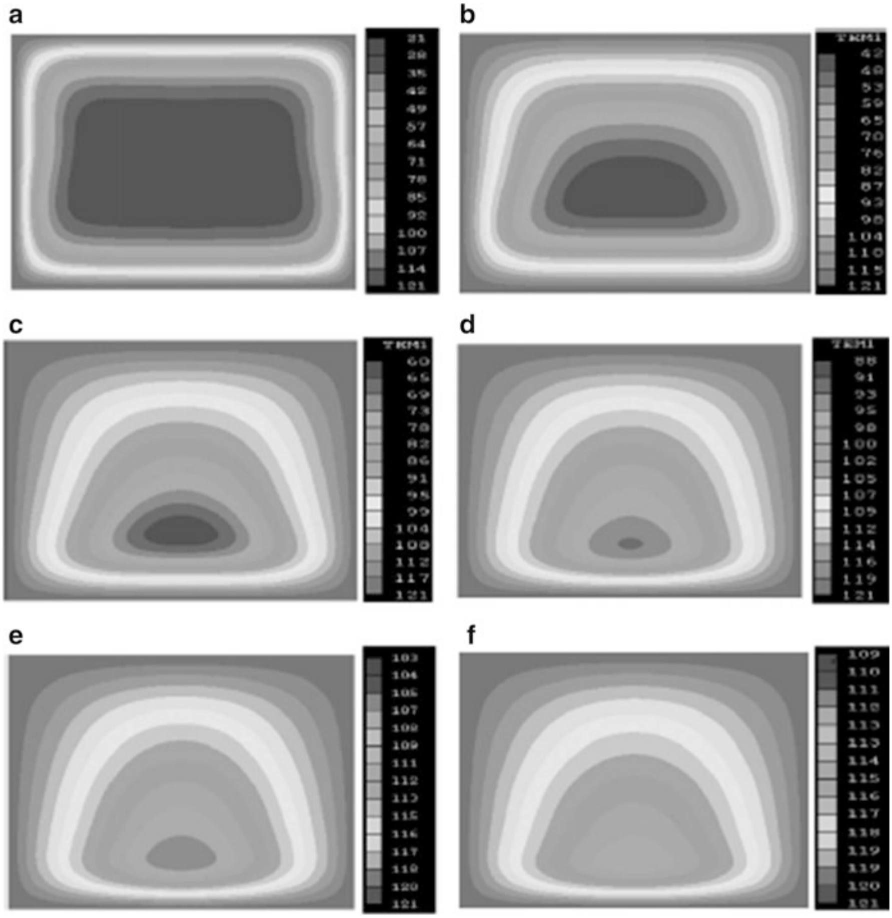


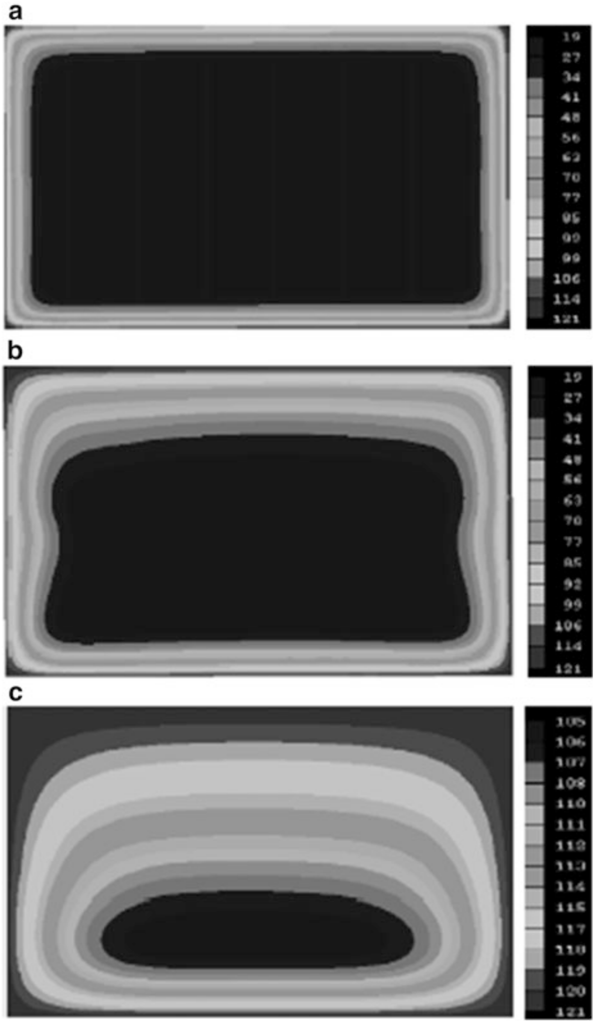
Fig. 18.4 *R–Z* plane temperature profiles of carrot–orange soup in a 3-D cylindrical can rotated axially at 10 rpm and heated by condensing steam after periods of (**a**) 180 s; (**b**) 600 s; (**c**) 1000 s; (**d**) 1800 s; (**e**) 2400 s; and (**f**) 3000 s (Ghani et al. 2003)

viscosity and orientation during the heating process. The results of CFD simulation show the importance of the rheological characteristics of liquid food material during the heating process, as shown in Fig. 18.8, where for the same process, water sterilization was 13 % higher than for any more viscous liquid and 7.5 times higher if only conduction is considered (solid food).

However, the orientation of brick-shaped packaging did not affect the sterilization values. Similar results with regard to orientation during the heating process were obtained in the case of the pasteurization of beer performed in can packaging (Augusto et al. 2010).

Some studies have been performed in liquid-solid mixture systems. For example, Dimou et al. (2013) studied the thermal processing of table olives in brine in a

Fig. 18.5 Temperature profiles of carrot–orange soup in a 3-D can lying horizontally and heated by condensing steam after periods of (**a**) 60 s; (**b**) 180 s; and (**c**) 3000 s (Ghani et al. 2003)



stationary metal can using CFD, with the aim of determining the fluid flow field, temperature evolution, distribution of F-values, and location of the critical point within the product along with the effect of the size/shape of the olives on the process. The results obtained show that CFD satisfactorily predicted the experimentally measured temperature (Fig. 18.9).

Additionally, the temperature contours for large Kalamata olives were obtained, showing that the olives located in the second row from the bottom and at the center of the can are the slowest heating olives within the container, and therefore the interior of these olives represents the slowest heating zone of the can. Moreover, due to brine motion, these olives were the fastest cooling during the cooling stage of

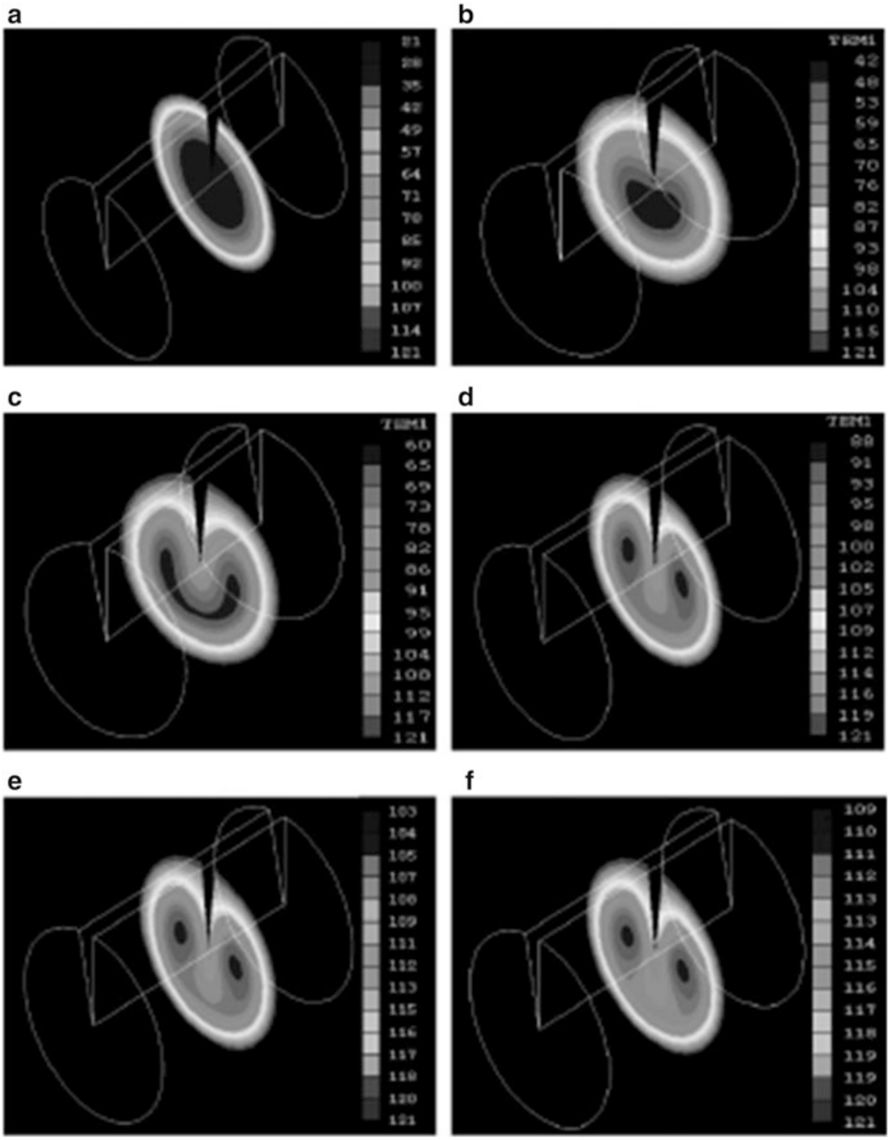


Fig. 18.6 *R*–*θ* plane temperature profiles of carrot–orange soup in a 3-D cylindrical can rotated axially at 10 rpm and heated by condensing steam after periods of (**a**) 180 s; (**b**) 600 s; (**c**) 1000 s; (**d**) 1800 s; (**e**) 2400 s; and (**f**) 3000 s (Ghani et al. 2003)

thermal process (Fig. 18.10). The same behavior was obtained for other varieties of olives with smaller sizes.

In the same way, Cordoli et al. (2015) conducted an experimental validation of CDF simulation for the thermal processing of canned fruit salad (five types of fruit)

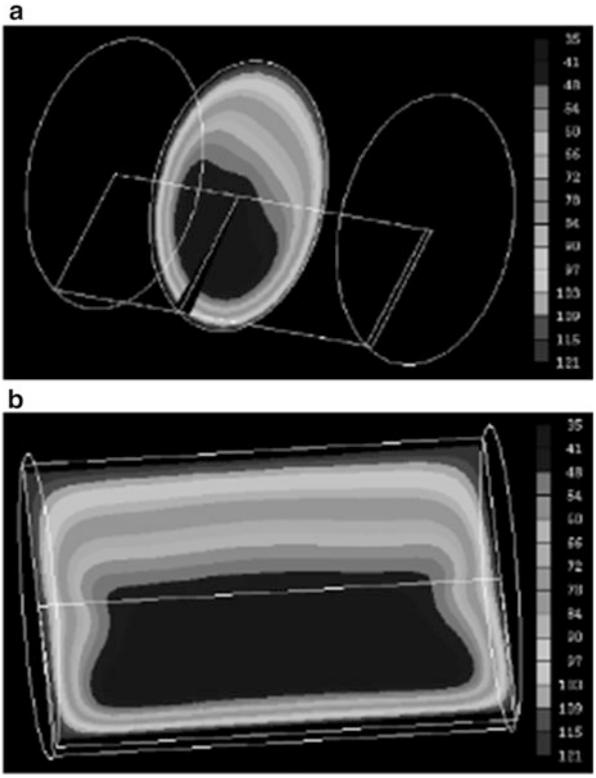


Fig. 18.7 Temperature profiles of carrot–orange soup in a 3-D cylindrical can lying horizontally and heated by condensing steam after 600 s in two different planes: in the direction of (**a**) the radial-angular plane and (**b**) the radial-vertical plane (Ghani et al. 2002)

in gallon jars, which allowed them to determine the location of the slowest heating zone (positioned at 19–20 % of the can height) and also that the F-value was influenced by the distance from the jar bottom as a function of the natural convection motion of the syrup. The validation was performed by the comparison of CFD data with experimental data, expressed as RMSE, which showed a good fitting, and therefore CFD can be considered for simulation and prediction for the design and optimization of the thermal processing of canned fruit salad.

18.3 Summary

Computational fluid dynamics (CFD) is an important tool that has been applied in food processing with the aim of improving the comprehensive understanding of the behavior of food material during heating processing through solving Navier-Stokes equations. This CFD simulation has been applied especially in liquid foods and solid-liquid food mixtures, where natural convection plays an important role during heating transfer, which can define the real processing time that allows good nutritional and sensorial quality by avoiding overprocessing. Additionally, CFD

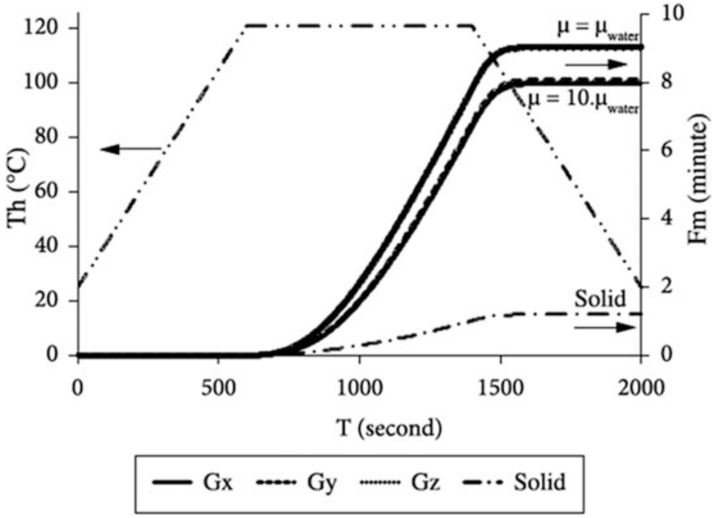


Fig. 18.8 Retort temperature (T_h) and mass average sterilization value (F_m) for water, a fluid with viscosity ten times higher than water, and a hypothetical solid with thermal properties similar to water during thermal sterilization: *Gx*, *Gy*, and *Gz* are the three orientations for the brick-shaped package (Augusto and Cristianini 2012)

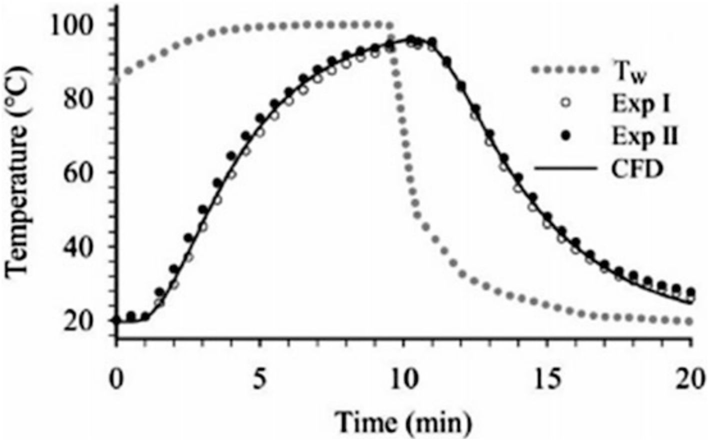


Fig. 18.9 Comparisons between experimental (Exp I and Exp II) and simulated (CFD) temperature data for large Kalamata olives (6 × 8 arrangement) in 4 % (w/v) brine in a stationary metal can during heating and cooling with water measured at the center of an olive located in the middle of the second row from the bottom. T_w represents the internal can wall temperature (Dimou et al. 2013)

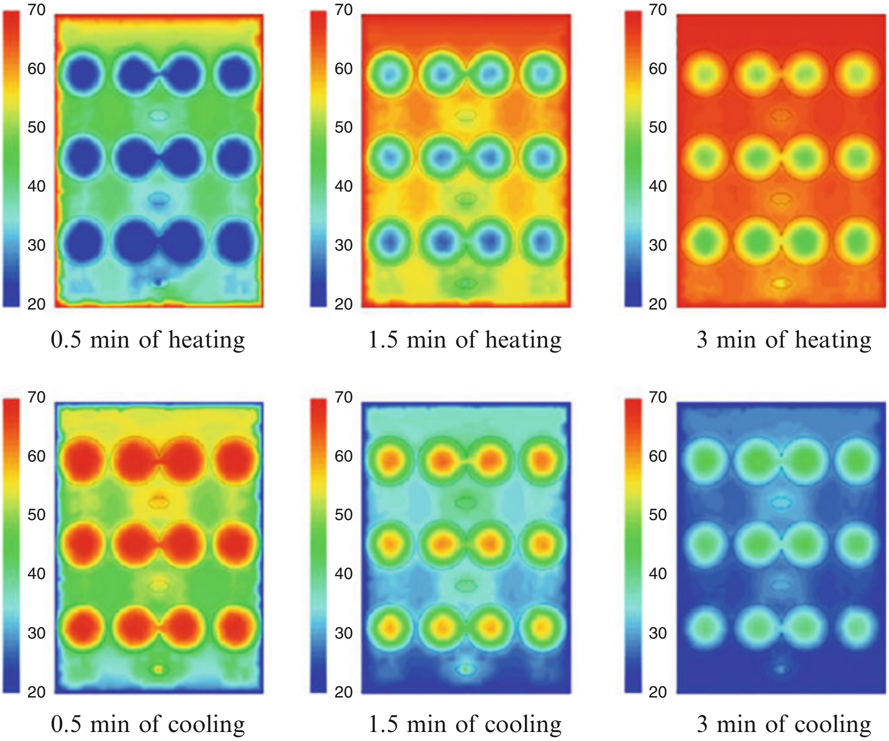


Fig. 18.10 Typical temperature contours for large Kalamata olives (6 × 8 arrangement) in 4 % brine in a stationary cylindrical metal can, initially held at 20 °C with different heating times at 70 °C and cooling times at 20 °C (Dimou et al. 2013)

has made it possible to evaluate the performance of different packaging geometries during the heating process at low operational cost. Therefore, we have obtained a new and powerful tool that can greatly benefit the food industry during the development of new products and processes.

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Chapter 19
Optimization of Thermal Food Processing

19.1 Introduction

The process that is delivered to a canned or packaged food not only inactivates the spoilage microorganisms, but also cooks the product to an acceptable texture. Canned foods, being convenience foods, are thermally processed to such a degree that they only require reheating prior to consumption. The amount of cooking that a product receives depends on its consistency, the thermal processing conditions, and the container or package size. For convection-heating products the internal mixing permits a fairly uniform cook for the whole product; however, for conduction-heating products the heating and, consequently, the degree of cooking vary from the outside to the inside of the food. The product nearest the container wall receives the maximum heat treatment and is consequently the most cooked portion of the food. In general this results in overcooking the outer layers, with a consequent loss of overall quality, especially for products in large-diameter cans. These products are generally perceived as being of lower nutritional value than their fresh or chilled counterparts, which has led to a vast amount of both theoretical and practical work in an attempt to reduce processing conditions (Holdsworth 1985, 2004).

The methods which have been employed to reduce thermal processes have included altering the geometry of the container, making it thinner, for example, by using plastic trays and pouches; storing the product under chilled conditions; acidification and pasteurization; and using different heating methods, including microwave and ohmic heating.

Some of the earliest work on this subject was empirically based, in particular that of Brown (1950) on canned vegetables and Tischer et al. (1953) on canned meat. In the former work, four different processing times and five different temperatures (110–132 °C) were used, and it was shown that the long processes at the lower temperatures had an adverse effect on the color and flavor of canned carrots compared with the higher-temperature, shorter-time processes. The texture of carrots, but not of peas, was influenced markedly by the duration of the process.

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The process conditions had little effect on the levels of carotene or ascorbic acid; however, vitamin B_1 was better preserved by the "high short" processes. The latter work was devoted to a study of the heat processing of beef in 300 × 308 cans in which changes in tenderness and drained juice levels were measured for temperatures in the range of 107–124 °C. The results were illustrated in three-dimensional graphs, and empirical correlations were developed relating the objective quality measurements to temperature. There is a wealth of work of this type in the literature, but here we are more concerned with optimizing the effects of quality changes and microbial inactivation using more basic definitions. The process engineer should also be aware, in general terms, of the effects of heating on foodstuffs; however, this subject is beyond the scope of this text, and the reader should consult specialized texts for further information, e.g., Hoyem and Kvale (1977), Holdsworth (1979), and food commodity texts.

19.2 Cooking Versus Microbial Inactivation

In the past it was common to use a two-stage process for some ready-meals such as beans in tomato sauce: The product was cooked in the container for a long time at a relatively low temperature and then sterilized at a higher temperature. Such two-stage processes have been superseded by single-stage processes, but they showed that there was an appreciation of the different needs for cooking and sterilization by the production company. Commercial processes are a balance between the requirements for microbiological inactivation and thermal cooking, and the art of canning has been to determine optimum processes for this purpose. In fact, a range of processes can be obtained which have the same F-value but different times and temperatures; such processes are described as *equivalent*. Similarly, there are equivalent cooking processes for different types of processes and conditions (Gillespy 1956; Atherton and Thorpe 1980). For example, Table 19.1 shows some

Table 19.1 Minimum equivalent processing times in minutes for sterilization and cooking of beans in tomato sauce in a rotary cooker

	Process temperature (°C)		
Can size	115.5	121.1	126.6
A1			
Sterilization	22	$13\frac{1}{2}$	10
Cooking	38	26	19
A2			
Sterilization	25	$16\frac{1}{2}$	$12\frac{1}{2}$
Cooking	40	28	21
A$2\frac{1}{2}$			
Sterilization	27	18	$14\frac{1}{2}$
Cooking	41	29	22
A10			
Sterilization	35	26	21
Cooking	46	34	27

processes for processing beans in tomato sauce, equivalent to a standard process of 40 min at 115.5 °C in an A2 can. The advantage of using the higher-temperature, shorter-time processes has been to increase the throughput of the canning plant. The main difference between cooking and other thermally degenerate processes, e.g., nutrient destruction, is that the kinetic parameters, z_c- and D_c-values, are very different. The z-values are generally much higher for cooking and nutrient degradation, 25–45 °C, than those for microbial inactivation, 7–12 °C. For detailed values, see Appendix A for microbial inactivation and Appendix B for thermally vulnerable components. In very general terms, for every 10 °C rise in temperature the cooking rate doubles, but the sterilization rate increases tenfold.

In Chap. 4 the criterion for cooking was discussed (Mansfield 1962, 1974; Ohlsson 1988). The basic equation for the cook value $C_{T_{\text{ref}}}^{Z}$ is given by

$$C = \int_0^t 10^{(T-T_{\text{ref}})/Zc} \mathrm{d}t. \tag{19.1}$$

The cook value parameters z_c and T_{ref} differ according to the particular thermolabile component considered. For cooking, the z_c-value chosen is usually 33.1 °C and the reference temperature 100 °C, and this is designated C_0, i.e., $C_{100}^{33.1}$ although $C_{121.1}^{33.1}$ is often used for comparison with F_0 values. It is important to define the constants z_c and T_{ref} clearly so that there is no misunderstanding.

Table 19.2 shows how F- and C-values vary for ideal circumstances, i.e., instant achievement of temperatures and a time of 1 min. For every 10° rise in temperature, the F-values vary by a factor of 10, and the C-values by a factor of approximately 2. Using the lower reference temperature of 100 °C, the C-values are higher than using the higher temperatures. In Table 19.3 the sterilizing value is kept constant and the variation of the C-values with processing temperature is observed. As the

Table 19.2 Variation of F- and C-values with different processing temperatures and a time of 1 min (Holdsworth 1992)

Temperature (°C)	$F_{121.1}^{10}$(min)	$C_{100}^{33.1}$(min)	$C_{121.1}^{33.1}$(min)
100	0.00776	1.0	0.23
110	0.0776	2.15	0.46
121.1	1.00	5.05	1.00
130	7.76	10.0	1.85
140	77.6	21.5	3.71
150	776.0	46.4	7.42

Table 19.3 Variation of C-values with temperature for a fixed F_0-value and a time of 1 min (Holdsworth 1992)

Temperature (°C)	$F_{121.1}^{10}$ (min)	$C_{100}^{33.1}$ (min)	$C_{121.1}^{33.1}$ (min)
100	4.0	515.3	118.0
110	4.0	103.0	23.8
121.1	4.0	17.35	4.0
130	4.0	4.15	0.96
140	4.0	0.80	0.19
150	4.0	0.17	0.04

temperature rises the amount of cooking, as shown by the C-value, decreases. This is the basis for high-temperature, short-time cooking strategies; ideally at the higher temperatures and with the shorter times less thermal damage will be done to the product. This will only apply if there is no heat transfer lag, and consequently does not apply to larger sizes of container filled with conduction-heated foods. It is, however, applicable to the continuous sterilization of thin liquids, e.g., milk (Holdsworth 1992), and to the processing of convection-heating products. There are, however, serious engineering problems in applying processes of 150 °C to canned products. These are the pressure limitations of many conventional retort systems and the problems of the come-up time.

19.3 Process Evaluation

19.3.1 Some Models for Predicting Nutrient and Cooking Effects

For evaluating processes for cooking and other effects, the C-value, known in optimization theory as an *objective function*, determined at the center of the pack, is of less value than the mass-average cook value, C_s. This is because of the uniform distribution of nutrients in the product and the fact that there is a different threshold for contribution to the equivalent of the lethality for heat-vulnerable components. The C_s-value is equivalent to the F_s-value for sterilization, which is the total integrated F-value for the whole volume of the container. It is obtained from the equivalent sterilization definitions,

$$C_S = D_{\mathrm{ref}} \log(c_0/c), \tag{19.2}$$

where D_{ref} is the decimal reduction time for the species being considered, and c and c_0 are the concentrations at times t and 0, respectively.

Silva et al. (1992b) have pointed out a way to use the C_s-value that, like the F_s-value, shows a dependence on the D_{ref}-value. The volume-average quality retention value is given by

$$c/c_0 = \frac{1}{V}\int_0^V 10^{-C_c/D_{\mathrm{ref}}}\,\mathrm{d}V, \tag{19.3}$$

where

$$C_c = \int_0^t 10^{(T-T_{\mathrm{ref}})/Z_c}\,\mathrm{d}t, \tag{19.4}$$

McKenna and Holdsworth (1990) have reviewed the published models for determining F_s and C_s. Other work in this area has been presented by Ohlson (1980a, b, c) and Tucker and Holdsworth (1990, 1991).

All the methods outlined in Chap. 6 may be used to evaluate these integrals. Preussker (1970) has given a simplified equation based on Ball's exponential integral equation (Ball and Olson 1957), in which a simple approximate algorithm for the $-Ei(-x)$ function is used, viz. $-Ei(-x) = \ln X^{-1} - 0.6$, which is as follows:

$$C = (L_0/n)\ [nt - (\ln(T_R\ -\ 10))\ +\ 2.06] \tag{19.5}$$

where $L_c = 10^{(T_R - 100)/33}$, T_R is the retort temperature, t is the processing time, n is $h/(15c\rho d)$, h is the heat-transfer coefficient, c is the specific heat, ρ is the density, and d is the can diameter.

