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# Effect of Convex and Concave Curvature on the Growth of Three-Dimensional Wall Jet in the Radial Decay Region

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**Abstract** - ***This paper presents the results obtained in the radial decay region of a three 0-dimensional wall jet developed on convex and concave curved surfaces. The velocity measurements were taken up to an axial distance of 60 times the diameter of the orifice selected in the present work. The flow properties considered in the present investigation are the mean velocity profiles both in the longitudinal and spanwise directions, maximum velocity decay and the growth of half width in the longitudinal and spanwise directions on both the surfaces. It is observed that the mean velocity profiles of the wall exhibit similarity both the curved surfaces when compared to plane surface profile in the longitudinal and spanwise directions. It is shown that the decay of the maximum velocity is slower on concave surface and faster on convex surface when compared with the decay on plane surface. It is also found that the growth of half width is higher on convex surface compared the growth on the concave curved surface and plane surface. It is also found that the growth of half width on the plane surface is high when compared to the growth on the concave surface.***

**Key Words:** *wall jet, maximum velocity decay, convex curvature, concave curvature, half width*.

## 1. INTRODUCTION

A wall jet is formed when a jet of 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 $90^0$, 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, the inner region and the outer region. 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 of three-dimensional wall jet on convex and concave curved surfaces in the radial decay region.

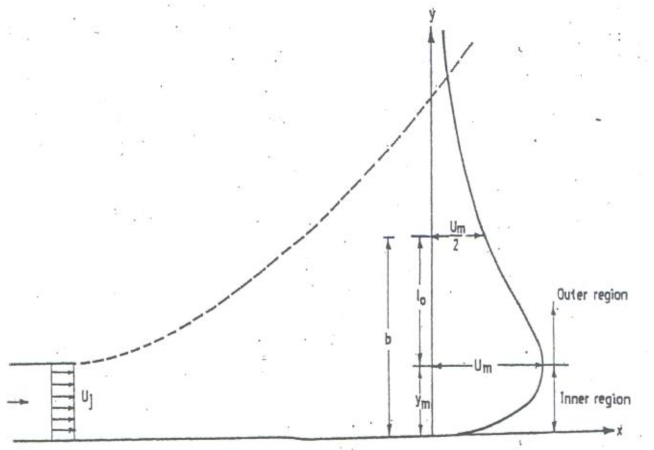



Fig.1 Definition sketch of a wall jet

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 four studies available on convex curved surface (Patankar and Sridhar, 1972; Catalano et al., 1977; Iida and Matsuda, 1988 and Gowda and Durbha, 1999). A very little investigation has been done on concave surfaces (Fujisawa et al., 1985, 1986). Wilson and Goldstein [1976] investigated the properties of a two-dimensional wall jet on circular cylindrical surface and compared the results obtained with those of plane surface. The curvature parameter is varied from 0.067 to 1.27. The growth of half width on the cylindrical surface was found to be non- linear with distance, unlike that for the plane surface and the growth is in the order of radius of the surface. 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 increased with convex curvature and reduced with concave curvature. Fujisawa and Shirai [1987], made measurements of two-dimensional wall jet developing on a highly convex surface (b/R ranging from 0.12 to 0.69). In their experiments, they have provided an initial straight portion of 50d and the remaining portion is curved. The mean velocity profiles exhibit similarity at various longitudinal stations and significant increase in the growth of half width observed. Kobayashi and Fujisawa (1983) made investigations on the concave surfaces with different radii. The range of curvature parameter varies from 0.008 to 1.48. It is found that no curvature effect was felt on the mean flow velocity profiles, but there is a decreasing trend observed in the case of growth of half width. But no literature is available dealing with the three-dimensional wall jet developing on concave curved surface and also there is no comparison available between the convex and concave curvature effects of three-dimensional wall jet.

In all the investigations dealing with the study of curvature effect, there are 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). Hence in the present investigation the influence of convex and concave curvature will be studied with 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 physical 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 convex and concave curvature on the mean flow characteristics of a three-dimensional wall jet.

