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Mean Flow Characteristics of a Three-Dimensional Wall Jet on Concave Surface in the Radial Decay Region

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Abstract

This paper presents the mean flow characteristics of a three-dimensional wall jet on concave surface. The velocity measurements were taken up to an axial distance of 60 times the diameter of the orifice selected in the present work. The mean flow properties considered in the present investigation are the mean velocity profiles, maximum velocity decay and the growth of half width in the normal direction to the plane surface and concave curved wall. It is observed that the mean velocity profiles of the wall exhibit similarity both on the plane surface and concave curved surface in the longitudinal direction. It is shown that the decay of the maximum velocity is slower on concave surface when compared with the decay on plane surface. It is also found that the growth of half width is higher on plane surface compared the growth on the concave curved surface. The velocity profiles are similar in the spanwise direction and no effect of curvature is felt.

Keywords: wall jet, maximum velocity decay, concave curvature, half width.

Introduction

A wall jet is formed when a high velocity fluid strikes a surface at an angle. The angle can be varying 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 plane wall jet. When the angle is 90^0, i.e., the jet impinges normally, the wall jet so formed is called radial wall jet (Glauert, 1956).

Wall jet flows are identified by the gradually reached, approximately self-preserving condition exhibiting a velocity profile as shown in Fig. 1. As seen from the figure, the fluid issues from a nozzle or orifice with uniform velocity U_j (at the absence of free jet) at the exit parallel to the plate on which the wall jet is formed. The shape of the velocity distribution suggests a possible division of the profile into two regions (1) the inner region extending from the wall to the point of maximum velocity, (2) the outer region extending from the point of maximum velocity to the periphery of the jet. At the two extremities of wall jet, the velocity is zero. The velocity parameters are usually the jet exit velocity U_j and the local maximum velocity U_m, at any station along the axis of jet.

The geometry of nozzle from which the fluid issues out on to a flat surface to form a wall jet decides whether the wall jet formed is two dimensional, axi-symmetric or three dimensional. When the aspect ratio of the jet issues onto a solid boundary is finite, the wall jet becomes three- dimensional (Sfroza and Herbest., 1970).

It is seen from the literature that extensive work has been done in the three-dimensional wall jets developing on flat surfaces. The present work highlights the comparison of mean flow properties on plane and concave curved surfaces.

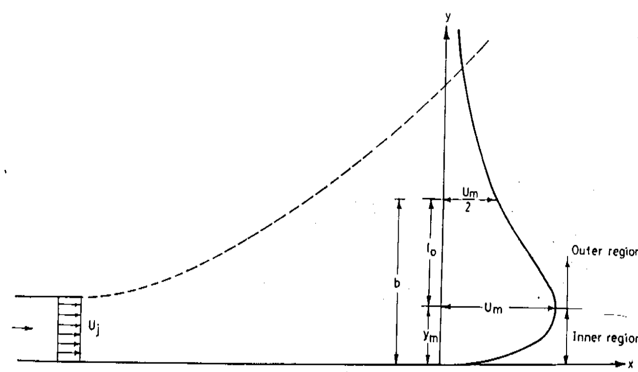


Fig.1.1 Definition sketch of a wall jet

In many practical applications of wall jets cited in the earlier investigations are the effect of curvature on the mean flow characteristics developing on the curved surfaces. Very few investigations were found in the case of two-dimensional wall jet developing on the concave curved surface. There appears to be only three studies available on convex curved surface (Patankar and Sridhar, 1972; Catalano et al., 1977; Iida and Matsuda, 1988 and Gowda and Durbha, 1997). A very little investigation has been done on concave surfaces (Fujisawa et al., 1985, 1986). But no literature available dealing with the three-dimensional wall jet developing on concave curved surface.

In all the investigations dealing with the study of curvature effect, there basically two types of approaches, 1. the radius of surface is kept constant (Wilson and Goldstein, 1976; Gowda and Durbha, 1997 and etc), 2. the curvature parameter (b/R; Fig. 2) is maintained constant along the length of curved surface (Giles et al., 1966, Guitton and Newman, 1977). In the latter case, taking into account the rate of growth of the half width b, the condition of having constant parameter along the length of the surface leads to logarithmic surfaces (the radius of surface vary continuously along the length of the surface). In the former case the surface will be having constant radius and the curvature parameter varies continuously along the length of the surface. There are advantages and disadvantages in both approaches. In the second case, the influence of a particular curvature parameter will be found when the wall jet forms on the surface, where as the properties of the wall jet change with the change of curvature parameter where the radius is constant. In practical situations, rarely once come across a situation where the radius of curvature is changing continuously along the flow direction resulting in a surface with constant curvature parameter. Hence in the present investigation the influence of concave curvature will be studied on the constant radius of surface along the length of the plate.

