Chapter 2

THEORY OF JETS

2.1 Introduction

In this chapter, the basic jet theory is explained in detail. An overview on jet flow is given to understand the basic jet classifications like free jet, confined jet and isothermal and non-isothermal jets. The structure and development of a free jet is explained to bring out the different zones in jet flow. Later, the factors affecting the jet spread are discussed in detail to illustrate the physics of jet flow.

2.2 Overview of Jet Flows

Over the past six decades, jets have been the subject of extensive experimental and analytical research. Circular and plane jets are used in a variety of applications. Some of the common applications of jets occur in drying processes, air curtains for room conditioning, heating and ventilating applications. In these, parameters like the jet spread rate and potential core decay play a strong role in deciding the efficiency of mixing for the process. Shear layer is the region in which most of the interactions and mixing between the ambient and jet fluids take place. Therefore, understanding the fluid dynamic phenomena in the shear layer during the downstream evolution of a jet is important.

In spite of the voluminous research literature available on turbulent jets issuing from circular and non circular nozzles, there are still some important aspects which require greater attention. For instance, in plane jets of large aspect ratio, primarily planar spreading occurs in the near field. But at larger distances, the differential rates of shear layer growth in two lateral directions results in 3-D features such as the axis switching phenomena. The jet shear layers also actively participate in the entrainment of ambient fluid and in the growth of turbulent flow fluctuations [Sato.H, 1964]. Far away from the nozzle exit, the jet loses any memory of the nozzle cross sectional shape and the flow asymptotically attains the self- similar profile of a round jet. The turbulent flow fluctuations also evolve as the jet spreads with increase in axial distance; the rates of evolution of the mean flow field and turbulent fluctuations however, are quite different.

Free jets can be defined as a pressure driven unrestricted flow of a fluid into a quiescent ambiance, the wall ceiling or obstruction does not influence the jet. Since a fluid boundary cannot sustain a pressure difference across it, the subsonic jet boundary is a free shear layer in which the static pressure is constant throughout. The boundary layer at the exit of the device develops as a free shear layer, mixing with the ambient fluid thereby entraining the ambient fluid in the jet stream. Thus, the mass flow at any cross section of the jet progressively increases thereby the jet spreads along the downstream direction. In order to conserve momentum, the jet centreline velocity decreases with downstream distance.

If the air jet performance is influenced by reverse flows, created by the same jet entraining ambient air, this is called a confined jet. Particularly if the air jet is attached to a surface, it is an attached air jet. When considering the temperature difference between the supply air and room ambient air, the air jets can be divided into isothermal jets and non-isothermal jets. The buoyancy forces will have a role in deciding the trajectory of jets, the location where the jet attaches and separates from the ceiling or floor and the spread of jet. In the present study the air jet is considered as confined isothermal jet discharging into a large volume.

2.3 Structure and Development of a Free Jet

A free jet is a fluid mass that discharges into an infinitely large environment of ambient fluid. The flow structure in a free jet has been studied by many researchers and four distinct zones have been identified from these studies. In ASHRAE literature the development of a jet is divided into four zones, related to centreline velocity decay. The structure of a free jet is shown in Fig 2.1 [Yue.Z, 1999]