Processes with differing values for T_{ref} and z_c can be interconverted using the following formulae:

$$CT_{\text{ref},1} = 10^{\left(T - T_{\text{ref},1}\right)/z_c} t, \tag{19.6}$$

$$CT_{\text{ref},2} = 10^{\left(T - T_{\text{ref},2}\right)/z_c} t, \tag{19.7}$$

Eliminating t,

$$\log C_{\text{ref},1}\ -\ \log C_{\text{ref},2}\ =\ (T_{\text{ref},2}\ -\ T_{\text{ref},1})/z_c \tag{19.8}$$

or

$$C_{100} = C_{121.1}\ \times\ 10^{(121.1-100)/z_c}.$$

Similarly, for a sterilization process with a given F-value and a cooking process with a given C-value, it can be shown that

$$\log C = (z/z_c)\log F\ +\ (121.1\ -\ 100)/z_c$$

for a process where $t = 1$ m*in*, or

$$\log(C/t) = (z/z_c)\log(F/t)\ +\ (121.1\ -\ 100)/z_c \tag{19.9}$$

for a process of duration t min. These equations apply essentially to instantaneous heating and cooling of the product; they do not take into account the realities of heat transfer under normal canning operations.

19.3.2 Some Typical C*-Values*

The way in which the $C_{121.1}$-value builds up with time is shown in Fig. 19.1, and this can be compared with the buildup of the F-value. Relatively few workers have produced target C-values in the same way as for F-values. Table 7.4 contains some

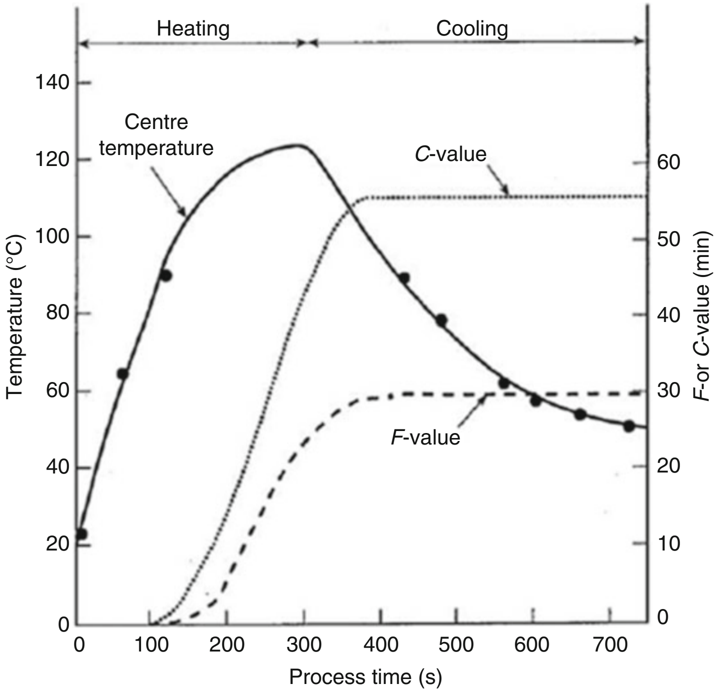


Fig. 19.1 Graph showing the cumulative increase in F- and C-values

typical practical values for processed ready-meals (Tucker and Holdsworth 1991). Other workers have produced C-values, in particular Preussker (1970) for static processes and Eisner (1988) for rotary processes (Table 19.4).

19.4 Optimization of Thermal Processing Conditions

19.4.1 Graphical Approach

The choice of processing conditions may be determined from a plot of log time versus temperature, on which are drawn two straight lines representing constant F- and C-values, as shown in Fig. 19.2. These lines divide the plot into four regions: The line F_1OF_2 marks the boundary between processes that give adequate sterilization and those that do not, while C_1OC_2 marks the boundary between adequate and inadequate cooking. Idealized graphs like this are useful for determining the suitability of various combinations of temperature and time. Table 19.5 lists workers who have used this procedure for process determination for different products. It should be noted that the graphs are based on instantaneous heating followed by instantaneous cooling of the product, in particular to thin films of

Table 19.4 Some C_0-values for commercial sterilization processes (from Tucker and Holdsworth 1991)

Product	Container size	Process temperature (°C)	Process time (min)	F_0 (heat) (min)	F_0 (total) (min)	f_h (min)	Thermal diffusivity ($\times 10^3$ cm^2 s^{-1})	C_0 (centre) (min)	C_0 (Volume-average) (min)
Beans in tomato sauce	A2	121.1	121	7.0	11.6	64.6	1.46	196.5	331.6
Beans in tomato sauce	UT	121.1	94	5.8	8.3	51.5	1.46	155.0	267.2
Carrot purée	A1	121.1	74	5.5	8.0	37.0	1.58	128.5	210.3
Celeriac purée	A1	121.1	72	4.2	6.0	39.0	1.50	117.2	199.8
Chicken supreme sauce	UT	121.1	86	4.5	6.6	49.0	1.54	138.3	242.1
Chili con carne	UT	121.1	91	4.5	6.6	52.2	1.44	144.0	255.3
Corned beef	300 × 200	121.1	39	4.5	6.6	28.5	1.73	80.9	124.5
Mackerel in tomato sauce	UT	121.1	97	7.0	10.9	50.8	1.49	168.0	280.5
Minced beef	UT	121.1	101	6.0	8.6	55.0	1.37	166.9	287.0
Mushroom soup, cream	A1	115.7	93	3.5	5.8	37.0	1.58	132.8	195.1
Pet food	UT	125.8	84	12.0	20	48.0	1.57	180.4	323.6
Stewed steak	UT	121.1	105	9.0	12	52.0	1.45	188.3	308.2
Spaghetti hoops in tomato sauce	U8	121.1	41	7.5	11.6	22.2	2.50	96.2	136.0
Spaghetti in tomato sauce	A2$\frac{1}{2}$	121.1	83	6.0	9.0	49.0	2.50	148.5	245.1
White wine sauce	UT	121.1	81	4.5	6.5	46.0	1.64	131.3	229.3

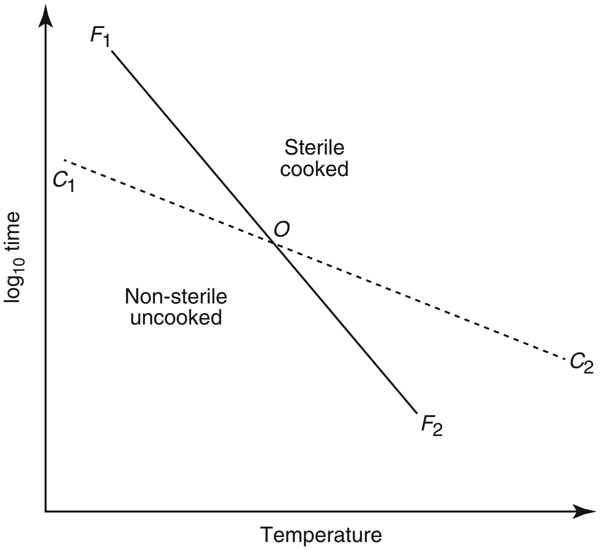


Fig. 19.2 Diagram of idealized $\log_{10}$ time versus temperature for microbial inactivation (F_1OF_2) and cooking (C_1OC_2) of food product, instantaneously heated

product. Under more realistic conditions it is necessary to include the effects of heat transfer and dimensions of the object being processed. When this is done the straight lines in Fig. 19.2 become curved, as shown in Fig. 19.3 (Holdsworth 1985), and the regions have different boundaries.

One of the advantages of this type of representation is that various effects may be plotted on the same graph. In Fig. 19.4, for example, the lines for differing percentages of vitamin retention or discoloration have been plotted and appropriate processes selected. While the technique is suited to thin-liquid products, e.g., milk and fruit juices, it is less useful for the average canned products, which show a degree of conduction and contain substantial quantities of particulate material. The advantages of using high-temperature, short-time processes for thin-liquid products are clearly demonstrated. For thicker materials, it is necessary to consider alternative methods of heating, e.g., microwave and ohmic heating, to overcome the problems of consistency of canned foods in general. At the present time this can only be achieved in continuous ohmic heating processes with aseptic filling, but in the future the use of microwave in-package sterilization will be realized on a fully commercialized scale.

19.4.2 Optimization Models

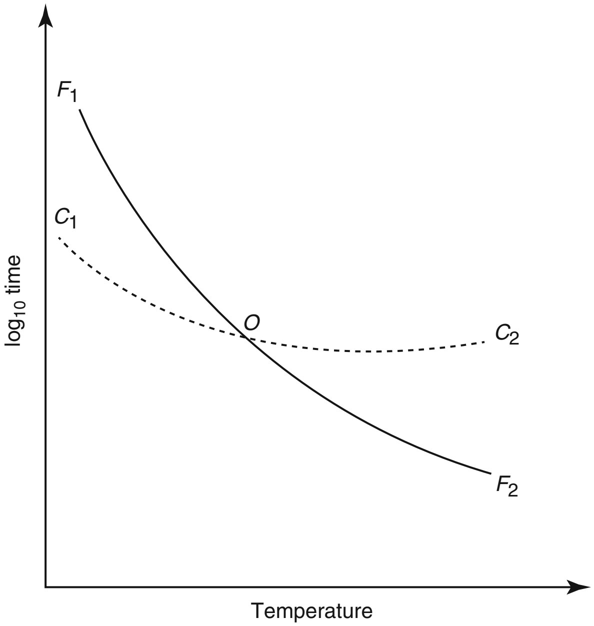
19.4.2.1 Simple Methods

One of the earliest mathematical treatments of the optimization of the process conditions for thiamin destruction versus sterilization, in cylindrical cans of conduction-heating product, was due to Teixeira et al. (1969). A finite-difference method was used for determining the temperature distribution and the

Table 19.5 Graphical optimization of microbial versus heat-vulnerable components (after Holdsworth 1985)

System					
Heat-vulnerable component			Microbial		
Description	Z_c (°C)	C_{100} (min)	z (°C)	$F_{121.1}$ (min)	References
Thiamin destruction in cured meat, 10, 20, and 50 %	–	–	10	0.25	Greenwood et al. (1944), Ball and Olson (1957), Jackson et al. (1945)
Cooking	33	5–30	10	2–30	Mansfield (1962)
Betanin destruction 5–99 %	–	–	10	1.0	Herrmann (1969)
Cooking effect of linear heating	33	0.1–50	10	0.1–50	Preussker (1970)
Enzymes in potatoes	10.3	–	10	2.5	Reichert (1977)
Enzymes	17.5	–	8.9	0.9	Reichert (1977)
Enzymes in green beans	48.9	–	8.9	0.9	Reichert (1977)
Vitamin C	23.2	–	8.9	0.9	Reichert (1977)
Vitamin B1	26.1	–	8.9	0.9	Reichert (1977)
Cooking	25–40	–	8.9	0.9	Reichert (1977)
Sensory	26.5	–	8.9	0.9	Reichert (1977)
Chlorophyll/green beans	87.8	–	8.9	0.9	Reichert (1977)
Cooking	33	10, 36, 52	10.0	1.0	Reichert (1974, 1977)
Cooking peas	29	42, 45, 62	10.0	76.0	Reichert (1974, 1977)
Vitamin B in liver, 5–90 % destruction	26.1	–	10.0	5–10	Bauder and Heiss (1975)
Microbial lipase	3.1	–	10.0	2.7	Svensson (1977)
Peroxidase	35	–	10.0	10.0	Svensson (1977)
Thiamin retention 90–99.5 %	–	–	10.0	5.0	Ohlsson (1980c)
Thiamin destruction, 1, 5, 20, and 50 %	–	–	10.0	6.0	Lund (1977)
Thiamin loss in milk, 3 %	–	–	10.5	2.0	Kessler (1981)
Lysine loss in milk, 1 %	–	–	10.5	2.0	Kessler (1981)
Protease inactivation, 90 %	–	–	10.5	2.0	Kessler (1981)
Lipase inactivation, 90 %	–	–	10.5	2.0	Kessler (1981)
No discoloration	–	–	10.5	2.0	Kessler (1981)
Enzymes/food particulates	27	–	10.0	3.0	Brown and Ayres (1982)
Anthocyanin in grapes, 90 % destruction	23	18	10.0	24.0	Newman and Steele (1984)
Browning and protease destruction	25	–	10.0	4.0	Jelen (1983)

Fig. 19.3 Diagram of $\log_{10}$ time versus temperature for microbial inactivation (F_1OF_2) and cooking (C_1OC_2) for the central point in a food product



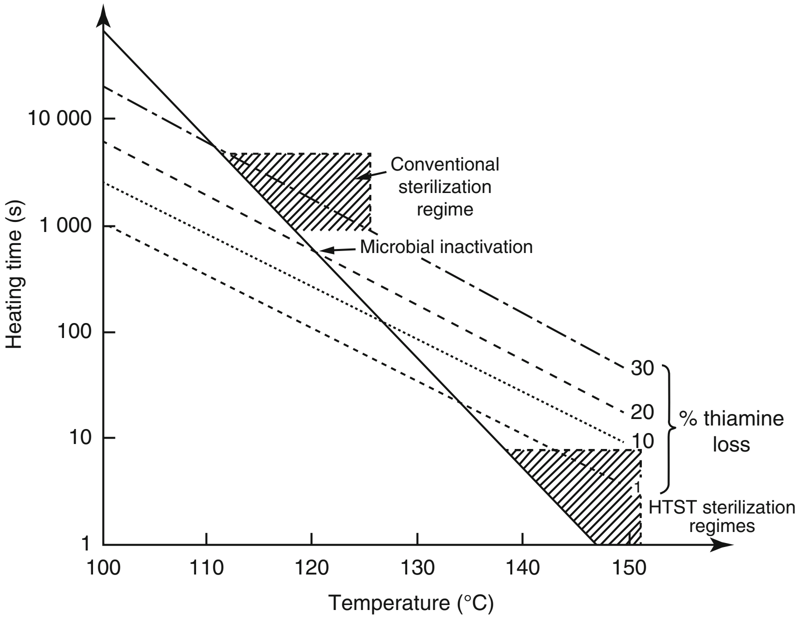


Fig. 19.4 Degradation of thiamine for different sterilization regimes

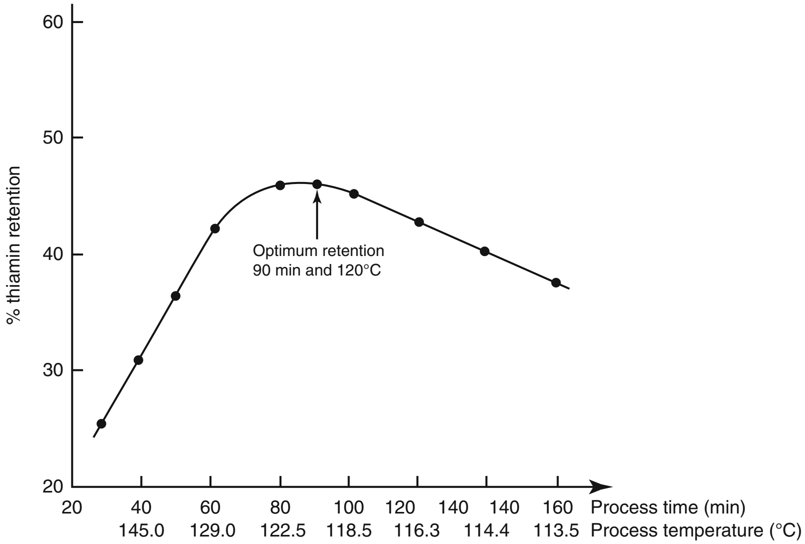


Fig. 19.5 Optimization curve for percentage thiamine retention ($z = 25$ °C) against equivalent process times/temperatures (from Teixeira et al. 1969)

corresponding thiamin distribution, employing first-order degradation kinetics. Figure 19.5 shows the percentage thiamin retention plotted against equivalent process times and temperatures, based on 84 min at 121.1 °C (Stumbo 1973). The curve shows that the maximum retention of thiamin is obtained for an optimum process of 120 °C for 90 min, which is very much a conventional canning process. The curve also shows that for conduction-heating products HTST conditions have an adverse effect on nutrient retention. The model was used for studying the effects of changing variables on the optimum conditions. For heat-vulnerable components with z_c-values lower than for thiamin, the optimum moves to the lower-temperature, shorter-time region and, correspondingly, in the opposite direction for higher z_c-values. Changing the D_c-values had no effect on the position of the maximum but increased the nutrient retention for increasing D_c-values.

In the same year, Hayakawa (1969) published a new procedure, based on dimensionless parameters, for calculating mass-average sterilizing values, F_s, which could be used as C_s-values with the appropriate D_c- and z_c-values (see Eq. (19.2)). He showed that the method was simpler to use than that of Ball and Olson (1957) and that the results compared more favorably with experimental determinations of nutrient retention. A more rigorous method of determining the mass-average value for a physical, chemical, or biological factor in food for various simple geometrical shapes was presented by Hayakawa (1971).

Jen et al. (1971) developed Stumbo's method (see Stumbo 1973) further for application to nutrients. In Stumbo's method for obtaining F_s-values a relationship, $F_\lambda - F_c = mv$ (discussed in Chap. 6), was used for determining F_λ, the F-value at $j = j_c/2$. The probability of microbial survival for values of the volume parameter v greater than 0.4 was considered negligible. While this is satisfactory for microbial inactivation, it is not so for nutrient degradation. Jen et al. (1971), starting with the equation

$$10^{-F_s/D_{\mathrm{ref}}} = \int_0^V 10^{-F_\lambda/D} \mathrm{d}V, \tag{19.10}$$

obtained the equation

$$F_s = F_c + \log\left[1 + AD_{\mathrm{ref}}^{-1}(F_\lambda + F_c\right), \tag{19.11}$$

which took into account the previously mentioned conditions for nutrient reactions; in Eq. (19.11)

$$A = -\ln 10/\ln(1 - v),$$

which, for a value of $\upsilon = 0.19$, gives $A = 10.927$. Newman and Holdsworth (1989) obtained some other values: For a cylindrical container, $A = 10.734$; for a sphere, $A = 9.284$; and for a brick, $A = 11.737$. The method was further extended by producing tables of f_h/U versus g (see Table 6.3) for values of $z = 10$, 24.5, and 25.5 °C.

Tables 19.6 and 19.7 show some comparative values of thiamin retention obtained using different methods. The Jen et al. (1971) method produced thiamin retention values close to the analytical values.

Downes and Hayakawa (1977) extended previous approaches to deal with the curvilinear portion of the heating curve and for conditions when f_h was not equal to f_c. New tables were produced for determining temperature distributions and the method compared better than others with analytical results (see Table 19.6).

Teixeira et al. (1975b) studied the effect of container size on thiamin retention in conduction-heating products and showed, as expected, that this had a major influence on nutrient retention. For equal volumes the thiamin retention decreased from 68 to 41 % for values of L/D increasing from 0.096 to 1.270 (No. 2 can) and then increased from 43 to 63 % for values of L/D increasing from 1.710 to 13.750. Using time-varying surface temperature conditions was found to have little effect on vitamin retention.

Lenz and Lund (1977) showed that for short processing times (less than 20 min), the statistical distribution of C_s-values was normal; however, for longer times the distribution exhibited an increasing standard deviation and a pronounced skewness.

Sjöström and Dagerskog (1977) studied the browning of canned chopped fish at temperatures between 110 and 145 °C using $z_c = 33$ °C. Using a series of process times and temperatures equivalent to $F = 7.5$ min, it was shown that the C-value was a minimum at about 127 °C and 60 min for a position intermediate between the surface and the center. The surface was least discolored at temperatures below 120 °C, and variable temperature heating profiles had little effect on color retention.

Thijssen and Kochen (1980) extended the previously derived shortcut method of process evaluation (Thijssen et al. 1978) to the case of variable heating temperature profiles but did not present any experimental data for food products.

Table 19.6 Comparisons of thiamin retention predictions using various methods

Product	Can size	Process temperature (°C)	Process time (min)	Stumbo (1953)	Ball and Olson (1957)	Hayakawa (1969)	Teixeira et al. (1969)	Jen et al. (1971)	Downes and Hayakawa (1971)	Thijssen et al. (1978)	Experimental	Reference
											Analysis	
Pea purée	211 × 300	121.1	30	–	75.5	84.1	86.0	89.0	86.1		86.7	Jen et al. (1971)
Pea purée	211 × 300	121.1	60	–	55.2	59.2	61.0	61.4	60.6		65.6	Jen et al. (1971)
Pea purée	211 × 300	115.5	30	–	82.1	91.0	91.5	93.5	92.9		93.6	Jen et al. (1971)
Pea purée	303 × 406	121.1	85	48.7	–	–	49.2	–	–		50.7	Teixeira et al. (1975a)
Pea purée	303 × 406	115.5	136	41.0	–	–	41.6	–	–		42.3	Teixeira et al. (1975a)
Pea purée	303 × 406	126.7	65	47.3	–	–	48.8	–	–		51.3	Teixeira et al. (1975a)
Pea purée	303 × 406	110[a]	–	–	–	–	53.5	–	–		53.5	Teixeira et al. (1975a)
Carrot purée	211 × 300	121.1	60	–	53.9	59.0	–	–	–	63.5	66.8	Thijssen et al. (1978)
Pea purée	211 × 300	121.1	60	–	55.2	59.5	61.4	61.0	–	64.6	65.6	Thijssen et al. (1978)
Pork purée	211 × 300	126.7	40	–	49.2	52.2	–	–	–	57.3	53.0	Thijssen et al. (1978)

[a] + 5.6° step increase every 20 min

Table 19.7 Some theoretical predictions for nutrient retention in canned products

Product	Can size	Process temperature (°C)	Process time (min)	Temperature (°C)	Thiamin	% reduction in experimental results	Chlorophyll	References
Conduction	211 × 400	110	80	20	69		85	Savage (1984)
Conduction	211 × 400	110	67	80	68		84	Savage (1984)
Conduction	211 × 400	120	45	20	60		71	Savage (1984)
Conduction	211 × 400	120	35	80	60		70	Savage (1984)
Conduction	211 × 400	130	35	20	64		68	Savage (1984)
Conduction	211 × 400	130	25	80	85		67	Savage (1984)
Simulated product	211 × 300	108.6	44.5	28.9	77.5	79.3	–	Barreiro Mendez et al. (1977)
Simulated product	307 × 409	95.1	59.0	27.9	79	79.8	–	Barreiro Mendez et al. (1977)
Simulated product	211 × 300	117.7	50	25.9	59.6	59.7	–	Barreiro Mendez et al. (1977)
Pork purée	307 × 409	121.11	67	71.11	48 approx.	44		Banga et al. (1991), Garcia et al. (2006)
Meat paste	144 × 35 mm	112	63			39		Barros et al. (2001)
Meat paste	144 × 35 mm	115	45			35		Barros et al. (2001)
Meat paste	144 × 35 mm	118	32			44		Barros et al. (2001)
Meat paste	144 × 35 mm	120	25					Barros et al. (2001)

Ohlsson (1980b, c, d) conducted an important series of experiments on the determination of C-values for a range of products (fish paste, liver paste, strained beef, strained vegetables, tomato sauce, and vanilla sauce) and for a range of different sensory qualities (odor, appearance, taste, consistency, hardness, coarseness, and lightness) in different shapes of container. It was shown that for a given F-value, the volume-average cook values for $z = 25$ °C showed minimum values that decreased with increasing temperature and decreasing can size. The optimal processing temperature, between 117 and 119 °C for a 73 × 99 mm can, was in agreement with the previous work of Teixiera et al. (1969).

Reichert (1980) developed a method of processing known as ΔT-cooking, in which a fixed temperature differential, ΔT, was maintained between the retort temperature and the temperature at the center of the can. This was further extended by Hendrickx (1987), using a numerical algorithm—transmission line matrix (TLM) modeling—to optimize quality retention in conduction-heated foods.

Richardson et al. (1988) developed a finite-difference model, for use on an IBM PC-XT to determine nutrient retention in conduction-heating packs. A practical observation from this work was that the results from the experiments were better correlated with the theoretical results when the temperature was measured at the surface of the container than when using the retort thermometer measurements. By this means the effect of the heat-transfer coefficient at the surface of the container, especially during the cooling period, was eliminated. This work was important for modeling the temperature distribution in real time for control purposes.

Alwis et al. (1992) used the SPEEDUP$^{\text{TM}}$ system (Simulating Program for Evaluating and Evolutionary Design of Unsteady-State Processes) developed by Sargent et al. (1982) for optimizing quality and processing effects of a conduction-heating meat product. This showed the need for higher temperatures and shorter times for obtaining better meat quality.

Hendrickx et al. (1992b) have used an ANSYS finite element package (De Salvo and Gorman 1989) to determine the maximum surface quality retention as a function of (a) product properties; (b) processing conditions, including geometry and dimensions of the food, surface heat-transfer coefficient, initial product temperature, and retort come-up-time; and (c) processing criteria, i.e., target F_0-value.

Kebede et al. (1996) studied heat transfer into high-barrier plastic trays containing an 8 % bentonite suspension containing ascorbic acid. The containers had a net volume of 460 ml, had dimensions 35 × 97 × 142 mm, and were made from (1) polypropylene/ethylene vinyl alcohol/polypropylene and (2) crystallized polyethylene terephthalate. The average retention of ascorbic acid after heating to achieve an F_0 of 11–12 min in the trays was 83 % compared with 75 % for the cans. Similarly the trays performed better than the cans during storage at 35 °C for 105 days.

Pornchaloempong et al. (2001, 2003) have conducted a theoretical evaluation of the effect of various product and processing factors on the quality retention in products in three conical-shaped containers. The factors studied included retort temperature processing times for equivalent lethalities, z-value, D-values, thermal diffusivity, surface heat transfer, and container geometry.

Simpson et al. (2004) have developed a finite-difference model for predicting the quality optimization of Jack mackerel frustum vacuum-packed in flexible plastic pouches utilizing variable retort temperature profile.

García et al. (2006) have developed retort control profiles for the optimization of thiamine retention in a 307 × 409 can filled with pork purée, using a dynamic optimization technique control vector parameterization (CVP) and the F&C relations of the form of Eq. 19.3.

Balsa-Canto et al. (2002a, b) have presented a novel and important method for optimization based on proper orthogonal decomposition to give reduced-order models that are easier to solve than the formal nonlinear partial differential equations. The method was successfully tested using data for canned pork purée.

Table 19.8 summarizes quality optimization studies.