The important application of the present study is when the fluid passes through the blade wall by several holes to create a film over the upper surface to protect the blade from hot gases. Impinging jets are a complementary possibility of obtaining a better cooling of the inside surface of the blade. They are also used to cool combustion chamber walls or other rotating parts of the engine (Venas et al. 1999). Due to the interesting physics and the engineering applications of wall jets (e.g. inlet devices in ventilation, separation control on airfoils and film-cooling of turbine blades), the present investigation is carried out to find the effect of concave curvature on the mean flow characteristics of a three-dimensional wall jet.

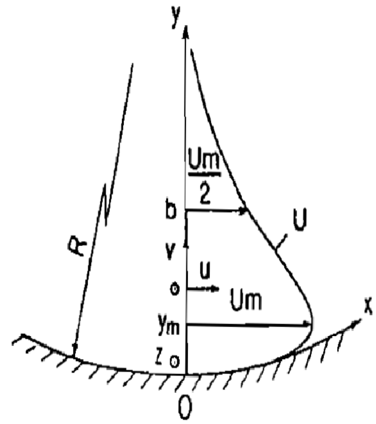


Fig. 2 Definition sketch of curvature parameter b/R

Experimental Arrangement

All the measurements were carried out using a low speed jet tunnel as shown in Fig. 3. 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 of a dimension 10mm 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. 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 measure 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.

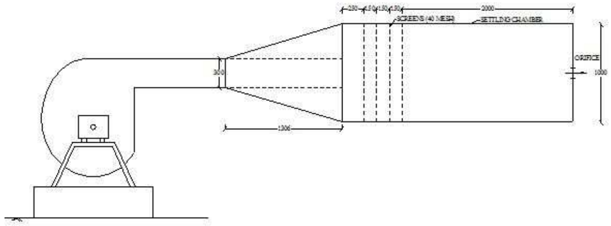


Fig. 3 Schematic experimental set-up

Results and Discussion

To find the curvature effects, initially measurements have been made on the plane surface for comparison purposes. Though, some earlier investigations are available on the plane surface, measurements have been done on the plane to find out the extent of characteristic decay region in the present study. Based on the measurements on the plane surface, it is concluded that the characteristic decay region extending upto 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 and its similarity form and c) the rate of expansion of half width of the wall jet. 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 $Re=5.48 \times 10^4$.

Decay of Maximum Velocity

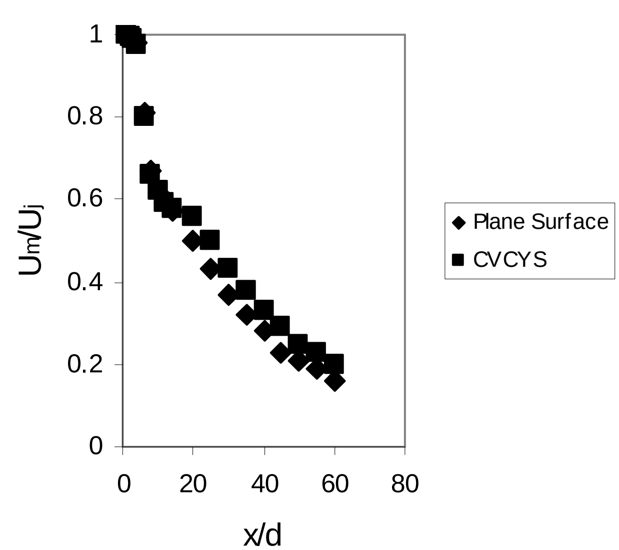
One of the gross characteristics of a three-dimensional wall jet is the decay of the maximum velocity in the plane of symmetry. The decay can be expressed in a power law form i.e.,

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

Where U_j is the jet exit velocity.

In a three-dimensional wall jet there are three regions identified by the mode of the decay of the maximum velocity U_m. 1 the potential core (PC) region where the maximum velocity is almost constant and equal to jet exit velocity, 2. The Characteristic Decay (CD) region, where the maximum velocity depend upon the geometry of the orifice, and 3. The Radial Decay (RD) region, where the velocity decays irrespective of the geometry of the orifice. Figure 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 1.06 in the case of Plane wall jet. A concave cylindrical wall has been designed for producing the curved wall jet. The radius of the cylindrical surface is 1500 mm and the curvature parameter (b/R) is found to be from 0.0087 to 0.0173. 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 decay of the maximum velocity is shown in Fig. 4. The results of Plane surface are included in the figure for comparison purposes. It is observed that the maximum velocity decays slower on the concave curved surface compared to plane surface. The decay exponent on the curved surface is lower than the plane surface decay and it is 0.974, whereas on the plane surface the decay exponent is found to be 1.04. The lower value of decay exponent is due to concave curvature effects and it is mainly due to destabilizing nature of the surface.

