Velocity profile for turbulent air jet engineering essay

Environment, Air

Pramod K. 1, Jayaram Thumbe2, Gangadharan K. V. 3, Ravikiran Kadoli31Postgraduate student, 2Research scholar, 3ProfessorDepartment of Mechanical EngineeringNational Institute of Technology KarnatakaSurathkal, Mangalore, Indiapramodkuntikana@rediffmail. com, jayramthumbe@rediffmail. com, kvganga@nitk. ac. in, rkkadoli@nitk. ac. inAbstract—Entrainment of secondary fluid in a turbulent jet flow is very significant for many applications. Theoretical and experimental studies have been carried out in order to estimate the velocity of jet and discharge which influence the secondary fluid entrainment. The present study is an attempt to further this analysis by using pipes of various diameters into which the jet of air is ejected. A constant jet velocity is maintained during experimentation having a Reynolds number of 12, 060. The results show that it is possible to obtain the maximum entrainment when the jet width equals to the diameter of the pipe. The experimental results are validated with Albertson's expressions. Keywords-Jet flow, Entrainment, Centreline Decay, Turbulent flow

Introduction

Turbulent jets are those produced when a fluid is discharged to the environment through a relatively narrow gap or conduit. The jet produces intensive mixing and turbulence because a velocity shear is created between the entering and ambient fluids as the moving fluid enters a quiescent fluid of the same density. Almost every case of turbulent flow requires a specific investigation since the properties of a turbulent flow depend greatly on the geometry of the flow domain and type of forces acting on the fluid. Examples of turbulent jets frequently encountered in engineering applications are jet pumps [4], ejectors [5], pulse jet filter bags, combustions chambers [6] etc. Turbulent entrainment in jets is the process of adding secondary fluid from the surroundings to the main flow domain. The entrainment of secondary fluid is especially important for many jet flow applications like pulse jet cleaning of filter bags in the industrial dust removal equipment or an ejector which is used in aircrafts. Thus the diffusion and entrainment properties of free jet have been the subject of extensive experimental and theoretical analysis in the research community. Turbulent mixing of incompressible fluid was theoretically analyzed by Tollmien in 1926 by the use of Prandtl's mixing length theory. In 1935 Kuethe developed an approximate method for computing the profiles near the exit of a round jet discharging air into a medium at rest [3]. From experimental results, Reichardt, in 1941, introduced the constant exchange coefficient concept over the mixing zone. In 1947 Leipmenn and Laufer using hot wire anemometer measured turbulent fluctuations, showed that neither the mixing length nor the exchange coefficient is constant over the mixing region. Albertson, et al, in1950, by presuming that the viscous effects have no influence on the mixing region concluded that the diffusion characteristics of the flow are dynamically similar under all the conditions [9]. Consequently they used the Gaussian normal probability function to describe the velocity profiles throughout the mixing region.

Velocity Profile For TurbulenT Air Jet

Jets penetrating into a quiescent fluid of the same density reveal that the envelope containing the turbulence caused by the jet adopts a nearly conical shape. In other words, the radius of the jet is proportional to the distance downstream from the discharge location. Further, the opening angle is always the same, regardless of the nature of the fluid (air or water) and of other circumstances (such as diameter of outlet and discharge speed). This universal angle is 11. 8º giving approximately 24º from side to opposite side as shown in figure 1. Schematic description of a jet penetrating in a fluid at rest (Lee et. al, 2003)Since the initial jet radius is not zero but the finite nozzle radius, equal to half the exit diameter , the distance must be counted not from the orifice but from a distance into the conduit. This point of origin is called the virtual source. The widening is linear with distance, and all cross-jet velocity profiles, except those very near the orifice, are similar to one another, after suitable averaging over turbulent fluctuations. Velocity profile across the jet exhibits a nearly Gaussian shape or bell shaped curve [9]. Therefore, we can write(1)Where is the downstream distance along the jet (counted from the virtual source), is the cross-jet radial distance from its centerline, is the maximum speed at the centerline, and is the standard deviation related to the spread of the profile across the centerline. From statistics we can get, , i. e., which leads(2)The velocity along the centerline of the jet decreases inversely with distance from the virtual source (i. e. the ratio increases linearly with distance. To this maximum velocity corresponds an average velocity defined by,(3)Jet flow features with the characteristic decay (Rajratnam, 1976)For subsonic jet, after the core the axial velocity decreases continuously due to the mixing process. This decay is rapid and is inversely proportional to the axial distance when the jet Mach number is subsonic. This popularity is called as characteristic decay [11]. The jet core is essentially a potential region where the jet retains its axial velocity at all points in the region. After the core, the entire jet field is dominated by viscous action. The core for a subsonic core jet is usually extends up to about the six times the nozzle diameter (). After the characteristic decay begins and that dominates from about 6 to about 12. After that the jet decay very slowly and gradually approaches zero velocity at a far downstream location. Theoretically this extends up to infinity. But in reality, the velocity becomes insignificant after about 30. The region from the end of the characteristic decay to infinity is also referred to as the self-similar region or fully developed region. The features of jet flow field- the jet core, characteristic decay and fully developed zones are shown in figure 2.

