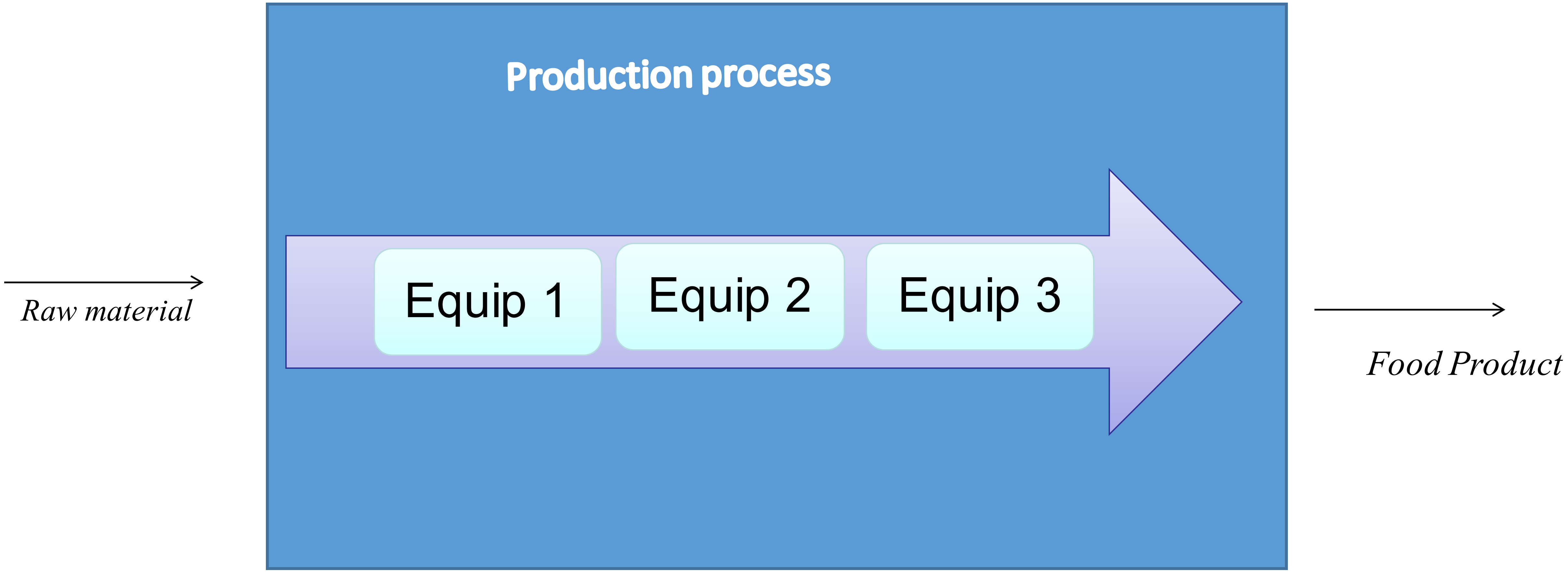
ADDIS ABABA UNIVERSITY
ADDIS ABABA INSTITUTE OF TECHNOLOGY SCHOOL OF CHEMICAL AND BIOENGINEERING

Course: Design and Development of Food Products and Equipment

PROCESS EQUIPMENT DESIGN

Introduction



Introduction(cont.)

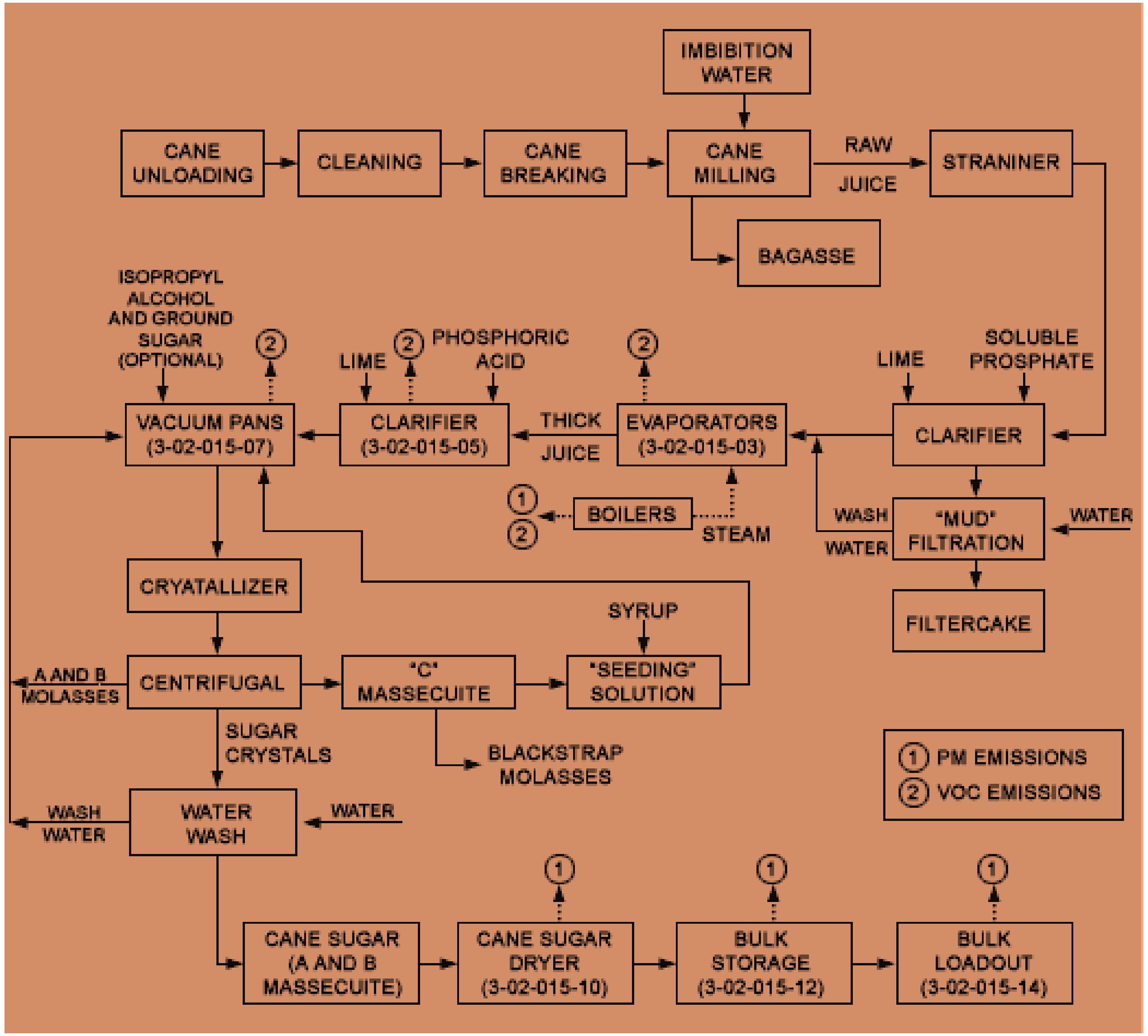
- Usually, the first step in the design of process equipment is the selection of the type that best suit for a particular conversion (chemical/ physical)
- Food production process usually involves many equipement connect in sequence to obtain the desired food product
- Production process, diagramatically, represented by a flowsheet

Types of process flow-sheet

- Block Flow Diagram (BFD)
- Process Flow Diagram(PFD)
- Process and Instrumentation Diagram (PID)

Cont.

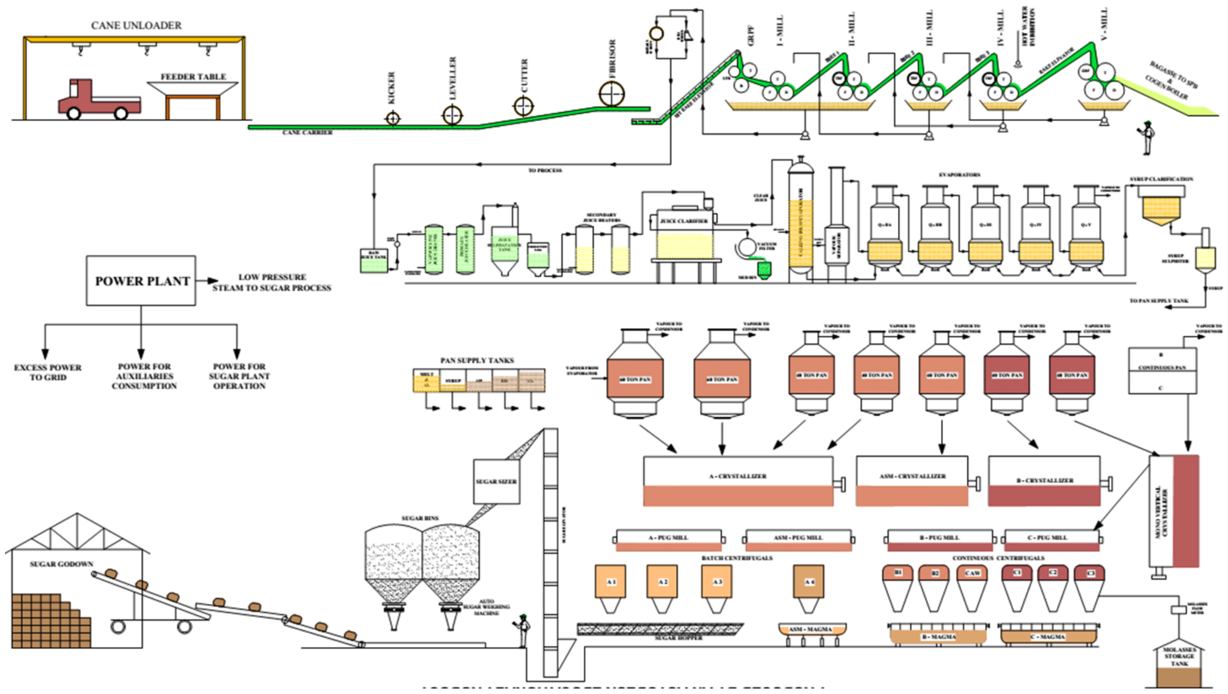
- Block flow diagram
  - ✓ the simplest form of process diagram
  - ✓ Each block represents a single piece of equipment or a complete stage in the process
  - ✓ They are used in reports and text books
  - ✓ Have only limited use as engineering document



IMBIBITION WATER
CANE UNLOADING
CLEANING
CANE BREAKING
CANE MILLING
RAW JUICE
STRANINER
BAGASSE
ISOPROPYL ALCOHOL AND GROUND SUGAR (OPTIONAL)
LIME
PHOSPHORIC ACID
LIME
SOLUBLE PROSPHATE
VACUUM PANS (3-02-015-07)
CLARIFIER (3-02-015-05)
THICK JUICE
EVAPORATORS (3-02-015-03)
CLARIFIER
BOILERS
STEAM
WASH WATER
"MUD" FILTRATION
WATER
FILTERCAKE
CRYATALLIZER
SYRUP
A AND B MOLASSES
CENTRIFUGAL
"C" MASSECUITE
"SEEDING" SOLUTION
SUGAR CRYSTALS
BLACKSTRAP MOLASSES
WASH WATER
WATER WASH
WATER
1 PM EMISSIONS
2 VOC EMISSIONS
CANE SUGAR (A AND B MASSECUITE)
CANE SUGAR DRYER (3-02-015-10)
BULK STORAGE (3-02-015-12)
BULK LOADOUT (3-02-015-14)

Cont.