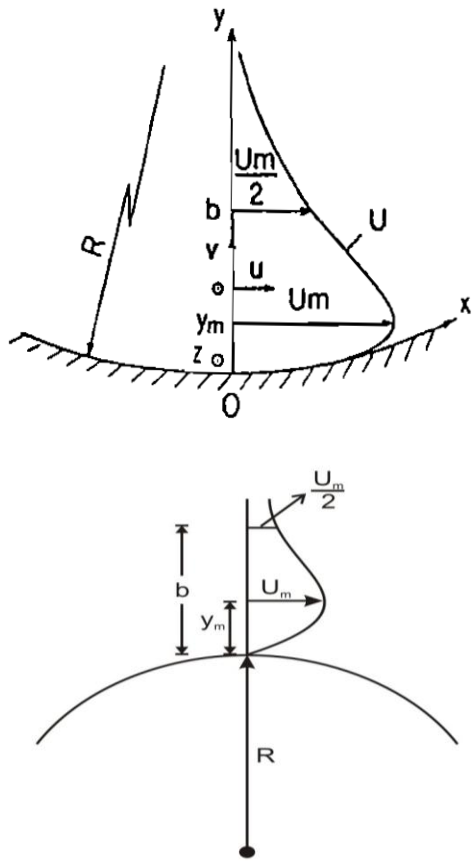



Fig. 2 Definition sketch of curvature parameter b/R

## 2. 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 be 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 radius of the convex and concave surfaces is chosen as 500mm. The constant radius of curvature is provided after an initial straight portion of 200mm i.e., 20d. 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. Measurements have been carried out both on the

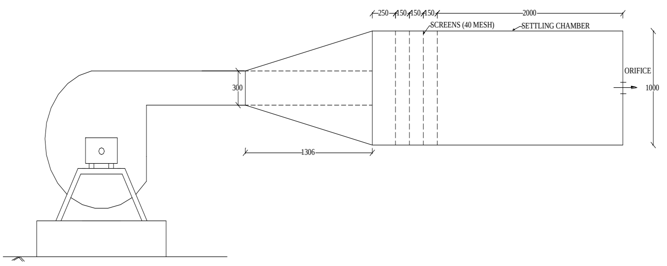



Fig. 3 Schematic experimental set-up

## 3. 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, convex and concave curved surfaces. 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 surfaces 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 position of maximum velocity and half width of the wall jet in the longitudinal and spanwise directions. 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 $Re=5.48 \times 10^4$.

### 3.1 Decay of Maximum Velocity

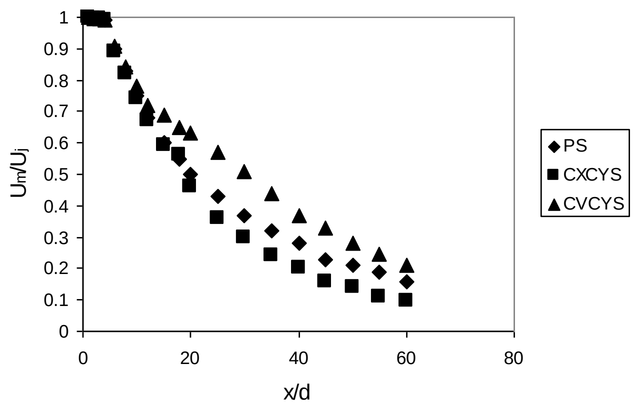
One of the gross characteristics of a three-dimensional wall jet is the decay of the maximum velocity in the plane of symmetry. The decay can be expressed in a power law form i.e.,

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

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 4 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 it 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 and convex cylindrical wall has been designed for producing the curved wall jet. The radius of the cylindrical surface is 500 mm for both the surfaces. The curvature parameter (b/R) is found to be from 0.038 to 0.24 on convex surface and 0.028 to 0.048 on the concave curved surface. 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, where the decay is faster on the convex curved surface when compared to both the plane and concave curved surface. The decay exponent on the concave curved surface is 0.98, whereas on the plane surface the decay exponent is found to be 1.06. Similarly the decay exponent on the convex curved surface is 1.44. The lower value of decay exponent is due to destabilizing nature of the concave curved surface (CVCYS) and stabilizing nature of the convex curved surface (CXCYS).