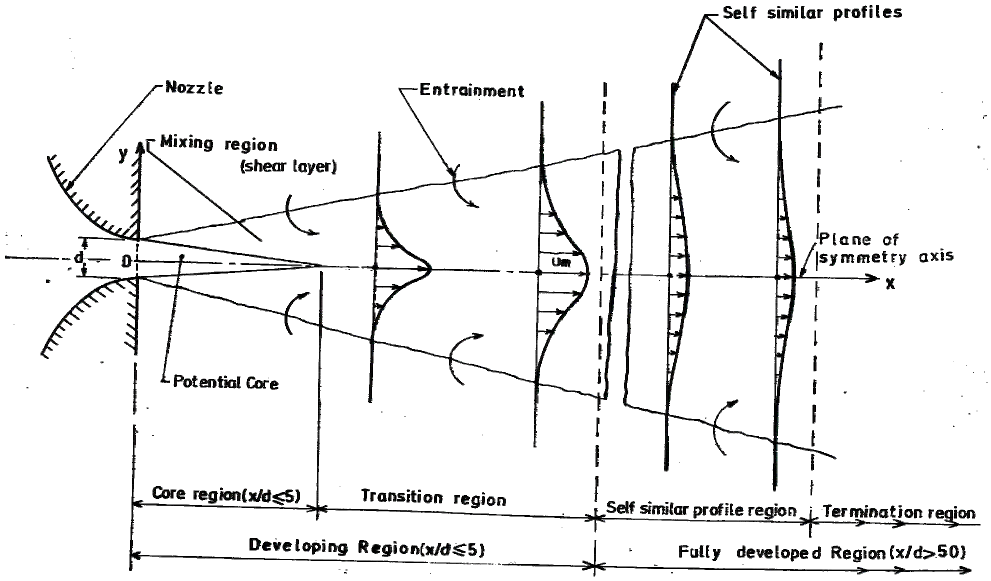

Fig 2.1 Flow structure of a free jet [Yue.Z, 1999]

Zone 1: The convergent zone: This region is called the potential core of the jet where the centreline velocity is equal to the nozzle outlet velocity. This region normally extends up to 4d to 6d, where d is the diameter of the nozzle exit.

Zone 2: This transition zone: Ii is the region in which the centreline velocity starts to decay. The velocity decay can be approximated as proportional to $x^{-0.5}$, where x is the axial distance. This usually corresponds to a region from 6d to 20d, and it is known as the interaction region where shear layers from both sides merge.

Zone 3: The self similar zone: In this region transverse velocity profiles are similar at different values of x and the centreline velocity decay is approximately proportional to x^{-1}.

Zone 4: The termination zone: In this region the centreline velocity decays rapidly. Although this zone has been studied by several researchers, the actual mechanisms in this zone are not understood properly.

For an axial jet, the first two zones are strongly influenced by the diffuser, the third zone is the developed jet, and the fourth zone is the zone of jet termination. In the first three zones, room air is entrained into the jet and mixed with supply air. In the fourth zone, the jet collapses inward from the boundaries and the supply air is distributed to the room air as the jet disintegrates [Rajaratnam.N, 1976].

It is sufficient to have knowledge of the first three zones in most engineering applications. Because of the large velocity difference at the surface of discontinuity between the jet fluid and ambient, large eddies are formed, which cause intense lateral mixing. As a result of this mixing, fluid within the jet is decelerated and the fluid surrounding the jet is accelerated and in fact it is entrained into the jet flow. As a consequence of entrainment, the width of the jet increases.

Fig. 2.2 illustrates the schematic view of plane jet emanating from rectangular nozzle of large aspect ratio with axial distance.

