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MEAN VELOCITY DISTRIBUTIONS OF AN INTERRUPTED JET

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SUMMARY A detailed experimental study of the mean velocity distributions of an interrupted jet by an 180° sharp edge is described. The flow is divided into the main jet flow, the wake flow and the redirected flow on the surface. For the main jet flow the regime before the interruption is independent of angular position. For the regime after the interruption the flow is deflected away from the jet central axis and is dependent on angular position. The wake flow is formed by the deflected high velocity portion of the jet flow hitting on and flowing over the sharp edge. The redirected flow along the sharp edge surface is formed by the deflected low velocity portion of the jet flow hitting on the sharp edge.

1 NOTATION

D_i	diameter of the interface
D_o	outer diameter of the jet
D_i/D_o	diameter ratio
r	radial position
$\overline{U}$	local mean axial velocity
$\overline{U}_o$	mean jet exit velocity
$\overline{U}/\overline{U}_o$	mean velocity ratio
$(\overline{U}/\overline{U}_o)_{max}$	maximum mean velocity ratio
x, y, z	axial, vertical and horizontal position
α	divergent angle of the forebody
θ	angular position

2 INTRODUCTION

Impingement of free air jet on a flat surface has been investigated by Scholtz and Trass (1970), Bradbury (1971), Foss and Kleis (1976), Lamont and Hunt (1980), Maki, Ito and Saigo (1980) and others. The investigations concerned both the normal and oblique impingement of free jet wholly on a fairly large surface. Measurements have been obtained on the mean properties of velocity and pressure, of fluctuating properties of turbulence and of heat transfer. These measurements covered the properties not only of the jet before, during and after impingement but also those on the flat surface. Measurements have also been obtained on the aero-acoustic mechanism of the interaction between the jet and the surface considered.

Except the study of Maki et al. (1980), other investigators utilized single jet for their studies. In the recent studies of Maki et al. (1980) the workers used a basic annular jet for the impingement. As has been reported by Ko and Chan (1979), the flow characteristics of the basic annular jet were affected by the standing vortices and their shedding downstream. This means that depending on the Strouhal number of these standing vortices and the shed wake vortices, the basic annular jet might or might not have the additional train of induced wake vortices in the outer mixing region. In this respect, without paying particular attention to the possible additional excitation of the basic annular jet by these vortices, interpretation of the results of Maki et al. (1980) might contain uncertainty.

The aim of the present study was to understand more the mean flow characteristics of a circular conical air jet partially interrupted by a sharp edge.

3 EXPERIMENTAL TECHNIQUE

The jet used for the present investigation was the conical annular jet which had the conical bullet behind the interface (Ko and Chan 1979). The outer diameter of the jet was 62 mm while the diameter of the interface and the base diameter of the conical bullet were 28 mm, giving the width of the annular slit 17 mm. The diameter ratio D_i/D_o was 0.45 and divergent angle α of the borebody was 0°. The length of the conical bullet was 1.5 D_o. The jet exit velocity $\overline{U}_o$ was 40 ms^{-1}.

The 180° sharp edge used has a thickness of 5 mm with the edge tapering off at an angle of 45°. The sharp edge has a size of 203 mm x 114 mm (3.3 D_o x 1.8 D_o) and was held broadside-on and normally to the jet and the tapered part on the downstream side (Figure 1). The sharp edge was located at $x/D_o = 3$ and $z/D_o = 0$. The centreline of the sharp edge intersected the central axis of the conical jet. The projected area of the sharp edge over the nozzle was 50% of the nozzle exit area.

Rectangular co-ordinates are adopted for the present investigation. As the annular jets of Ko and Chan (1979), the origin occurs at the centre of the nozzle outlet (Figure 1). Occasionally, polar co-ordinates (r, θ) are more convenient than the rectangular co-ordinates (y, z) and are also adopted for presentation.

The mean velocity was obtained by constant temperature hot-wire anemometer. The single hot wire used was of 5 x 10^{-6} m tungsten wire with a sensing length of 2 mm.

