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Mean Flow Characteristics of a Three-dimensional Wall Jet on Concave Curved Surface

DVS Bhagavanulu
Professor, Department of Civil Engineering,
Sree Vidyanikethan Engineering College, Tirupati

Abstract

The effect of concave curvature on the mean flow characteristics of a three-dimensional wall jet is investigated experimentally. The flow field is generated by the impingement of a free jet issuing tangentially onto a concave cylindrical surface, issuing from a circular orifice. Measurements are also carried out on a plane surface for comparison purposes. The curved surface plate is provided with an initial straight portion of twenty times the diameter of the orifice and remaining portion is with concave curved surface. The radius of the concave curved surface is 500mm. The curvature parameter (b/R) ranges from 0.0228 to 0.048. The mean velocity profiles in the longitudinal and spanwise directions, growth of maximum velocity, growth of length scales and mean velocities in y direction (V) and z direction (W) in the longitudinal direction are presented. From the results, it is found that the decay of the maximum velocity on the concave surface is slower than the decay on the plane surface. The shape of the mean velocity profiles in the spanwise and in the longitudinal directions for both surfaces is similar and no effect of curvature was found. The growth of half width in the longitudinal direction on the concave surface is lesser than the growth of half width on the plane surface and this is attributed to curvature effects. The mean velocities (V and W) are 15% less in the longitudinal direction when compared to the results of plane surface.

1. Introduction

A wall jet is formed when a jet of fluid strikes a surface at an angle. The angle can vary between 0^0 to 90^0. When the angle is 0^0, i.e., the jet flows over the surface tangentially, the wall jet so formed is called a plane wall jet. When the angle is 90^0 i.e., the jet impinges on the surfaces normally, the wall jet is called radial wall jet (Glauert, 1956). Jet impingement cooling has been widely used for elements exposed to high temperatures and/or high heat flux because of its advantages in effective removal of locally concentrated heat and easy adjustment to the location where cooling is needed. Typically, applications will include paper drying, electronics cooling, annealing of glass. In particular, this jet impingement cooling has been effectively used to eliminate excessive thermal load near the leading edge of gas turbine blade inner surface. Wall jets are also finding increasing applications in fluidic devices. The profile of the wall jet is given in Fig. 1.

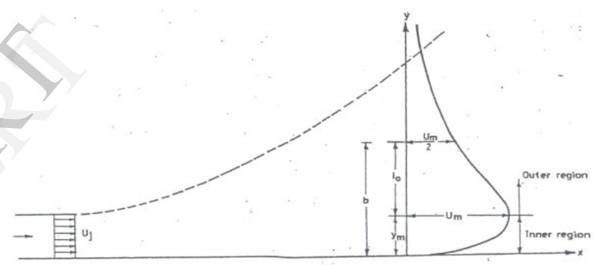


Fig.1 Definition sketch of a wall jet

As mentioned earlier that the wall jet flow are self preserving and when a jet strikes the jet formed is know as wall jet irrespective of the shape of the surface. In all the investigations dealing with the study of curvature effects, there are basically two types of approaches, 1.the radius of curvature of the surface is kept constant (Wilson and Goldstein, 1976), 2. The curvature parameter (b/R; Fig.2) is maintained constant along the length of the curved surface (Giles et al., 1966; Guitton and Newman, 1977). In the present case the radius of concave curvature is kept constant and the curvature parameter (b/R) varies from 0.0228 to 0.048.