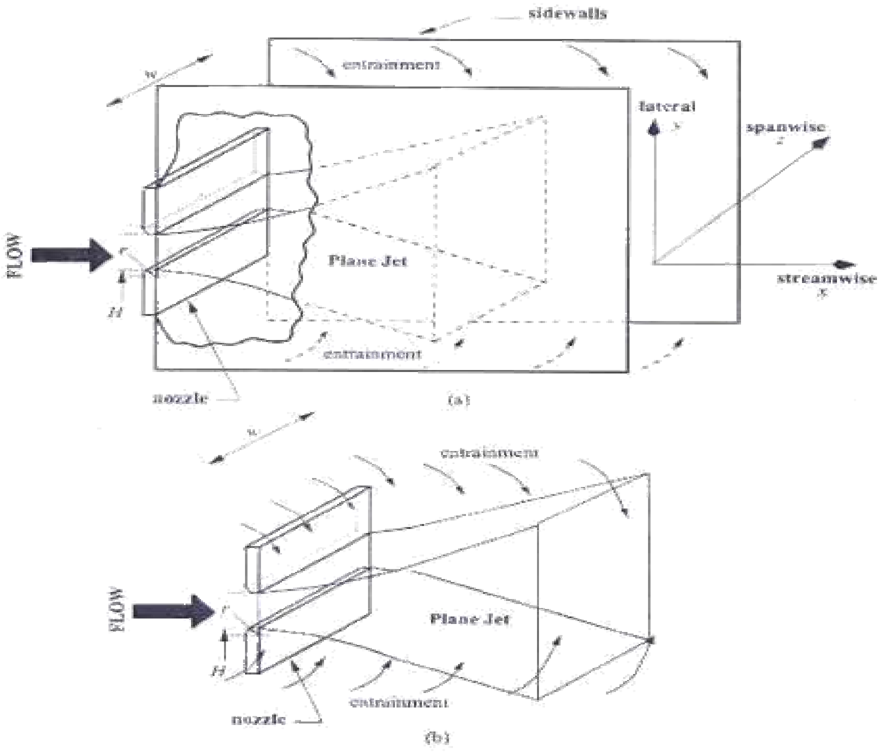

Fig 2.2 Development of a plane jet with side walls

The jet is confined within two parallel sidewalls attached to the short sides of the nozzle and oriented in the x-y plane. Such a configuration excludes the spread of the jet in the z-direction.

2.4 Factors Influencing Jet Spread

Several factors such as the jet inlet velocity profile, nozzle geometry, jet Reynolds number and fluid temperature at the inlet, affect the jet spread. Here, a brief account of the factors and phenomena which influence jet growth is presented.

2.4.1 Inlet Velocity Profile

The initial condition of the jet influences the downstream development of flow. The flow profile at jet inlet can be generally categorized into one of the four types: laminar, nominally laminar, highly disturbed and fully turbulent. The laminar and fully turbulent conditions are asymptotic limiting states, and the second or third case is typically achieved. The mean velocity profile in the shear layer at jet inlet is identical to the Blassius profile in the laminar case. The shear layer instability induced fluctuations will occur with peak values near the jet boundaries. The spectrum for the laminar shear layer flow has typically a few peaks, but without considerable broadband components. The parameters that are usually obtained to assess the nozzle exit (i.e. jet inlet) conditions are;

Displacement thickness $$\delta = \int_{-\infty}^{\infty} (1 - \frac{U}{U_\infty}) dy \text{ ----------------------------(2.1)}$$

Momentum thickness $$\theta = \int_{-\infty}^{\infty} \frac{U}{U_\infty}(1 - \frac{U}{U_\infty}) dy \text{ ------------------------------(2.2)}$$

Shape factor $$H = \frac{\delta}{\theta} \text{ ---(2.3)}$$

The value of shape factor is 2.5 for a laminar boundary layer condition at the nozzle exit and 1.4 for fully developed turbulent boundary layer condition. A value falling in between this range of shape factor means that the boundary layers are transitional in nature.

2.4.2 Nozzle Geometry

The feature of the jet flow is significantly affected by the nozzle geometry. The far field mean centreline velocity function of a round jet and plane jet are different. The former is a function of x^{-1} while the later $x^{0.5}$. The transition characteristics of the jets also depend on the nozzle cross sectional shape. Non-circular jets, especially rectangular jets with large aspect ratios undergo the phenomenon of axis switching. During this phenomenon, the major and minor axes switch with axial distance. This is due to the different spread rates for the jet in the two lateral directions. This phenomenon is absent in round jets. Nozzle geometries has got important role to play in defining the initial velocity profile of the jet. Sharp edged orifice geometry may produce a saddle-backed initial velocity profile [Elbanna *et al.,* 1983] while a top hat profile is obtained with a smooth contraction nozzle. Depending on the Reynolds number, fully developed laminar or turbulent profiles at the exit are obtained for jets discharging from long two dimensional channels.

2.4.3 Jet Reynolds Number

Reynolds number of a plane jet is defined in terms of the height of the nozzle, bulk mean velocity U_0 and kinematic viscosity ν of the jet fluid as

$$\mathrm{Re} = \frac{U_o d}{\nu} \text{ -- } (2.4)$$

If the jet discharges through a contoured plane nozzle, the velocity variation at jet inlet will be a top hat profile and bulk mean velocity is close to the nozzle exit centreline velocity. An alternative definition of the Reynolds number can be based on the local jet half width and the local centreline velocity, in the form

$$\mathrm{Re}_{b_u} = \frac{U_c b_u}{\nu} \text{ ---(2.5)}$$

2.4.4 Half Width and Virtual Origin of the Jet

Jet half width at any axial location is defined as the distance between the centreline and a transverse plane where the mean velocity becomes half of the corresponding centreline velocity. Half width generally increases linearly with x except in regions of axis switching. Slope of the half width line in the axial direction is called as spread rate. Usually, the spread rate of a high Reynolds number turbulent jet is 0.11 while that of a laminar jet is around 0.4. Virtual origin is the point from which the jet appears to be originating as shown in fig. 2.3.