Theoretical Calculations of Entrainment Properties

The volumetric flux is not constant along the jet because of entrainment of quiescent surrounding fluid [3]. At any distance, downstream the total volume flow rate can be expressed as,(4)Discharge is found to increase linearly with distance [8]. The entrainment rate can be defined as the rate at which the volumetric flux grows with distance, namely(5)From this, we can also introduce an entrainment velocity, which is the radial velocity necessary to carry this entrainment. Volume conservation along a section of the jet requires:(6)Where is the transverse velocity feeding the entrainment and is the lateral area of this section of the jet. Substitution of and further substitution of in terms of the distance provides(7)Equating this with the previous expression for yields the value of the entrainment velocity:(8)It can be shown that the flux of kinetic energy behaves in the opposite way; it decreases with distance. The preceding remarks dealt with averaged properties of the jet, its width, mean velocity and entrainment velocity. Albertson et al. in 1948 developed the theoretical expression for the discharge calculation of the free jet ejected from the nozzle for two different regions of the jet flow, viz. Zone of Flow Establishment (ZFE) and Zone of Established Flow (ZEF) from the fundamentals of Gaussian and Top hat velocity profile forms [9]. For the flow in Zone of Flow Establishment(9)and for the flow in Zone of Established Flow(10)The expressions (9) and (10) are used for the theoretical prediction of the discharge at any cross section of the jet ejecting from the nozzle.

General Features of Experimental Setup

Experimental setup of free jet is shown schematically in figure 3. It consists of a reciprocating air compressor that supplies compressed air to air reservoir. A needle valve is used to maintain constant pressure by controlling the mass flow rate so that velocity of the jet will remain constant. An orifice meter is fitted to the jet delivery unit to measure the discharge of the jet with the help of U-tube manometer. A sliding bar mechanism is provided to facilitate the movement of the Pitot tube in radial and axial direction to measure the velocity of the jet at various points of the flow field. Wooden scales are mounted on the side supports for the measurement of movement of the Pitot tube both in axial and radial directions. Pitot tube is fitted on the sliding bars and which is connected to the projection manometer containing 100% alcohol. A separate stand with a v-groove and clamps is used to hold the pipe firmly, to study the amount of air entrained by the jet flow. The stand can be moved independently with respect to the jet exit. The jet is mounted on a height adjustable stand, so that the jet can be aligned coaxially with the pipe at the time of measurement of the jet entrainment. The jet entrainment and centerline velocity decay can be determined with the same setup. Schematics of experimental setup for measuring Jet velocity and entrainment