Fig. 4 Decay of maximum velocity in the longitudinal direction




## 3.2 Mean Velocity Profiles

The normalized mean velocity profiles in the longitudinal direction in the curved portion of both the curved surfaces are shown in Fig. 5. The profiles presented on both the surfaces at x/d=40 and 60. The mean profile on the plane surface is included for comparison. 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 at y/b=0.2 for plane and convex surface and for the concave curved surface it is slightly shifted toward the wall (y/b=0.15).

The mean velocity profiles in the spanwise direction are also shown in Fig. 6 and the mean velocity profiles on the plane surface are included for the comparison purposes. It is also observed that the results are well satisfied and no effect of curvature is felt.

Fig. 5 Mean velocity proifles in the longitudinal direction

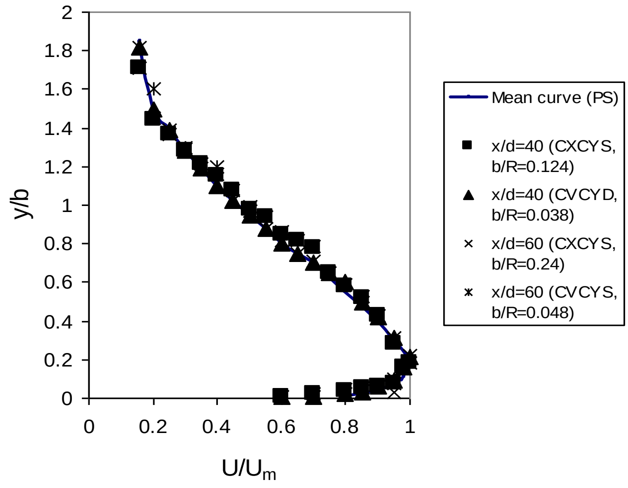
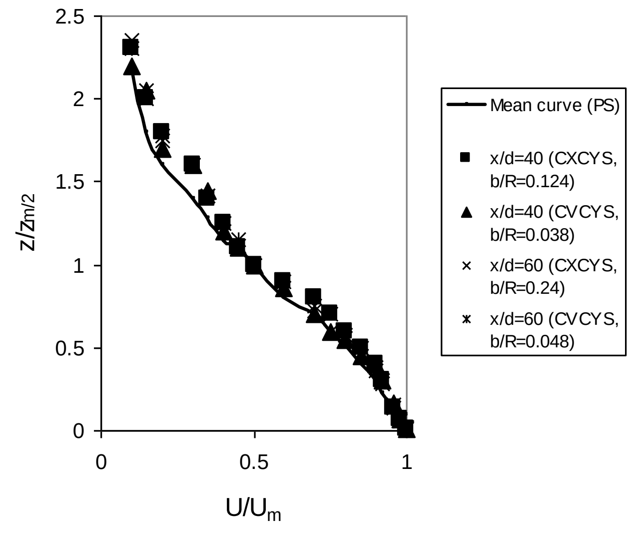



Fig. 6 Mean velocity profiles in the spanwise direction




## 3.3 Variation of Length Scales

The variation of various length scales (b/d, $y_m$/d and $z_{m/2}$/d) are shown in Fig. 7. It is seen that the growth of half width and position of maximum velocity (thickness of inner region) on concave surface in the longitudinal direction is lower compared to the plane surface. Kobayashi and Fujisawa (1985) observed similar phenomenon in the case of growth of half width in the longitudinal direction for two-dimensional wall jets on conave surfaces. 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. Whereas the growth of half width and position of maximum velocity on convex surface is much higher when compared to the growth of half width on the plane surface. The growth of half width in the longitudinal direction is almost equal to the growth of half width in spanwise direction. Hence, it is concluded that the vortex stretching on convex surface results in higher growth in the longitudinal direction. A similar feature is observed by Gowda and Durbha (1999), Wilson and Goldstein (1976), Launder and Rodi (1981), Giles et al., (1966) for the growth of half width on convex surface in the longitudinal direction. The growth of half width in the spanwise direction remains same on all the surfaces.