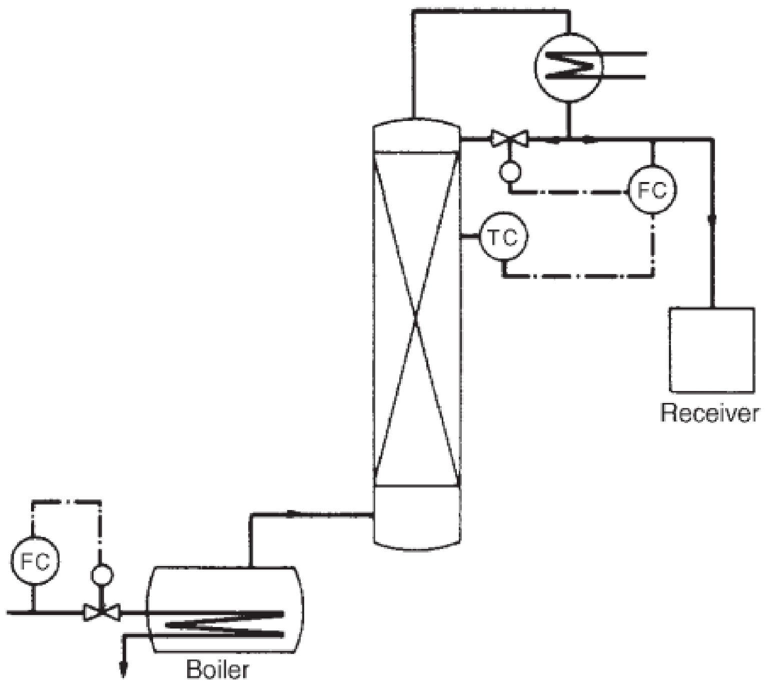
- Process flow digram



Cont.

- Process and Instrumentation Diagram (PID)
  - ✓ The Piping and Instrument diagram (P and I diagram or PID) shows the engineering details of the equipment, instruments, piping, valves and fittings; and their arrangement
  - ✓ It is often called the Engineering Flow-sheet or Engineering Line Diagram

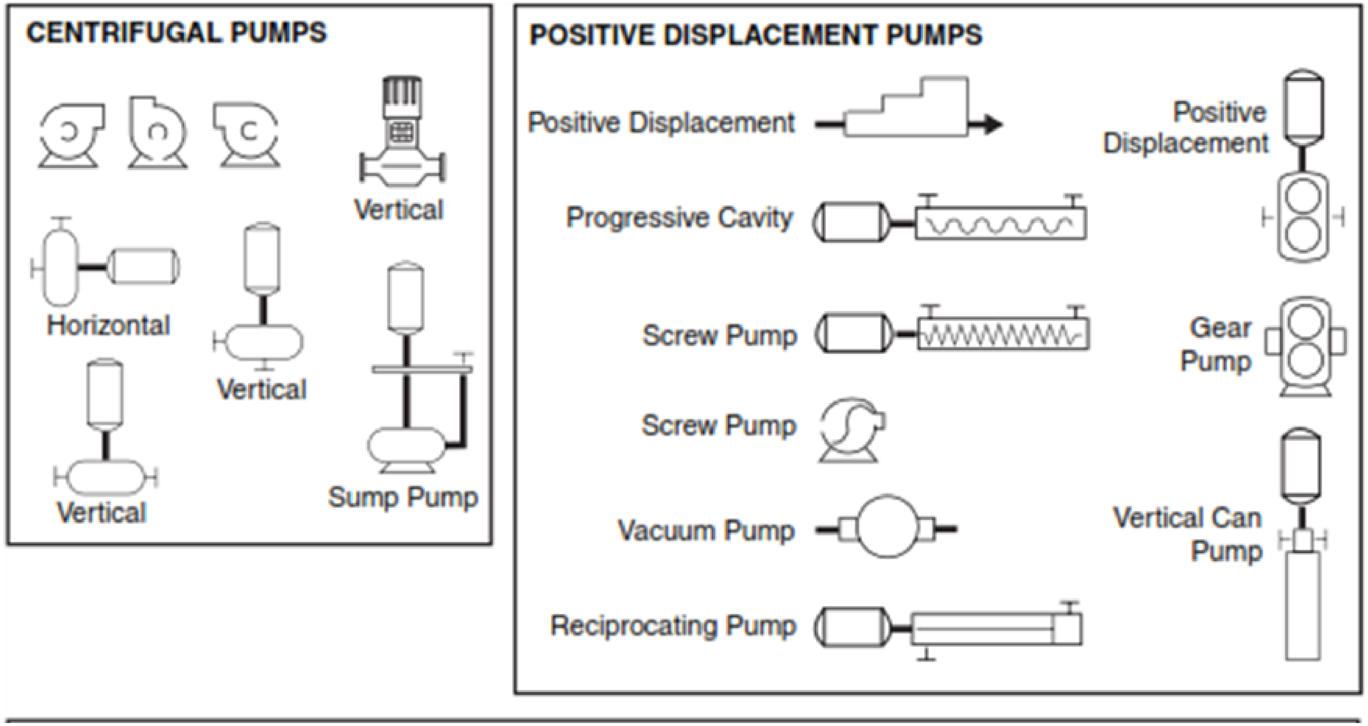
PID (cont.)