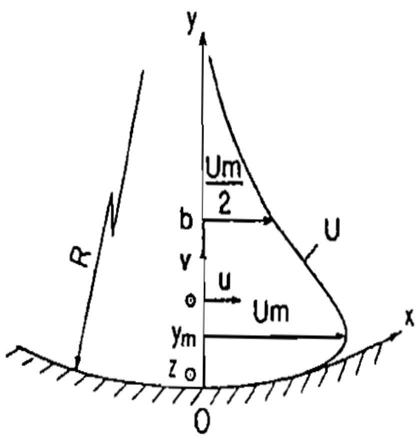


Fig. 2 Curvature Parameter

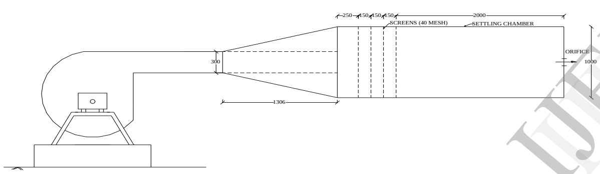
Launder and Rodi [1981] have considered two-dimensional wall jets developing on plane surface, convex surface (both logarithmic and cylindrical) and concave surface (both logarithmic and cylindrical) investigated. It is stated that the mean velocity profiles have not changed the shape with the curvature but growth of half width increases with convex curvature and reduced with concave curvature. Mansoo Choi et al [2000], made an experimental study of fluid flow and heat transfer for jet impingement on a semi-circular concave surface. They found that the occurrence and location of secondary peaks in connection with mean velocity and velocity fluctuations on the concave surface and the thickness of the wall jet is smaller. M. Fenot et al [2008], made an experimental investigation of heat transfer due to a row of air jets impinging on a concave semi-cylindrical surface is presented. It is observed that concavity provokes the decrease of these local extremes (wall jet boundaries). Lastly, relative curvature seems to have two opposite effects over the Nusselt number distributions. The first involves overall reduction of the Nusselt number. Since Nusselt number is also reduced for a semi-confined flat plate, this effect is probably of the confinement variety. As for the second effect, it enhances heat transfer near the impinging zone. Fujisawa [1986], studied the effect of curvature (convex and concave) on the mean and turbulent characteristics for the curvature parameter ranging from -0.1 to 0.1. They presented a modified version of two-equation Reynolds stress model and found that no effect of curvature on the mean velocity profiles in the longitudinal direction. The growth of half width decreased on the concave surface and increased over the convex surface. Kobayashi and Fujisawa [1986], studied the curvature effects on two-dimensional wall jet along concave curved surfaces. In their study, the curvature parameter varied from 0.025 to 0.095. Also, it is observed that the growth of half width is decreased with the decrease in radius of curvature. The velocity profiles are similar and no effect of curvature felt in the longitudinal direction.

From the literature it is observed that most of the work has been done only for the case of two-dimensional jets. Very little work has done in the case of three-dimensional wall jets. Most of the above mentioned studies of jet impingement flow on curved surfaces mainly focused on mean flow parameters, heat and/or mass transfer measurements and lacking detailed mean flow characteristics data. The intent of the present study is to provide quantitative measurement data of the mean flow characteristics on the concave curved surface. The present wall jet on concave surface data can also serve as bench-marking data for three-dimensional velocities in the longitudinal direction.

2. Experimental Set-up

All the measurements were carried out using a low speed jet tunnel facility. Figure 3 shows the schematic diagram of the jet tunnel and the general layout of the experimental arrangement with the flat plate on which the plane wall jet generated. Air is supplied from a centrifugal blower. There is a by-pass control which can also used to regulate the flow. The airstream is led into a settling chamber through a set of screens. At the end of settling chamber an orifice plate of made of mild steel having a 10mm diameter circular orifice is fitted. A smooth polished plate of size 1.4mX1.7mX20mm thick made of teak wood is used to produce the wall jet on the flat surface. Similarly another plate of radius 500mm with concave curvature has been fabricated. An initial straight portion of 20d has been fixed to the curved surface. The plate was fixed vertically by brackets on rigid stand made of mild steel channels. The stand is provided with levelling screws at bottom. The leading edge of the plate is chamfered to 45^0 to avoid pressure gradient. A traversing mechanism was used for traversing the total pressure probe. This is an arrangement for movement in three mutually perpendicular directions and the probes could be accomplished about a vertical axis and about the axis of the probe holder. It is observed that the static pressure variation along the flow is negligible. The probe was calibrated against a standard probe and the confidence level is about 99.2%. The velocities are measured using a micromanometer which works on the principle of Bernoulli's theorem. The micromanometer not only gives the velocities at a particular point also gives pressure in mm of water. Its capacity is 200mm of water column. The three-dimensional velocities are measured using 5-hole probe shown in Fig. 4. The mean velocities are measured using a 5-hole probe with the following equations.