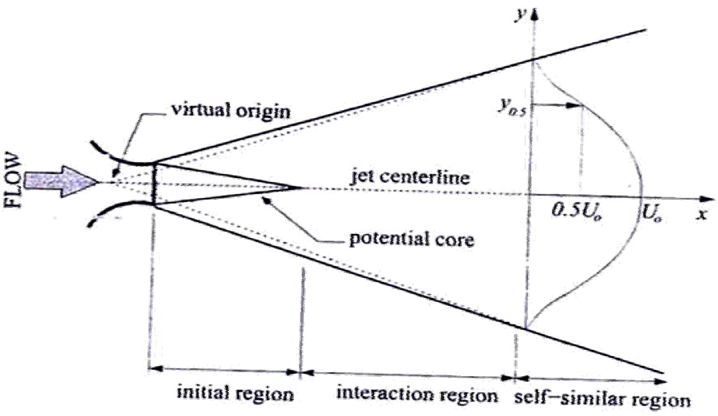

Fig 2.3 Virtual origin and half width

It may be different from the geometric origin and may be located inside or outside the nozzle, depending upon the nozzle exit boundary layer profiles. Virtual origin is related to the half width through the expression

$$\frac{b_u}{d} = K_{2u}\left(\frac{x}{d} \pm C_{2u}\right) \text{ ---(2.6)}$$

Where C_{2u} is the virtual origin and K_{2u} is the spread rate. Also, b_u is the jet half width.

2.4.5 Jet Instabilities

Depending on the initial velocity profile, beyond certain axial distance, the jet fluid discharging from the nozzle develops flow oscillations in the shear layer. These oscillations will roll up to form vortices which increase in size and strength with the axial distance. The vortices will influence the entrainment of the ambient fluid and the mixing of the ambient fluid and the jet fluid. The vortex interactions will result in the transition of the flow to turbulent regime. Flow visualization studies reveal stark differences in the development of circular and non- circular jets [Batchelor *et al.*, 2000]. The development of vortices in the shear layer and the ultimate transition of an initially laminar jet to turbulent flow, are shown in Fig 2.4