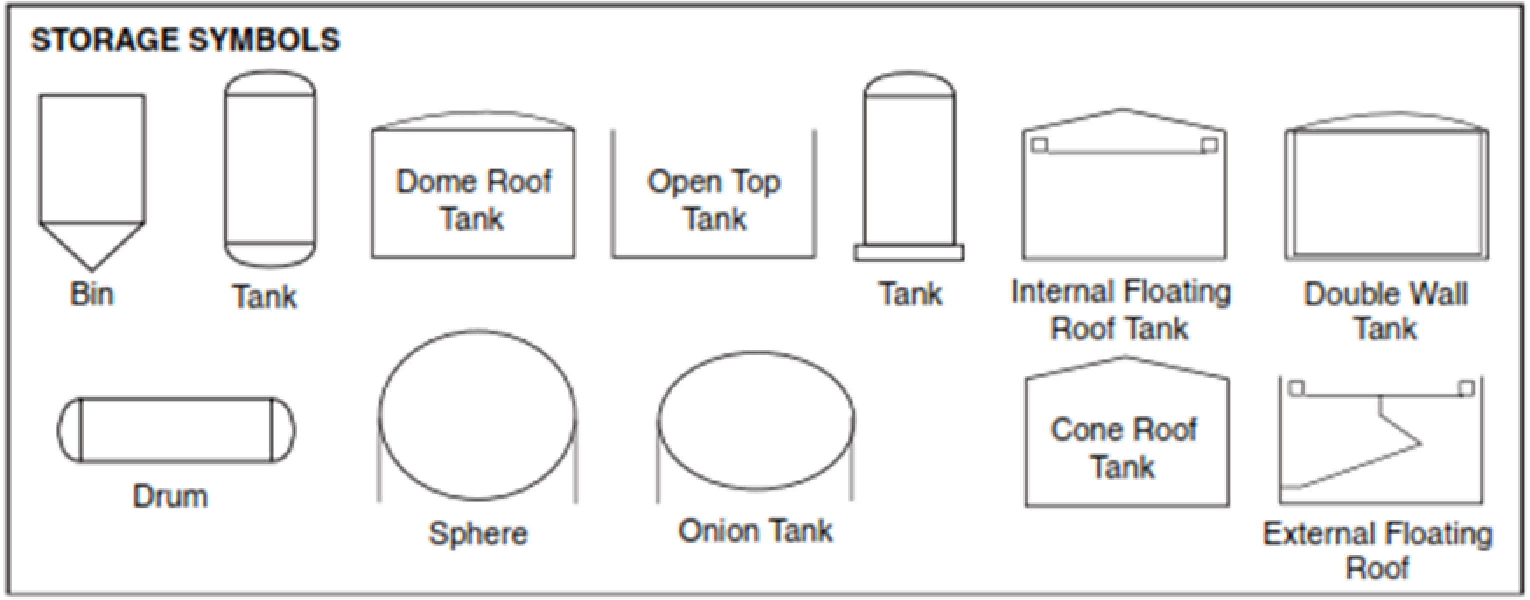
Simplified

- Chemical Engineering Symbols

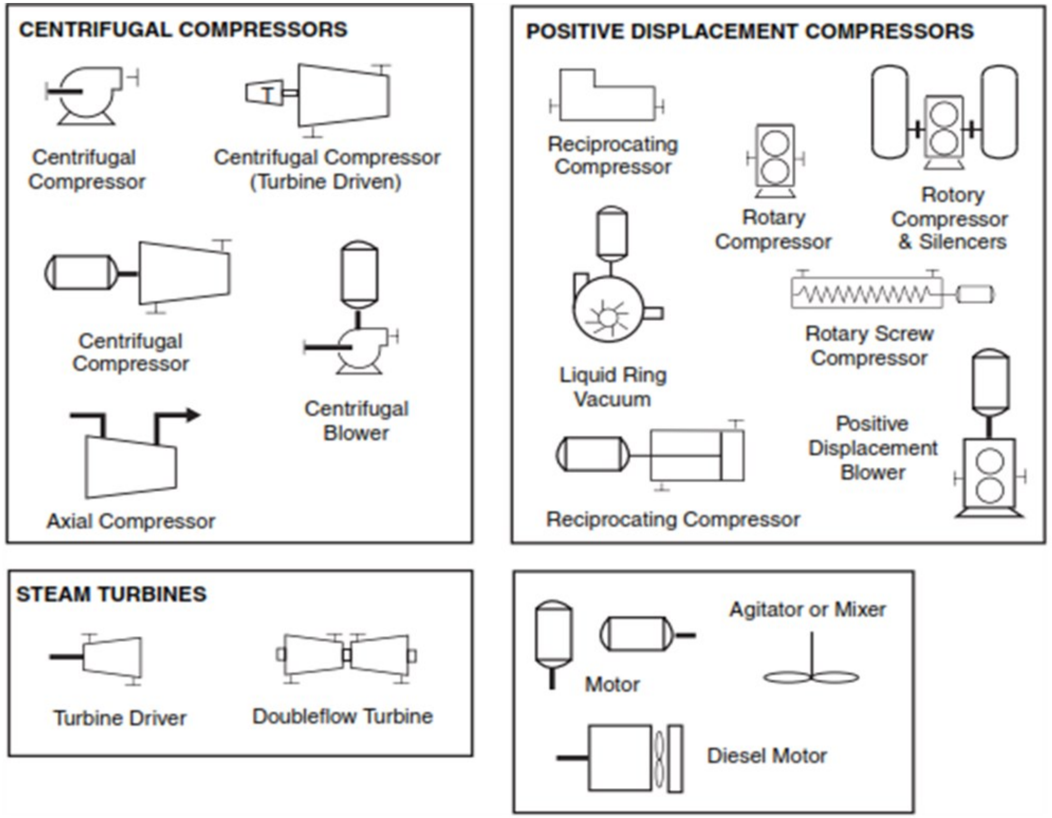
✓Pump symbols



- Chemcal Eng’g symbols (cont.)
  - ✓Tank symbols



✓Compressor, steam turbine, and motor symbols



- Equipment design yields quantitative data on required equipment, such as dimensions of pipes, power of pumps, surface area of heat exchangers, surface area of evaporator heaters, dimensions of distillation or extraction columns, and dimensions of dryers
- Whenever possible, standard or "off-the-shelf" equipment should be used, which is generally less expensive and more reliable than nonstandard equipment

- When specialized or nonconventional equipment is needed, detailed specifications are required which will help the fabricator to construct the appropriate unit (e.g. filters, chemical reactors, special dryers, and distillation columns)
- Sometimes, special equipment is needed for a new process, for which there is no industrial experience. In such cases, a pilot plant installation may be required, which will supply the specifications for the desired industrial equipment

Equipment Design-sizing

- The sizing of food processing equipment is based on material and energy balances around each process unit
- In equipment sizing, a safety or overdesign factor of 15 - 20% is normally used

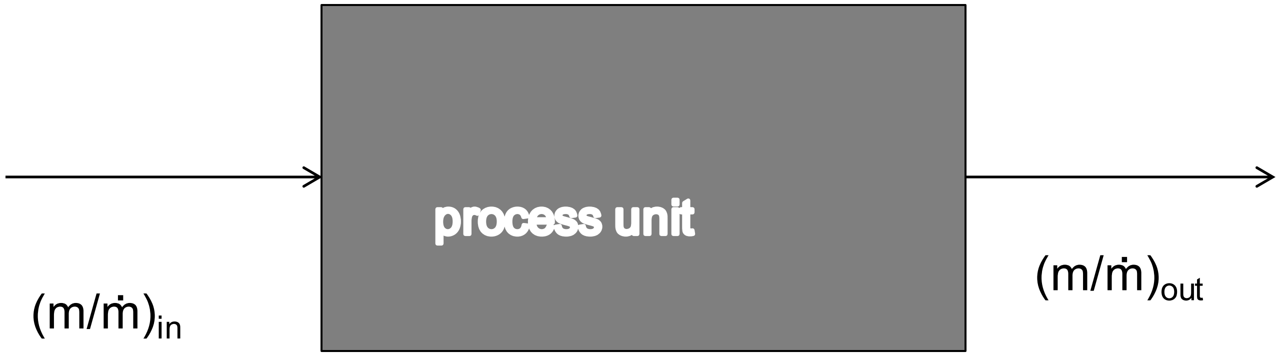
➢ This is to overcome the uncertanities and erros that will arise during the design calculations

❖ Uncertanities from

  - Data collection/analysis process
  - Approximations etc.

Equipment Design (Cont.)

- Material and Energy Balance
  - ✓ Material balance



Equipment design (cont.)

- ✓ A balance on a conserved quantity (total mass, mass of a particular species, energy, momentum) in a system (a single process unit, a collection of units, or an entire process) may be written in the following general way

input + generation – consumption – output = accumulation

Input = enters through system boundary

Generation= produced within the system

Consumption= consumed within the system

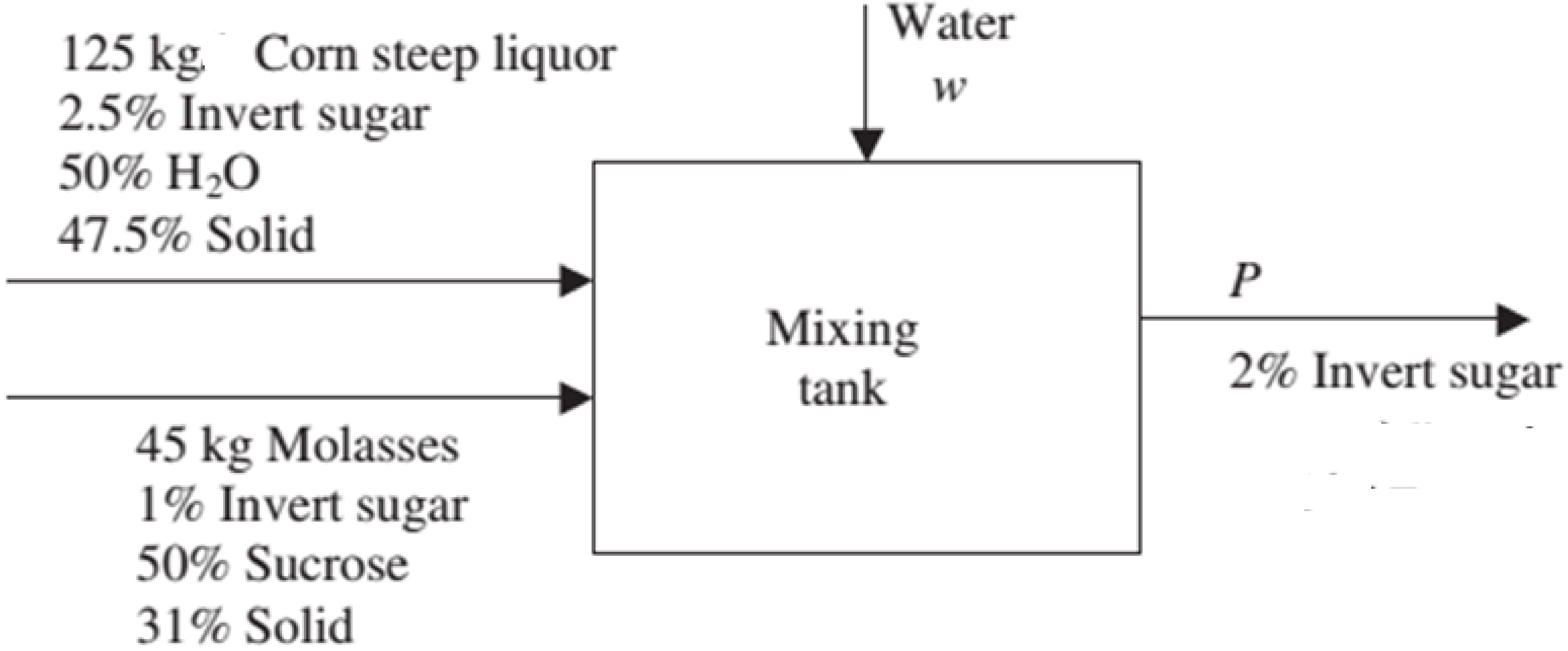
Output = leaves through system boundary

Accumulation = buildup within the system

Example

- Corn-steep liquor contains 2.5% invert sugars and 50% water; the rest can be considered solids. Beet molasses containing 50% sucrose, 1% invert sugars, 18% water and the remainder solids, is mixed with corn-steep liquor in a mixing tank. Water is added to produce a diluted sugar mixture containing 2% (w/w) invert sugars. 125 kg corn-steep liquor and 45 kg molasses are fed into the tank

Calculate: a) amount of water added b) volume of the tank


125 kg Corn steep liquor
2.5% Invert sugar
50% H_2O
47.5% Solid
Water
w
Mixing
tank
P
2% Invert sugar
45 kg Molasses
1% Invert sugar
50% Sucrose
31% Solid