Fig. 3 Experimental Set up



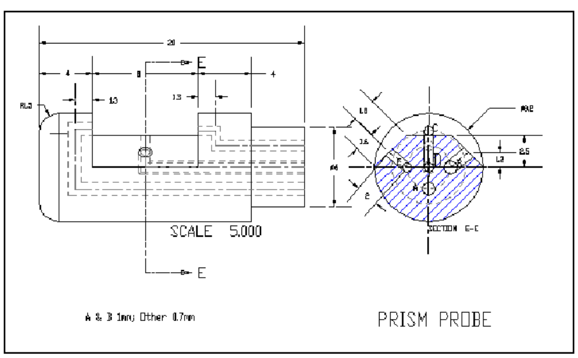


Fig. 4 Five hole probe

$$C_{p(yaw)} = (P_2-P_3)/(P_1-P_{avg})$$

$$C_{p(pitch)} = (P_4-P_5)/(P_1-P_{avg})$$

$$C_{p(total)} = (P_1-P_{total})/(P_1-P_{avg})$$

$$C_{p(static)} = (P_{avg}-P_{static})/(P_1-P_{avg})$$

$$P_{avg} = (P_2+P_3+P_4+P_5)/4$$

$$V_{mean} = SQRT(2(P_{total}-P_{static})/(\rho))$$

$$U = V_{mean}\cos\alpha \cos\beta$$

$$V = V_{mean} \cos\alpha \sin\beta$$

$$W = V_{mean} \sin\beta$$

β = Yaw angle

α = Pitch angle

3. Results and Discussion

To find the concave curvature effects, initially measurements have been made on the plane surface for comparison purposes. Based on the measurements on the plane surface, it is concluded that the characteristic decay region extending up to a distance of 20 times diameter of the orifice from the exit of the orifice. The measurements have been extended up to an axial distance of 60d in the longitudinal direction both on the plane and concave curved surface. The axial distance along the jet axis has been normalized by the diameter of the orifice (d). The velocity scale is U_m, the local maximum velocity at any station considered along the jet axis. Measurements in the longitudinal direction have been carried out in the plane of symmetry and in the spanwise direction at $y=y_m$, the location of maximum velocity in the plane of symmetry. The same procedure has been applied in the case curved surface also. In the present investigation the following parameters have been found; a) The decay of the maximum velocity, b) The mean velocity profiles in the longitudinal direction c) the rate of expansion of the wall half width and d) three-dimensional velocities V and W in the longitudinal direction. In all the results presented, the distance x along the jet axis is reckoned from the face of the orifice. The results obtained at an exit Reynolds number Re=5.48 x 10^4.

Decay of Maximum Velocity

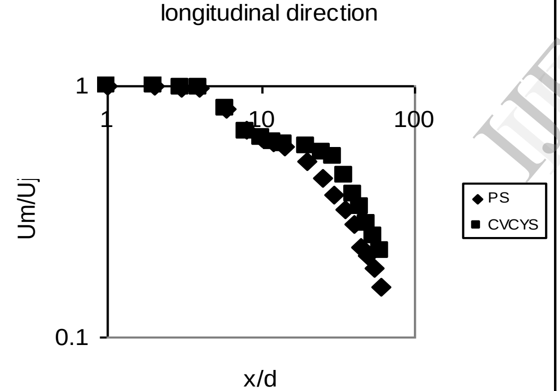
One of the gross characteristics of a three-dimensional wall jet is the decay of the maximum velocity in the plane of symmetry. The decay can be expressed in a power law form i.e.,

$$(U_m/U_j) \propto (x/d)^{-n}$$

Where U_j is the jet exit velocity.