Experimental Procedure

The experiments are conducted to study the jet entrainment using the rigid hollow pipe set up. A PVC pipe having diameter of 0. 0254m (1 inch) and length of 0. 5m is mounted on the stand and is clamped firmly. The pipe center is aligned to the jet center by making the vertical and horizontal adjustments of the pipe holder. The reservoir pressure is maintained at 4. 2 bars. The needle vale is opened and the flow rate is adjusted in order to get a velocity of 23. 5 m/s by maintaining a differential pressure of 0. 045 m of water column across the orifice. This ensures that the flow is turbulent with a Reynolds number greater than 4000. The discharge and the velocity at the outlet of the pipe are measured using the vane anemometer by varying the distance between the jet and the pipe inlet as shown in figure 4. The experiments are repeated for pipes of diameters varying from 0. 0254 (1 inch) to 0. 1143 m (4. 5 inch). Experimental ParametersExperimental parametersValueReservoir pressure4. 2 barsDifferential pressure across the orifice0. 045 m of water columnExit diameter of the nozzle0. 008 mNozzle exit velocity23. 5 m/sReynolds Number at nozzle exit12, 060Schematics of jet entrainment measurement

Centerline velocity measurements

The center line velocity decay is measured by using the pitot static tube. For this, pitot static tube is moved along the jet axis. The center line jet velocity measurements at various distances from the jet exit are taken.

Resuls and Discussion

Experiment on jet entrainment

The velocity and discharge variations are plotted with the distance of the pipe from the nozzle exit. From figure 5 it is clear that, the velocity at the exit of the pipe increases from a finite value to the optimum depending on the pipe diameters. It then decreases by a small extent and after that it remains more or less constant. The optimum velocity is different for different pipe diameters. The maximum velocity is obtained for smaller diameter pipe. This is due to the reason that the reduction in flow area causes the increase in flow velocity. Velocity variations along the jet axis for pipes of various diameters placed at different distances from the jet exitDischarge variations along the jet axis for pipes of various diameters placed at different distances from the jet exitFrom figure 6 it is clear that the amount of air entrained increases with the increase in distance from the jet exit. The discharge of the jet equals the discharge from the exit of the pipe when the distance from the jet exit to the pipe inlet is zero. When the diameter of the pipe increases the amount of air entrained also increases. This can be attributed to the increase in the area of exposure for jet entrainment. The discharge at the pipe exit remains constant for a distance greater than 0. 03m. This is due to the fact that the width of jet exceeds the pipe diameter after moving a particular distance, which will prevent the intrusion of the external fluid. The results can be summarized into three cases. The first case in which jet width at the inlet of the pipe is less than the pipe diameter; the second case in which the jet width equals the pipe diameter and the third case in case jet width exceeds the pipe diameter. This is illustrated in figure 7. Jet entrainment into the hollow pipe for three different situations depending on the distance of the pipe entrance from the jet exit

Centerline velocity measurements

The centerline velocity decay of the jet measured by using pitot static tube is plotted as shown in figure 8. An exponential curve was fitted for the measured values. By the use of this curve it is possible to predict the jet velocity at any cross section for a given radius. Fitted expression for center line velocity of the jet is: Center line velocity decay from experiment by using pitot static tube

Comparison of the discharges obtained from experiment and theory

The experimental discharge was compared with the theoretical discharge which is obtained by using Albertson's expressions and is plotted as shown in figure 9. The experimental measurements showed well agreement with theoretically predicted discharge values. The values of discharge obtained from the experiment was quite higher compared to theoretical one, this may be because of the interaction of excess air with the jet due to minute wind movements. Comparison of experimental discharge with theoretical for various distance from nozzle exit

Conclusion

The jet entrainment is a very complex phenomenon which finds many engineering applications and is one of the current research topics among the jet flow researchers. In the present work the jet entrainment process of a turbulent air jet with Reynolds number of 12, 060 was studied experimentally and the same was verified theoretically. Albertson's discharge expression was used for the theoretical prediction of the discharge. The maximum discharge at the pipe exit was observed when the jet width at the inlet of pipe equals the pipe diameter due to maximum entrainment. This can be used for optimizing the performance of devices like jet pump, pulse je fabric bag etc. The decay of the centerline velocity is plotted for the experimental readings which denote the existence of secondary air entrainment. For experimental values an exponential curve was fitted which can be used for the estimation of velocity at any point at a particular cross section of the jet.