Table 19.8 Some quality optimization studies

(1) Optimization studies with constant retort temperature		
Static process	Thiamin retention	Lund (1977)
Static process	Effect of packaging	Silva et al. (1994a)
Static process	Average and surface quality	Silva et al. (1994b, c, d)
Static and rotary water cascade retorts	Effect of process	Smout et al. (2001)
Static process	Thiamin retention	Teixeira et al. (1969)
Static process	Thiamin retention	Chen and Ramaswamy (2002b)
Static process	Effect of variability in thermal properties	Baucour et al. (2003)
Static and rotary water cascade retort	Effect of variability in white and green beans	Avila et al. (2006)
Rotary retort	Texture and color of vegetables	Abbatemarco and Ramaswamy (1994)
(2) Optimization studies with variable retort temperature		
Average (volumetric) retention		
Static process	Surface quality: canned salmon	Durance (1997); Durance et al. (1997)
Static process	Effect of heating and cooling profiles	Nadkarni and Hatton (1985)
Static process	Pea purée	Saguy and Karel (1979)
Static process	Pea purée	Teixeira et al. (1975b)
Static process	Thiamin in cylinders and spheres	Erdögdu and Balaban (2003a)
(b) Optimization of surface quality, process time, and energy conservation		
Static process	Energy optimization	Almonacid-Merino et al. (1993)
Static process	Surface quality, minimum process time	Banga et al. (1991)
Static process	Energy and surface quality—canned salmon	Durance et al. (1997) Noronha et al. (1993)
Static process	Theoretical effect on surface quality, process time	Chen and Ramaswamy (2002c)

19.4.2.2 Formal Optimization Techniques

Saguy and Karel (1979) used an elegant multi-iterative mathematical technique, based on the continuous maximum principle theory of Pontryagin et al. (1962), to optimize thiamin retention in pea purée in a 303 × 406 can and pork purée in a 401 × 411 can. The method produced a variable-temperature heating profile that optimized the nutrient retention. A constant heating temperature regime was shown to be almost as good as the theoretically derived profile.

Norback (1980) reviewed the methods of optimization and suggested that the best method was dynamic programming. This could also be applied to process control.

Hildenbrand (1980) developed a two-part approach to solving the problem of optimal temperature control. In the first part, the unsteady-state equation for heat transfer into a finite cylinder was solved using Green's functions. In the second part, a method to ensure that the container received the calculated temperature profile was determined. While the approach seems interesting, no further development appears to have taken place.

Nardkarni and Hatton (1985) examined the previous work and considered that the methods were not sufficiently rigorous to obtain the best optimization results. These workers used the minimum principle of optimal control theory to obtain optimal solutions. Again, simple heating and cooling profiles were better than complex heating profiles.

Banga et al. (1991) developed an optimization algorithm, Integrated Control Random Search (ICRS), for three objective functions: maximum overall nutrient retention, maximum retention of a quality factor at the surface of the food, and minimum process time. It was concluded that the use of a variable-temperature profile was advantageous for preserving optimum surface quality. Similar profiles to those shown in Fig. 19.5 were obtained for both overall nutrient retention and surface quality retention.

According to Simpson et al. (2008) global optimization algorithms and software based on adaptive random search techniques show considerable promise as more rapid and efficient approach to process optimization in the food industry. Considerable work has been reported in the literature showing that variable retort temperature (VRT) processing can be used to marginally improve the quality of canned food and alternatively reduce the sterilization process time in comparison to traditional constant retort temperature (CRT) processing (Banga et al. 1991; Banga et al. 2003; Teixeira et al. 1975b; Almonacid-Merino et al. 1993). The usefulness and advantages of some global optimization algorithm based on the utilization of Gaussian probability distribution for VRT thermal processing optimization were presented by Banga et al. (1991, 2003). Other global optimization algorithms—genetic algorithms (GA)—were also successfully implemented for VRT thermal processing Chen and Ramaswamy (2002c). Also the use of a cubic spline approximation for the optimum dynamic temperature profiles to simplify the problem by reducing the number of variables (dimensional space of the random search) has been developed by Simpson et al. (2008). The results obtained showed that global optimization with random search techniques can be used effectively to search for optimum VRT processes that will either maximize quality retention subject to achieving minimum target lethality or minimize process time to reach target lethality subject to holding quality retention to a specified minimum. Moreover, the use of the cubic spline in approaching global optimization problem with random search techniques can produce superior results over discrete stepwise functions in cases when the optimal VRT profiles are expected to be smooth curve and so can be better approximated by the implementation of cubic spline (instead of increasing the number of discretization points of the domain) (Fig. 19.6)

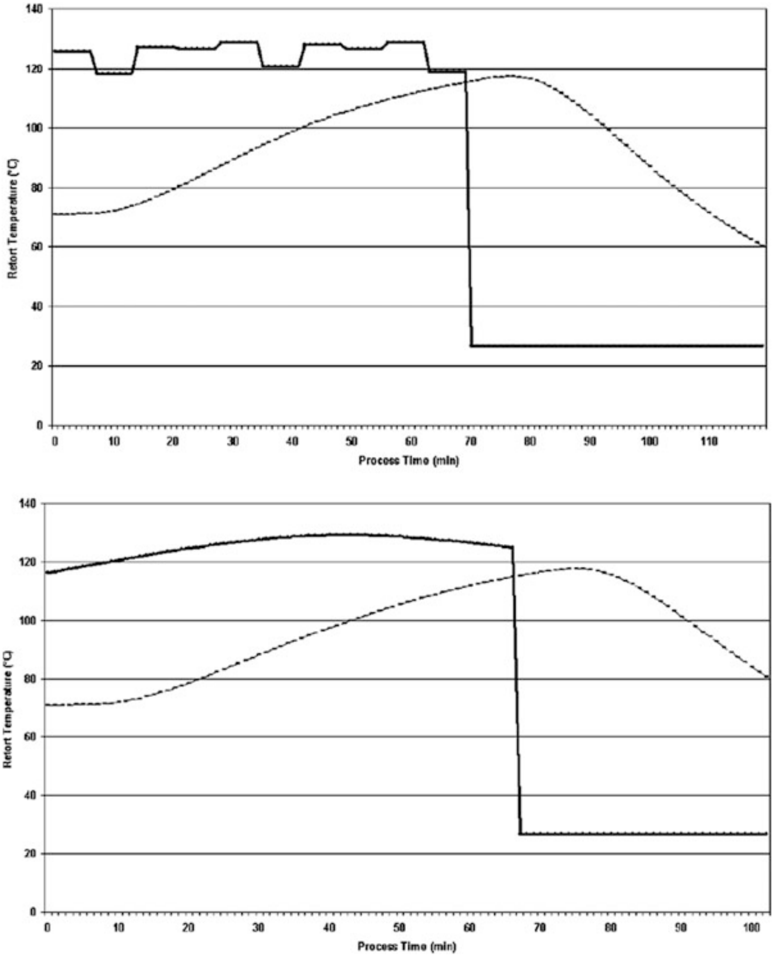


Fig. 19.6 Optimum VRT profile to minimize process time while assuring maximum thiamine retention (50 %) from random search using (**a**) discrete stepwise function with 10 steps and 5000 iterations and (**b**) cubic spline approximation and 1000 iterations

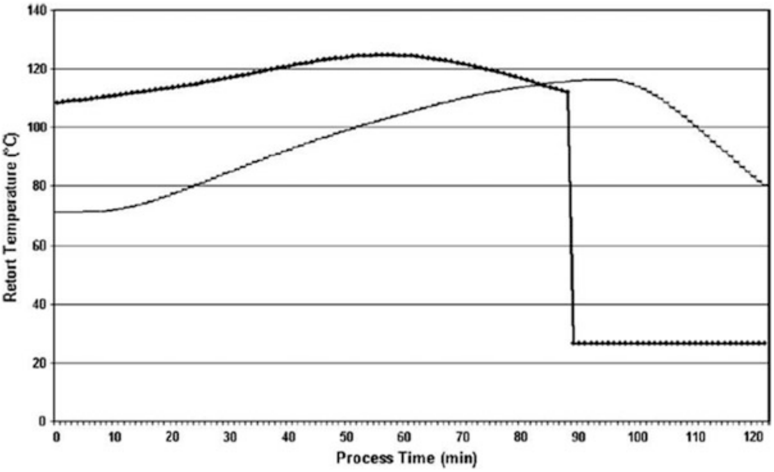


Fig. 19.7 Optimum VRT profile for maximum thiamine retention (55 %) from modified random search using cubic spline approximation and 600 iterations

Some modification to random search method was implemented by Abakarov et al. (2009) mainly based on the utilization of the well-known logistic function or logistic curve in order to improve the random search adaptation characteristics. The algorithm tested results show the advantage of the random search modification over the previous random search organization, especially in the case of solving the multimodal or dynamics optimization, whereas minimum optimization problem computations as possible to reach global optimum location are needed. For example in Fig. 19.7 is presented an optimum VRT profile that compared with basic random search (Fig. 19.6b) is possible to note an increasing in thiamine retention for the same process time, but also the optimization is performed with less iterations (600) which implies less computer time.

Some other optimization methods are listed in Tables 19.8 and 19.9.

19.4.2.3 Objective Functions

Silva et al. (1992a) reviewed and critically examined the objective functions, volume-average retention, and volume-average cook value used for optimization purposes. They concluded that for high *D*-values, e.g., vitamin destruction, the two functions were equivalent; however, for low *D*-values, e.g., texture and color, this is not the case. The volume-average cook value does not take into account the effect of the *D*-value and consequently underestimates the optimum processing temperature. The effect of finite surface heat-transfer coefficients on the optimal sterilization temperature was found to be significant; however, the initial temperature and the come-up time had little effect (Silva et al. 1992b).

Table 19.9 Some optimization techniques applicable to thermal processing

Technique	Application	Comment	References
Continuous minimum principle (Pontryagin et al. 1962)	Cylindrical can; thiamin retention; conduction-heating pack; pea purée	Optimum retort temperature; profile determined	Saguy and Karel (1979)
General review of techniques	–	Definition of terms, continuous and discrete problems	Norback (1980)
Comparison of optimization techniques	–	Excellent review of method	Nakai (1982)
Continuous minimum principle (Pontryagin et al. 1962)	Cylindrical can; thiamin retention; conduction-heating pack; pork purée	Optimum temperature profiles, optimal control policies	Nardkarni and Hatton (1985)
Super-simplex optimization	–	Modified optimization technique	Nakai et al. (1984); Aishima and Nakai (1986)
Computer program	Batch retorting of canned foods	Optimal temperature profiles for nutrient retention	Kok (1986)
Control vector parameterization (CVP)	Thiamin retention; conduction-heating pack	Optimal temperature profiles for nutrient retention	García et al. (2006)
Complex method	Batch retorting canned foods	Nonlinear constraint technique (Kozmierczak (1996)	Erdögdu and Balaban (2001); 2002; 2003b)
Neural network	Batch retorting canned foods	Prediction of safety and quality	Kseibat et al. (2004)
Proper orthogonal decomposition (POD)	Thiamin retention; canned pork	Retort temperature profiles	Balsa-Canto et al. (2002a, 2002b)
Dynamic optimization g-OPT[a]	Thiamin retention; canned pork purée	Optimum temperature profiles and good review of methods	Garcia et al. (2006)
Neural networks and genetic algorithms ANN-GA	Idealized system	Effect of variable retort temperature	Chen and Ramaswamy (2002a)

[a] g-OPT is the dynamic optimization tool of g-PROMS (available from Process Systems Enterprise Ltd., London)

The use of optimization techniques has been discussed in terms of commercial objectives as well as quality and sterilization (Oliveira 2004; Simpson 2004). Business objectives have not been fully studied to date, although Simpson et al. (2003) have produced a comprehensive analysis of the canning operation.

19.4.2.4 Semiempirical Equations

Hendrickx et al. (1989, 1993) developed a semiempirical model approach to determining optimal temperatures to minimize surface quality and nutrient losses. This approach was extended to include the effect of the cooling phase and external finite heat transfer, using simple geometrical models, viz. infinite slab, infinite cylinder, and sphere (Hendrickx et al. 1992a). The optimized temperatures were obtained for a minimum surface cook value with the constraint of the sterilization requirement.

The basic empirical formula had the general form

$$T_{\mathrm{op}} = a + b \log(F_t/f_h) + c \ln z_q + \mathrm{d}T_0, \tag{19.12}$$

where T_{op} is the optimal temperature, F_t is the sterilization value constraint, f_h is the heat penetration factor, z_q is the temperature sensitivity factor for surface quality degradation, and T_0 is the initial temperature of the pack. The regressed values for the various coefficients were $a = 86.68$, $b = 9.73$, $c = 10.46$, and $d = 0.025$. It was shown that variation of the initial temperature and the come-up time had a negligible effect on T_{op}; however, they changed linearly with $\ln z_q$ and $1/Bi$, where Bi is the Biot number (hd/k, in which h is the heat-transfer coefficient, d the characteristic linear dimension, and k the thermal conductivity). The effect of water processing with a reduced external heat-transfer coefficient was slightly to increase T_{op}, compared with steam processing. Noronha et al. (1993) studied the effects of variable temperature profiles on maximizing the surface quality retention and found that variable-temperature profiles improved the surface quality by up to 20 % compared with constant-temperature retort profiles.

This technique was used by Van Loey et al. (1994) to optimize the thermal process for canned white beans using both static and rotary processing. The rotary end-over-end process produced the better quality pack.

Silva et al. (1994a, b, c) studied the maximization of the surface quality retention of one-dimensional conduction-heated foods, e.g., pouches. Optimal temperatures were determined for a range of conditions. The semiempirical approach to determining optimal processing temperatures for quality retention in packaged foods has been shown to be an effective and simple method compared with the complexities of the more formal methods.

Noronha et al. (1996) have optimized the surface quality for three food systems, viz. (1) a meal-set consisting of chili con carne/white rice/peach slices in syrup in a plastic pouch, (2) a meal-set consisting of meat/potatoes/spinach in a plastic pouch, and (3) a meal-set comprising a mixture of four vegetables: green beans/peas/corn/carrots in glass. The surface quality retention was studied under conditions of constant and variable retort temperatures, and it was shown that the latter conditions had an advantage. A similar advantage has also been shown in the case of cooked white beans in glass.

19.4.2.5 Computer Software

Nicolai et al. (2001) have developed a number of packages, e.g., CookSim and ChefCad, that deal with a range of food processes, including sterilization operations. The CookSim package is a knowledge-based system that uses a finite-element approach for solving the heat-transfer, sterilization, and cooking equations. ChefCad is used for computer design of complicated recipes consisting of consecutive heating/cooling stages.

19.5 Quality Assessment Through Mass Balance

The hypothesis is that in food processing applications, quality—in most cases—can be treated by a mass balance. The conditions to carry out a mass balance for a given attribute are the ability to express it in concentration terms (w/w or w/v) and also to account for a kinetic expression (e.g., degradation of quality attribute as a function of time and temperature). Most quality factors, like vitamins, enzymes, and color pigments, can be expressed in terms of concentration. In addition, a large amount of work in the area of kinetics for different target attributes has been carried out in the past three decades.

Firstly, the general mass balance equation for the quality of attribute j through the system is

$$\begin{aligned}&\left[A_j\right]_{\mathrm{IN}} - \left[A_j\right]_{\mathrm{OUT}} + \left[\text{Generation } A_j\right] + \left[\text{Consumption } A_j\right]\\&\quad = \left[\text{Accumulation } A_j\right]_{\mathrm{SYSTEM}}\end{aligned}$$

where

A_j: Mass of attribute j per unit time (w/t)

As follows, we are presenting the general expression for differential and integral balances, from which we can obtain the adequate balance for the specific thermal processing application.

In general, for an open system in an unsteady-state (transient) condition, the following equation is proposed for a quality balance of factor j in system S.

Differential form (unsteady state):

$$\begin{aligned}&[FQ]_{j,L} - [F(Q+\delta Q)]_{j,L+\delta L} + \delta V\left[\frac{dQ}{dt}\right]_{j,A} + \delta V\left[\frac{dQ}{dt}\right]_{j,I}\\&\quad = \left[\frac{d((\delta V)Q)}{dt}\right]_{j,S}\end{aligned} \tag{19.13}$$

where

F: Flux (L/h)
Q: Quality attribute (kg/L)

V: Volume (L)
t: Time (h)
δL *and* δV: Small quantity, in this case a very short tube length and a very small volume.

Subindices

L: Position L
A: Activation
I: Inactivation
S: System

Under steady state:

$$[FQ]_{j,L} - [F(Q+\delta Q)]_{j,L+\delta L} + \delta V\left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,A} + \delta V\left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,I} = 0 \tag{19.14}$$

Integral form (unsteady state):

$$[FQ]_{j,i} - [FQ]_{j,o} + V\left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,A} + V\left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,I} = \left[\frac{\mathrm{d}(VQ)}{\mathrm{d}t}\right]_{j,S} \tag{19.15}$$

And, under steady state:

$$[FQ]_{j,i} - [FQ]_{j,o} + V\left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,A} + V\left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,I} = 0 \tag{19.16}$$

And, for a closed system under unsteady state:

$$\left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,I} = \left[\frac{\mathrm{d}(Q)}{\mathrm{d}t}\right]_{j,S}. \tag{19.17}$$

19.5.1 Demonstration Examples

Examples have been chosen specifically for situations where the classical approach of cooking value concept fails.

19.5.1.1 Quality Evaluation in a Plug Flow Holding Tube (Fluid Without Particles and Constant Temperature)

In a Plug Flow (Fig. 19.8) the fluid passes through in a coherent manner, so that the residence time is the same for all fluid elements. The coherent fluid passing through the ideal reactor is known as a plug. As a plug flows through the tube, the fluid is perfectly mixed in the radial direction but not in the axial direction (forwards or

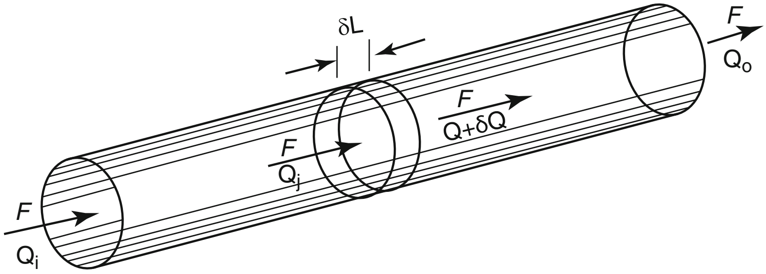


Fig. 19.8 Quality balance in a Plug Flow system

backwards). Each plug of differential volume is considered as a separate entity (practically a batch reactor) as it flows down the tubular Plug Flow.

This is a classic example where it is imperative to do a differential balance. The concentration of the target attribute is changing through the tube length, meaning that we cannot select the whole tube as a system. Therefore, to do the balance, first, a differential element at positions L and $L + \delta L$ is defined. Because the differential system is very small, we can assume that within this small system the concentration of the target attribute j is homogeneous and equal to $Q_{j,L}$.

According to Eq. (19.13) and considering steady-state condition, Eq. (19.14), we can write

$$[FQ]_{j,L} - [F(Q + \delta Q)]_{j,L+\delta L} + \delta V \left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,A} + \delta V \left[\frac{\mathrm{d}Q}{\mathrm{d}t}\right]_{j,I} = 0$$

Then, considering a first-order inactivation kinetics (without an activation term), we obtain

$$[FQ]_{j,L} - [F(Q + \delta Q)]_{j,L+\delta L} - k_{j,L} Q_{j,L} \delta V = 0. \tag{19.18}$$

Therefore

$$-F\delta Q_{j,L} - k_{j,L} Q_{j,L} \delta V = 0 \tag{19.19}$$

where

$$\delta V = A\delta L \tag{19.20}$$

Replacing Eq. (19.20) into Eq. (19.19)

$$-F\delta Q_{j,L} - k_{j,L} Q_{j,L} A\delta L = 0 \tag{19.21}$$

Separating variables and integrating from 0 to L and from $Q_{j,i}$ to $Q_{j,o}$

$$Q_{j,o} = Q_{j,i} \mathrm{e}^{-k_j \frac{V}{F}} = Q_{j,i} \mathrm{e}^{-k_j \tau} \tag{19.22}$$

Output quality for target attribute j ($Q_{j,o}$) can be evaluated knowing the initial quality ($Q_{j,i}$), process temperature, residence time, and reaction constant (k_j). Equation (19.22) can be reformulated to compare with cooking value concept discussed in Chap. 4. In order to relate Eq. (19.22) to cooking value it is necessary to replace k by D and then express D as a function of temperature:

$$k = \frac{\ln 10}{D} \text{ and } D = D_r 10^{\frac{T_r - T}{z}}$$

Expressing $Q_{j,o}$ as a function of $Q_{j,i}$ by $Q_{j,o} = Q_{j,I}/10^x$ and replacing into Eq. (19.22)

$$C_r = xD_r = 10^{\frac{T - T_r}{z_c}} \tau \tag{19.23}$$

where, for a constant temperature process, Eq. (19.23) is similar and comparable with Eq. (5.26), although Eq. (5.26) was derived for a closed and unsteady-state system and Eq. (19.23) was obtained for an open steady-state system.

19.5.1.2 Quality Evaluation in a Series of CSTR Reactors

The application of CSTR, as shown in Fig. 19.9, is useful for modeling process systems, since it has good mixing characteristics.

In this case we are considering each reactor as a system and assuming steady-state, first-order kinetic for inactivation of target attribute and neglecting the activation term, and then, from Eq. (19.16), we obtain first reactor:

$$FQ_{i,1} - FQ_{o,1} - k_1 Q_{o,1} V_1 = 0 \tag{19.24}$$

Second reactor

$$FQ_{i,2} - FQ_{o,2} - k_2 Q_{o,2} V_2 = 0 \tag{19.25}$$

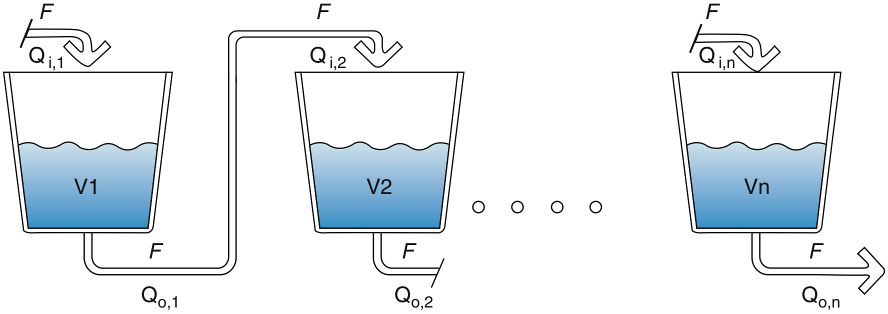


Fig. 19.9 Quality balance in a series of CSTR reactors

By recurrence we are able to derive an equation for the *N*th reactor:

$$FQ_{i,N} - FQ_{o,N} - k_N Q_{o,N} V_N = 0 \tag{19.26}$$

Considering that $Q_o j = Q_i j_{+1}$ and rearranging, we obtain

$$Q_{o,N} = \frac{F^N Q_{i,1}}{\Pi_{j=1}^{N}\left(F + k_j V_j\right)} \tag{19.27}$$

Knowing the quality of the food product at the entrance ($Q_{i,1}$) and system characteristics (F, V_j), it is possible to evaluate quality at the output flux ($Q_{o,N}$). Although we are not attempting to relate this expression to cooking value concept (Eq. 5.26), by inspection of Eq. (19.27), it is not clear that it will be possible to derive such an expression.

19.5.2 Corollary

A general approach to assess quality has been proposed and exemplified through two demonstration examples. The referred approach can be directly extended to assess process safety.

According to the proposed methodology, it is necessary to define a system and carry out a mass balance of the target attribute(s), meaning that it is necessary to express quality in terms of concentration (w/w or w/v) and to have an adequate kinetics expression to account for target attribute(s) degradation. Experience has shown us that most quality attributes can be expressed in concentration terms; in addition, a large amount of work in the area of kinetics has been carried out in the last three decades.

19.6 Summary

The subject of determining suitable processing conditions to maximize quality factors in foods undergoing thermal processing is currently being actively investigated. A variety of theoretical models have been developed for predicting optimum temperatures and temperature profiles. While the theoretical aspects have been extensively considered, there is relatively little work on actual food products. It is this aspect that requires further investigation in order to produce equations that may be used by the industry to control or improve the quality of processed products. This is a particularly difficult area in some ways, since it may involve producing a somewhat different product than the consistent brand image required and coveted by marketing people. It is easier to alter the quality attributes while at the same time altering the geometry and characteristics of the packaging material, e.g., using plastic pouches and cartons. Optimization is an important subject and deserves to be studied in detail. It is not only concerned with defining the conditions for producing certain quality attributes, but can also be used in process and quality control (see Chap. 21).

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Chapter 20
Multiobjective Optimization in Thermal Food Processing

20.1 Introduction

In general, many of the problems that we must resolve in real life must be addressed in a multiobjective way because we often have conflicting objectives (particular objective functions) where it is possible to compute more than one optimal solution. Such solutions are called nondominated or Pareto-optimal solutions (Steuer 1985). Each Pareto-optimal solution can be considered as a final "compromise" solution of a multiobjective optimization (MOO) problem because it has no a priori advantage over other Pareto-optimal solutions. Therefore, the ability to compute the maximum possible Pareto-optimal solutions is very important (Abakarov et al. 2009). The purpose of multiobjective optimization is ideally to generate the set of solutions involving optimal trade-offs among the different objectives.

Consumers seek safe, nutritional, palatable, and even gourmet food. In this sense, thermal processing is an important method of food preservation in the manufacture of shelf-stable packaged foods that can satisfy the actual consumer needs. For this reason it has been the cornerstone of the food processing industry for more than a century (Teixeira 1992). The basic function of a thermal process is to inactivate bacterial spores of public health significance as well as food spoilage microorganisms in sealed containers of food, using heat treatments at temperatures well above the ambient boiling point of water in pressurized steam retorts (autoclaves). Excessive heat treatments should be avoided because they are detrimental to food quality and underutilize plant capacity (Simpson et al. 2003). Therefore, process optimization is important to find the heating temperature profile and the processing time that maximize the nutrient retention of a heated canned food while assuring the microbiological lethality. However, other criteria can also be considered, such as minimizing the total process time, maximizing energy efficiency, and so on (Sendín et al. 2010). The common optimization problem for nutrients and texture can be considered as a multiobjective optimization problem, as there are two conflicting criteria: one is that the food must remain at high temperature for a

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specific time to ensure the minimal desired lethality, and the other is related to the negative effects of the heating process on nutrients and texture. Therefore, a compromise between the two criteria should be found, bearing in mind that microbiological safety must be the primary objective (Sendín et al. 2010; Abakarov et al. 2009).