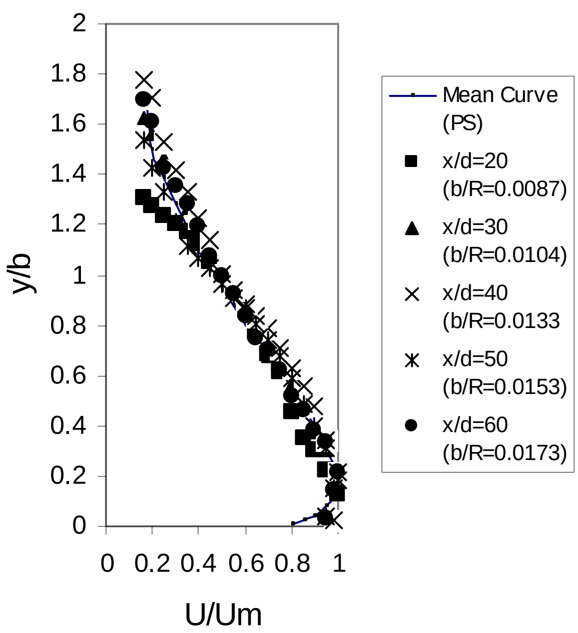
Fig. 4 Decay of maximum velocity in the longitudinal direction



Mean Velocity Profiles

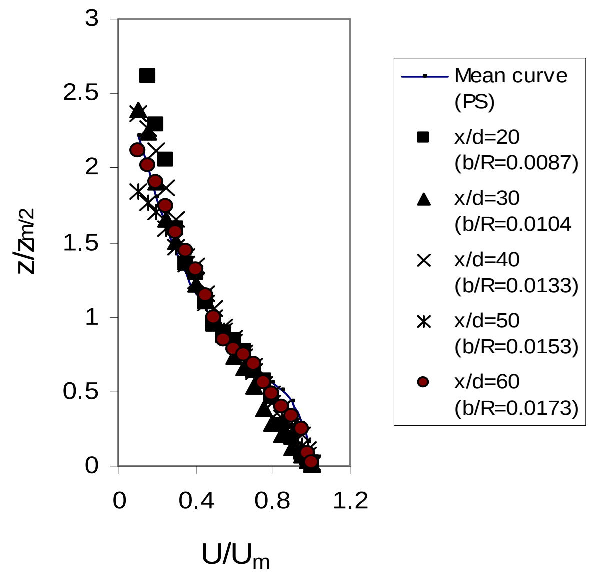
The normalized mean velocity profiles in the longitudinal direction in the curved portion of CVCYS are shown in Fig. 5. It is seen that the good similarity observed when compared to the mean velocity profile measured on the plane surface. Initially measurements were carried out on the plane surface and results compared with the results of Gowda and Durbha (1999) and found that the results are well compared. Also, it is seen that the position of maximum velocity is slightly shifted towards the wall.

Fig. 5 Mean velocity profiles in the longitudinal direction



The mean velocity profiles in the spanwise direction is also shown in Fig. 6 and the mean velocity profiles of Gowda and Durbha (1999) has been included for the comparison purposes. It is also observed that the results of Gowda and Durbha (1999) are well satisfied with the free jet solution.

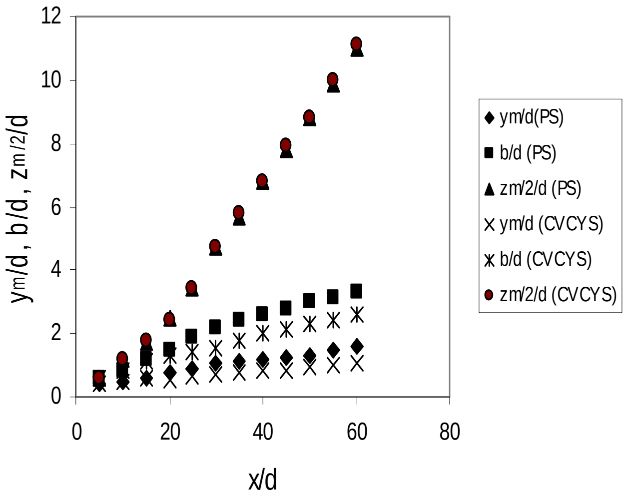
Fig. 6 Mean Velocity profiles in the spanwise direction



Variation of Length Scales

The variation of various length scales (b/d, y_m/d and zm/2/d) are shown in Fig. 7. It is seen that the growth in the longitudinal direction is lower 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 remain same on both the plane and concave surfaces. Also, it is found that the growth in longitudinal direction. A similar feature is observed by Kobayashi and Fujisawa for two-dimensional wall jets . This is mainly attributed to destabilizing nature of the concave surface and the fluid layer move close to the wall when compared to movement on the plane surface.

Fig. 7. Variation of length scales in the longitudinal direction



Concluding Remarks

The mean velcity profiles follows the trend as that observed on the plane surface. The posisiton of maximum velcoity slightly shifted towards the wall. The spnawise velcity profiels remain same both in on the plane surface and curved surface. The decay rate is higher on the curved surface compared to plane surface and the decay exponent is 0.974 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 with the increase in curvature parameter. There is no vation of length scale in the spnawise direction both on the plane and concave surface.

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