Fig. 7 Variation of length scales in the longitudinal direction

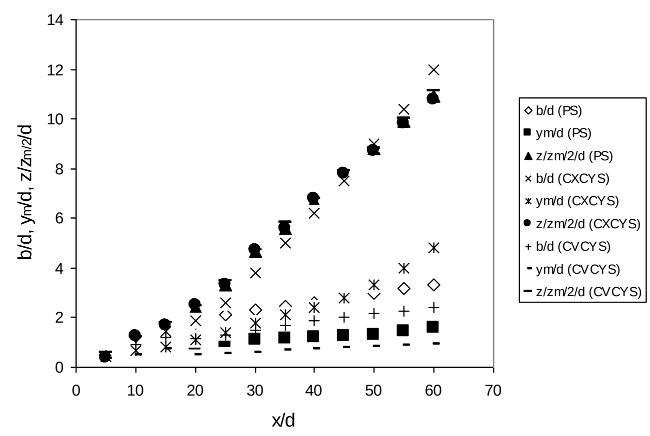
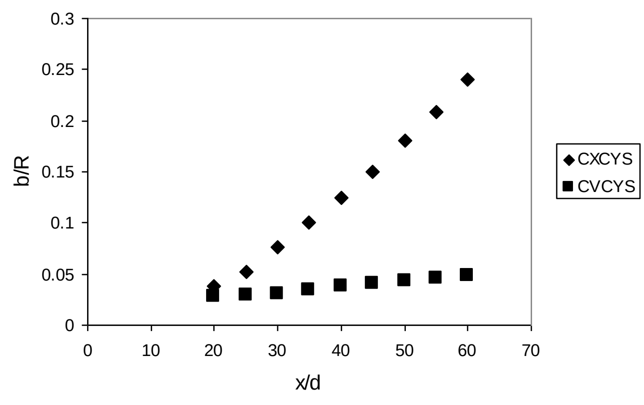



Figure 8 shows the variation of curvature parameter in the longitudinal direction on both the surfaces. It is observed that growth of half width is much higher on the convex surface when compared to the growth of half width on the concave surface (Fig. 7). Hence, the vortex stretching on convex surface is much higher in the longitudinal direction and the formation of secondary flows increases the velcoities in the outer region of the wall jet. Also, it is observed from the earlier investigations that the growth of half width on the concave survace is much lower wehen compared to the growth over the plane surface (Fujisawa and Shirai, 1987) which confirms the stabilizing nature of the concave surface particulary in the inner region of the wall jet and hence, the overall expansion of the velcity profiles in much lower when compared to the width of the velcity profile over plane and convex curved surfaces.

Fig. 8 Variation of curvature parameter in the longitudinal direction




## 4. CONCLUDING REMARKS

The mean velcity profiles follows the trend as that observed on the plane surface. The position of maximum velcoity slightly shifted towards the wall on concave surface and remain same for both convex and plane surfaces . The spanwise velcity profiles remain same both in on the plane surface and curved surfaces. The decay rate is faster on the convex curved surface compared to plane surface and the decay exponent is 1.44 on convex curved surface where as it is 1.06 on the plane surface, where as the decay exponent is 0.98 on concave surface. The growth of half width and the thickness of inner region are much lower when compared to the growth on the plane and convex surfaces. The growth of half width in the longitudnal direction on convex surface is six times higher than the growth of half width on the concave surface. There is no variation of length scale in the spanwise direction both on the plane, convex and concave surfaces.

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