20.2 Optimization Methods Applied to Solve Multiobjective Optimization in Thermal Process

Various optimization methods to solve multiobjective optimization problems have been proposed over the last few decades. These methods can be divided into two classes. ***Aggregating functions*** (Andersson 2000) consist of transforming multiobjective optimization problems into a single global optimization problem such that their optimal solutions for several chosen parameters yield just one Pareto-optimal point. The optimization of the obtained single optimization problem can be accomplished by any of the existing optimization methods, including deterministic ones, such as gradient-based or various direct search algorithms (Himmelblau 1972). However, the implementation of such methods in practice is usually avoided in view of the multiextremal nature of the single optimization problems to be solved. Other global optimization algorithms such as genetic algorithms (Goldberg 1989), simulated annealing (Czyzak and Jaszkiewicz 1998; Bandyopadhyay et al. 2008), complex methods (Erdogdu and Balaban 2003), tabu searches (Cavin et al. 2004; Jaeggi et al. 2008), and other types of random search methods are preferable in this case.

Multiobjective evolutionary algorithms are based on the utilization of genetic algorithms. The great advantage of the multiobjective evolutionary algorithm is that its nature allows an entire set of multiobjective solutions to be evolved in a single run of the algorithm, instead of having to perform a series of separate runs, as in the case of the aggregating function method (Deb 1999a, b; Sarkar and Modak 2005). However, the aggregation method has certain disadvantages related to sensibility to the shape of the Pareto-optimal front, features of the particular multiobjective functions, the spread of Pareto-optimal solutions and the requirement for specific knowledge of the problem to be solved. A potential disadvantage of the genetic algorithms is the need for many more function evaluations compared with other stochastic global optimization algorithms, which is the effect of the parameterization of critical dependences on genetic algorithms (Solomatine 1998, 2005). These issues could, however, be avoided by choosing the appropriate optimization algorithm and aggregating functions. It should also be noted that aggregating function methods are very easy to implement and computationally efficient.

20.3 Basic Principles of Multiobjective Optimization

20.3.1 Pareto-Optimal Solutions

A general multiobjective optimization problem can be formulated as follows:

$$\Phi(x) = \langle f_1(x), f_2(x), \ldots, f_l(x)\rangle \to \min_{x \in X} \tag{20.1}$$

where $X \subset R^n$ is a non-empty set of feasible decisions (a proper subset of R^n), $x = \langle x_1, x_2, \ldots, x_n\rangle \in X$ is a real n-vector decision variable, and $f_i = R^n \to R$ are particular multiobjective functions.

We assume that all of the constraints are included in the particular objective functions (20.1) by utilizing the penalty functions (Himmelblau 1972).

If no vector $x^* = \langle x_1^*, x_2^*, \ldots, x_n^*\rangle \in X$ exists, such $x^* = \text{argmin}_{x \in X} f_i(x)$, $\forall i \in 1 : l$, that is, if no vector exists that is optimal for all objectives concurrently, then there is no unique optimal solution. If it exists we call such a solution a utopian solution, and a concept of an acceptable solution is needed. The subset

$$\text{WP}(X) = \{x^{\text{p}} \in X\text{: such that there does not exist an } x \in X \text{ with } f_i(x) \leq f_i(x^{\text{p}}), \quad \forall i \in 1 : l\}$$

is called the set of Pareto-optimal solutions of a multiobjective optimization problem, as any other solution can be improved. Pareto-optimal solutions are also known as nondominated or efficient solutions. The space in E^l formed by the points of the set $P(X) = \{x | x \in \text{WP}(X)\}$ is called a Pareto-optimal frontier or front. From the local Pareto-optimal solution, it is possible to ensure that the set of solutions belongs to the local Pareto-optimal set, considering the following:

$$\begin{aligned} &f_i(x') \leq f_i(x), \qquad \forall i \in 1 : l \\ &x \in B_\varepsilon(X) \subset X, \quad B_\varepsilon(X) = \{x | \|x - x'\| \leq \delta\} \end{aligned} \tag{20.2}$$

where δ corresponds to a small positive number.

The multiobjective optimization approach used in this study is based on optimizing the following aggregating functions:

- Linear weighted sum aggregation
- Weighted min–max aggregation function
- ξ-perturbation or ξ-constant with modification proposed by Abakarov et al. (2009).

by using the adaptive random search method (Sushkov 1969; Abakarov and Sushkov 2002; Simpson et al. 2008; Abakarov et al. 2009):

20.4 Multiobjective Optimization for Thermal Processing

Multiobjective optimization techniques have been applied to solving the optimization problem of the thermal processing of packaged foods related to ensuring lethality without loss of food quality (nutritional and texture). For example, Abakarov et al. (2009) studied the application of a multiobjective optimization where food quality factors (thiamine and texture retentions of pork puree) and processing time were considered as particular objective functions. The applicability of the proposed approach was further illustrated by solving widely used multiobjective test problems taken from the literature (Srinivas and Deb 1994; Deb 1999a, b).

In the particular case of a cylindrical container with radius R and height $2L$, the mathematical model describing heat transfer by conduction is a mixed boundary problem, as follows (Teixeira et al. 1969):

$$\frac{\partial T}{\partial t} = \alpha\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r} + \frac{\partial^2 T}{\partial z^2}\right) \tag{20.3}$$

where T is the temperature, t is time, r and z are the radial and vertical locations inside the can, and α is the thermal diffusivity of the food product.

This model has the following initial boundary conditions (by symmetry):

$$\begin{aligned} T(R,z,t) &= T_{\mathrm{rt}}(t), \\ T(r,L,t) &= T_{\mathrm{rt}}(t), \\ \frac{\partial T}{\partial r}(0,z,t) &= 0, \\ \frac{\partial T}{\partial z}(r,0,t) &= 0, \\ T(r,z,0) &= T_{\mathrm{in}}, \end{aligned} \tag{20.4}$$

where $T_{\mathrm{rt}}(t)$, $t \in [0, t_{\mathrm{f}}]$ is the retort temperature as a function of time, and T_{in} is the initial temperature of food at $t = 0$.

The lethality constraint can be specified as follows:

1. $F_0(t_{\mathrm{f}}) \geq F_0^{\mathrm{d}}$ where F_0^{d} is the final required lethality and is calculated as a function of time and temperature at the critical point (cold spot), normally the geometric center of the container (in the case of conduction-heated canned foods), according to the following equation:

$$F_0(t) = \int_0^{t_{\mathrm{f}}} 10^{\frac{(T - T_{\mathrm{ref}})}{z}} \mathrm{d}t \tag{20.5}$$

where T is the temperature at the cold spot, and T_{ref} is the reference temperature (121.1 °C).

2. Quality retention, on the other hand, is greatly affected by the nonuniform temperature distribution within the package from the heated boundary to the cold spot, and it must be integrated in space over the volume of the container as well as over time. To accomplish this integration over both space and time, it was considered that $\overline{C(t_\mathrm{f})} \geq C^\mathrm{d}$, where C^d is the desired volume-average final quality retention value and is calculated by the following equation:

$$\overline{C(t)} = C_0 \frac{2}{L \cdot R^2} \int_0^L \int_0^R \exp\left[-\frac{\ln 10}{D_\mathrm{ref}} \int_0^{t_\mathrm{f}} 10^{\frac{(T-T_\mathrm{ref})}{z}}\right] \mathrm{d}r\mathrm{d}z \qquad (20.6)$$

In this study, the food quality factors of thiamine content and texture retention of pork puree were considered as particular objective functions. Each of the quality factors can be computed from expression (20.6) with its corresponding D_ref and z values. The last chosen particular objective is the thermal process time; therefore, the following multiobjective optimization of the thermal process optimization problem considered in this study was

$$\langle \Phi_1(u), \Phi_2(u), \Phi_3(u) \rangle \rightarrow \min_{u \in U} \qquad (20.7)$$

subject to

$$\begin{aligned} F_0(t_\mathrm{f}) &\geq F_0^\mathrm{d} \\ \Phi_1(u) &\geq C_1^\mathrm{d} \\ \Phi_2(u) &\geq C_2^\mathrm{d} \\ T^\mathrm{l} \leq \Phi_3(u) &\leq T^\mathrm{r} \end{aligned} \qquad (20.8)$$

where u is the domain of control variables u_i, $i \in 1 : \left(N_\mathrm{p} - 1\right)$, Φ_1 is the thiamine retention multiplied by -1, Φ_2 is the texture retention multiplied by -1, Φ_3 is the thermal process time, C_1^d and C_2^d are the desired retention values, and T^l and T^r are the left and right limits of the process, respectively.

The parameters utilized in this study are presented in Table 20.1 (García et al. 2006; Holdsworth and Simpson 2007).

As a first step in the multiobjective optimization problem for thermal processing, it was necessary to find all combinations of constant retort temperature (CRT) and processing time for the conditions listed in Table 20.1 that would deliver the same final lethality. In this example, a target lethality of $F_0^\mathrm{d} = 6\,\mathrm{min}$ was chosen to produce the iso-lethality curve shown in Fig. 20.1. Each point on this curve defines a constant retort temperature and process time that result in a final target lethality of $F_0^\mathrm{d} = 6\,\mathrm{min}$.

For each of these equivalent processes, the final levels of thiamine and texture retention were calculated and are presented in Fig. 20.1. Figure 20.1 shows that the

Table 20.1 Parameters used in the thermal processing simulation study

Can radius (m)	0.04375
Can height (m)	0.1160
Thermal diffusivity a ($\mathrm{m^2 s^{-1}}$)	1.5443×10^{-7}
T_0 (°C)	45.00
Microorganism	*Bacillus stearothermophilus*
$Z_{\mathrm{M,ref}}$ (°C)	10
$T_{\mathrm{M,ref}}$ (°C)	121.11
Nutrient	Thiamine
$Z_{\mathrm{N,ref}}$ (°C)	25.0
D_{ref} (min)	176.6
$T_{\mathrm{N,ref}}$ (°C)	121.11
Quality factor	Texture
$T_{\mathrm{N,ref}}$ (°C)	45.0
D_{ref} (min)	178.6
$T_{\mathrm{N,ref}}$ (°C)	121.11
$F_0^{\mathrm{d}}(min)$	60
$C_1^{\mathrm{d}}(\%)$	35.0
$C_2^{\mathrm{d}}(\%)$	40.0
T^{l} (min)	45
T^{r} (min)	115

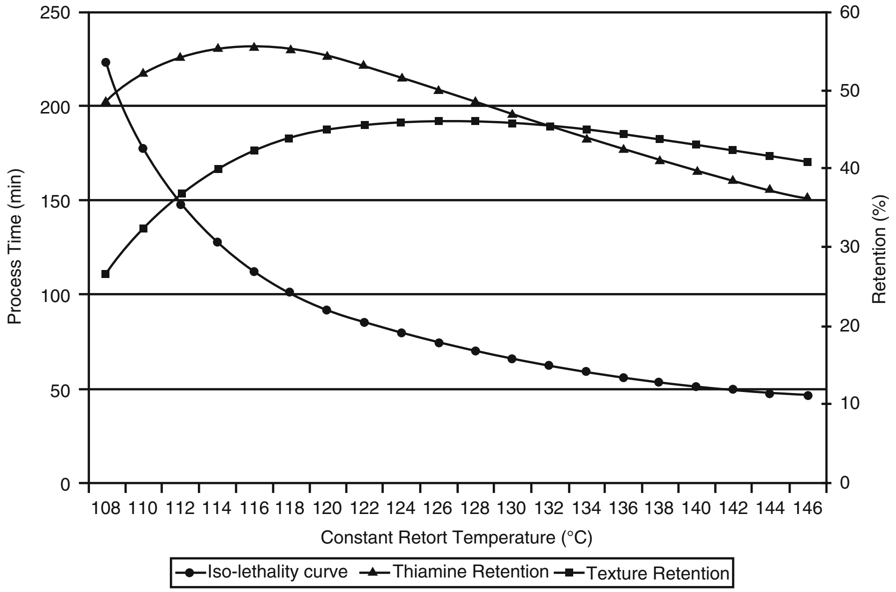

Fig. 20.1 Isolethality curve for $F_0^{\mathrm{d}} = 6\,\mathrm{min}$, showing equivalent process combinations of retort temperature and processing time, with curves showing thiamine and texture retention (quality attributes)

maximum level of thiamine retention with a constant retort temperature (CRT) was approximately 55 % over the range of possibilities and could be as low as 36 %. The maximum and minimum levels of texture retention were 46 % and 27 %, respectively. The optimum CRT process for the product chosen in terms of thiamine retention is one in which the retort temperature is held constant at 116 °C, with a corresponding processing time of 112 min. The optimal conditions for the texture retention were obtained at 128 °C constant temperature and 69 min of processing time. Taking into account the value of texture retention at 116 °C with a corresponding processing time of 112 min and the value of thiamine retention at 128 °C and 69 min, we obtained two solutions for thermal processing (see Table 20.2).

As a second step, the Pareto-optimal solutions of the thermal processing optimization problem were computed by utilizing a linear weighted sum aggregation function, weighted min–max aggregation function, modification of ξ-perturbations, and VRT profiles. For the thermal processing problem, the values 0 and 115 were taken as the left (T^{l}) and right (T^{r}) limits of the processing time and the values 35 % and 40 % as the desired retention values C_1^d, C_2^d, respectively. Tables 20.3, 20.4, and 20.5 present the Pareto-optimal solutions obtained for thermal processing.

The 800 computations of each aggregating function were performed by the ARSM to obtain nondominated thermal processing solutions (profiles). One of the obtained profiles is presented in Fig. 20.2. The values $p_{\min} = 0.75$ and $q_{\min} = 0.35$ were selected for all numerical experiments. The maximum computation time spent by the aggregating function for computation of the Pareto-optimal solutions for thermal processing did not exceed 2000 s.

From Tables 20.2, 20.3, 20.4, and 20.5, we can see that the VRT profiles are capable of achieving higher levels of quality retention with lower processing time, and thereby the VRT optimization involved in the multiobjective optimization of

Table 20.2 Solution obtained utilizing CRT

Process time (min)	Thiamine retention (%)	Texture retention (%)
112	55	42
69	48	46

Table 20.3 Summary of results from linear weighted sum aggregation function

Linear weighted sum aggregating function		
Process time (min)	Thiamine retention (%)	Texture retention (%)
111	53	47
100	57	46
76	52	47
71	50	47
60	45	45
52	40	44
47	38	42

Table 20.4 Summary of results from min–max aggregation function

Weighted min–max aggregating function		
Process time (min)	Thiamine retention (%)	Texture retention (%)
112	59	45
91	56	47
85	55	47
69	49	48
65	47	47
61	45	46
50	39	43

Table 20.5 Summary of results from penalty aggregation function

Penalty aggregating function		
Process time (min)	Thiamine retention (%)	Texture retention (%)
106	58	45
90	55	48
80	53	47
76	51	48
56	45	43
49	38	43

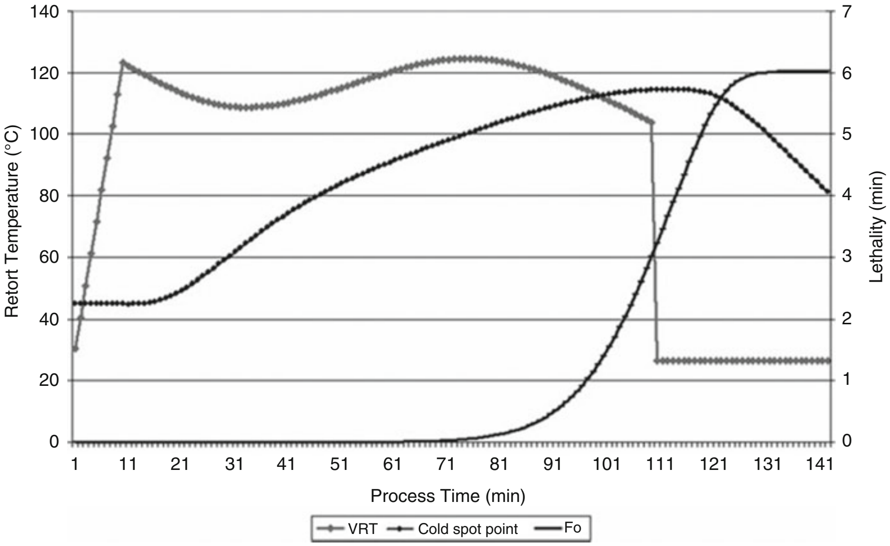

Fig. 20.2 Optimum VRT profile for multiobjective thermal processing optimization problem for processing time equal to 100 min

the thermal processing of food makes it possible to obtain global Pareto-optimal solutions. Depending on the real-world application, expert food engineers can choose a suitable "best" solution from among the ones presented in Tables 20.3, 20.4, and 20.5.

20.5 Summary

The multiobjective optimization approach has been demonstrated to allow the resolution of optimization problems in thermal food processing for canned food. In the example presented, this technique was able to obtain a set of nondominated solutions of processing time, quality retention and texture loss under a specific criteria of processing temperature (T_{RT}). For this reason, multiobjective optimization is a remarkable tool but requires the expertise of a process engineer to distinguish a suitable best solution from among all the nondominated solutions a suitable best solution. It should be noted that the set of particular criteria used in this study cannot be considered to be unique, and depending on a practical situation, this set can be changed, and the processing profiles can be recomputed.

As presented, the applicability of the three aggregating functions used for the different types of Pareto-optimal fronts and the ability of the adaptive random search method to solve the obtained single-optimization problems in a reasonable computation time make the proposed approach usable and effective for solving multiobjective food engineering problems.

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Chapter 21
Process Instrumentation, Online Control, and Plant Automation

21.1 Process Instrumentation

21.1.1 Introduction

The main objective of a control system is to ensure that an adequate thermal process is delivered to the product. For this purpose a sensor is required for each variable, an indicator and recording system, control valves, and a system for operating the valves correctly. The systems may be entirely manually operated or automatically controlled; alternatively, as in many cases with batch retorts, just one variable is automatically controlled, e.g., the temperature.

Process instrumentation is concerned with the equipment with which a canning process is controlled, either manually or automatically. It includes the measurement, recording, and manipulation of process variables. The main variables with which the process operator is concerned are:

(a) The temperature of the heating and cooling process;
(b) The time to achieve the desired process;
(c) The pressure to maintain the required process temperatures during heating and cooling, as well as maintaining the package integrity;
(d) The water level, especially during the cooling operation;
(e) The rotation speed of each container in any agitating process.

Manual operation of batch retorts can be difficult, and it requires a skilled process operator to maintain an adequate flow of cans from a bank of batch retorts. In particular, the start of the cooling operation needs particular attention, since the pressure will be changing rapidly during the initial stages. After the steam is turned off and the cooling water turned on it is necessary, in some cases, to introduce air and control the pressure of the system to match the differential pressure on the can, to prevent irreversible distortion. This is a particular case where pneumatically or electrically operated control valves are useful.

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Food Engineering Series, DOI 10.1007/978-3-319-24904-9_21

The accuracy of measurements must be considered and the effects of a change of temperature appreciated. For example, if the thermometer is incorrectly calibrated and gives a reading of 121 °C when the actual temperature is only 120 °C, then the process will be of 20 % lower lethal value. Similarly, failure to measure the process temperature correctly can lead to errors. In sterilization operations any shortfall in the time allowed can lead to a sublethal process, since most of the lethality accrues during the latter part of the process.

The advantages of automatic control for the heating and cooling process are obvious. The need to be aware of fluctuations in the temperature of the process and to maintain a constant temperature is paramount to canning operations.

The UK recommendations (Department of Health 1994) require the following minimum level of instrumentation on each retort or processing system:

(a) Master temperature indicator (MTI)—platinum resistance thermometer or mercury-in-glass of suitable specification;
(b) Temperature controller—accuracy −0.5 to +1 °C;
(c) Temperature/time recording device—usually associated with (b), and should agree with (a);
(d) Pressure gauge—accuracy ±1 % of full-scale deflection;
(e) Indicating timing device—calibrated to 1 min intervals and to facilitate the correct operation of the above;
(f) Bleeds in the retort lid and the instrument pocket to ensure that air is eliminated from the system and does not interact with the steam to give a potentially lower temperature.

National codes of practice for other countries are available, e.g., for the USA, the Food and Drug Administration Regulations (FDA 1983). While these give details for many different types of retort, the principles are essentially the same for each country.

While there have been many changes in the last decade, with the development of newer types of electronic devices, it is necessary to remember that these must be calibrated to identifiable and traceable standards. The systems should also have a “fail-safe” policy associated with their operation.

21.1.2 Temperature Measurement

We now consider the main methods of measuring temperature in canning retorts.

21.1.2.1 Mercury-in-Glass Thermometers

This type of thermometer has been used on canning retorts since the beginning of retorting. The main requirements are that the stem should have a scale not less than 150 mm, which should be graduated at intervals of not more than 1 °C (2 °F) over a range of about 50 °C (100 °F), and readable to 0.5 °C (1 °F). The longer the mercury tailpiece, the more sensitive and responsive the instrument, but the more difficult to install. The minimum length is about 90 mm. In selecting this type of thermometer it is essential to make sure that the instrument has a rapid response time. Some instruments, by virtue of their design and bulb shielding, have very slow response times, and for this reason are unsatisfactory. The mercury column and the calibrations should be easily seen by the operator. Calibration of these instruments is not easy. For some time it was customary to use an oil bath and to calibrate against a calibrated NPL (National Physical Laboratory, UK) thermometer. However, it was ultimately established that the base and brass fittings of these thermometers were subject to different heat-transfer conditions when mounted on a hot radiating retort. The bulk of the thermometer when immersed in an oil bath was sufficiently great for heat to be conducted away from the oil bath at a greater rate than it could be supplied. It was therefore recommended that these thermometers should be calibrated in a steam pipe with fittings similar to those in a retort. The standard NPL thermometer was also mounted in a similar case so that the mountings of both the test thermometer and the standard were similar. This is now the accepted method of calibration in the UK, and has been proved to be most satisfactory in operation. It is important that all thermometers of this type are calibrated frequently and all the records preserved. The instrument pocket on the side of the retort should be continuously bled with a petcock during the heating operation, so that the steam is free from air.

Another system using constant temperature blocks has been developed by Cossey (1991). This can also be used on-site in factories, since it is portable.

21.1.2.2 Thermocouples

Thermocouples are widely used in the food industry for determining the temperatures in cans and for carrying out venting trials in retorts. The most common type in use is the type T, which has a temperature range from 200 to 400 °F and consists of copper and copper/nickel wires. Thermocouples are unsuitable for use as MTIs, the main problems resulting from the nonlinear temperature–voltage relationship and the problems of cold junction compensation. The practical problems of conduction errors in thermocouples have been discussed by Withers et al. (1993).

21.1.2.3 Platinum Resistance Thermometers (PRTs)

These devices consist of a sensing resistor within a protective sheath, fitted with internal conducting wires and external terminals. These are connected to a digital display unit. The sensor is a precision resistor of known temperature coefficient and consists either of a coil of wire wound on a former or a film device where platinum is deposited on a substrate. The sensing element is mounted in a stainless steel sheath, which is insulated from the sensor. The accuracy’ of these sensors must conform to certain standards, e.g., BS 1904: 1964 and 1984, and DIN 43 760: 1980. In general the resistor should have a resistance of 100 Ω at 0 °C and 138.5 Ω at 100 °C. The main advantages of PRTs over mercury-in-glass thermometers are:

(a) Digital displays are less prone to reading errors;
(b) The ability to measure temperatures in remote places and display the readings locally;
(c) The ability to replay to a secondary display, recorder, controller, or control computer;
(d) System components are interchangeable within overall measurement tolerances;
(e) The elimination of mercury and glass from the food-processing environment;
(f) Improved measurement resolution and overall measurement tolerances.

Extensive research (Bown and Slight 1980, 1982; Bown 1984) has shown that the PRTs are entirely suitable for canning retort operation. It has taken a considerable period of time, however, to convince the industry. A standard for PRTs for use in the food industry was developed by Richardson and Bown (1987). A system of calibration, using constant temperature blocks, has the advantage of being portable and can be used in factories, where the sensors may be in remote situations (Cossey 1991). Every retort is required to have a device fitted which continuously records the temperature and time during the retort operation, so that a permanent record is available for future reference, should the need arise. Various devices for doing this are available, most of them having a feedback control system to control an automatically operated control valve. Electronic recording systems, including computer control systems, are replacing older types of instruments. Whatever type of system is operated, the MTI is the absolute standard for processing operations. It is recommended, in comparing the MTI with the recorder controller, that the temperature difference should not exceed more than ±0.5 °C for a total of more than 1 min.

21.1.3 Pressure Measurement

Legislation for pressure vessels demands that every pressure vessel is fitted with a pressure-indicating device. For canning purposes the pressure gauge is used to ensure that the pressure is correct in relation to the steam temperature, so that air in the steam may be detected. It should never be used to control the temperature of the steam heating operation, but only for assisting in applying the correct cooling overpressure protocol to prevent can "peaking."

Pressure gauges are usually of the Bourdon tube type with a range of 0–2 bar, with the scale divided into 0.1 bar divisions. The pressure gauge is usually mounted adjacent to the MTI.

Pressure transducers are used with computer control systems; these are either of the strain gauge or piezo-electric crystal type. It is essential in this type of operation that the transducers are sufficiently robust to withstand the cannery environment.

Closely associated with this topic are pressure-relief valves, which must be fitted to the retort, and a steam distribution system to ensure that the safe working pressure of the retort cannot be exceeded under any operating conditions. This applies to steam, water and compressed air supplies.

21.1.4 Water Level

For manual operation of batch retorts, a sight glass is used to detect the level of water in the retort during the cooling operation. For automatic or electronic operation conductivity or capacitance, probe sensors are used. The signals from these devices are used to determine the initiation of the cooling cycle by controlling the water in venting, drain and overflow valves. Level control is also necessary in many types of cooker/cooler, especially hydrostatic cookers, where the level of water in the hydrostatic legs has to be controlled, and in hot water sterilizing retorts, where separate tanks are used to heat the water and store it during circulation.

21.1.5 Rotation Monitors

For the satisfactory operation of rotary retorts it is necessary to have devices for sensing and controlling their rotation or movement when agitated-pack processing is being used. It is particularly important during such processes that the speed of rotation is rigidly maintained at a constant rate, otherwise there is a danger of understerilization. Withers (1991) devised a can rotation counter for use in reel and spiral sterilizers (see also Saguy and Kiploks 1989; Withers and Richardson 1992).