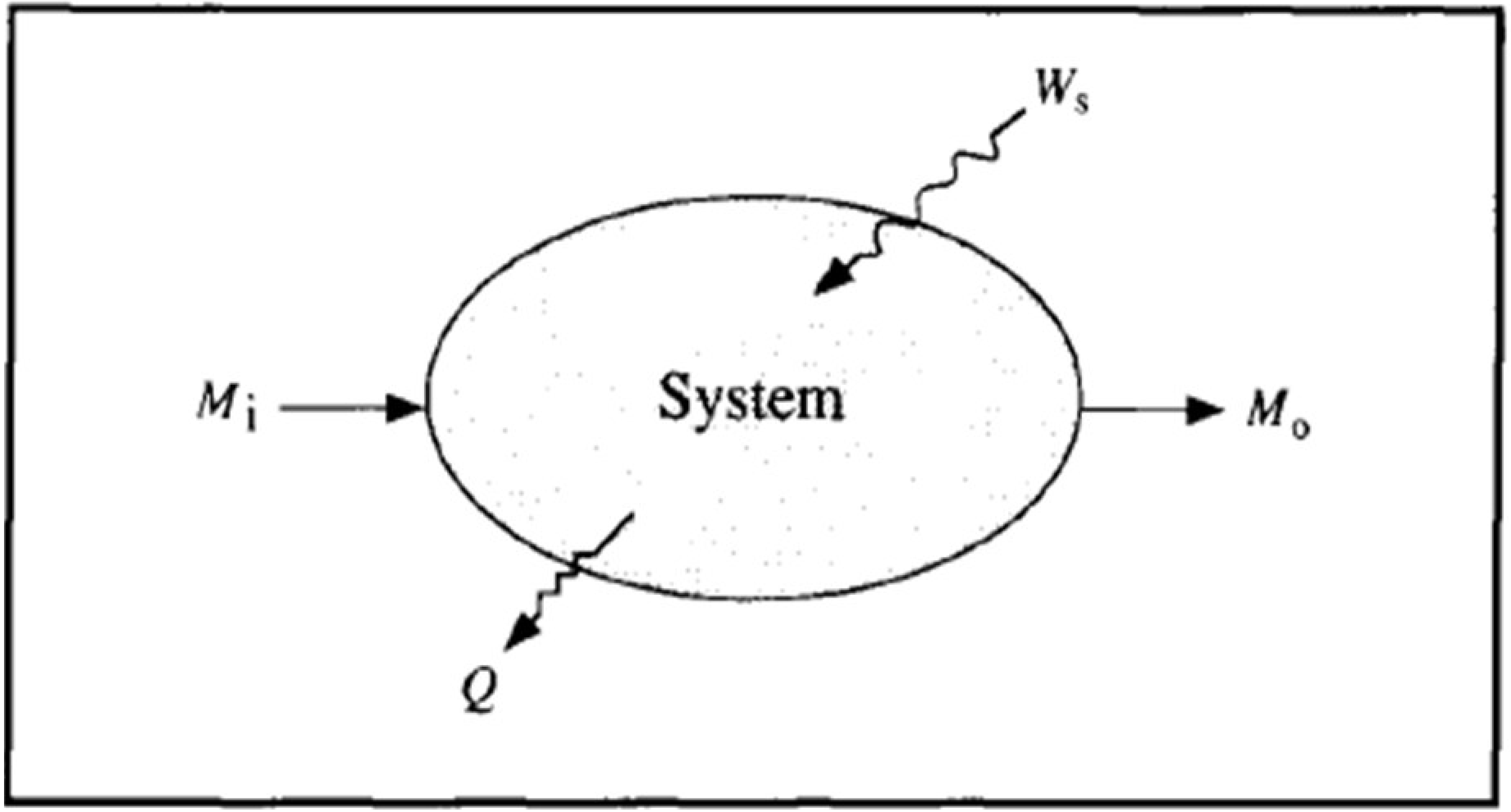
- Energy balance
  - ✓ An energy accounting system can be setup to determine the amount of steam or cooling water required to maintain optimum process temperatures
  - ✓ Forms of Energy
    - Kinetic energy, Ek
    - Potential energy, Ep
    - Internal energy, U

Cont.

- ✓Kinetic energy is the energy possessed by a moving system because of its velocity
- ✓Potential energy is due to the position of the system in a gravitational or electromagnetic field, or due to the conformation of the system relative to an equilibrium position (e.g. compression of a spring)
- ✓Internal energy is the sum of all molecular, atomic and sub-atomic energies of matter

Cont.

- Energy is transferred as either heat or work
  - ✓ Heat is energy which flows across system boundaries because of a temperature difference between the system and surroundings
  - ✓ Work is energy transferred as a result of any driving force other than temperature difference
    - Shaft work
    - Flow work



Flow system for energy-balance calculations

Cont.

- The Law of Conservation Energy

$$\left\{\begin{matrix}\text{energy in through}\\ \text{system boundaries}\end{matrix}\right\} - \left\{\begin{matrix}\text{energy out through}\\ \text{system boundaries}\end{matrix}\right\} = \left\{\begin{matrix}\text{energy accumulated}\\ \text{within the system}\end{matrix}\right\}$$

$$M_i\,(u+e_k+e_p+pv)_i - M_o\,(u+e_k+e_p+pv)_o - Q + W_s = \Delta E$$

$$H = U + pV$$

- Substituting enthalpy ***h*** for ***u + pv***

$$\sum_{\substack{\text{input}\\\text{streams}}} M(h+e_k+e_p) - \sum_{\substack{\text{output}\\\text{streams}}} M(h+e_k+e_p) - Q + W_s = \Delta E$$

- Special cases
  - ✓ If both kinetic and potential energies are negligible

$$\sum_{\substack{\text{input}\\\text{streams}}} (Mh) - \sum_{\substack{\text{output}\\\text{streams}}} (Mh) - Q + W_s = \Delta E$$

And, the process is steady

$$\sum_{\substack{\text{input}\\\text{streams}}} (Mh) - \sum_{\substack{\text{output}\\\text{streams}}} (Mh) - Q + W_s = 0$$

- Adiabatic process: is a process in which **no heat is transferred to or from the system**; if the system has an adiabatic wall it cannot receive or release heat to the surroundings

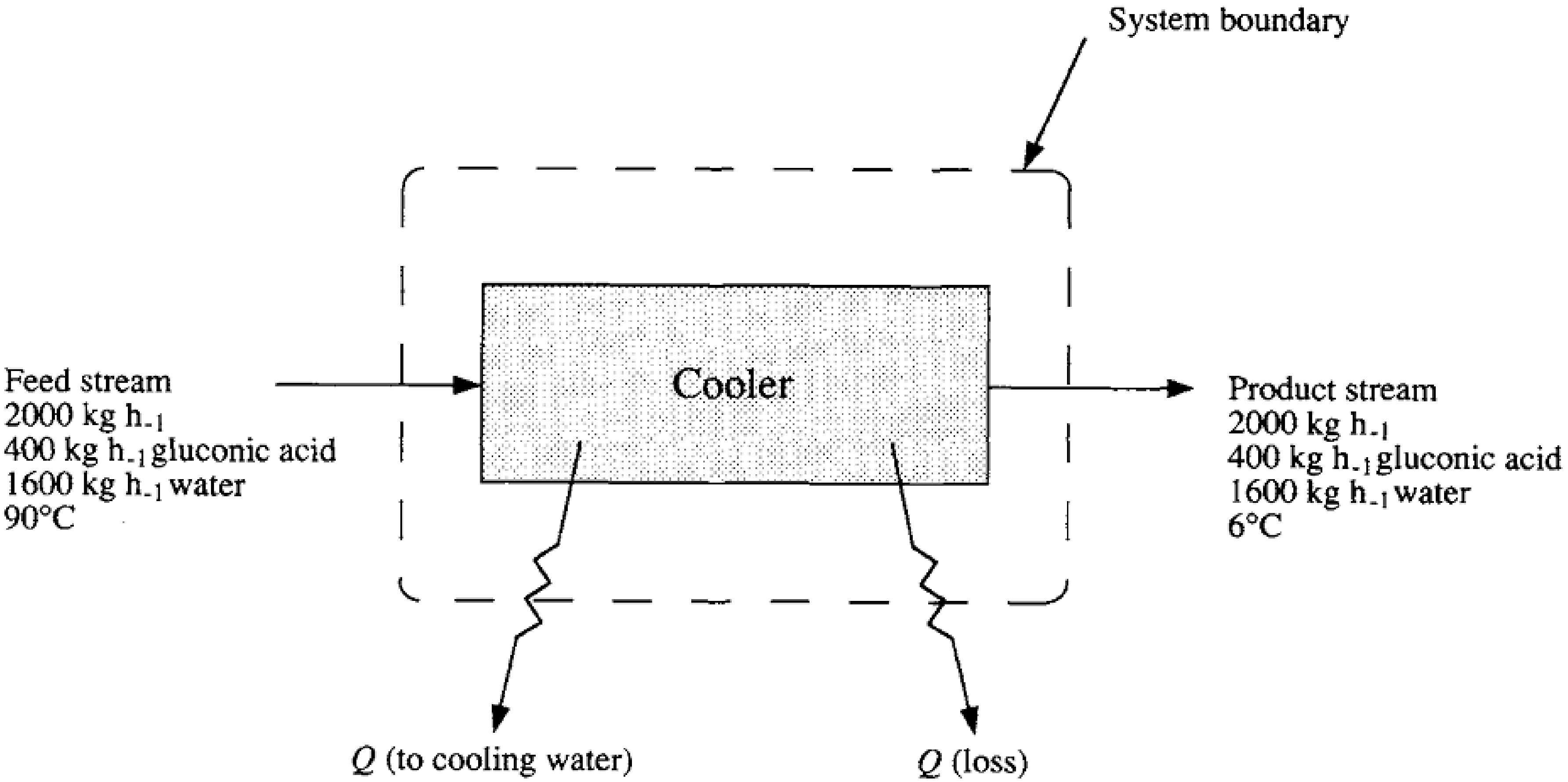
$$\sum_{\substack{\text{input}\\ \text{streams}}} (Mh) - \sum_{\substack{\text{output}\\ \text{streams}}} (Mh) + W_s = \Delta E$$

  - To apply the equations we must know the **specific enthalpy h** of **flow streams entering** or **leaving the system**

Example

2) In downstream processing of gluconic acid, concentrated fermentation broth containing 20% (w/w) gluconic acid is cooled in a heat exchanger prior to crystallization. 2000 kg h^{-1} liquid leaving an evaporator at 90°C must be cooled to 6°C. Cooling is achieved by heat exchange with 2700 kg h^{-1} water initially at 2°C. If the final temperature of the cooling water is 50°C, what is the rate of heat loss from the gluconic acid solution to the surroundings?

Assume the heat capacity of gluconic acid is 1.47 kJ kg^{-1} °C^{-1}.