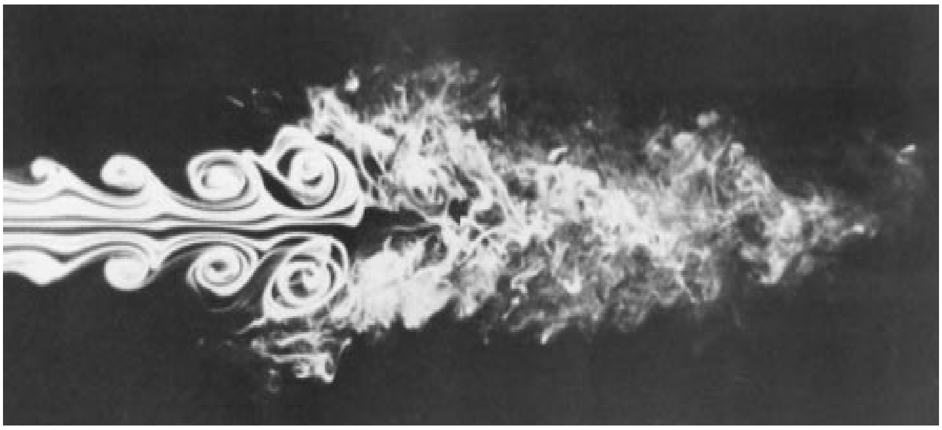

Fig 2.4 Shear layer instabilities in a jet

2.4.6 Coherent Structures

Coherent structure are defined as a connected, large scale turbulent fluid mass with a phase correlated vorticity over its spatial extent i.e. underlying the three dimensional random vorticity fluctuations characterizing turbulence, there is an organized component of the vorticity which is phase correlated (coherent) over the whole structure [Hussain, 1983]. Development of coherent structures in a jet is dependent on initial conditions and hence amenable to control. It is possible to find out the frequency of formation of such structures and can be controlled by using acoustic excitation. The enhanced fundamental mode modifies the flow in such a way so as to destroy the fine grained turbulence production mechanisms. Because of viscous dissipation, the fine scale turbulence then decays downstream, allowing the coherent structures to amplify and spread the mean motion. Structures start developing in the highly unstable shear layer near the nozzle lips [Thomas F.O, 1986]. These will then grow by engulfing the ambient fluid till a distance of 20 times nozzle height. Further downstream, some of the coherent structures merge and form larger structures. Thus, even in the far field, presence of coherent structures can be identified.

2.4.7 Isothermal and Non- isothermal Jet Spreading

An isothermal jet is one in which the jet fluid temperature and the surrounding fluid temperature are the same. On the other hand, in the case of a non-isothermal jet, the jet fluid temperature is different from that of the medium into which it is discharged. Non- isothermal jets may be buoyant or non- buoyant. When the Richardson number is very small, the fluid temperature has the role of a passive scalar and buoyancy effects are insignificant in such a case [Kotsovinos. N.E, 1977]. The dynamics of instabilities and turbulence development are considerably different in non-isothermal jets.

2.4.8 Self Similarity

Self preservation or self-similarity is said to occur when the profiles of velocity (or any other quantity) can be brought to congruence by simple scale factors which depend on only one transformed coordinate. A consequence of self preservation is that the governing equations of jet flow can be reduced to ordinary differential equation form. Alternatively, a flow is said to be self preserving if there exist solutions to its dynamical equations and boundary conditions for which, throughout its evolution, all terms have the same relative value at the same relative location. Thus, self preservation implies that the flow has reached a kind of equilibrium where all of its dynamical influences evolve together, and no further relative dynamical readjustment is necessary. Self preservation is therefore an asymptotic state [Carazzo *et al.,* 2006] in which a particular flow attains after its internal adjustments are completed. Several kinds of self preservation states are possible, for instance: 1) Flows can be fully self preserving at all orders of the turbulence moments and at all scales of motion. 2) Flows can be partially self preserving in that they are self preserving at the level of the mean momentum equations only , or up to only certain orders of the turbulence moments or at certain scales. For example, a general mathematical expression for jet flow that has attained self- similarity for mean velocity is given by

$$\frac{U}{U_c} = f\left(\frac{y}{\delta}\right) \text{---} (2.7)$$

Where U and U_c are the local and centreline velocities in a transverse plane and δ is a measure of the local jet width.

2.4.9 Role of Side Walls in Jet Flow

The walls placed parallel to the x-y plane will force two dimensional spreading behaviours of a jet by preventing entrainment from sides. This is illustrated in fig 2.2. Though two-dimensionality is enforced in the near region, boundary layers start growing from the sidewalls [Deo.R.C, *et al.,* November *2007*]. Therefore, downstream development of flow will be different for a plane jet discharging through a rectangular nozzle with and without side walls. Though the presence of a side wall can extend the region of two- dimensionality, it is also important to note that the boundary layers growing from the sidewalls influence the jet development in the far field as shown in Fig 2.5.