21.1.6 Lethality Measurement

The use of direct online measurement of lethality has only been realized with the development of suitable transducers containing programmed microchips. It had been realized for many years that if it were possible to measure the temperature inside a can during processing, then the process could be continuously controlled on this signal by determining the lethality. This could only be achieved if the temperature could be measured remotely, since the possibility of leading wires into batch retorts during operation was decidedly not a practical proposition. The use of radiotelemetry and other techniques was actively progressed for many years, with regrettably limited success. A method progressed by Holdsworth (1974), based on work on analog computation of sterilization values by Overington (1975), made use of the retort temperature profile and subsequent conversion of this into a lethality value using a mathematical model (see Fig. 21.1). This was developed

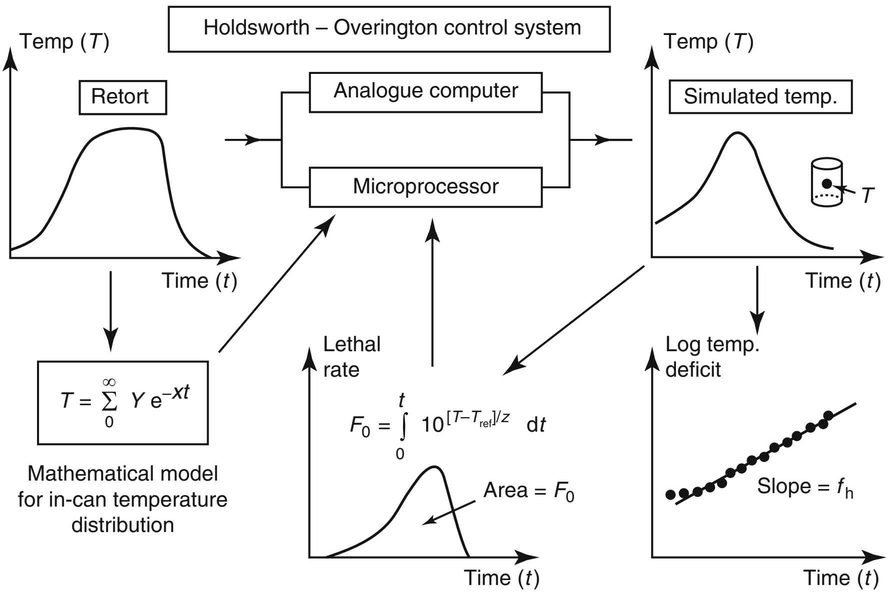

Fig. 21.1 Retort control system using process mathematical model

further by Bown (1982, 1983) using a microprocessor system; however, implementation was slow, in terms of lethality control, because of the problems of computing the lethality in real time on the available facilities.

A transducer for the direct measurement of lethal rates has been devised by David and Shoemaker (1985); the transducer, a log/antilog amplifier, has the ability to convert the voltage signal generated by a thermocouple into an exponential relationship of the lethality type. This is a simple alternative to using elaborate PCs. Many commercial retorts and experimental retort simulators have built-in computerized systems for programmed operation of the retort sequences and the simultaneous determination of achieved lethality. Current trade literature shows the ever increasing use of microelectronics for the safe operation of retort systems.

Data acquisition units have already been mentioned for determining heat penetration into cans (see Chap. 6). They may also be used for determining environmental temperatures in retorts, especially in continuous cookers. For a range of current devices, see May and Withers (1993). The design of these devices changes so rapidly with the development of new microelectronic devices that it is difficult to keep up with the new developments.

Teixeira and Tucker (1996) have discussed the development of online computer simulation control for sterilization equipment and have outlined the critical points to ensure the systems perform correctly. In particular they have stressed the need to look carefully at the factors that determine the performance of the model, e.g., the apparent thermal diffusivity, of the system.

21.2 Process Control

21.2.1 Introduction

A process control system may be entirely manual, with the process operator manipulating the control valves; semiautomatic, with, for example, the stream being controlled and the other operations manual; or fully automatic. While some batch retort operations are semiautomatically controlled, most processes are now continuously controlled, with operator supervision at a computer terminal.

There are three elements of process control: a sensor, giving either an analog or a digital output, often with a visual display of the measured variable; a control valve, often described as a final control element; and a controller to produce an output signal from a sensor input. In this section it is only possible to give a general review of the application of control systems in canning. The subject is developing very rapidly, and readers requiring more detailed knowledge should consult books on process control, e.g., Stephanopoulos (1984) and Smith and Corripio (1985).

21.2.2 Control Valves and Actuators

Control valves for automatic systems are modifications of the standard types of valve with either an electric motor or a pneumatic system to actuate the motion of the valve spindle. The valve motion may be up and down or rotary, depending on the type of response required. A large number of retorts are fitted with the simplest type of pneumatic valve with compressed air applied to a diaphragm. The method of imparting motion to a valve is known as actuation and the device as an actuator. The air signal applied to the actuator's diaphragm comes from a pneumatic controller. Electrical valve actuators often impart a rotary motion and are controlled by an electrical signal from an electric or electronic controller.

Valves may be either "on–off," e.g., gate valves, or continuously modulated types, e.g., globe valves, depending on the type of operation. For the control of the steam to a retort the valves are usually continuously modulated, so that the temperature in the retort may be finely controlled. If compressed air actuated valves are used, then it is necessary to convert the electrical input signal to a compressed air output signal. The electrical output from the controller is usually a 4–20 mA current loop and I/P (current I to air pressure P) converters are used. The output pressures are 0.2–1.00 bar, corresponding to 4–20 mA electrical current. A pressure greater than the minimum applied to the actuator diaphragm overcomes the initial force in the actuator return spring, and causes the valve to open. If the pressure fails then the valve closes and shuts down the operation. Baines (1985) reviewed the available types of valves and actuators available for the control of steam. Cossey (1988, 1990) made a practical examination of the performance of control valves used on canning retorts over a 15 month period. This showed that there was little change in the performance of the valves and system.

21.2.3 Interfaces

The interfaces between the control systems and the control valve fit into four basic categories:

(a) Digital inputs—on–off devices, e.g., relays, thermostats;
(b) Digital outputs—on–off devices, e.g., pilot solenoid valves;
(c) Analog inputs—modulating devices, e.g., temperature sensors;
(d) Analog outputs—*I*/*P* converters.

For the automatic control of retorts a selection of the above types of interface are required so that the incoming signals to the controller can be converted into the appropriate outgoing signals to actuate the valves. Analog to digital (A/D) converters are widely used to convert signals into an appropriate form.

21.2.4 Control Systems

The standard type of pneumatic controller, widely used on canning retorts, consists of a comparator device which compares the measured signal with the desired signal, and a method of regulating the output to conform with the requirements of the deviant or error signal. Several types of controller action are possible:

1. On–off control is the simplest type, but tends to produce an oscillating response.
2. Proportional (P) action has an output signal proportional to the deviation, and produces a control value which has an inherent offset and oscillating response.
3. Integral (I) action (also known as automatic reset) has an output signal proportional to the time integral of the error, and is generally used with proportional action to reduce the offset.
4. Derivative (D) action (also known as rate control) has an output proportional to the derivative of the error.

Types 3 and 4 are used in conjunction with type 2, as follows:

(a) P + I: This reduces the offset inherent in P-only control;
(b) P + D: This reduces oscillations as well as offset;
(c) P + I + D: This reduces oscillations, offset and returns the control value to a stable condition fastest.

Each of the control values can be adjusted to match the process load and conditions. The required setting values can be calculated from the theory of process control, e.g., Ziegler–Nichols procedure, or obtained by trial and error.

There are electric and electronic versions of the pneumatic controller that have the same capabilities.

21.2.5 Computer Control

21.2.5.1 Direct Digital Control

In this type of control, conventional controllers are replaced by signals generated by a digital computer. The required set points are entered into the computer directly by the operator or are created via a computer program. This type of system is becoming more widespread, but requires knowledge of the dynamics of the process to be operated.

Microprocessors have been widely used in the control of process plants; these do not have the computational power of large computers but are ideally suitable for process control of batch systems (Bown 1985a, b).

21.2.5.2 Supervisory Digital Control

This is used for more complex systems, and would include not only the retort operation but the whole of the factory operations. Again some knowledge of the dynamic behavior of the operation is required in the form of a mathematical or empirical model. The system can be used with existing types of controller or with a direct digital control system.

21.2.6 Process Dynamics

The process dynamics of a system may be studied by altering the level of one of the inputs, e.g., temperature of steam to a retort, and studying the change in temperature of the system with time, i.e., the response. This can then be modeled and an equation developed that will predict the behavior when process disturbance occurs. The nature of the change of input may be a Dirac impulse, step-function, linear ramp or a sinusoidally varying function. In general the step-function behavior is used.

One of the earliest studies was carried out by Biro (1978), who developed differential equations for the heat and material balances for a batch retort, in which jars were heated in water by steam injection. A Dirac function was used as the system disturbance in the steam flow, and the response determined using Laplace transformations (see Chap. 2). Mulvaney (1987) used a Hydrolock simulator (see Chap. 8) with a microprocessor-based control system (Mulvaney and Rizvi 1984), to study the step-response of the retort. The PI control model used was derived as a discrete algorithm, rather than in the classical linear form. The results of the simulation were shown graphically; the simulation model developed a PI control, which was controlled to within ±0.1 °C (see Mulvaney et al. 1990). More recently Alonso et al. (1993a, b) have extended the Mulvaney PI control model to quality control and retort cooling. Ryniecki and Jayas (1993) also used the step-function method to study the dynamic response of a retort with respect to the lethality delivered to the processed cans. The method was sufficiently accurate for the online prediction of lethality for use in process control. One notable aspect of the development of dynamic modeling is the effect of venting procedures and the come-up time. From venting experiments it has been shown that the response of the batch retort corresponds to a series of two first-order systems or an overdamped second-order system (del Valle and Soule 1987a, b). A simple relation for the temperature during the come-up period of the venting schedule was used by Sumer and Esin (1992).

A computer program was developed from a mathematical analysis of a Barriquand 1300 Steriflow retort in order to simulate the dynamic properties. This enables a control protocol to be established for the heat exchange system, which consists of an external heat exchanger and a horizontal over-pressure retort vessel (Loucka 1997).

A number of models for the energy distribution in retorts have also been developed, e.g., Singh (1977) and Bhowmik et al. (1985), but without studying the dynamic response.

21.3 Plant Automation: Retort Control

21.3.1 Control of Batch Retorts

21.3.1.1 Conventional Control

The main operating stages have already been listed in Chap. 8, and the typical lay-out of process valves is given in Thorpe et al. (1975). The simplest system consists of a control valve on the steam supply with a manual by-pass valve for venting. This is usually described as a semiautomatic system. The temperature of the retort is continuously measured in the pocket of the retort and the signal fed to the controller. The system may be extended by introducing further automatic valves on the steam by-pass, vent and air pressure for cooling with a single controller. Hughes (1971a, b) gives a variety of different methods of controlling retorts with increasing complexity. The problem with increasing the degree of control on batch retorts is that the cost of additional valves increases with the number of retorts and this is prohibitive for many canners; consequently, smaller canneries tend to have only the simplest steam control.

One of the important parts of the retort cycle is the control of pressure in the retort during the cooling of the cans in order to prevent the deformation of the cans, especially those with large diameters. Various strategies for controlling the pressure have been presented by Alonso et al. (1994). A microcomputer system was developed for batch retort control using digital PI (proportional + integral) control, and six retort temperature profiles were studied including 3 isothermal, sinusoidal, step and ramp retort temperature profiles (Fastag et al. 1996).

The use of oxygen analyzers (Pederson 1984; Tracey 1982) and thermostatic air vents (Felmingham and Leigh 1966) for controlling venting have been investigated; however, they are not yet recommended for commercial use.

The developments in the control of retort systems have been reviewed by Holdsworth (1983, 1985, 1988, 1989) and Richardson and Holdsworth (1989).

21.3.1.2 Computer Control

Most of the developments in the application of computer control have taken place in the 1980s with the availability of microprocessors and minicomputers. Table 21.1 shows some of the work that has been done on different aspects of computer control, mainly in the form of laboratory demonstrations. One of the first systems to be used in a UK cannery was due to Bown (1982, 1983, 1985a, b, 1986) and colleagues (see Bown and Duxbury 1986). The temperature and pressure signals from three banks of eight retorts were linked respectively with three microprocessor

Table 21.1 Some investigations into computer control of sterilizing retorts

Author(s)	System/study	Comment
Earle and Navankasattusas (1974)	Laboratory batch retort	Electrical analog of sterilization value
Navankasattusas and Lund (1978)	Laboratory batch retort	Online measurement of accomplished lethality
Getchell (1980)	General	Discussion of principles
Steele (1980a, b)	Horizontal retort	General principles
Hildenbrand (1980)	Theoretical study	Optimal temperature control
Teixeira and Manson (1982)	Theoretical study	Discussion of basic principles
Bown (1985a, b)	Three-crate batch retort	Microprocessor application
Datta et al. (1986)	Theoretical study	Online correction of process deviations
Lappo and Povey (1986)	Laboratory batch retort	Temperature deviations and errors investigated
Richardson et al. (1988)	Theoretical study	Lethality model
Gill et al. (1989)	Thermal process simulator	Online data acquisition: process deviations, lethality calculations
Bermudez de Castro A and Martinez Varela (1989)	Theoretical study	Optimal control theory
Laurenceau et al. (1991)	Hydrolock simulator	Lethality control model
Mihori et al. (1991)	Theoretical study	Control strategy for 1D heat transfer
Simpson et al. (1993)	Theoretical study	Control strategy for conduction-heating products
Ramesh et al. (1994)	Theoretical study	Optimal sterilization

units (MACSYM 350). The data from the sensors were displayed on graphics terminals and were refreshed every 3 s. Data could also be printed out for reference purposes. This commercial system was shown to be very effective in the factory environment.

The *LOG-TECH™-E System* is marketed by FMC of St. Jose, CA, and used with their retorts. LOG-TECH includes a dedicated controller system with recipe-selection system, automatic temperature deviation correction, using the Ball formula calculation and numerical estimation of the F_0-value of the process. This is linked to a host PC screen with options, including a fully graphic representation of the retort system and data logging facilities. The Numeri-CAL™ thermal process calculation model is also incorporated which can be used online for real-time predictive modeling (see Sect. 21.3.5) (Martens and Clifton 2002).

21.3.2 Efficient and General Online Correction of Process Deviations in Batch Retort

The following online control analysis has been summarized from the work done by Simpson et al. (2007). The aim of this research study was the development of a safe, simple, efficient and easy to use procedure to manage online corrections of unexpected process deviations in any canning plant facility. Specific objectives were to:

1. Develop strategy to correct the process deviation by an alternative "proportional-corrected" process that delivers no less than final target lethality, but with near minimum extended process time at the recovered retort temperature.
2. Demonstrate strategy performance by comparing "proportional-corrected" with "commercial-corrected" and "exact-corrected" process times.
3. Demonstrate consistent safety of the strategy by exhaustive search over an extensive domain of product and process conditions to find a case in which safety is compromised.
4. Estimate potential economic impact of chosen online correction strategy in terms of gains in manufacturing efficiency or productivity of a typical food cannery.

21.3.2.1 Scope of the Strategy

To reach the objectives stated above, the approach to this work was carried out in four tasks, one in support of each objective. Task 1 consisted of developing the strategy for online correction of process deviations with minimum extended process time using the method of "proportional correction." Task 2 consisted of choosing appropriate mathematical heat-transfer models for construction of the equivalent lethality curves or “look-up tables” needed for use with each respective strategy and for determining the final lethality and quality retention for each of the thousands of cases simulated in the study. Task 3 included the complex optimization search routine that was carried out to demonstrate validity and consistent safety of the strategy. The fourth and final task was to estimate the impact on plant production capacity of alternative corrected process times used in response to the same frequency and type of deviations occurring annually in a typical cannery. Methodology employed in carrying out each of these tasks is described in greater detail below.

Task 1: Proportional Correction Strategy Development

The objective for the strategy required in this task was to accomplish an online correction of an unexpected retort temperature deviation by an alternative process that delivers final target lethality, but with minimum extended process time at the recovered retort temperature. This would be accomplished with use of the same alternative process “look-up tables” that would normally be used with currently accepted methods of online correction of process deviations, but with a “proportional correction” applied to the alternative process time that would reduce it to a minimum without compromising safety. In order to fully understand this strategy, it will be helpful to first review the currently accepted method that is in common practice throughout the industry. Commercial systems currently in use for online correction of process deviations do so by extending process time to that which would be needed to deliver the same final lethality had the entire process been carried out with an alternative lower constant retort temperature equal to that reached at the lowest point in the deviation. These alternative retort temperature–time combinations that deliver the same final process lethality (F_0) are called equivalent lethality processes. When these equivalent time-temperature combinations are plotted on a graph of process time versus retort temperature, they fall along a smooth curve called an equivalent lethality curve. These curves are predetermined for each product from heat penetration tests and thermal process calculations carried out for different retort temperatures.

In practice, the new process times obtained from these curves at such low alternative temperatures can be as much as two or three times longer than the originally scheduled process time required to reach the same final target lethality, resulting in considerable quality deterioration and costly disruption to scheduled retort operations. Nonetheless, these systems are versatile because they are applicable to any kind of food under any size, type or container shape, as well as mode of heat transfer (Larkin 2002). These consequences are particularly painful when, as in most cases the deviation recovers quickly, and the alternative extended process time is carried out at the recovered original retort temperature. Canned food products subjected to such “corrected” processes become severely over processed, with final lethalities far in excess of that required and quality deterioration often reaching levels below consumer acceptance, a safe correction, but by no means optimal or efficient (Alonso et al. 1993a; Von Oetinger 1997). To avoid these painful corrections processors normally operate at retort temperatures 3–4 °C over the registered retort temperature.

$$t_{\mathrm{D}} = t_{\mathrm{TRT}} + \sum_{i=1}^{n} \left(t_{\mathrm{D}_i} - t_{\mathrm{TRT}}\right)\left(\frac{\Delta t_i}{t_{\mathrm{TRT}}}\right); \quad t_{\mathrm{D}_i} \geq t_{\mathrm{TRT}}$$

The "proportional-correction" strategy developed in this research significantly avoids such excessive over processing by taking advantage of the short duration of most recovered retort temperature deviations, and the lethality delivered by carrying out the corrected process at the recovered retort temperature. The strategy will calculate the corrected process time (t_{D}) as a function of the temperature drop experienced during the deviation, but also the time duration of the deviation. The following expression illustrates mathematically how this "proportional-corrected" process time would be calculated for any number (n) of deviations occurring throughout the course of a single process:

$$t_{\mathrm{D}} = t_{\mathrm{TRT}} + \sum_{i=1}^{n} \left(t_{\mathrm{D}_i} - t_{\mathrm{TRT}}\right)\left(\frac{\Delta t_i}{t_{\mathrm{TRT}}}\right); \quad t_{\mathrm{D}_i} \geq t_{\mathrm{TRT}}$$

Where

n: Number of deviations occurring during the process.
t_{D}: Corrected process time.
t_{TRT}: Preestablished process time at retort temperature TRT.
Δt_i: Duration of deviation i.
$t_{\mathrm{D}i}$: Process time at the deviation temperature TRT_i
TRT_i: Lowest temperature during the deviation i.
TRT: Retort temperature.

For example, in the case of a single deviation, the corrected process time would be calculated by first finding the alternative process time that would be required to deliver the same final lethality had the entire process been carried out with an alternative lower constant retort temperature equal to that reached at the lowest point in the deviation (t_{D}). This would be done by use of the equivalent lethality process curve or look-up table described earlier. The difference between this longer alternative process time and the originally scheduled process time ($t_{\mathrm{D}} - t_{\mathrm{TRT}}$) is the extra time that would normally be added to the original process time to correct the process according to current industry practice. However, in the new strategy proposed here, this extra process time differential ($t_{\mathrm{D}} - t_{\mathrm{TRT}}$) is multiplied by a proportionality factor consisting of the ratio, [time duration of the deviation]: [originally scheduled process time], or expressed mathematically as ($\Delta t/t_{\mathrm{TRT}}$). This proportionality factor is always less than or equal to one and always results in a corrected process that delivers no less than the final target lethality specified for the original process, but with near minimum extended process time.

The logic behind this “proportional-correction” strategy stems from the following rationale:

- The current industry practice is necessary only when the deviation fails to recover, and retort temperature remains at the lowest point for the duration of the process.
- This practice is unnecessary when the deviation recovers and processing resumes at the original scheduled retort temperature over the “corrected” extended time.
- If the extended process time is chosen to be in proportion to the duration of the deviation as a fraction of original scheduled process time, we are making the assumption that the amount of lethality lost during the deviation duration time is the amount that would have accumulated at retort temperature.
- In reality, this amount of lost lethality is much less, since the actual retort temperature had fallen during the deviation to some lower level where lethality would accumulate at a slower rate.
- Therefore, the “proportional-correction” should always deliver total final lethality greater than that originally specified for the scheduled process.
- With the implementation of this novel and efficient online strategy it will be unnecessary for processors to operate at higher retort temperatures.

Task 2: Performance Demonstration

This task consisted of demonstrating the performance of these strategies by simulating the occurrence of process deviations happening at different times during the process (early, late, and randomly) to both solid and liquid canned food products, calculating the alternative corrected process times, and predicting the outcomes of each corrected process in terms of final lethality and quality retention. For each deviation, three different alternative corrected process times were calculated:

- “Exact correction,” giving corrected process time to reach precisely the final target lethality specified for the scheduled process, using computer simulation with heat transfer models;
- “Proportional-correction,” using the strategy described in this research with look-up tables; and,
- “Commercial correction,” using current industry practice with look-up tables (manually or computerized).

The heat transfer models were explicitly chosen to simulate the two extreme heat-transfer cases encountered in thermal processing of canned foods. The rationale behind this decision was that canned foods possess heating characteristics between these two extreme situations. Conclusions extracted from these simulations will be extended to all canned foods. First was the case of pure conduction heating of a solid product under a still-cook retort process. The second was the case of forced convection heating of a liquid product under mechanical agitation. In both cases, the container shape of a finite cylinder was assumed, typical of a metal can or wide-mouthed glass jar. However, suitable models appropriate for a true container shapes can be used as required for this purpose. Examples of such models can be

Table 21.2 Product and process conditions used for online correction strategy simulations

Product simulated	Dimensions (cm)			Properties		Normal process	
	Major	Intermedium	Minor	alfa (m^2/s)	f_h	Time (min)	TRT (°C)
Pure conduction can							
Biot > 40	11.3	–	7.3	1.70E−07	44.4	64.1	120
Forced convection can							
Biot < 1	11.3	–	7.3	–	4.4	15.6	120

Table 21.3 Problem domain for search routine

Process variable	Description of process variable	Minimum value	Maximum value
TRT	Scheduled Retort Temperature	110 °C	135 °C
TRT_i	Lowest retort temperature reached during deviation *i*	100 °C	TRT—0.5 °C
t_{CUT}	Initial come up time of retort to reach TRT	5 [min]	15 [min]
$t_{\mathrm{dev}-i}$	Time during the process at which the deviation *i* begins	t_{cut}	t_{TRT}
t_i	Time duration of the deviation *i*	0.5 [min]	$t_{\mathrm{TRT}} - t_{\mathrm{dev}-i}$
T_{ini}	Initial product temperature	20 °C	70 °C

found in the literature (Teixeira et al. 1969; Manson et al. 1970; Manson et al. 1974; Datta et al. 1986; Simpson et al. 1989, 2007). The product and process conditions chosen to carry out the demonstrated simulations for each case are given in Table 21.2.

Task 3: Demonstration of Safety Assurance by Complex Optimization Search Routine

This online correction strategy was validated and tested for safety assurance by executing a strict and exhaustive search routine with the use of the heat-transfer models selected in Task 2 on high-speed computer. The problem to be solved by the search routine was to determine if the minimum final lethality delivered by all the corrected processes that could be found among all the various types of deviations and process conditions considered in the problem domain met the criterion that it had to be greater than or equal to the lethality specified for the original scheduled process. This criterion can be expressed mathematically:

$$\underset{\mathrm{U}}{\mathrm{Min}} \left\lfloor F_{\mathrm{proportional}} - F_{\mathrm{Tol}} \right\rfloor \geq 0$$

Where

$F_{\mathrm{proportional}}$: F-value calculated with the proportional correction
F_{TOL}: F-value specified for normal scheduled process
U: Universe of feasible process conditions in search routine

Table 21.3 identifies the various types of deviations and process conditions that were explored and evaluated in the search routine (problem domain). The search routine was designed as an attempt to find a set of conditions under which the required search constraint was not met. The table gives the symbol used to represent each variable and a description of that variable, along with the minimum and maximum values limiting the range over which the search was conducted.

Task 4: Economic and Quality Impact of Online Correction Strategy
The purpose of this task was to estimate the impact on plant production capacity of alternative corrected process times used in response to the same frequency and type of deviations occurring annually in a typical cannery. The rationale behind Task 4 stems from the realization that every time a process deviation is corrected in this way with any given retort in the cook room of a canning factory, the number of batches processed that day will be less than normal capacity, which can be translated into cost of lost productivity over the course of a canning season. This can be approached mathematically with the algorithm described below.

The following expression allows the calculation of the number of batch per autoclave at the processing plant:

$$N_{\mathrm{Bi}} = \frac{H}{t_{\mathrm{ci}} + t_{\mathrm{o\,j}} + t_{\mathrm{di}}} \tag{21.1}$$

Where:

N_{Bi}: Number of batches processed per retort i during the season.
H: Operating time of the plant during the season (h)
t_{ci}: Time to load retort i with product j (h)
t_{oj}: Time to operate retort i (process cycle time) with product j (h)
t_{di}: Time to download retort i with product j (h)

To simplify the analysis and to be able to have an estimate of the impact of operating time on plant production capacity, the following assumptions were made:

(a) The plant has N_{A} retorts and all of them are of equal size.
(b) The number of containers (units) processed in each retort is the same ($N_{\mathrm{CBi}} = N_{\mathrm{CB}}$)
(c) The plant is processing a single product ($t_{\mathrm{oj}} = t_{\mathrm{o}}$; $t_{\mathrm{ci}} = t_{\mathrm{c}}$ and $t_{\mathrm{di}} = t_{\mathrm{d}}$)

Therefore, the total number of units that can be processed in the whole season (N_{t}) can be expressed by the following equation:

$$N_{\mathrm{t}} = \frac{N_{\mathrm{A}}^{*} N_{\mathrm{cB}}^{*} H}{t_{\mathrm{c}} + t_{\mathrm{o}} + t_{\mathrm{d}}} \tag{21.2}$$

According to Eq. (21.2) an extension in process time (t_{o}) will decrease plant production capacity (N_{t}). In addition, considering processing time as a variable and utilizing Eq. (21.2), it is possible to quantify the impact of processing time in terms of plant production capacity. Another way to assess the impact of the adopted strategy will be to consider that processors are operating at much higher retort temperature to avoid deviant processes. For the purposes of analysis it was considered that processors operate each batch process at a temperature that is 2–3 °C (common practice in the USA, although some plants even operate at higher temperatures) higher than the registered process, and with this practice processors are completely avoiding deviant processes. As was mentioned before the product and process conditions chosen to carry out the simulations to evaluate the impact on product quality are given in Table 21.3.