System boundary
Cooler
Feed stream
2000 kg h.-1
400 kg h.-1 gluconic acid
1600 kg h.-1 water
90°C
Product stream
2000 kg h.-1
400 kg h.-1 gluconic acid
1600 kg h.-1 water
6°C
Q (to cooling water)
Q (loss)

Cont.

- **Enthalpy Change Due to Reaction**
  - ✓Large changes in internal energy and enthalpy occur as bonds between atoms are rearranged.
  - ✓*Heat of reaction* ΔH_{rxn} *is the energy released or* absorbed during reaction, and is equal to the difference in enthalpy of reactants and products

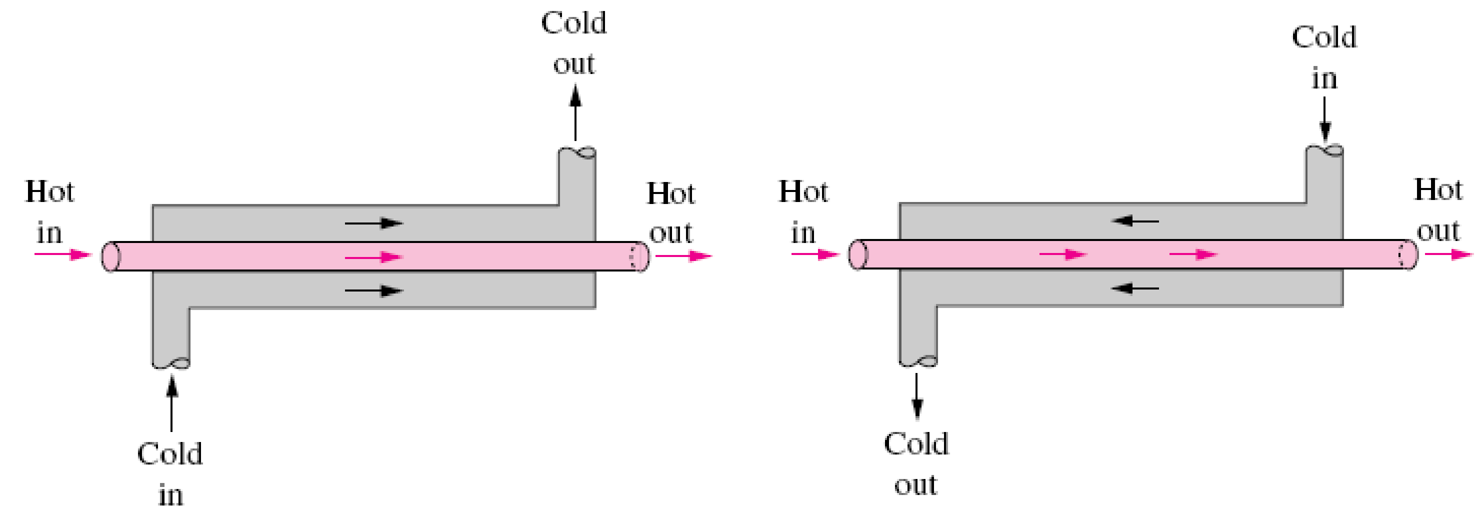
$$\Delta H_{rxn} = \sum_{products} Mh - \sum_{reactants} Mh$$

Heat Exchanger Design

- Heat exchangers are devices that facilitate the exchange of heat between two fluids that are at different temperatures while keeping them from mixing with each other
- Heat exchangers are typically classified according to flow arrangement and type of construction

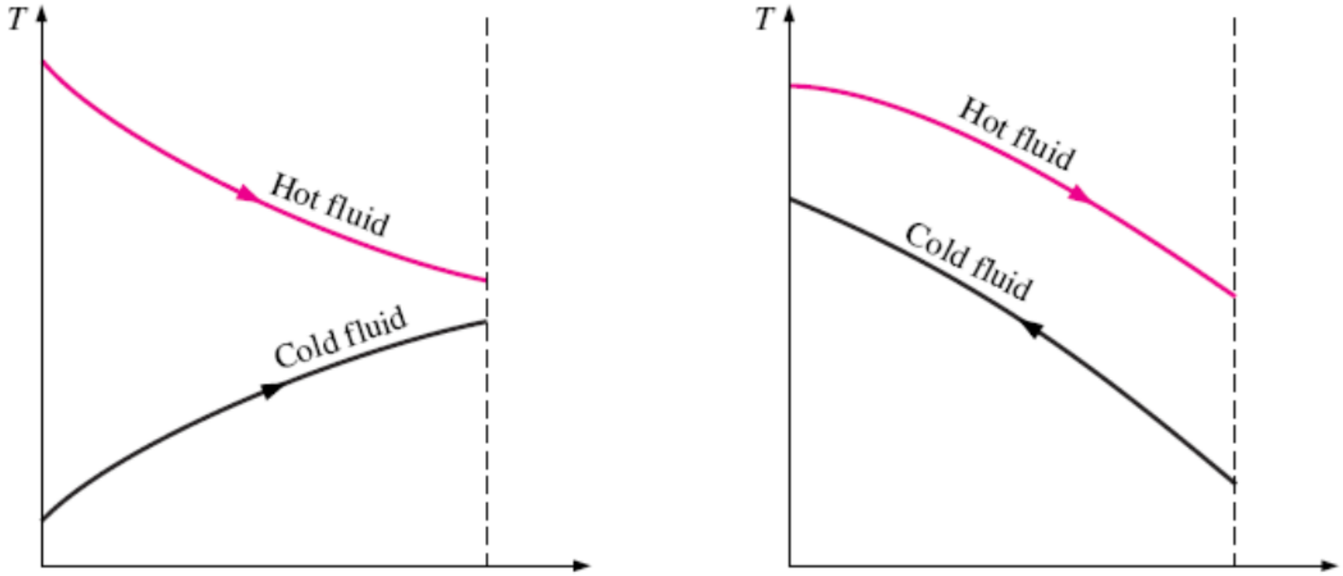
Types of Heat Exchangers

- Double pipe



(*a*) Parallel flow

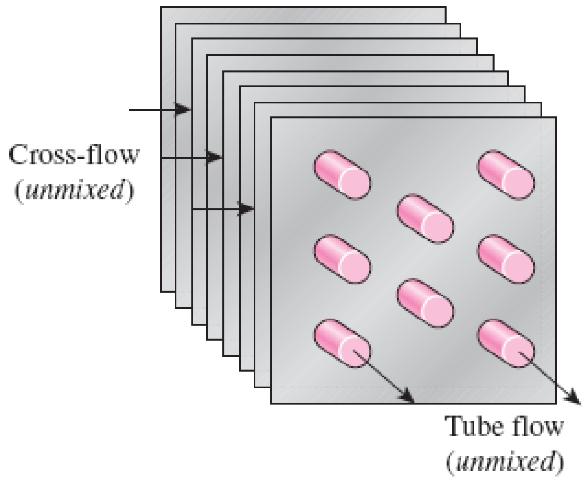
(*b*) Counter flow



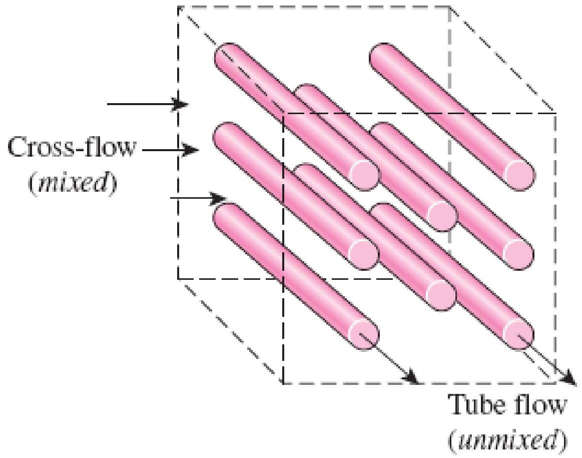
- **Compact heat exchanger:**

It has a large heat transfer surface area per unit volume (e.g.,car radiator, residential radiator). A heat exchanger with the *area density* $\beta > 700$ m^2/m^3 is classified as being compact

  - Liquid to gas / Gas to gas



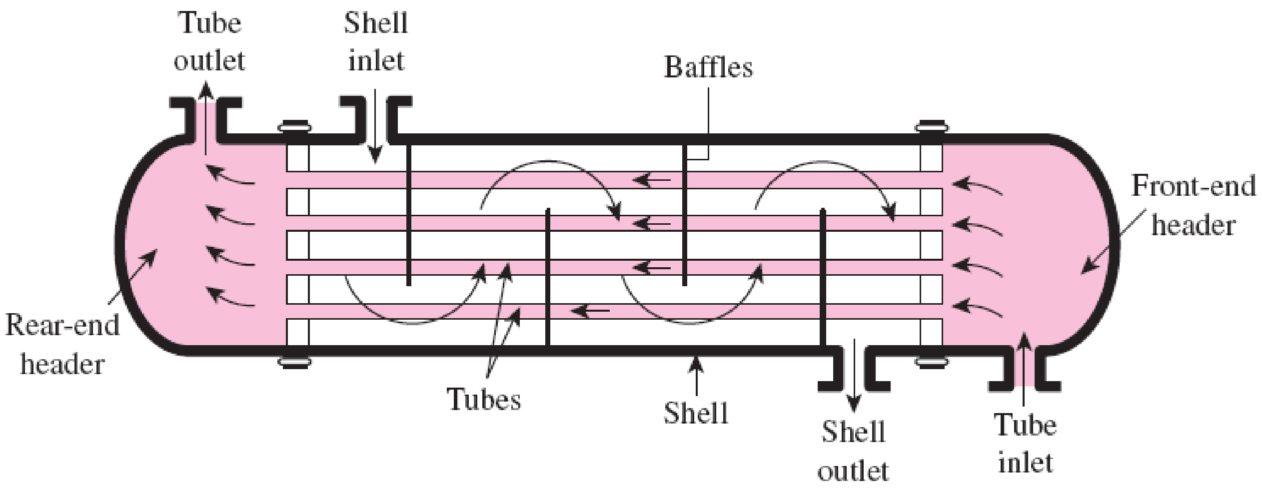
(a) Both fluids unmixed



(b) One fluid mixed, one fluid unmixed

Shell-and-tube heat exchanger:

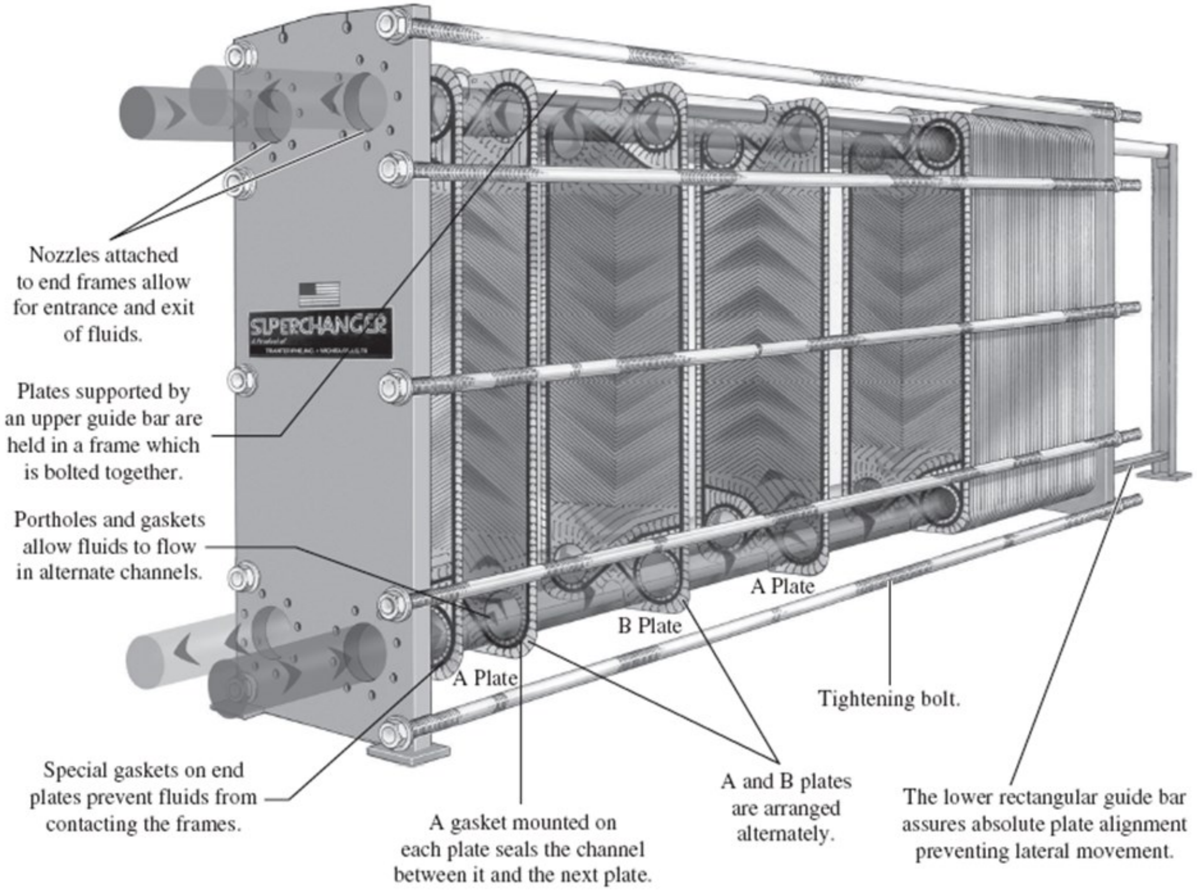
- The most common type of heat exchanger in industrial applications
- They contain a large number of tubes (sometimes several hundred) packed in a shell with their axes parallel to that of the shell. Heat transfer takes place as one fluid flows inside the tubes while the other fluid flows outside the tubes through the shell



The schematic of a shell-and-tube heat exchanger (one-shell pass and one-tube pass).

Plate and frame (or just plate) heat exchanger:

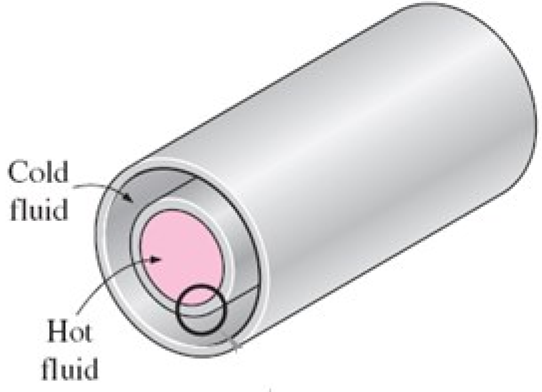
Consists of a series of plates with corrugated flat flow passages. The hot and cold fluids flow in alternate passages, and thus each cold fluid stream is surrounded by two hot fluid streams, resulting in very effective heat transfer. Well suited for liquid-to-liquid applications



Heat-exchanger size estimation

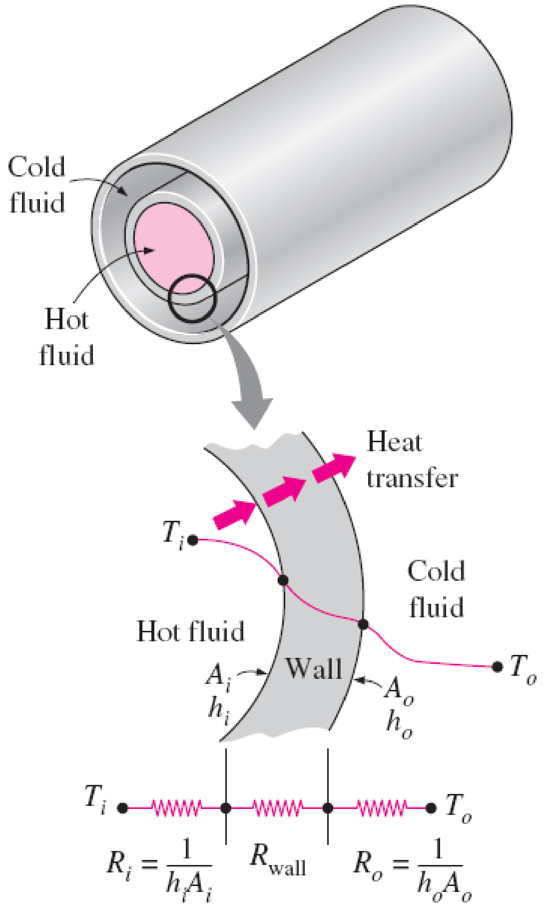
$$\dot{Q} = \dot{m}_c c_{pc}(T_{c,\text{out}} - T_{c,\text{in}}) = \dot{Q} = \dot{m}_h c_{ph}(T_{h,\text{in}} - T_{h,\text{out}})$$

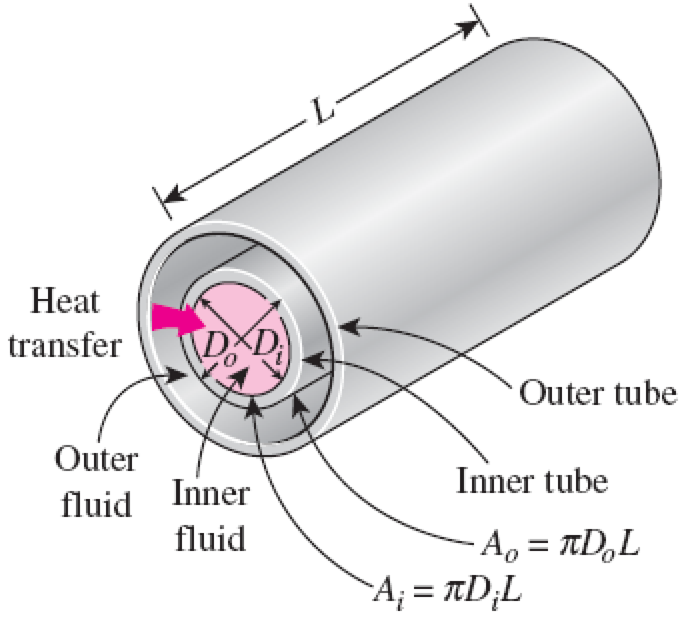
$$\dot{Q} = \dot{m}_c c_{pc}(T_{c,\text{out}} - T_{c,\text{in}}) = UA_s\,\Delta T_{\text{lm}}$$



The overall heat transfer coefficient (*U*)

- A heat exchanger typically involves two flowing fluids separated by a solid wall
- Heat is first transferred from the hot fluid to the wall by *convection,* through the wall by *conduction,* and from the wall to the cold fluid again by *convection*





$$\dot{Q} = \frac{\Delta T}{R} = UA\Delta T = U_i A_i \Delta T = U_o A_o \Delta T$$

U the overall heat transfer coefficient, W/m²·°C

$$R = R_{\text{total}} = R_i + R_{\text{wall}} + R_o = \frac{1}{h_i A_i} + \frac{\ln(D_o/D_i)}{2\pi k L} + \frac{1}{h_o A_o}$$

(for thin tubes, $D_i \approx D_o$ and thus $A_i \approx A_o$).

$$\frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = R = \frac{1}{h_i A_i} + R_{\text{wall}} + \frac{1}{h_o A_o}$$

Overall heat transfer coefficient (cont.)