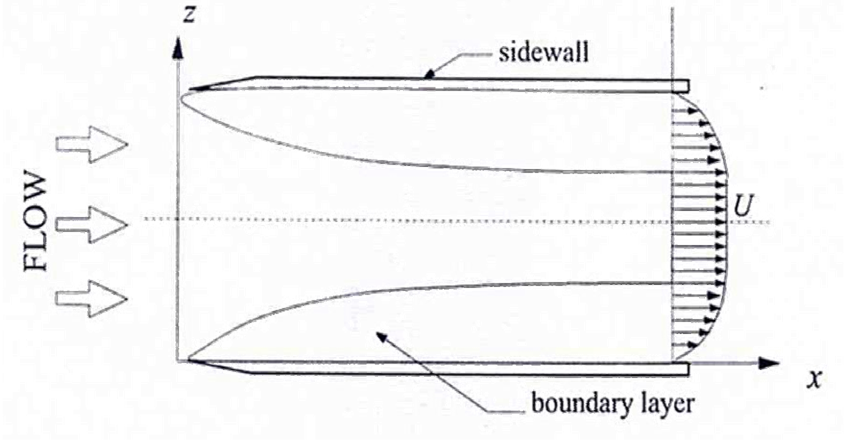

Fig 2.5 Development of boundary layers on side walls

2.4.10 Turbulent Length Scales

The turbulent flow consists of eddies of different sizes. Kinetic energy from the main flow is transferred to the turbulent eddy cascade (through production mechanism), at the largest scales of motion. This energy is then handed down to smaller and smaller scales through an inviscid process called vortex stretching [Pope, 2000]. At the smallest scales, the eddy kinetic energy is dissipated by viscous action. The large scale motion is often non-isotropic with strongly preferred directions. However, for many turbulent flows, the fine scale motion is locally isotropic. The average size of large eddies is called as integral length scale. The size of the smallest eddy at which dissipation is taking place is called as the Kolmogorov scale. Taylor micro- scale is the size of an intermediate eddy in the energy cascade process.

2.4.11 Aspect Ratio

The jet aspect ratio, (at nozzle exit) is an important factor for non circular jets that influences phenomena such as axis- switching and the jet evolution with axial distance. The growth of the shear layers along the major and minor axis directions is likely to be different. For rectangular nozzles in particular, the corner vortices at the sharp corners exert some influence on jet spreading in the near field [Deo.R.C, August 2007]. The ratio of the major axis (z) to minor axis (y) dimensions is defined as the aspect ratio (AR) of a rectangular jet. In the present case, AR = w/d. A high aspect ratio will ensure that, when measured in the centre plane (z=0) of the plane jet, the flow is statistically two dimensional and free from the effects of side walls, for a major part of the jet flow. The pictorial view of a rectangular jet nozzle of large aspect ratio is shown in Fig 2.6. [Krothapalli *et al., 1981*]

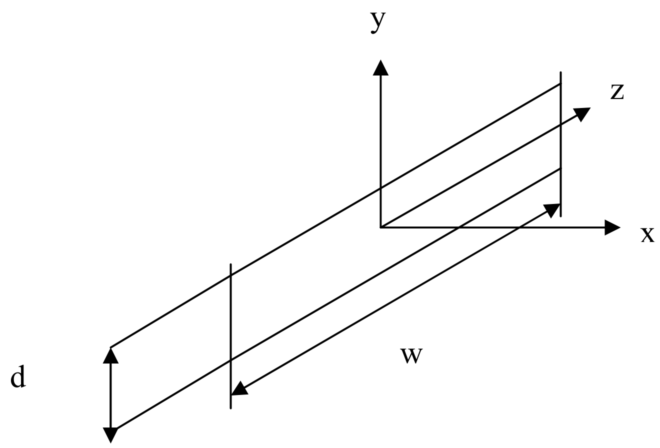

Fig 2.6 Aspect ratio of a rectangular jet nozzle

2.4.12 Intermittency

Flow visualization studies reveal that there is a highly contorted moving surface called viscous super layer that separates regions of turbulent and non- turbulent flow [List.E.J, 1982]. Regions of turbulent flow are characterized by large vorticity whereas non-turbulent flow is often irrotational. At a fixed location towards the edge of the flow, the fluid motion is some times turbulent and sometimes non turbulent. This type of flow is said to be intermittent.

2.5 Conclusion

The basic flow characteristics and the terminologies involved in the jet flow are explained in detail. The present study focuses on confined isothermal jet for its further analysis. The half width of the jet and the centerline velocity decay are taken as major criteria for the selection of jet in the proposed study. The present study is not intended to go in depth with the theory of development of jets. The basic flow characteristics of a jet flow are used to select different orifice configurations for getting better air flow pattern in the data centre environment.

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