This research has described a practical, simple and efficient strategy for online correction of thermal process deviations during retort sterilization of canned foods. The strategy is intended for easy implementation in any cannery around the world. This strategy takes into account the duration of the deviation in addition to the magnitude of the temperature drop. It calculates a "proportional" extended process time at the recovered retort temperature that will deliver the final specified target lethality with very little over processing in comparison to current industry practice. Results from an exhaustive search routine using the complex method support the logic and rationale behind the strategy by showing that the proposed strategy will always result in a corrected process that delivers no less than the final target lethality specified for the originally scheduled process. Economic impact of adopting this strategy over that currently used in industry practice can be a significant increase in production capacity for a typical cannery, as well as, canned products that are of much higher quality.

21.3.3 Control of Hydrostatic Sterilizers

The general features of a hydrostatic sterilizer were discussed in Chap. 8. The steam flow to the central sterilizing chamber is regulated by a controller, which uses the temperature measured in the sterilizing chamber, about half way up the side. Two other controllers are used to control the feed leg and the discharge leg, with temperatures measured near to the base of the feed leg. A fourth controller measures the level of water in the sterilizing chamber and maintains it at a constant level; this also sets the levels in the hydrostatic legs. The control system provides a fresh supply of water to the incoming level and operates a drain valve at the base of the discharge leg. When there is an additional spray cooling section to the sterilizer, the flow of fresh cooling water is regulated by the temperature at the base of the second cooling section.

Guidelines for the operation of hydrostatic sterilizers have been produced by Austin and Atherton (1981, 1984a, b). Recently has been published an interesting paper analyzing the online control of hydrostatic sterilizers (Chen et al. 2008).

21.3.4 *Control of Continuous Reel-and-Spiral Pressure Cookers*

The initial stages of venting and come-up of continuous cooker/coolers are done without any containers going through the system. The cookers are fitted with several vent valves and lines (5 cm diameter pipes). The venting cycle depends on the size of the units and steam flows, but is usually of the order of 6–8 min to a temperature of 105 °C with the vent valves wide open and the drain valve partially open. An alternative labor-saving method involves only the use of the bleeders, drain and purge lines, rather than the main vent valves (Adams et al. 1985). The temperature is regulated by automatic PID controllers and measured by thermocouples in the shell of the cooker and the cooler, and the flow of steam and water regulated accordingly. Bratt et al. (1990) have produced detailed guidelines for the operation of reel-and-spiral cooker/coolers.

21.3.5 *Derived-Value Control*

Figure 21.1 shows a sequence of operations that could be used to control a process based on the lethality developed in the product (Holdsworth 1974, 1983, 1985). Essentially the cooling cycle would be activated when the heating cycle had produced a specified F-value. The system would require knowledge of the temperature–time relationship as measured at the point of slowest heating in the food in the container. This could only be obtained, under commercial processing conditions, by calculation from known heating characteristics of the pack. In the computer system developed by Bown (see Sect. 21.3.1.2), it was originally intended that this type of calculation would be carried out, and the microprocessor would implement a control strategy based on the mathematically derived F-value. At the time of installation this was not possible because the program running this part was too slow. Consequently, to use this type of derived value control it is necessary to be able to compute temperatures in real time. One of the important advantages of this type of system is to be able to deal with process deviations and to make judgements on the need for further processing or otherwise.

The technique has been developed further and extended to the control of hydrostatic cookers (Scott 1992). An important conduction-heating model, which can be used for any j-value, has been developed (Teixeira et al. 1992; Teixeira and Tucker 1997). A method of dealing with process deviations using online retort control has been discussed by Akterian (1999). Optimal control theory has been used to develop a model to determine the optimum retort temperature for conduction-heating retort pouches, which involves a 1-D heat conduction model (Terajima and Nonaka 1996). An account of the application of control strategies to thermal processing operations has been presented by Ryniecki and Jayas (1997). A sophisticated closed-loop receding horizon optimal control system has been developed for controlling the temperature profile, which will minimize costs and loss of quality (Chalabi et al. 1999). The problems of retro fitting retorts for online control have been discussed by Kumar et al. (2001). The system was used for the retorting of canned vegetables, and the results showed that using the online system the process time could be reduced from 17 to 33 %.

21.3.6 Guidelines for Computer Control

The NFPA (2002) in the USA have published revised guidelines for the validation of computer control systems. Whereas the original *Bulletin 43L* dealt with aseptic processing systems only, this edition includes retort processing. The object of the current procedures is to establish documented evidence that provides a high degree of reassurance that a specific process or system will produce a product meeting its predetermined specifications and quality attributes. It includes life-cycle definition and planning, system design and development, system qualification, system operation, maintenance and ongoing verification, system security requirements, and documentation (Deniston 2004).

21.4 Plant Automation: Industrial Automation of Batch Retorts

Many of the most recent advances made in the design of industrial batch retorts has come about in response to the increasing popularity of flexible retort pouches and retortable semirigid microwavable plastic dinner trays and lunch bowls. These flexible and semirigid containers lack the strength of traditional metal cans and glass jars to withstand the large pressure differences experienced across the container during normal retort operations. To safely process these types of flexible packages, careful control of overriding air pressure is needed during retort processing, and pure saturated steam, alone, cannot be used as the heat exchange medium. Instead, new retorts designed to be used with pressure-controlled steam–air mixtures, water spray, or water cascade have been recently developed for this purpose (Blattner 2004). Examples of some of these new retort designs are given in Fig. 21.2. A close-up view of some of the specially designed racking configurations used to hold flexible retortable packages in place during retorting is shown in Fig. 21.3.

Perhaps the most significant advances made in the food canning industry to date have been in the area of automated materials handling systems for loading and unloading batch retorts. Traditionally, the loading and unloading of batch retorts has been the most labor-intensive component in food canning factories. Unprocessed sealed containers would be manually stacked into baskets, crates or

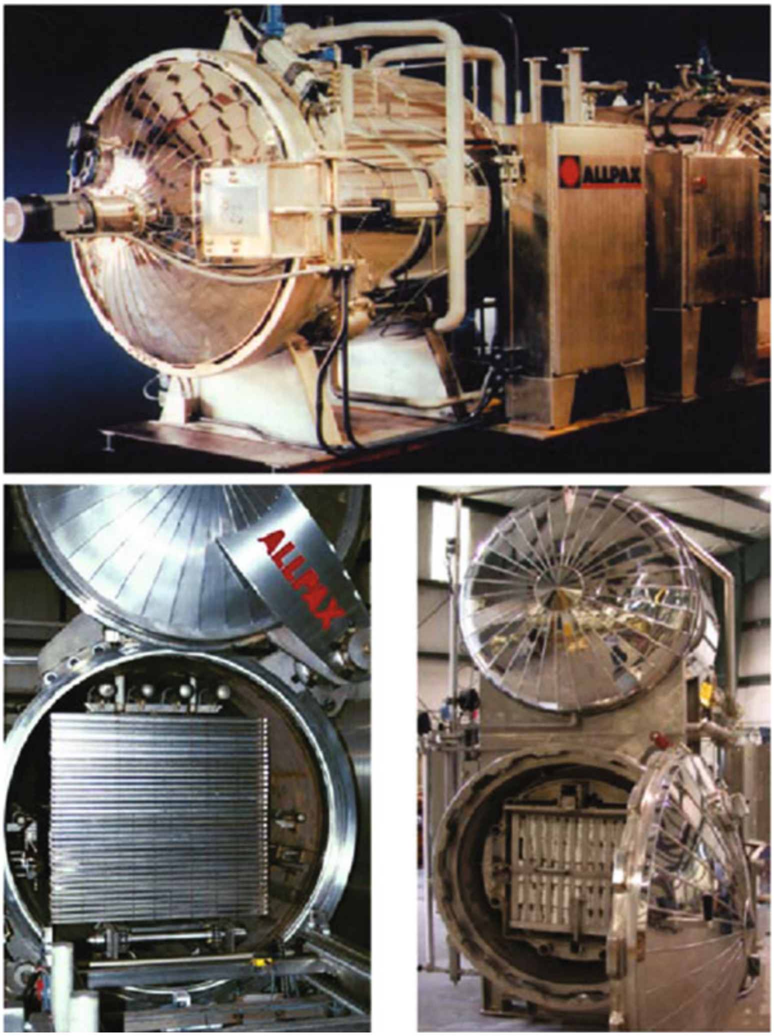

Fig. 21.2 New retort systems (rotating and still-cook) with specially designed racking configurations for processing flexible and semirigid packages (Courtesy of ALLPAX, Covington, LA)

carts. Then, the baskets or crates would be loaded into empty vertical retorts with the aid of chain hoist, or wheeled carts would be loaded into horizontal retorts with the aid of track rails for this purpose. In recent years leading manufacturers of retort systems have been hard at work designing and offering a host of new automated materials handling systems to automate this retort loading and unloading operation.

Most of the new automated systems available to date are based on the use of either automated guided vehicles (Heyliger 2004), or orthogonal direction shuttle systems (Blattner 2004; Heyliger 2004). Both types of systems are designed for use with horizontal retorts. The automated guided vehicles (AGV) work like robots.

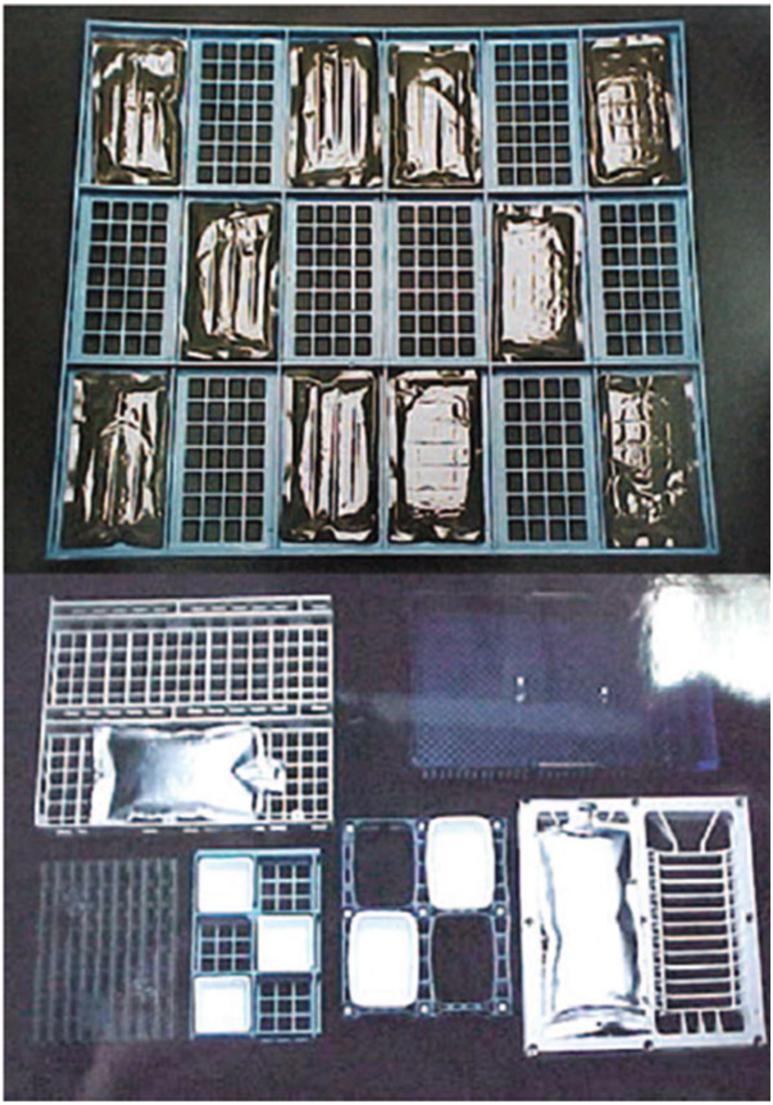

Fig. 21.3 Rack designs for flexible and semirigid retortable packaging systems (Courtesy, ALLPAX, Covington, LA)

They carry the loaded crates of unprocessed product from the loading station to any designated retort on the cook room floor that is ready to be loaded. They also carry the loaded crates of finished processed product from the unloaded retort to the unloading station for discharge as out-going product exiting the cook room to the case-packing operations. These robotic AGV's are designed to integrate with the loading station in such a way that sealed product containers arriving on a

Fig. 21.4 Automated batch retort system with use of automated guided vehicles in large Cook room operation (Courtesy, FMC Food Tech., Madera, CA)

conveyor automatically stack into the crate carried by the AGV, which later inserts the entire crate into the designated retort.

Unloading at the unloading station for finished product discharge is likewise accomplished in a similar automated way, but in reverse. The AGVs are guided by an underground wire tracking system buried beneath the cook room floor. This leaves the cook room floor space open and free of any rail tracks or guide rails that would otherwise impede the safe movement of factory workers in their normal work flow operations. A panoramic view of a large cook room operation using an automated batch retort system with automated guided vehicles is shown in Fig. 21.4 (Heyliger 2004), and a close-up view of an automated guided vehicle in the process of loading or unloading a horizontal retort is shown in Fig. 21.5.

An alternative to the automated guided vehicle (AGV) system is the shuttle system offered by several retort manufacturers. Unlike the AGV system, the shuttle system relies upon a set of tracks or rails that are fixed in place on the cook room floor. These rails span the length of the cook room along the row of horizontal retorts, allowing a shuttle carrying loaded crates to slide along these rails until it has aligned itself in front of the designated retort waiting to be loaded. In a similar fashion, when a retort is ready for unloading, an empty shuttle slides along these rails until it has aligned itself with that retort to receive the loaded crates of processed product. Then the shuttle slides along the rails to the far end of the cook room where unloading of processed product takes place for discharge out of the cook room. Normally, the unprocessed product loading station and the processed product unloading stations are located at opposite ends of the cook room (Fig. 21.6). Figures 21.7 and 21.8 illustrate the shuttle systems offered by ALLPAX and FMC, respectively.

Fig. 21.5 Automated guided vehicle for batch retort loading/unloading (Courtesy, FMC Food Tech., Madera, CA)

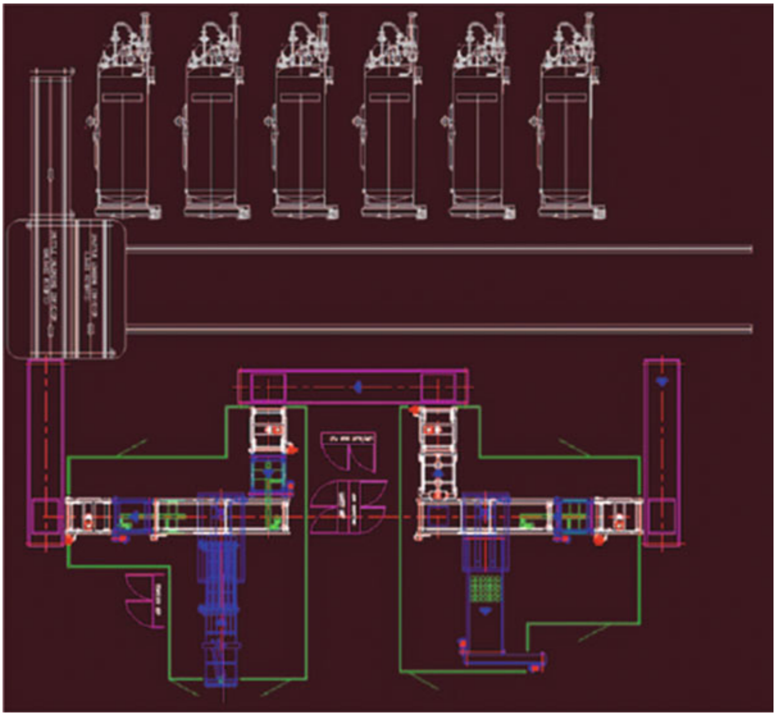

Fig. 21.6 Automated shuttle-based batch retort control system (Courtesy, ALLPAX, Covington, LA)

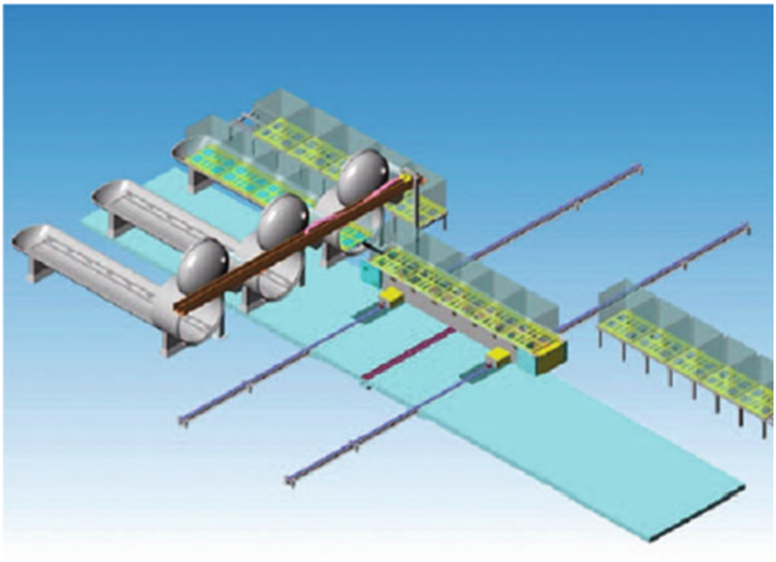

Fig. 21.7 Automated shuttle batch retort system (Courtesy of ALLPAX, Covington, LA)

Fig. 21.8 FMC shuttle system for automated batch retort loading/unloading (Courtesy, FMC Food Tech., Madera, CA)

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Part V
Innovative Thermal Food Processing

Chapter 22
High-Pressure Thermal Sterilization (HPTS) and Ohmic Heating (OH) Applied to Thermal Food Processing

22.1 Introduction

The traditional thermal processing method for food preservation has the main objective of extending the food shelf life and guaranteeing food safety by the reduction of pathogen microorganism and spores. However, the application of heating to cans or bottles can produce a detrimental food quality, especially through the reduction of nutrients, texture, and color, due to the slow heating and cooling rate (Matser et al. 2004).

For these reason, many researchers are focused on the development of technologies that improve the heating rate and thus reduce dwell times and lower the thermal load on the product. For this purpose, high-pressure thermal sterilization (HPTS) and ohmic heating (OH) are two promising technologies focused on lowering the processing time through a faster increase in the heating rate of the food and thus increase the food quality and nutrient retention.

In the next section, we describe both methods and their application in thermal food processing.

22.2 High-Pressure Thermal Sterilization (HPTS)

The use of high pressure at high temperatures as a tool for sterilization may lead to benefits in terms of food safety and food quality compared to conventional thermal processing (Leadley et al. 2008; Mártinez-Monteagudo et al. 2012; Sevenich et al., 2014). The combination of high pressure and high temperature results in a promising technology called high-pressure thermal sterilization (HPTS), which through synergistic effects of elevated temperature (90–121 °C) and pressure above or equal to 600 MPa can rapidly achieve adequate inactivation of endospores (Sevenich et al., 2014).

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Sterilization with high pressure is interesting due to the combined effect of pressure and temperature resulting in adiabatic heating, uniform temperature distribution, and relatively short treatment times. Adiabatic heating is the uniform temperature increase within the product, which is solely caused by pressurization (Matser et al. 2004).

The magnitude of the temperature rise is determined by the initial product temperature, and the thermophysical properties of the product are described in the following equation:

$$\frac{\mathrm{d}T}{\mathrm{d}p} = \frac{\alpha T}{\rho C_{\mathrm{p}}} \tag{22.1}$$

where T is temperature (K); p is pressure (Pa); α is the volumetric expansion coefficient (1/K); ρ is density (kg/m^3); and C_{p} is specific heat (J/kg K).

Equally, upon the removal of pressure, cooling is also rapid: this phenomenon could, in theory, reduce process times and improve food quality (Leadley et al. 2008). Therefore, the successful use of compression heating can result in reduced processing time and, as a consequence, higher quality and lower energy consumption (Wilson et al. 2008). For example, Leadley et al. 2008 showed that the application of high-pressure sterilization significantly improved the firmness of green beans compared with canned samples ($F_0 = 3$ min), being twice as high in the case of pressure treatment with a peak value of 6.8 N (canned green beans 2.5 N). Mártinez-Monteagudo et al. (2012) studied the retention of conjugated linoleic acid in milk using HPTS processing and conventional thermal sterilization. Their results showed a strong effect of pressure applied to linoleic acid retention. For example, at 100 MPa, conjugated linoleic acid was relatively stable up to 14 min of treatment regardless of the temperature (60, 90 or 120 °C) with retention ranging between 76 and 85 %. However, the retention values were strongly reduced when the samples were heated at 90 and 120 °C and pressurized at 350 MPa. Moreover, retention of 3 % was obtained with operational conditions of 120 °C and 600 MPa. According to Mártinez-Monteagudo et al. (2012), three reaction steps could be affected by pressure and temperature: (1) pressure could promote homolysis and free radical reactions, which favor the oxidation of linoleic acid; (2) dissolved oxygen at high pressure becomes more reactive; (3) pressure affects the milk protein, producing leaching of complexed metals, such as Zn, Fe, and Cu, that might catalyze oxidation reactions. Therefore, pressure and temperature produce a loss of acid linoleic by oxidation reactions catalyzed by free metals ions released during pressure processing.

Foods are multicomponent materials, and therefore many food properties are unknown or have estimated values for a specific range of temperature, pressure, and water content. For example, Barbosa-Cánovas and Juliano (2008) showed that compression heating rates are highly dependent on food composition. Thus, the compression heating rate of fats and oils can be up to three times higher than for water (Fig. 22.1).

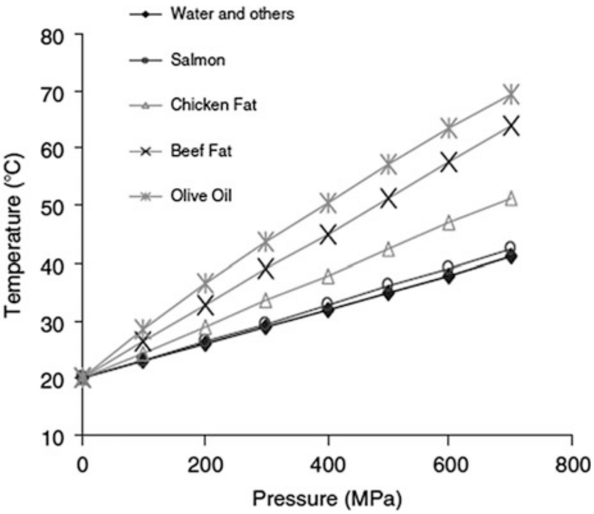


Fig. 22.1 Temperature elevation from room temperature due to pressurization up to 700 MPa (from Barbosa-Cánovas and Juliano 2008)

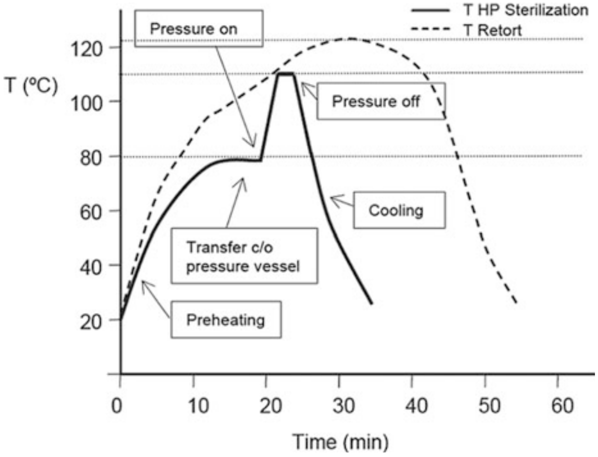
Depending on the food system, the temperature increase can range from 3 to 9 °C per 100 MPa (Mártinez-Monteagudo et al. 2012; Sevenich et al., 2014). Therefore, the product needs to be preheated to 70–90 °C, and through internal compression heating, during the pressure increase, the processing temperature can reach 90–130 °C (Sevenich et al. 2013). Several papers indicate that there is a synergistic effect between temperature and pressure on spore inactivation (Reineke et al. 2011; Wimalaratne and Farid 2008). However, some spore strains such as *Bacillus subtilis* or *Geobacillus stearothermophilus* are more resistant under specific pressure–temperature conditions (Reineke et al. 2013).

The mechanism by which pressure performs spore inactivation has been previously studied (Reineke et al. 2013; Silva et al. 2012; Reineke et al. 2011; Ramaswamy et al., 2010; Seim et al. 2015). When food is preheated at moderate temperatures (>60 °C) and then high pressure is applied, the inactivation of spores can proceed mainly via the delivery of dipicolinic acid (DPA) due to high pressure. Generally, the release of DPA occurs in parallel with the activation of lytic enzymes, which are responsible for degradation of the cortex. Thus, spore resistance could depend on the ability to retain DPA. Thus, DPA release is the first indicator for pressure-induced loss of heat resistance and the rate-limiting step for successful spore inactivation in a high-pressure thermal sterilization process (Reineke et al. 2013).

However, this technology has not been implemented in food industry. According to Sevenich et al. (2015), there are three reasons for the non-implementation of HPTS at the industrial scale:

1. There is no sterilization indicator microorganism to guarantee the required inactivation of pathogenic and spoilage bacteria spores.

Fig. 22.2 Typical product temperature profiles in a retort and PATS process. Processing steps during pressurization. (From Barbosa-Cánovas and Juliano 2008)



2. Food ingredients such as sugar, fats, salts and water activity can act as baroprotector agents of microorganisms, and therefore spore inactivation could be retarded or simply produce incomplete inactivation.
3. The temperature distribution in the food must be homogeneous to ensure the inactivation of the microorganisms and enzymes. For high-pressure processing, the only variable that could lead to nonuniformity during the processing is the temperature. This issue has been observed in a horizontal industrial-scale high-pressure system where the temperature treatment chamber varied by 10 °C between the bottom and the top of the chamber.

The only process within the HPTS that was certified by the U.S. FDA in 2009 is the so-called pressure-assisted thermal sterilization (PATS), which is basically a process where pressure is used to produce rapid and homogeneous heating in food until it reaches the sterilization temperature (Sevenich et al. 2015). PATS involves the use of moderate initial chamber temperatures between 60 and 90 °C, and through internal compression heating at pressures of 600 MPa or greater, in-process temperatures can reach 90–130 °C. PATS offer shorter processing times than typical or advanced retorting processing and therefore can result in even better quality products (Barbosa-Cánovas et al. 2014) (Fig. 22.2).

22.3 Ohmic Heating for Thermal Sterilization (OH)

Ohmic heating is basically a process in which an electric current is passed through the food to induce internal heating due to the resistance offered by the food to the passage of current. This current flow also induces an electric field that produces a non-thermal effect of this process.

Ohmic heating has potential as an alternative heating technology because its capability to produce rapid heating in the food makes it possible to avoid overheating and therefore improve the food quality compared with a traditional heating process. As heat is generated and distributed internally in the food, ohmic heating can achieve close to 100 % energy transfer efficiency and therefore eliminates the need for an external heat transfer medium and surfaces that are associated with conventional heating technologies (Somavat et al. 2012a).