Representative values of the overall heat transfer coefficients in heat exchangers

Type of heat exchanger	U, W/m²·K*
Water-to-water	850–1700
Water-to-oil	100–350
Water-to-gasoline or kerosene	300–1000
Feedwater heaters	1000–8500
Steam-to-light fuel oil	200–400
Steam-to-heavy fuel oil	50–200
Steam condenser	1000–6000
Freon condenser (water cooled)	300–1000
Ammonia condenser (water cooled)	800–1400
Alcohol condensers (water cooled)	250–700
Gas-to-gas	10–40
Water-to-air in finned tubes (water in tubes)	30–60†
	400–850†
Steam-to-air in finned tubes (steam in tubes)	30–300†
	400–4000‡

$$\dot{Q} = \frac{\Delta T}{R} = UA\Delta T$$

Fouling factor

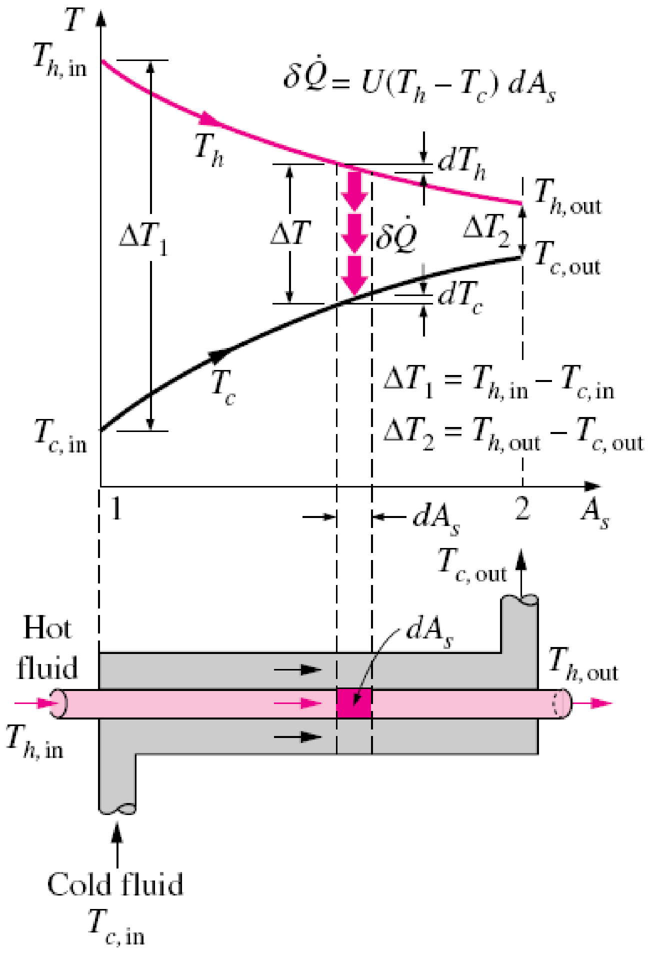
The performance of heat exchangers usually deteriorates with time as a result of accumulation of *deposits* on heat transfer surfaces. The layer of deposits represents *additional resistance* to heat transfer. This is represented by a fouling factor R_f.

$$\frac{1}{UA_s} = \frac{1}{U_i A_i} = \frac{1}{U_o A_o} = R = \frac{1}{h_i A_i} + \frac{R_{f,i}}{A_i} + \frac{\ln(D_o/D_i)}{2\pi k L} + \frac{R_{f,o}}{A_o} + \frac{1}{h_o A_o}$$

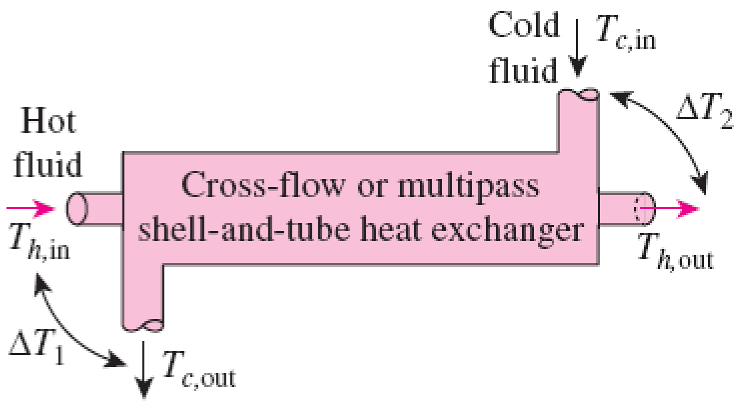
The fouling factor increases with the *operating temperature and* the length of service and decreases with the *velocity* of the fluids.

Cont.

$$\Delta T_{lm} = \frac{\Delta T_1 - \Delta T_2}{\ln(\Delta T_1/\Delta T_2)}$$



Multipass and Cross-Flow Heat Exchangers: Use of a Correction Factor



$$\Delta T_{lm} = F\,\Delta T_{lm,\,CF}$$

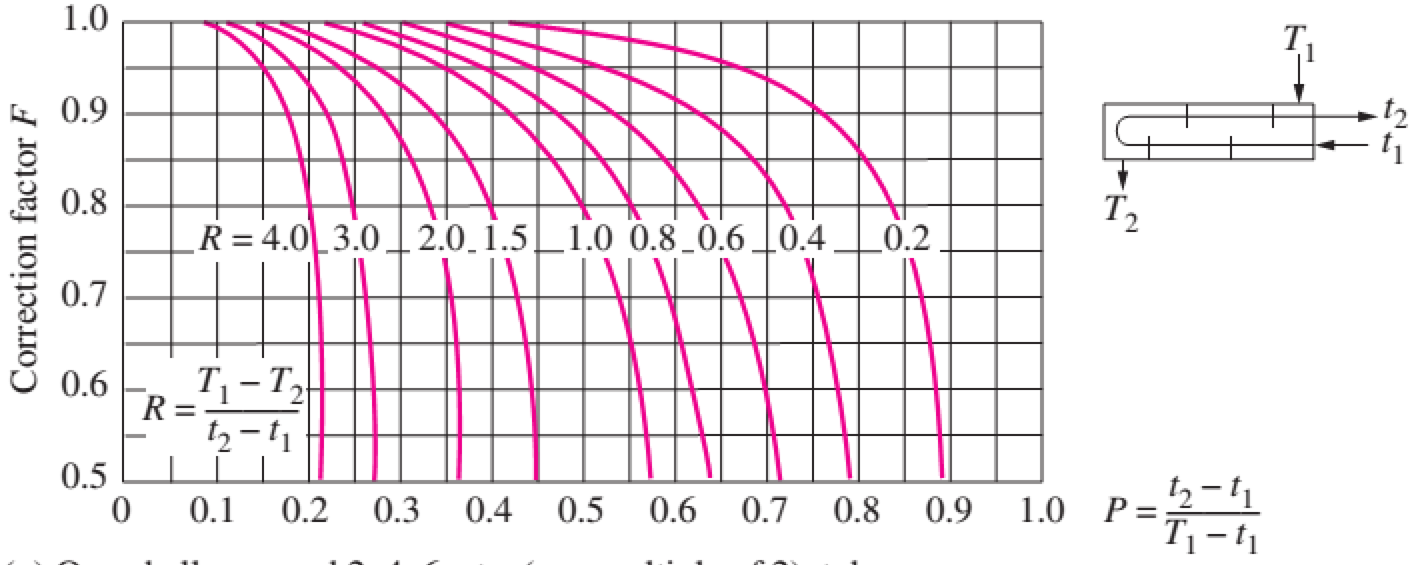
***F* correction factor** depends on the *geometry* of the heat exchanger and the inlet and outlet temperatures of the hot and cold fluid streams.

F for common cross-flow and shell-and-tube heat exchanger configurations is given in the following figures versus two temperature ratios *P* and *R* defined as

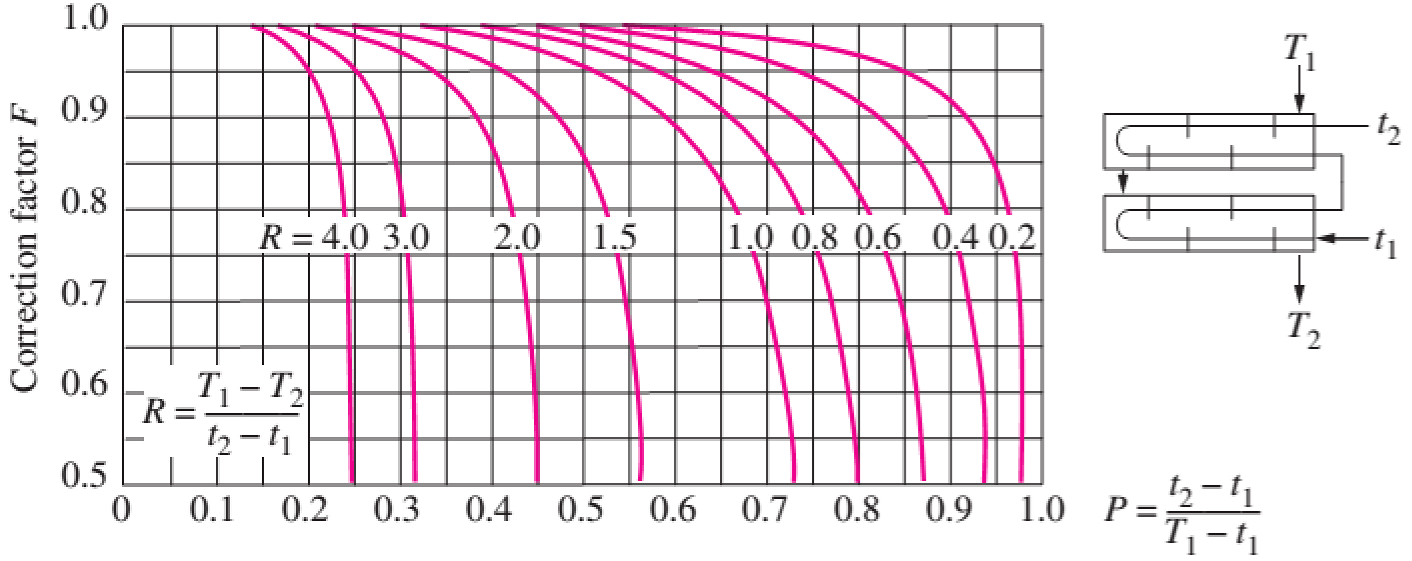
$$P = \frac{t_2 - t_1}{T_1 - t_1} \qquad R = \frac{T_1 - T_2}{t_2 - t_1} = \frac{(\dot{m}c_p)_{\text{tube side}}}{(\dot{m}c_p)_{\text{shell side}}}$$