Figure 5 shows the decay of the maximum velocity in the longitudinal direction. The region of constant maximum velocity extends up to x/d=4 which is PC region. There is a small region of transition from x/d=5 to 10. From x/d=10 to x/d=20, the decay pattern follows that is neither two-dimensional nor radial. It is the CD region in which the influence of the geometry of the orifice felt. The decay rate in the RD region is found to be 1.04 in the case of Plane wall jet. The radius of the concave cylindrical surface is 500 mm and the curvature parameter (b/R) is found to be from 0.028 to 0.048. The curved portion has been provided from x/d=20 i.e., at the end of the characteristic decay region. All the measurements were done in the RD region where the jet profiles similar to radial wall jet. The results of Plane surface are included in the figure for comparison purposes. It is observed that the maximum velocity decays faster on the plane surface compared to concave curved surface. The decay exponent on the curved surface is higher than the plane surface decay and it is 0.96, whereas on the plane surface the decay exponent is found to be 1.04. The lower value of decay exponent is due to curvature effects.

Fig. 5 Decay of Maximum velocity in the longitudinal direction



Mean Velocity Profiles

The normalized mean velocity profiles in the longitudinal direction in the curved portion of CVCYS are shown in Fig. 6. It is seen that the good similarity observed when compared to the mean profile on the plane surface. Also, it is seen that the position of maximum velocity is slightly shifted towards the wall and it is found at y/b=0.18 and where as for the place surface it is at y/b=0.2.

The mean velocity profiles in the spanwise direction is also shown in Fig. 7 and the mean velocity profile on the plane surface is included and found that there is no effect of curvature in the spanwise direction.

The three-dimensional velocities are measured using a five-hole probe in the longitudinal direction and presented in the Figs. 8 and 9. From these figures, it is observed that the trend of the profile on the CVCYS is remaining same as that on the plane surface. The values are lower than the plane surface results and it is around 15% when compared with the values of the plane surface.