Ohmic heating is generally applied to foods that contain a sufficient amount of water and electrolytes to allow the passage of electrical current. Many factors can affect the heating rate of foods during ohmic heating, including electrical conductivity, specific heat, elements associated with food structure (e.g., particle size and shape and orientation in the electric field) and solute concentration (Knirsch et al. 2010; Zareifard et al. 2003).

Generally, a food is a complex, anisotropic, and multicomponent matrix; thus, it is necessary to consider that the overall resistance of the food will control the heating rate under ohmic heating conditions (Zareifard et al. 2003). Homogeneous cooking is highly dependent on how food components are organized in the food structure. For example, Zareifard et al. (2003) studied the effect of ohmic heating in multiphase food carrot–starch mixtures, finding that particle size and concentration influenced the heating time and the overall electrical conductivity of the multiphase food. The distribution of heat into the food is faster than with conventional methods, which helps to maintain the flavor and texture of the food (McKenna et al. 2006).

However, the transfer of heat in the product will be highly dependent on the properties of the materials used. Two models have been developed to describe heat transfer during ohmic heating of a solid into a liquid: the De Alwis-Fryer model and the Sastry-Palaniappan model. The first was proposed by De Alwis and Fryer (1990). This model uses the solution to the Laplace equation to calculate a heat generation rate with a transient energy balance during the application of an electric field along the tube into a single cylindrical particle that is localized in the middle of a tube filled with a non-convecting fluid.

The second model was proposed by Sastry and Palaniappan (1992): in this model, the electric current and heat generation for a system that is static and perfectly agitated is summarized in an electrical circuit, and this circuit yields the effective electrical resistance of the cell. A comparison of the two methods by Sastry and Salengke (1998) confirms the importance of the differences in conductivity between the liquid and the solid when developing the model. If the conductivities of both phases are equal, both models yield similar results. In the event that the electrical conductivity of the solid phase is less than for the liquid phase, the model proposed by Sastry and Palaniappan (1992) proves to be more conservative and safer than the model proposed by De Alwis and Fryer (1990). When the solid particle is less conductive than the liquid medium (static), the area around the borders of the particle is overheated, with a slow warming of the ends (front and back) of the particle. This effect generally results in rapid and nonhomogeneous heating. Using agitation under the same conditions prevents overheating of the sides of the particle; therefore, the ratio of net heat transfer is lower, and the particle is heated slowly and uniformly (Sastry and Salengke 1998).

The application of OH as a cooking system in a meat matrix has been widely studied and compared with traditional cooking (Bozkurt and Icier 2010). For example, Shirsat et al. (2004) found that OH did not affect the chemical composition of meat compared to traditional treatment with steam cooking. Moreover, the cooking time required by OH to reach the maximum temperature was significantly shorter, with a faster heating rate and great power absorption in the cooking time (Bozkurt and Icier 2010). For this reason, cooking losses are lower, and as a result the meat is juicier (Zell et al. 2009). Additionally, significant changes in texture are not perceived compared to traditional cooking (Shirsat et al. 2004; Zell et al. 2009). However, the springiness values are significantly lower, suggesting that the samples do not recover their original shape after compression to the same extent as steam-cooked samples, indicating a less elastic and soft structure in ohmically heated samples. Shirsat et al. (2004) attributed these changes to a structural phenomenon in which the protein–protein interactions predominate over the protein–water interactions due to the rapid cooking of processed material with OH. Because the formation of a sorted array of protein–water–protein is less likely, the effect of the "mattress" given by the incompressible nature of water is lost. Zell et al. (2010) attributed this effect of OH on the texture to the rapid heating, causing less myofibrillar coagulation and less collagen gelation, which affects the ability to bind and entrap water within the cooked meat.

Moreover, the homogeneity of OH cooking is strongly influenced by the distribution of electrolytes in the sample. To assess this distribution, Zell et al. (2009), applied three strategies to incorporate electrolytes into the meat matrix: center injection, soaking, and multi-injection with "in bag" tumbling step, showing that multi-injection produced a better distribution of salt within the meat with the concentration differences between the center and outer regions of 0.08–0.03 %, and thus more uniform cooking of the entire sample was achieved. Considering the importance of incorporating homogeneous electrolyte in the matrix, the application of technologies such as vacuum impregnation may be advantageous to access more internal areas and thus improve the OH cooking. Furthermore, there must be special regard for the type of cut to which OH is applied, mainly from the structural perspective, which determines the ease with which the electrolyte in the sample can migrate to deeper areas.

Some studies have suggested that OH could have a significant impact on food sterilization. The results for the sterilization of milk indicate that OH was able to achieve similar results to conventional methods, in terms of both cell inactivation and protein content. It is also important to emphasize the non-thermal effect on the OH product due to the induced electric field at the microscopic level that promotes cell inactivation, which depends on the electric current and the applied frequency (Sun et al. 2008). Other researchers have explained the phenomenon of the non-thermal inactivation of microorganisms based on the expulsion of intracellular proteins into the medium through cell membrane permeabilization, which is enhanced with increasing electric potential (Yoon et al. 2002). OH is classified as a purely thermal process, mainly because of an inadequate understanding of the non-thermal effect of electricity on microorganism (Somavat et al. 2013).

The non-thermal effect is attributed to electroporation of the membrane cells. For electroporation, the cell membranes are considered to act as a capacitor with a low dielectric constant. Free charges of opposite polarities are present on both sides of the membrane (internal and external), resulting in a naturally occurring transmembrane potential. Exposing the cell to an electric field induces the accumulation of charges across the membrane and therefore an increase in the transmembrane potential. Additional potential induced from an external electric field raises the compression pressure on the membrane due to the attraction between opposite charges on both sides of the membrane, which induces membrane thinning. Electrostatic attraction between the two sides of a membrane is further increased due to the thinning of a membrane. Therefore, when electrocompression is higher than the elastic resistance of a membrane, a local rupture with pore formation occurs (Grimi et al. 2011; Knirsch et al. 2010; Soliva-Fortuny et al. 2009), which induces high membrane permeability because the cells attempt to restore the balance to both the electrochemical and electrical potential between the cytoplasm and the membrane. At the same time, transmembrane gradient neutralization irreversibly occurs, affecting osmoregulation systems and causing cell death (Heinz et al. 2001).

This non-thermal effect on microorganism inactivation has been shown by Somavat et al. 2012a, b, 2013. For example, Somavat et al. (2012a, b), applied OH at 10 kHz and 60 Hz to a preparation of *Geobacillus stearothermophilus* spores, showing a high inactivation of thermophilic bacterial spores compared to conventional heating. In Somavat et al. (2013), the results obtained in a preparation containing *Bacillus coagulans* spores suggest that OH considerably increased the inactivation of spores during CUT compared to conventional heating. This result could be because during the heat activation of dormant spores, a synergic effect of electrical current and temperature increases the release of ionic compounds such as DPA and fragments of denatured spore protein enzymes from the coat. Additionally, the electric field could interact with the ionic molecules leaching from the spore, which could promote the activation rate of the spore and therefore make it more susceptible to additional thermal effects of electricity. According to this explanation provided by Somavat et al. (2013), electroporation is not relevant in the case of spores due to structural differences compared with a vegetative cell.

OH applied to food sterilization has not been widely studied, and some work has presented promising results. For example, Somavat et al. (2012b) developed a rectangular ohmic pouch capable of sterilizing food (Fig. 22.3). The pouch,

Fig. 22.3 Foil electrode pasted on the laminate cut using food grade adhesive. The figure also shows the *fold lines* used to shape the pouch. (From Somavat et al. 2012b)

containing flat and parallel electrodes, has shown to have a uniform electric field across its geometry. External polyimide heaters were used along the non-electrode sides to improve the heating profile and eliminate cold spots The results showed that holding times of 6 min at 121 °C and 1 min at 130 °C were adequate for killing more than 5 logs of G. *stearothermophilus* spores. Surviving spore counts were below the detection limit of 1 log cfu/ml for 12 min treatment at 121 °C and for 1 and 2 min treatments at 130 °C. The pouch concept represents a novel method of sterilization and heating of packaged food.

With the aim to reduce the thermal processing time to avoid the overexposure of food to high temperatures, researchers have developed at lab scale a process that combines ohmic heating with high pressure for thermal sterilization (Park et al. 2014). The experiment was performed on carrots, which were ohmically heated until 105 °C using 30 V/cm under 600 MPa of pressure. The results of this process, called pressure ohmic thermal sterilization (POTS), showed a significantly rapid temperature increase compared with OH and pressure assistance thermal sterilization (Fig. 22.4). POTS minimized thermal abuse because of its rapid temperature rise through the combined effects of pressure and electric field, and in addition, rapid cooling of POTS carrot samples was possible during decompression to 0.1 MPa. POTS exhibited better textural retention compared to carrots treated with PATP (Park et al. 2014).

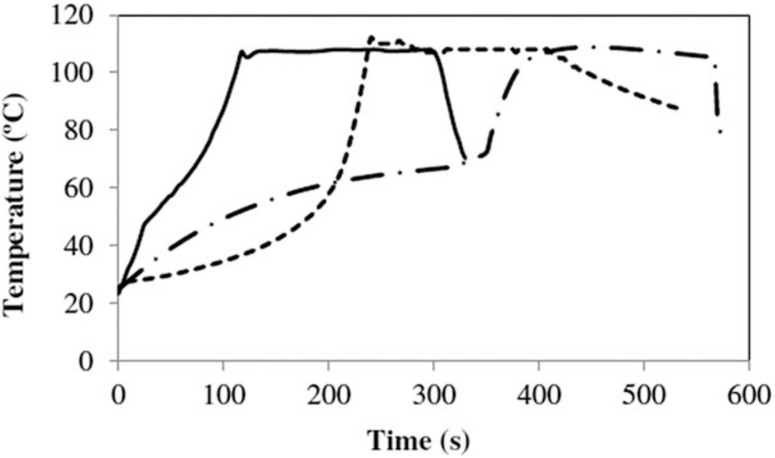


Fig. 22.4 Comparison of sample temperature during POTS (600 MPa, 30 V/cm, 105 °C), PATP (600 MPa, 0 V/cm, 105 °C), and ohmic heating (0.12 MPa, 30 V/cm, 105 °C); POTS:-; PATP:--·; ohmic heating:--- (From Park et al. 2014)

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Appendix A: Kinetic Factors for Microbial Inactivation

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Table A.1 Kinetic factors: microbial inactivation by moist heat

Organism	Temperature range, T (°C)	pH	T_{ref} (°C)	Reaction rate, k_{T} (s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} (s)	*z*-value (°C)	Reference (see at the end of this Appendix)
Bacillus stearothermophilus									
TH 24 aqueous	120–160	–	120	2.303×10^{-3}	423	53.7	1000	7.3	Davies et al. (1977)
TH 24 aqueous	120–160	–	160	10.49	513	63.0	0.22	7.3	Perkin et al. (1977)
TH 24 milk	120–160	–	120	4.92×10^{-3}	276	345	468	11.2	
TH 24 milk	120–160	–	160	7.19	335	41.3	0.32	11.2	
FS 7954 phosphate buf.	127–144	7	121	9.38	374	49.2	6.0	8.3	Wang et al. (1964)
FS 7954 phosphate buf.	121	6.9	121	0.17	383	50.4	13.2	8.1	Scharer (1965)
NCIB 8919 water	121	–	121	0.01	443	56.8	186	7.0	Briggs (1966)
ATCC 7953 water	121	–	121	0.068	384	49.8	33.6	8.0	Miller and Kandler (1967)
ATCC 7953 phos. buf.	111–125	7	121	0.018	365	46.7	126	8.5	Jonsson et al. (1977)
NCIB 8710 phos. buf.	100–140	7	121	0.01	256	32	210	12.1	Navani et al. (1970)
NCIB 8919 phos. buf.	100–140	7	121	0.015	217	27	149	14.25	Navani et al. (1970)
NCIB 8923 phos. buf.	100–140	7	121	0.13	252	31.5	170	12.3	Navani et al. (1970)
NCIB 8924 phos. buf.	100–140	7	121	0.01	265	33.2	226	11.7	Navani et al. (1970)
– Glucose sol.	120–127	–	121	0.012	478	61.5	189	6.5	Reichert (1979)
IAM 1053 phos. buf.	120	–	120	6.1×10^{-3}	374	47.6	378	8.3	Matsuda et al. (1981)
– Heat-activated	100–145	–	120	0.23	485	63.9	10	6.4	Srimani et al. (1990)
C 953 aqueous	143–152	–	143	1.95	342	43.3	1.18	10.1	Dodeja et al. (1990)
C 953 aqueous	143–152	–	145	3.07	345	43.6	0.75		Dodeja et al. (1990)
C 953 aqueous	143–152	–	150	9.20	354	44.7	0.25		Dodeja et al. (1990)
C 953 aqueous	143–152	–	152	11.5	358	45.1	0.20		Dodeja et al. (1990)
TH 24 (NCDO 1096) FS 122A (NCIB 8919)	115–155	–	121	0.26	333	43.6	8.7	9.3	David and Merson (1990)
80 % Pea purée/water	121	–	121	5.3×10^{-3}	–	–	435	–	Atherton and Brown (1973)
20 % Pea purée/water	121	–	121	5.0×10^{-3}	–	–	462	–	Brown (1974)

100 % Pea purée/water	121	–	121	8.0×10^{-3}	–	–	282	–	Brown (1974)
FS 128 buffer	110–135	7	110	2.3×10^{-4}	386	49	10^{4}	7.7	Brown (1974)
FS 128 buffer	110–135	7	135	0.2	–	–	11.4	–	Brown (1974)
FS 128 buffer	104.5–138	6	104.5	8.3×10^{-5}	343	43.5	2.5×10^{4}	8.7	Brown (1975)
FS 128 buffer	104.5–138	6	138	0.265	–	–	8.7	–	Brown (1975)
FS 128 buffer	110–138	7	110	9.0×10^{-4}	294	37	2.5×10^{3}	10.25	Brown (1975)
FS 128 buffer	110–138	7	138	0.29	–	–	7.92	–	Brown (1975)
NCA 1518 skim milk	128–140	–	128	0.17	436	56	134	7.8	Busta (1967)
NCA 1518 skim milk	128–140	–	140	4.6	–	–	0.5	–	Busta (1967)
NCA 1518 milk conc.	120–128	–	–	–	255	–	–	12.16	Segner et al. (1963)
FS 210 (TH 24) phosph.	110–130	7	120	8.0×10^{-3}	302	38	288	10.26	Gaze et al. (1990)
FS 210 (TH 24) phosph.	110–130	7	130	0.064	–	–	36	–	Gaze et al. (1990)
FS 218 (NCIB 8919) phosph.	110–130	7	120	6.2×10^{-3}	370	47	385	8.4	Gaze et al. (1990)
FS 218 (NCIB 8919) phosph.	110–130	7	130	0.076	–	–	30	–	Gaze et al. (1990)
FS 219 (NCA 1518) phosph.	110–130	7	120	4.3×10^{-3}	387.5	49.2	533	8.0	Gaze et al. (1990)
FS 219 (NCA 1518) phosph.	110–130	7	130	0.082	–	–	26.4	–	Gaze et al. (1990)
NCA 1518 water	120–130	–	121	8.2×10^{-3}	361	45.8	281	8.6	Neaves and Jarvis (1978a)
FD 7954 water	105–120	–	121	0.017	287.5	36.4	138.2	10.43	Aiba et al. (1965)
ATCC 7553 water	105–130	–	121	0.038	–	–	60	–	Abraham et al. (1990)
Bacillus subtilis									
5230 aqueous	105–132	6.6	121	0.038	374	48.2	6.0	8.3	Jacobs et al. (1973)
5230 aqueous	100–110	–	100	3.3×10^{-3}	367	49	698	7.6	Briggs (1966)
5230 aqueous	124–140	–	121	0.076	220	28	30.3	14.1	Fox and Pflug (1968)
– Phosphate buffer	127–144	7	121	0.105	350	45.5	21.9	8.8	Wang et al. (1964)
– Aqueous	124–130	–	121	0.08	330	42.7	28.8	9.4	Jacobs et al. (1965)
9372 aqueous	100–148	–	120	2.3×10^{-3}	839	109	1×10^{-3}	3.7	Srimani et al. (1990)

(continued)

Table A.1 (continued)

Organism	Temperature range, T (°C)	pH	T_{ref} (°C)	Reaction rate, k_T (s^{-1})	Activation energy, E_A (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_T (s)	z-value (°C)	Reference (see at the end of this Appendix)
A skim milk	112.5–135	–	112.5	0.025	352	46.7	20	8.8	Edwards et al. (1965)
A skim milk	112.5–135	–	135	3.29	–	–	0.7	–	Edwards et al. (1965)
Clostridium beijerinckii									
NCIB 9362 phosphate	80–97	<4.5	90	0.063	330	46.3	36	8.0	Gaze et al. (1987)
Clostridium botulinum									
Type C aqueous	93–104	–	104	0.038	507	69	60	5.6	Segner and Schmidt (1971)
Type A aqueous	115.6–121	–	121	1.9	310	41.5	1.2	10	Schmidt (1964)
NCTC 7272	115–135	–	121	0.72	86	11.3	3.2	36.1	Neaves and Jarvis (1978b)
NCTC 7273	115–135	–	121	0.72	120	15.8	3.2	26.0	Neaves and Jarvis (1978b)
BOT 44 phosphate buffer	100–120	–	120	0.68	378	50.2	3.36	8.2	Gaze et al. (1990)
BOT 44 phosphate buffer	101–150	–	120	1.53	310	40	1.5	9.8	Simpson and Williams (1974)
213B phosphate buffer	104–116	–	110	0.027	376	49.8	85.3	7.8	Kaplan et al. (1974)
213B beets	104–116	–	110	0.035	264	34.6	65.8	11.1	Kaplan et al. (1974)
213B carrots	104–116	–	107	0.016	259	33.86	143.9	11.3	Kaplan et al. (1974)
213B corn	104–116	–	110	0.025	264	34.5	92.1	11.1	Kaplan et al. (1974)
213B snap beans	104–113	–	110	0.038	333	44.0	60.6	8.8	Kaplan et al. (1974)
213B spinach	107–110	–	110	0.026	302	39.6	88.5	9.7	Kaplan et al. (1974)
213B sea food	100–113	5.9	121	0.76	367	48.6	3.0	7.4	Perkin et al. (1975)
213B poultry	100–113	–	121	0.76	367	48.6	3.0	7.4	Perkin et al. (1975)
213B meat and vegetable	100–113	–	121	0.34	384	50.5	6.6	9.8	Perkin et al. (1975)
213B phosphate buffer	120–140	7	120	0.26	310	39.7	8.75	10	Gaze and Brown (1988)
213B phosphate buffer	120–140	7	140	14.4	310	40.0	0.16	10	Gaze and Brown (1988)
213B corn purée	110–115.5	7	115.5	4.7×10^{-3}	300	38.0	489	10.1	Sognefast et al. (1948)

213B pea purée	107–112.7	7.2	115.5	3.4×10^{-3}	364	46.54	669	8.3	Sognefast et al. (1948)
213B spinach purée	110–118.3	8.6	115.5	4.2×10^{-3}	293	37.0	549	10.3	Sognefast et al. (1948)
213B 1 % fat milk	104–113	7	113	0.16	351	46.8	14.3	8.5	Denny et al. (1980)
213B neutral phosphate	104–113	7	113	0.28	260	34.7	8.2	11.4	Denny et al. (1980)
213B phosphate buffer	110	7	110	0.024	284	37.2	96	10.3	Matsuda et al. (1981))
62A macaroni creole	110–118	4	110	0.078	306	40.7	29.5	9.6	Xezones and Hutchings (1965)
62A macaroni creole	110–118	7	110	0.015	313	–	153.5	–	Xezones and Hutchings (1965)
62A Spanish rice	110–118	4	110	0.088	306	40.75	26.2	9.6	Xezones and Hutchings (1965)
62A Spanish rice	110–118	7	110	0.016	304	–	143.9	–	Xezones and Hutchings (1965)
62A phosphate	104–127	7	121	0.288	357	46.8	7.98	9.0	Stumbo et al. (1950)
62A water	104–127	7	121	0.75	334	44.2	3.06	8.5	Stumbo et al. (1950)
62A puréed peas	104–127	7	121	0.44	374	49.3	5.34	8.3	Stumbo et al. (1950)
62A strained squash	104–127	7	121	0.64	373	49.3	3.6	8.2	Stumbo et al. (1950)
A35B phosphate buffer	105–115.5	6.8	121	0.12	287.5	37.3	19.2	10.8	Knock and Lambrechts (1956)
A35B rock lobster	105–115.5	6.6	121	0.13	287.5	9.18	18.0	10.8	Knock and Lambrechts (1956)
Clostridium butyricum									
NCIB 7423 phosphate	80–97	<4.5	90	0.038	329	46	60	8.1	Gaze et al. (1987)
Strain 1 buffer and milk	85	<4.5	85	2.74×10^{-3}	–	–	840	–	Cerf et al. (1967)
Strain 2 buffer and milk	85	<4.5	85	3.2×10^{-3}	–	–	720	–	Cerf et al. (1967)
Clostridium thermosaccharolyticum									
S9 McIlvaine spore form	99–127	–	121	0.045	211	26.7	51	14.7	Gillespy (1948)
S9 acid spore form	99–127	–	121	0.012	318	40.4	192	9.76	Gillespy (1948)
S9 water	124–132	–	132	0.523	476	61.2	4.4	6.89	Xezones et al. (1965)
S9 molasses	124–132	–	132	0.698	322	41.4	3.3	10.2	Xezones et al. (1965)

(continued)

Table A.1 (continued)

Organism	Temperature range, T (°C)	pH	T_{ref} (°C)	Reaction rate, k_{T} (s^{-1})	Activation energy, E_{A} ($\mathrm{kJ\ mol}^{-1}$)	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} (s)	*z*-value (°C)	Reference (see at the end of this Appendix)
Tree bark compost	115.5–127	–	121	5.6×10^{-4}	270	32.7	4080	11.5	Alcock and Brown (1982), Brown and Alcock (1983)
Desulfotomaculum nigrificans									
ATCC 7946 infant food	121–131	–	121	1.48×10^{-3}	463	58.8	1550	6.7	Donnelly and Busta (1980)
RGI 66	121–131	–	121	7.06×10^{-4}	327	40.4	3260	9.5	Donnelly and Busta (1980)
Escherichia coli									
Nutrient broth	56	–	56	8.6×10^{-3}	442	68.2	270	4.9	Chambers et al. (1957)
Aqueous	55	–	55	9.6×10^{-3}	–	–	240	–	Lemcke and White (1959)
Aqueous	57.2	–	57.2	0.32	–	–	72	–	Goepfert et al. (1970)
Aqueous	55–60	–	55	5.7×10^{-3}	604	94.0	402	3.6	Reichert (1979)
Aqueous	55–60	–	60	0.14	–	–	16.2	–	Reichert (1979)
Milk	62–82	–	82	66.9	378	57.5	–	–	Evans et al. (1970)
Milk solution 10 % solids	52–62	–	58	0.03	462	71.5	76.8	–	Dega et al. (1972)
Milk solution 51 % solids	52–62	–	58	2.85×10^{-3}	245	–	800	–	Dega et al. (1972)
ATCC 9637 raw milk	52–80	–	57	0.03	375	58	76.8	–	Read et al. (1961)
ATCC 9637 chocolate milk	52–80	–	57	0.015	375	57.6	153.5	–	Read et al. (1961)
ATCC 9637 40 % raw cream	52–80	–	57	0.015	375	57.6	153.5	–	Read et al. (1961)
ATCC 9637 ice cream mix	52–80	–	57	7.5×10^{-3}	371	56.7	307	–	Read et al. (1961)

Putrefactive anaerobe									
PA 3679 white corn purée	110–127	4.5	k–119: D–121	0.01	390	50	230	8.8	Sognefast et al. (1948)
PA 3679 white corn purée	110–127	7.1	k–119: D–121	–	322	–	–	11.1	Sognefast et al. (1948)
PA 3679 yellow corn purée	110–127	5.0	k–119: D–121	7.45×10^{-3}	390	49.8	309	7.8	Sognefast et al. (1948)
PA 3679 yellow corn purée	110–127	6.8	k–119: D–121	–	262	–	–	11.6	Sognefast et al. (1948)
PA 3679 pea purée	110–140	4.5	k–119: D–121	9.25×10^{-3}	305	38.6	249	6.6	Sognefast et al. (1948)
PA 3679 pea purée	110–140	8.0	k–119: D–121	–	–	–	–	10.0	Sognefast et al. (1948)
PA 3679 sweet potato purée	110–127	5.0	k–119: D–121	9.25×10^{-3}	494	63.7	249	7.8	Sognefast et al. (1948)
PA 3679 sweet potato purée	110–127	8.0	k–119: D–121	–	275	–	–	11.7	Sognefast et al. (1948)
PA 3679 pumpkin purée	110–127	5.0	k–119: D–121	9.25×10^{-3}	494	63.7	249	6.1	Sognefast et al. (1948)
PA 3679 pumpkin purée	110–127	9.0	k–119: D–121	–	390	–	–	7.8	Sognefast et al. (1948)
PA 3679 skim milk	115–135	–	115	0.28	180	24	8.0	18.8	Busta (1967)
PA 3679 skim milk	115–135	–	135	2.30	–	–	1.0	–	Busta (1967)
PA 3679 3:1 milk concentrate	120–128	–	–	–	277	–	–	11.2	Segner et al. (1963)
PA 3679 pea purée	115.5–143.3	–	121	0.38	317	40.8	60	9.8	Secrist and Stumbo (1958)
PA 3679 pea purée	115.5–143.3	–	143.3	3.8	–	–	0.6	–	Secrist and Stumbo (1958)

(continued)

Table A.1 (continued)

Organism	Temperature range, T (°C)	pH	T_{ref} (°C)	Reaction rate, k_T (s^{-1})	Activation energy, E_A ($\mathrm{kJ\ mol}^{-1}$)	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_T (s)	z-value (°C)	Reference (see at the end of this Appendix)
PA 3679 distilled water	115.5–143.3	–	115.5	0.06	310	40	39	10.4	Secrist and Stumbo (1958)
PA 3679 distilled water	115.5–143.3	–	143.3	–	–	–	–	0.3	Secrist and Stumbo (1958)
PA 3679 phosphate buffer	100–120	–	110	0.44	309	40.8	5.2	9.5	Townsend et al. (1938)
PA 3679 asparagus buffer	100–120	–	110	0.225	309	40.5	10.2	9.4	Townsend et al. (1938)
PA 3679 phosphate buffer	77–157	7.0	121	0.038	113.5	13.6	60	26.4	Alcock et al. (1981)
PA 3679 aqueous	110–132.2	–	121	0.048	312	40.3	48	9.8	Stumbo et al. (1950)
PA 3679 pea purée	110–132.2	–	121	0.025	317	40.6	91.2	9.6	Stumbo et al. (1950)
PA 3679 strained spinach	110–132.2	–	121	0.045	302	38.8	51.0	10.1	Stumbo et al. (1950)
PA 3679 whole kernel corn	110–132.2	–	121	0.032	330	42.5	70.8	9.2	Stumbo et al. (1950)
PA 3679 uncooked pork	110–132.2	–	121	0.027	305	39.0	83.4	10.0	Stumbo et al. (1950)
PA 3679 cooked pork	110–132.2	–	121	0.045	302	38.8	92.6	9.7	Stumbo et al. (1950)
PA 3679 white sauce	110–132.2	–	121	0.031	330	42.5	73.8	9.2	Stumbo et al. (1950)
PA 3679 evaporated milk	110–132.2	–	121	0.029	281	35.9	77.4	11.1	Stumbo et al. (1950)
PA 3679 20 % cream	110–132.2	–	121	0.017	292	37.3	91.2	10.4	Stumbo et al. (1950)
PA 3679 beef	110–121	–	121	0.017	263	33.3	133.8	11.8	Kaplan et al. (1974)
PA 3679 corn	110–121	–	121	0.019	282	35.8	120.0	11.0	Kaplan et al. (1974)
PA 3679 lima beans	110–121	–	121	0.015	290	36.8	153.6	10.72	Kaplan et al. (1974)
PA 3679 mushrooms	110–121	–	121	0.019	335	43.0	118.8	9.27	Kaplan et al. (1974)
PA 3679 peas	110–121	–	121	0.017	314	40.0	133.8	9.88	Kaplan et al. (1974)
PA 3679 pork	110–121	–	121	0.017	310	39.5	128.4	10.0	Kaplan et al. (1974)
PA 3679 asparagus	110–127	5	121	9.4×10^{-3}	543	70.3	245.0	5.5	Sognefast et al. (1948)
PA 3679 asparagus	110–127	9	121	–	342	–	–	8.8	Sognefast et al. (1948)
PA 3679 green bean purée	110–135	5	121	9.4×10^{-3}	419	53.8	245.0	7.3	Sognefast et al. (1948)
PA 3679 green bean purée	110–135	9	121	–	332	–	–	10.0	Sognefast et al. (1948)

PA 3679 beet purée	110–138	5.5	121	9.4×10^{-3}	336	42.7	245.0	10.0	Sognefast et al. (1948)
PA 3679 carrot purée	110–127	9	121	9.4×10^{-3}	342	43.5	245.0	8.8	Sognefast et al. (1948)
PA 449 phosphate buffer (NCIB 8053 *CI. sporogenes*)	100–120	7.0	120	0.15	340	44.5	15	9.11	Gaze et al. (1990)
PA 3679 pea purée	115 and 121	6.13	121				380	10.41	Körmendy and Mohácsi-Farkas (2000).
PA 3679	121.0	6.7–4.65	121.0				40.2–43.2	10.16–10.26	Ocio et al. (2000)
PA ATTC 7533	121.1		121.1				240		Le Jean et al. (1994).