1 and 2 *inlet* and *outlet*
T* and *t *shell*- and *tube-side* temperatures

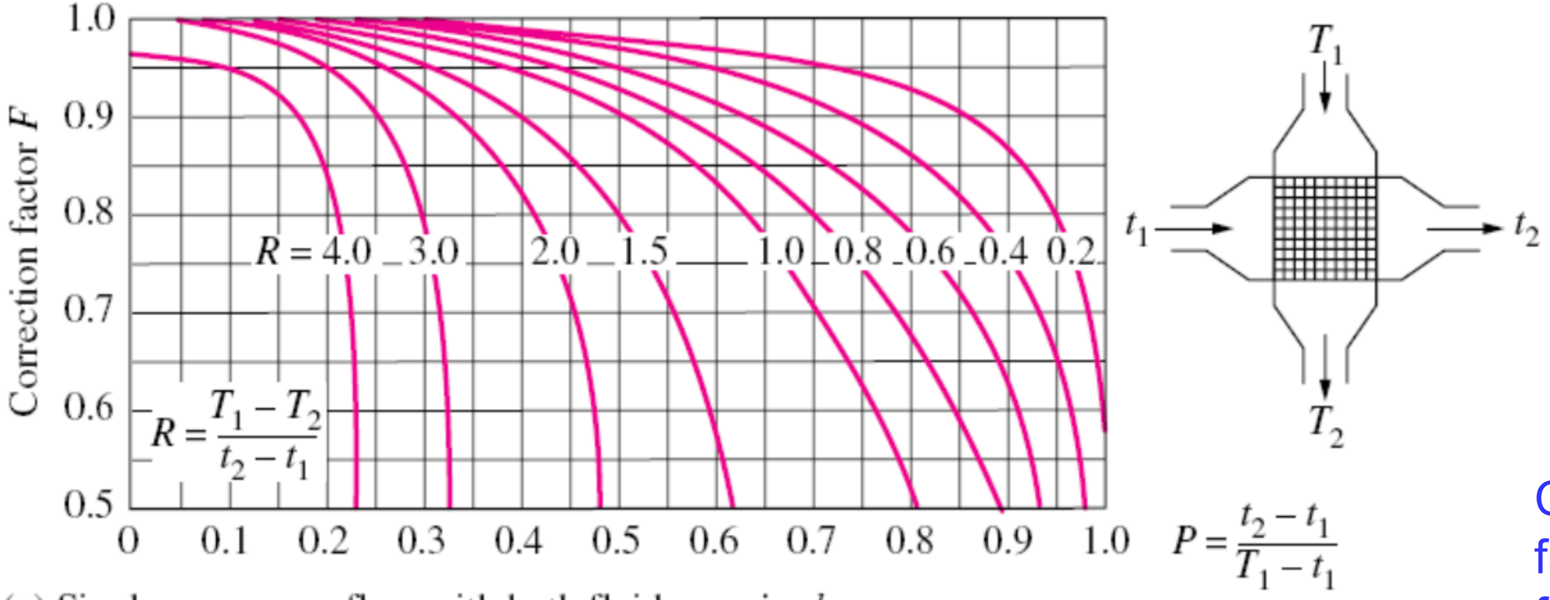
***F* = 1 for a condenser or boiler**



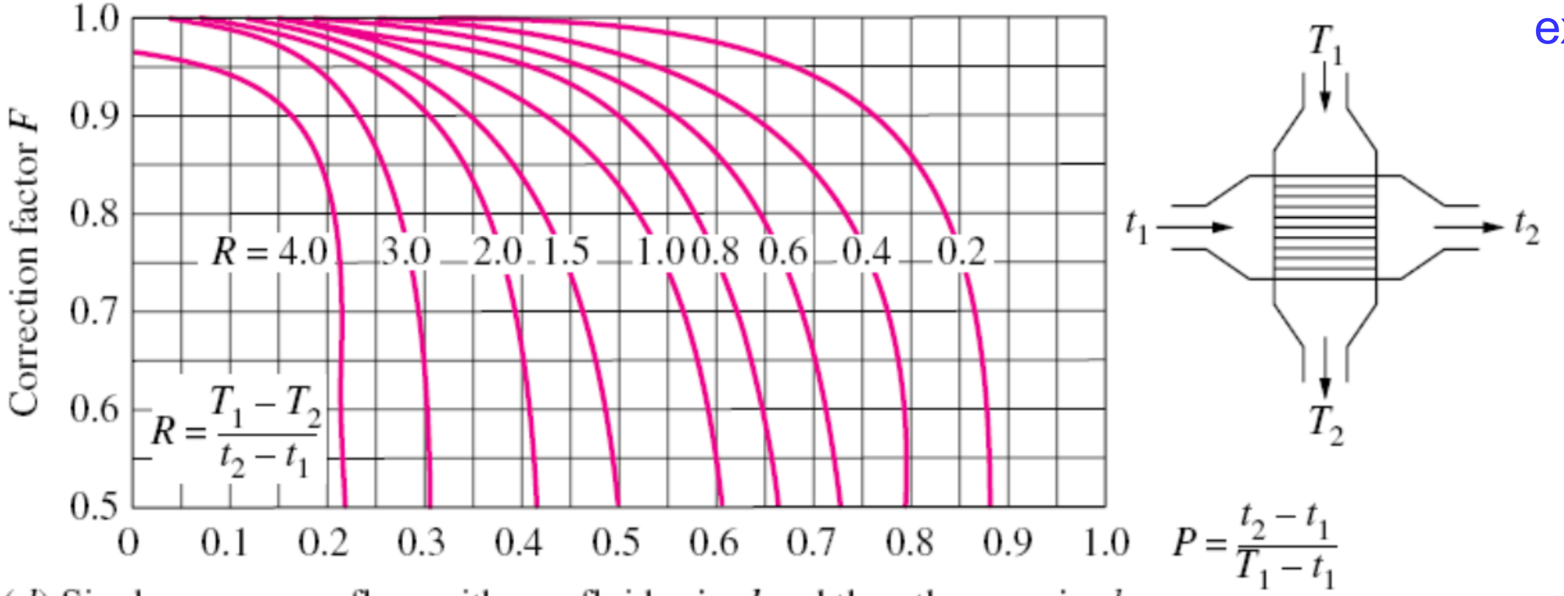
(*a*) One-shell pass and 2, 4, 6, etc. (any multiple of 2), tube passes



(*b*) Two-shell passes and 4, 8, 12, etc. (any multiple of 4), tube passes



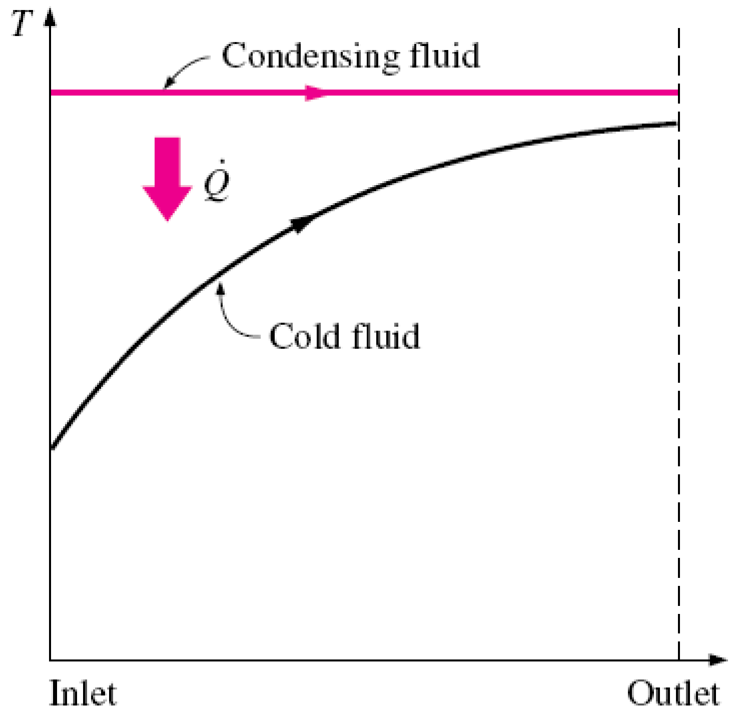
(c) Single-pass cross-flow with both fluids *unmixed*

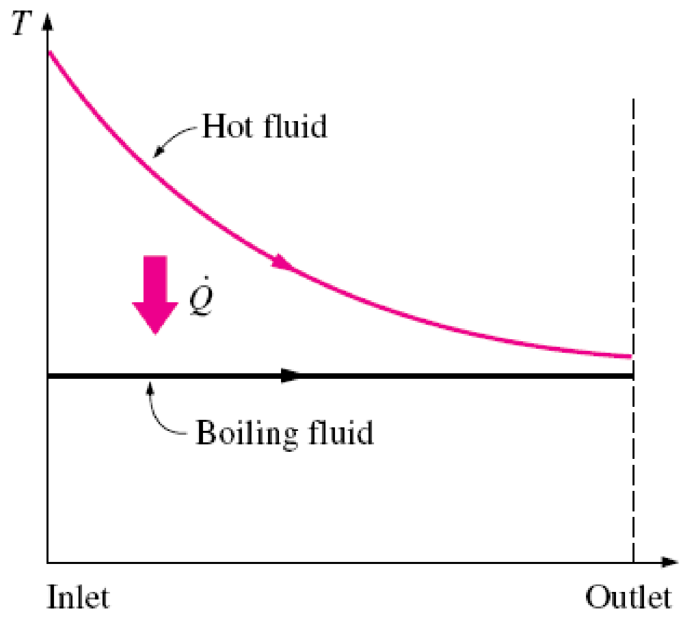


(d) Single-pass cross-flow with one fluid *mixed* and the other *unmixed*

Correction factor *F* charts for common cross-flow heat exchangers.

Cont.





$$\dot{Q} = \dot{m}h_{fg} = UA_s\,\Delta T_{\text{lm}}$$

Question

- A double-pipe counter-flow heat exchanger is to cool milk (Cp = 3930 J/kg·°C) flowing at a rate of 3.5kg/s from 80 °C to 25 °C by water (Cp = 4180 J/kg°C) that enters at 20°C and leaves at 65°C. The overall heat transfer coefficient based on the inner surface area of the tube is 250 W/m2°C. Determine the heat transfer surface area on the inner side of the tube

Thank you