Fig. 6 Mean velocity profiles in the longitudinal direction on CVCYS

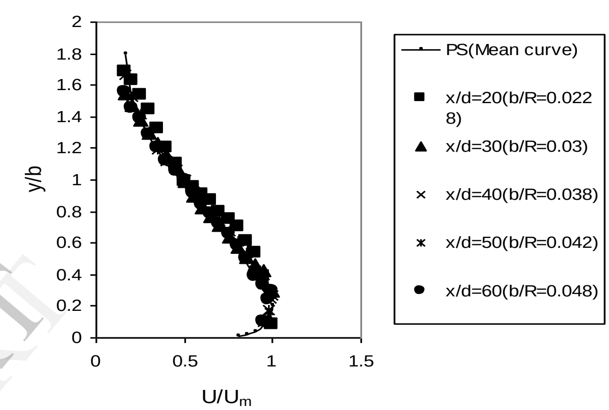


Fig. 7 Mean velocity profiles in the spanwise direction on CVCYS

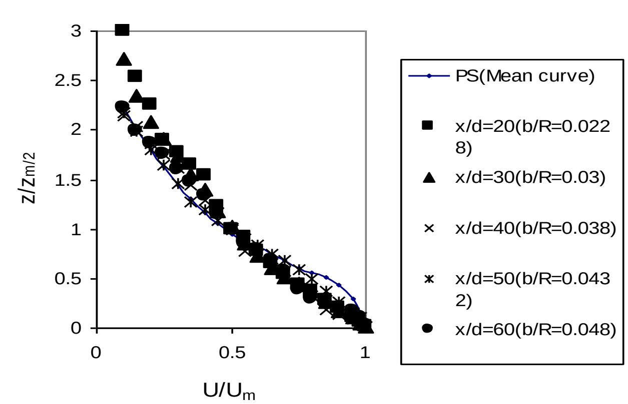


Fig. 8 Distribution of V in the longitudinal direction

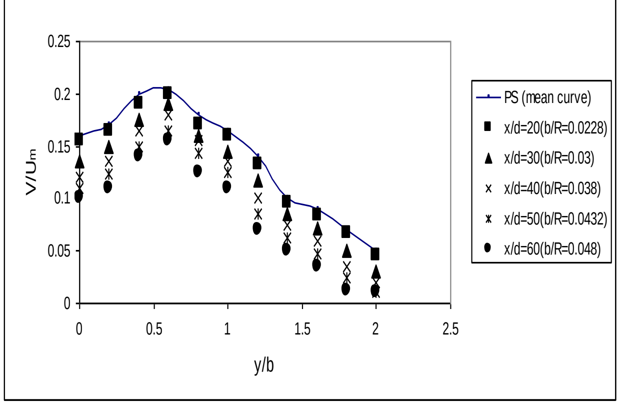
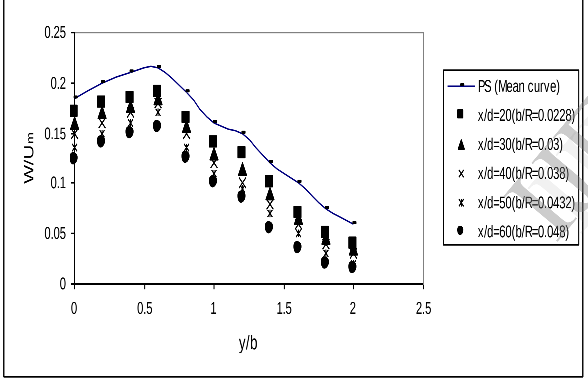
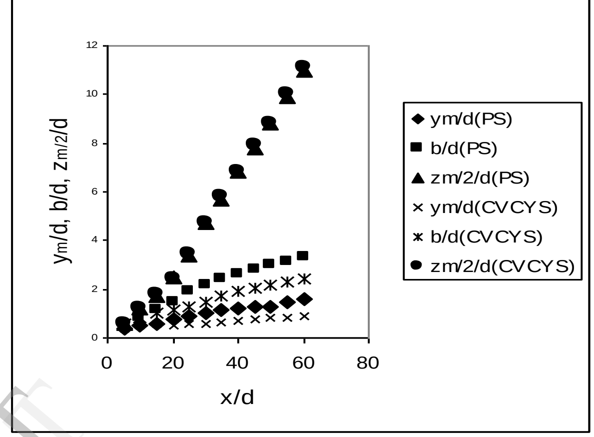


Fig. 9 Distribution of W in the longitudinal direction



The variation of various length scales (b/d, y_m/d and $z_{m/2}$/d) are shown in Fig. 8. It is seen that the growth in the longitudinal direction is higher compared to the plane surface results. Similar observation is made in the thickness of the inner region. The growth of half width in the spanwise direction is remaining same on both the plane and concave surfaces. Also, it is found that the growth in longitudinal direction. Hence, it is concluded that the length scales increases on the convex surface curvature. This is mainly attributed to centrifugal instability. For flows on the surface with concave curvature, the centripetal force due to the curvature makes the flow unstable usually and the so-called Taylor-Goertler type vortex is produced. Such a vortex has its axis parallel to the flow direction and is known to enhance momentum and energy transfer and thereby reduction of velocities in the outer region of the wall jet. Hence, the flow tends to attach the concave surface instead of moving away from the surface. This is the reason for the growth of half width is lesser on concave surface compare to plane surface.

Fig. 10 Variation of length scales on the CVCYS



4. Concluding Remarks

The mean velcity profiles follows the trend as that observed on the plane surface. The posisiton oef maximum velocity slightly shifted towards the wall. The spnawise velocity profiels remain same both in on the plane surface and curved surface. The decay rate is higher on the plane surface when compared to concave curved surface. The decay exponent is 0.96 on curved surface where as it is 1.04 on the plane surface. The growth of half width and the thickness of inner region decreased over concave surface. There is no variation of length scale in the spanwise direction both on the plane and concave surface surface. The three-dimnsional velocities V and W are 15% lower when comapred to plane surface results. The distrubution trend of the velocities are remain same both on the plane and conave curved surface.

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