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Appendix B: Kinetic Factors for Quality Attributes

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Table B.1 Kinetic factors: vitamin degradation

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Vitamin A, beta carotene								
Beef liver purée	103–127	122	0.95	112.6	12.0	2.40	23.0	Wilkinson et al. (1981, 1982)
Carrot juice	104–132	104	0.09	106.4	10.2	23.60	25.5	Hojilla et al. (1985)
Vitamin B_1, thiamin								
Range	84–150	–	–	84–130	–	–	23–35	Mauri et al. (1989)
Buffer solution pH 6	109–150	109	0.24	127.0	13.3	9.50	24.0	Feliciotti and Esselen (1957)
	109–150	150	12.0	127.0	13.8	0.20	24.0	Feliciotti and Esselen (1957)
Carrots	109–150	150	2.80	155.4	16.6	0.83	22.0	Feliciotti and Esselen (1957)
Green beans	109–150	150	2.90	155.4	16.5	0.80	22.0	Feliciotti and Esselen (1957)
Spinach	109–150	150	3.80	155.4	16.8	0.61	22.0	Feliciotti and Esselen (1957)
	70–100	100	1.80	41.0	3.0	1.28	67.8	Paulus et al. (1975)
Pea purée	109–150	150	2.76	155.4	16.7	0.83	22.0	Feliciotti and Esselen (1957)
	121.1	121.1	0.23	95.8	9.1	10.0	31.3	Bendix et al. (1951)
	122	122	0.16	112.5	11.2	14.0	26.6	Mulley et al. (1975)
	–	126.6	0.166	100.5	–	–	–	Lenz and Lund (1977)
	103–116	121.1	–	–	–	18.0	30.3	Nasri et al. (1993)
Beef heart	109–150	150	3.62	135.0	14.3	0.64	25.0	Feliciotti and Esselen (1957)
Beef liver	109–150	150	3.76	131.1	13.8	0.59	26.0	Feliciotti and Esselen (1957)
Beef purée	122	122	0.16	112.5	11.2	14.60	26.6	Mulley et al. (1975)

Lamb purée	109–150	150	3.20	135.0	15.4	0.71	25.0	Feliciotti and Esselen (1957)
Pork purée	109–150	150	2.80	135.0	14.15	8.82	25.0	Feliciotti and Esselen (1957)
Pork luncheon meat	100–127	127	0.36	86.0	8.0	6.30	35.0	Greenwood et al. (1944)
	–	126.6	0.64	108.8	–	–	–	Lenz and Lund (1977)
Meat loaf	70.5–98	98	4.18	113.3	11.40	0.55	23.8	Skjöldebrand et al. (1983)
Meat purée	120	–	–	118.1	–	–	25.4	Weir (1948)
Salmon	118–130	121	0.39	71.9	6.16	5.76	41.7	Greene (1983)
Milk	–	–	–	100	–	–	av.30.0	Bayoumi and Reuter (1980)
	35–150	120	0.30	100.8	9.80	7.70	29.7	Kessler and Fink (1986)
	120–150	120	0.30	100.4	10.33	7.65	28.8	Horak and Kessler (1981), Horak (1980)
Aqueous solution	110–150	120	0.12	72.0	5.67	19.00	38.0	Ramaswamy et al. (1990)
M/15 phosphate buffer	112–142	140	4.40	127.3	13.80	0.52	25.6	Matsuda et al. (1981))
Vitamin B_6								
Cauliflower	106–138	121	0.09	66.7	4.82	24.00	45.00	Navankattusas and Lund (1982)
Pyridoxine hydrochloride								
Pyridoxine model sol.	105–133	118	0.04	119.7	12.64	54.8	22.0	Gregory and Hiner (1983)
Pyridoxamine	105–133	118	0.11	100.0	7.6	20.9	26.0	Gregory and Hiner (1983)
Pyridoxal	105–133	118	0.15	86.6	7.8	15.0	30.0	Gregory and Hiner (1983)

(continued)

Table B.1 (continued)

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^{3}$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Folic acid								
Apple juice	100–140	140	0.23	83.4	6.9	100.0	31.0	Mnkeni and Beveridge (1982)
Pteroyl glutamic acid								
Tomato juice	100–140	140	0.20	83.4	6.86	115.0	31.0	Mnkeni and Beveridge (1982)
Citrate buffer	100–140	140	0.65	93.8	3.5	3.5	28.0	Mnkeni and Beveridge (1982)
	100–140	140	0.06	81.2	6.60	100.0	35.0	Mnkeni and Beveridge (1982)
	100–140	140	0.06	74.5	5.20	410.0	35.0	Mnkeni and Beveridge (1982)
Pantothenic acid								
Beef purée pH 4.5	118–143	121.1	0.017	83.7	6.34	138.0	35.8	Hamm and Lund (1978)
Pea purée pH 7	118–143	121.1	0.017	154.8	15.70	135.0	18.3	Hamm and Lund (1978)
Buffer pH 4	118–143	121.1	0.165	83.7	7.3	14.0	35.8	Hamm and Lund (1978)
pH 5	118–143	121.1	0.024	92.0	7.60	96.0	32.5	Hamm and Lund (1978)
pH 6	118–143	121.1	0.020	113.0	10.3	117.0	26.5	Hamm and Lund (1978)
Vitamin C, ascorbic acid								
Cupuaçu nectar pH 3.2	60–99	80	0.53	74				Vieira et al. (2000)
Grapefruit juice 11.2° brix	61–96	96	0.04	20.8	1.4	17.76	130.0	Saguy et al. (1978c)

62.5° brix	61–69	96	0.03	47.3	3.15	8.2	57.5	Saguy et al. (1978c)
Grape fruit juice	20–92	85				50.57	44	Alvarado and Viteri (1989)
Lemon juice (Sierra)	20–92	85				68.82	72	Alvarado and Viteri (1989)
Lime juice	20–92	85				44.46	44	Alvarado and Viteri (1989)
Mandarin juice (Sierra)	20–92	85				24.36	47	Alvarado and Viteri (1989)
Mandarin juice (Costa)	20–92	85				32.52	58	Alvarado and Viteri (1989)
Peas	110–132	121.1	0.04	164.5	17.5	50.0	18.2	Lathrop and Leung (1980)
Spinach var. Fruhjahr	70–100	100	2.92	36.4	2.57	25.9	74.4	Paulus et al. (1975)
Spinach var. Herbst	70–100	100	2.16	30.5	1.61	1.07	91.2	Paulus et al. (1975)
Beef, restructured	100–30	121.1	6.7	111.3				Street and Tong (1994)
Model solution								
Buffer pH 4	30–100	100	0.56	87.0	8.97	4.07	31.9	Huelin (1953)
	110–127	120	0.07	78.6	–	31.2	39.4	Ghazala et al. (1989)

Table B.2 Kinetic factors: proteins

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3\ \mathrm{s}^{-1}$)	Activation energy, E_{A} ($\mathrm{kJ\ mol}^{-1}$)	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	*z*-value (°C)	Reference
Whey protein denaturation								
Milk	70–90	–	–	208–212	–	–	10.6–14.4	Agrawala and Reuter (1979)
	120–160	–	–	98.4	–	–	30–37	Agrawala and Reuter (1979) see also Mulvihill and Donovan (1987)
Casein								
Milk	–	–	–	146.5	–	–	20.5	White and Sweetsur (1977)
Skim milk	–	–	–	104–146.5	–	–	20.5–28.8	White and Sweetsur (1977)
Hemoglobin								
Beef	–	–	–	53.2	–	–	56.4	Haurowitz et al. (1954)
Oxyhemoglobin								
Beef	–	–	–	90.8	–	–	33.0	Haurowitz et al. (1954)
Methionine								
Model systems	60–90	90	0.53	125.7	14.8	4.3	20.0	Martens (1980)
Milk	110–126	121.1	0.01	129.0	12.2	209	25.3	Martens (1980)
Methylmethionine sulfonium chloride								
Buffer solution pH 6	121.1–132.2	121.1	5.10	135.4	15.8	451	22.0	Berry et al. (1989)
Model system pH 5	126.7	126.7	2.51	121.2	13.2	916	24.7	Berry et al. (1989)

pH 4	82–99	99	0.18	125.6	13.9	120	20.0	Williams and Nelson (1974)
pH 8	82–99	99	750	117.6	16.4	2.7×10^{-3}	21.3	Williams and Nelson (1974)
Sweet corn pH 7	82–99	99	0.78	132.2	16.2	2.9	19.0	Williams and Nelson (1974)
Tomato pH 7	82–99	99	0.20	116.3	12.65	1.0	21.6	Williams and Nelson (1974)
Lysine								
Milk	130–160	160	0.03	109.0	10.29	69.8	32.8	Kessler and Fink (1986)

Table B.3 Kinetic factors: enzymes[a]

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3\ \mathrm{s}^{-1}$)	Activation energy, E_{A} ($\mathrm{kJ\ mol}^{-1}$)	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Peroxidase								
Horseradish pH 7	85–150	85	0.269	105	11.81	8.56	22.8	Joffe and Ball (1962)
pH 5.6	60–160	120	2.8	100	10.76	0.83	27.8	Adams (1978)
In aq. methanol	76–87	82	0.9	88.3	8.7	2.56	27.1	Ling and Lund (1978)
Corn on the cob	70–100	100	1.5×10^{-3}	75	9.7	15.5	37.0	Naveh et al. (1982)
	93	93	3.48	84	9.5	0.66	30.0	Yamamoto et al. (1962)
	80–100	100	23.0	83	10.0	0.10	33.5	Luna et al. (1986)
Green bean purée	104–177	104	51.0	76	9.25	4.5×10^{-2}	36.6	Resendre et al. (1969)
	104–132	104	13.2	82	9.5	3.3×10^{-2}	33.9	Zoueil and Esselen (1958)
	70–110	110	2.6	82	8.6	0.885	34.15	Adams (1978)
Pea purée	70–110	110	4.4	84.5	9.2	0.523	33.16	Adams (1978)
Potato purée	100–140	120	33.0	80	9.16	7.0×10^{-2}	35.0	Svensson (1977)
Spinach purée	77–92	77	327	138	20.14	7.0×10^{-3}	18.0	Resendre et al. (1969)
Turnip purée	82–132	104	95.0	205	25.4	2.4	13.56	Zoueil and Esselen (1958)

Catalase								
Spinach extract	60	60	38	253	38.5	6.0×10^{-2}	8.3	Sapers and Nickerson (1962)
Lipoxygenase								
Pea/soya extract	50–80	77	3.2	676	98.6	0.72	3.4	Farkas and Goldblith (1962)
Pea/buffer pH 6	60–72	60	370	584	89.3	62	3.6	Svensson and Eriksson (1974)
O-diphenyl oxidase								
Fruits pH 3.4–6.2	30–100	75	1.0	210	29.5	0.21	10.0	Dimick et al. (1951)
Pectinesterase								
Guava pH 4	74.94	96	6.0	157.6	21.0	3.5×10^{-2}	16.5	Nath and Ranganna (1983)
Mandarin Orange juice pH 3.6	82–94	85				0.13	11.4	Nath and Rangana (1977)
Papaya (acidified) pH 3.8	77	77				0.12	7.8	Dos et al. (1999)
Papaya nectar pH 3.8	75–85	85				0.30	15.1	Argáiz (1994)
Papaya pulp	75–80	80	–	72.7	–	16.7–3.7	7.8	Massaguer et al. (1994)
Papaya pulp pH 4.0	82–102	85				0.23	15.0	Nath and Rangana (1981)

(continued)

Table B.3 (continued)

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Papaya purée pH 3.5	75–85	85				0.28	14.8	Argáiz (1994)
pH 3.8	75–85	85				0.23	14.7	Argáiz (1994)
pH 4.0	75–85	85				0.43	14.2	Argáiz (1994)
Polyphenol oxidase								
Potato	80–100	89	23	322	44.9	0.10	7.8	Dagerskog (1977)

[a] See Aylward and Haisman (1969) for an excellent review of earlier work

Table B.4 Kinetic factors: overall sensory quality

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^{3}$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Beef purée	110–134	121.1	–	136–158	–	–	19–22	Ohlsson (1980)
Fish cake	110–134	121.1	–	103–130	–	–	23–29	Ohlsson (1980)
Liver paté	110–134	121.1	–	88.2–120	–	–	25–34	Ohlsson (1980)
Tomato sauce	110–134	121.1	–	111–187	–	–	16–27	Ohlsson (1980)
Vanilla sauce	110–134	121.1	–	136–230	–	–	13–22	Ohlsson (1980)
Vegetable purée	110–134	121.1	–	125–167	–	–	18–24	Ohlsson (1980)
Beetroot	80–110	121.1	19.0	142	17.2	0.12	19	Mansfield (1974)
Broccoli	100–121	121.1	8.7	54.4	5.16	0.26	44.4	Lund (1975)
Carrots	80–116	121.1	27.0	160	19.7	0.084	16.7	Lund (1975)
Corn, whole kernel	100–121	121.1	16.0	67	7.1	0.15	36.6	Lund (1975)
Corn, whole kernel	80–148	121.1	70.0	94.6	11.4	0.26	31.7	Hayakawa et al. (1977)
Green beans	80–148	121.1	10.0	104	11.8	0.20	28.8	Hayakawa et al. (1977)

(continued)

Table B.4 (continued)

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Green beans	84–116	121.1	38.0	171.6	21.3	0.06	15.6	Mansfield (1974)
Peas	100–121	121.1	16.0	81.6	9.01	0.15	32.2	Mansfield (1974)
Peas	80–148	121.1	23.0	106	12.45	0.096	28.3	Hayakawa et al. (1977)
Potatoes	72–121	121.1	35.0	115	13.76	0.072	23.0	Mansfield (1974)
Squash	84–116	121.1	38.0	171.6	21.36	0.06	15.6	Mansfield (1974)

Table B.5 Kinetic factors: texture and softening

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^{3}$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Fish cake	110–134	121.1	47.0	130	15.9	0.049	23	Ohlsson (1980)
Asparagus (green)	70–98	84	26–45	100.8				Lau et al. (2000)
Asparagus (green)	115	115	3.65	56.4				Rodrigo et al. (1998)
Beetroot	104.4–121.1	121.1	7.13	65.3av.	6.52	0.32	46	Huang and Bourne (1983)
Beets	60–100	–	61.6 and 112.8	–	–	–	–	Buckenhuskes et al. (1990)
Beans, black	98–127	120	6.4	148.6	17.6	0.36	19	Quast and da Silva (1977)
Beans, brown	98–127	120	10.0	156.9	18.9	0.22	18	Quast and da Silva (1977)
Beans, white	90–122	100	0.028	130.8	–	84.9	21.3	Van Loey et al. (1995)
Brussels sprouts	100–150	120	1.8	125.7	13.9	1.28	23.8	Tijskens and Schijvens (1987)
Carrot, Nantes	104.4–121.1	121.1	3.9	63.6	6.0	0.59	47	Huang and Bourne (1983)
Carrot, –	79–99	121.1	83	153.5	19.3	0.027	19.5	Tijskens and Schijvens (1987)
Carrot, –	–	121.1	–	112.5	–	–	2.66	Paulas and Saguy (1980)

(continued)

Table B.5 (continued)

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_T ($\times 10^3$ s^{-1})	Activation energy, E_A (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_T ($\times 10^{-3}$ s)	z-value (°C)	Reference
Carrot, –	100	100	k_1:5.34 k_2: 1.5					Ramesh et al. (1998)
Corn, whole kernel	80–148	121.1	9.6	81.6	8.8	0.24	34.3	Hayakawa et al. (1977)
Dry white beans	104.4–121.1	120	66	104.2	10.7	0.22	28.7	Huang and Bourne (1983)
Green beans	79–99	121.1	19	177	21.7	0.12	16.9	Tijskens and Schijvens (1987)
Green beans, cut	80–148	121.1	9.6	92	10.2	0.24	32.5	Hayakawa et al. (1977)
Haricot beans	115–130	120	7.4	118.5	13.6	0.31	25.0	Michiels (1973)
Khol-khol	100	100	k_1: 8.34 k_2: 1.98					Ramesh et al. (1998)
Peas	80–148	121.1	16	94.2	10.7	0.14	31.8	Hayakawa et al. (1977)
	90–122	100	0.07	94.9	–	33.24	28.5	Van Loey et al. (1995)
	100	100	k_1: 8.46 k$_2$: 1.5					Ramesh et al. (1998)
Radish	100	100	3.00					Ramesh et al. (1998)
Soya beans	98–127	125	13	182	22.0	0.17	16.0	Quast and da Silva (1977)

Potato (3 var.)	80–110	100	48	163.6	21.63	0.048	17.0	Dagerskog (1977)
	110	110	23	148	18.5	0.100	18.8	Harada et al. (1985)
	–	–	–	176.6	–	–	17.0	Pravisani et al. (1985)
	–	–	–	176.6	–	–	17.0	Ohlsson (1986)
	88–100	99	8.6	176.4	21.35	0.26	17.0	Loh and Breene (1981)
	80–100	100	6.4	114	15.2	0.36	24.2	Kubota et al. (1978)
(4 var.)	74–104	100	3.16	126	15.1	0.72	21.2	Kozempel (1988)
	60–110	100	8.9	151–152	6–8.3	–	–	Rahardjo and Sastry (1993)
	110–128	100	9.1	58.2–74.1	12–19	–	–	Rahardjo and Sastry (1993)
Potato cylinders	80–100	100	–	–	–	0.24	27.7	Linders et al. (1990)
Rice	75–110	75	0.5	79.5	8.65	4.6	35.2	Suzuki et al. (1976)
	110–150	110	3.3	36.8	2.54	0.69	75.0	Suzuki et al. (1976)
Starch gel.	60–100	100	0.0125–0.0144	98–106	–	–	–	Verlinden et al. (1995)
Sweet potato	80–100	100	15	131	18.1	0.17	21.2	Kubota et al. (1978)
Vegetable particles	80–100	–	–	–	–	0.97	109.7	Linders et al. (1990)

(continued)

Table B.5 (continued)

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Apple, Cortl and	70–120	108	0.24	66.4	5.5	9.6	42.2	Anantheswaran et al. (1985)
Spigold	70–120	108	0.24	113	11.9	9.6	42.2	Anantheswaran et al. (1985)
Gould Reinette	80–100	100	5.6	11	13.3	0.41	25.0	Tijskens and Schijvens (1987)
Golden Delicious	80–100	100	4.1	87	9.8	0.56	32.0	Tijskens and Schijvens (1987)
5 varieties	80–98	98	4.5	14.5	–	0.48	22.0	Lacroix and Bourne (1990)
Shrimp	115–140	121.1	0.66	102	10.4	3.45	29.4	Ma et al. (1983)
Meat	55–60	–	–	586	–	–	3.75	Lund (1982)

Table B.6 Kinetic factors: color degradation and browning

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3\ \text{s}^{-1}$)	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
Green pigments, chlorophylls								
Asparagus	80–140	121.1	2.25	71	6.79	1.02	41.6	Hayakawa and Timbers (1971)
	70–89	84	0.11	54.6				Lau et al. (2000)
Cupaça	100	100		31–36				Silva and Silva (1999)
Green beans	80–148	121.1	1.8	72	6.81	1.26	38.8	Hayakawa and Timbers (1971)
Peas	80–148	121.1	1.5	76	7.26	1.50	39.4	Hayakawa and Timbers (1971)
	121–148	–	–	52.3	–	–	57.3	Epstein (1959)
	–	100	1.23	67.9	6.11	31.1	42.9	Shin and Bhowmik (1995)
	90–122	100	0.09	102.4	–	25.8	26.4	Van Loey et al. (1995)
Pea purée	94–132.2	121.1	0.34	92.0	8.74	6.90	32.5	Lenz and Lund (1980)
Spinach, chlorophyll A	127–148	148.8	0.10	66.9	6.3	0.21	51.1	Gupta et al. (1964)
	116–126	121	2.8	114.2	12.6	0.82	26.2	Schwartz and von Elbe (1983)
Chlorophyll B	127–148	148.8	5.0	34.8	2.0	0.46	98.3	Gupta et al. (1964)
	116–148	121	1.36	103.4	10.9	1.70	29.0	Schwartz and von Elbe (1983)
Chlorophylls	94–132.2	121.1	0.23	79.5	6.9	9.80	17.7	Lenz and Lund (1980)
Red pigments								
Betanin pH 4.8	61.5–100	100	1.8	76.2	7.9	1.28	36.5	Saguy et al. (1978a), Saguy (1979)

(continued)

Table B.6 (continued)

Product	Temperature range, T (°C)	Reference temperature, T_{ref} (°C)	Reaction rate, k_{T} ($\times 10^3$ s^{-1})	Activation energy, E_{A} (kJ mol^{-1})	Frequency factor, log A (s^{-1})	Thermal destruction rate, D_{T} ($\times 10^{-3}$ s)	z-value (°C)	Reference
pH 6.2	61.5–100	100	1.96	83.4	8.0	1.17	33.4	Saguy et al. (1978a), Saguy (1979)
Vulgaxanthin	61.5–100	100	2.2	64.5	6.4	1.05	43.1	Saguy et al. (1978a), Saguy (1979) see also Huang and von Elbe (1985)
Blackberry juice	24–70	70	0.02	62.8	4.8	117	35.8	Debicki-Pospisil et al. (1983)
Pomegranate	70–92	92	0.3	104.6	10.47	7.5	24.8	Mishkin and Saguy (1982)
Grapes	77–121	121	0.3	54.8	3.75	7.2	54.7	Mishkin and Saguy (1982)
	85–95	95	0.08	79.1	12.1	2.76	31.8	Calvi and Francis (1978)
Raspberry juice	78–108	108	0.32	92.1	9.15	7.0	30.4	Tanchev (1983)
Other juices	–	–	–	–	–	–	–	Ioncheva and Tanchev (1974)
Browning reactions								
Chestnut paste	105–128	121.1	0.16	122	11.4	141	24.6	Nunes et al. (1988)
Grapefruit juice, 11.2° brix	60–96	95	0.4	63.2	5.6	5.6	42.7	Saguy et al. (1978b)
63.5° brix	60–96	95	2.3	99.6	11.5	0.9	27.1	Saguy et al. (1978b)
Milk	50–160	130	184	139	17.3	0.012	26.7	Kessler and Fink (1986)
Peach puree	110–135	122.5	2.9	106		0.03		Ávila and Silva (1999)
Pear puree 11° brix	80–98	100		62.5–126.5	5.0–9.5		1.6	Ibarz et al. (1999)

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Appendix C: Heat Penetration Protocols

IFTPS

The Institute for Thermal Processing Specialists (*IFTPS*) is a not-for-profit corporation of the State of Virginia (USA) organized to serve the needs of those working in thermal processing. The Institute was conceived in 1981 by a group of individuals working in the field of thermal processing to advance professionalism through educational presentations and the development of uniform standards of procedure. More information about *IFTPS* can be found at www.iftps.org

The referred WEB site has important information on thermal processing, mainly in the area of protocols for thermal processing studies.

IFTPS Protocols

- Nomenclature for Studies in thermal Processing.
- Protocol for Carrying out Neat Penetration Studies.
- Temperature distribution Protocol for Processing in Steam Still Retorts, Excluding Crateless Retorts.
- Temperature Distribution Protocol for Processing in still, Water Immersion Retorts, including Agitating Systems Operated in a Still Mode.
- Protocol for Conducting Temperature Distributions Studies in Water-Cascade and Water-Spray Retorts Operated in a Still Mode, Including Agitating Systems Operated in the Still Mode.
- Nomenclature Pour Les Études De Traitement Thermique.
- Protocole De Mesure De La Pénétration De La Chaleur.
- Protocole De Mesure De La Distribution De Température Lors De Traitement Thermique En Autoclaves Statiques Traditionnels, A L’ exclusión Des Autoclaves Sans Panier.

IFTPS protocols can be accessed at: http://www.iftps.org/protocols.html

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Appendix D: FDA Food Process Filing

Important information can be obtained through the Web's page of Food and Drug Administration (FDA). In particular the "Importer's Guide Low-Acid Canned & Acidified Foods" can be accessed through: http://www.cfsan.fda.gov/~lrd/lacf.html

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