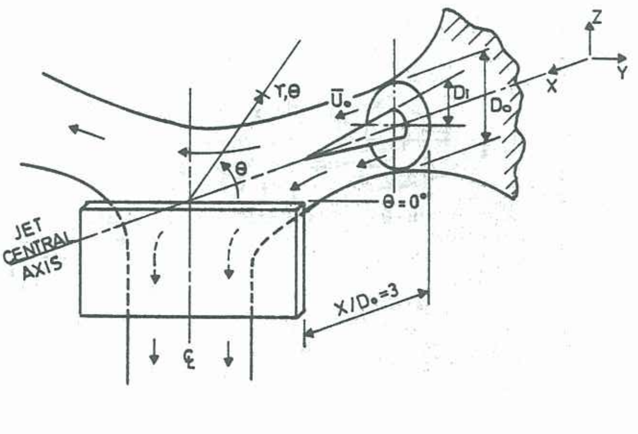
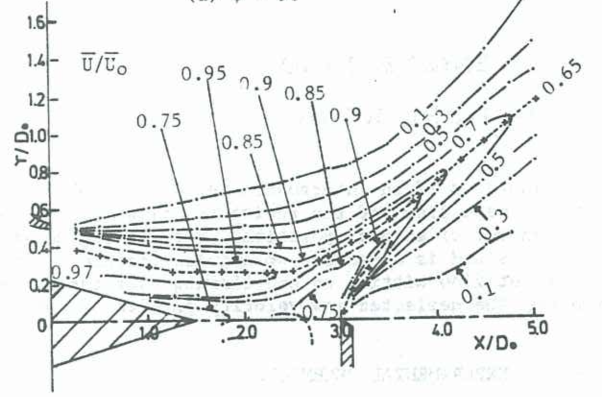


Figure 1. Schematic layout of interrupted jet.

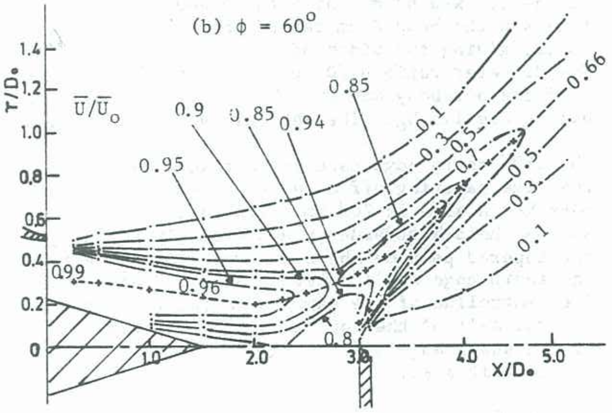
4 RESULTS

As has been observed from the flow visualization work of an interrupted jet of Ko (1981), with the presence of the 180° or flat sharp edge the mean flow field is roughly divided into the main jet flow, the wake flow behind the sharp edge and the redirected flow on the surface.

(a) $\phi = 90^o$



(b) $\phi = 60^o$



(c) $\phi = 30^o$

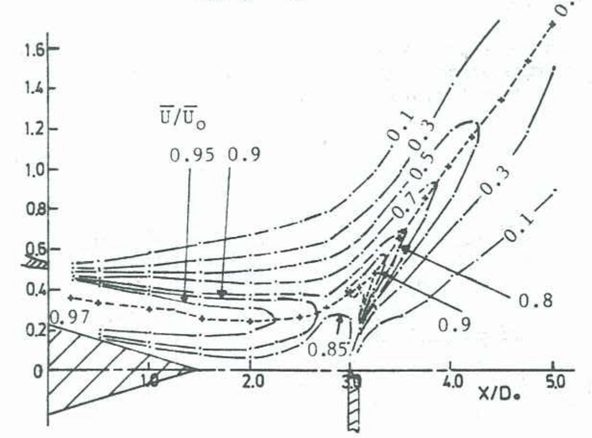


Figure 2. Distributions of mean velocity ratio.

The distributions of the mean velocity ratio $\overline{U}/\overline{U}_o$ of the main jet flow and the wake flow are shown in Figures 2(a) to (c). The figures show the distributions at the plane of θ of 90°, 60° and 30°. In Figure 2(a) the distribution at the 90° plane indicates that for $x/D_o < 1.5$ the uninterrupted part of the jet flow emerging from the nozzle exit deflects slightly towards the jet central axis. For $1.5 < x/D_o < 2.3$ the flow is nearly parallel to the axis. For $x/D_o > 2.3$ the flow is deflected away from the jet central axis. The point of outward deflection is further upstream than the location of the sharp edge at $x/D_o = 3$. The inward and outward deflections of the jet flow can be more easily seen from the locii of the local maximum mean velocity at different axial positions.

In Figure 2(a) besides the high mean velocity region due to the main jet, there is another but small region of high velocity. It is found right behind the sharp edge and is deflecting away from it. This may be due the deflection of the other parts of the jet flow which are interrupted by the sharp edge and which are deflected over the sharp edge into the un-interrupted part of the main jet flow. It merges with the mean jet flow at $x/D_o \approx 3.6$, immediate downstream of the sharp edge. Again, the outward deflection is more clearly seen from the locii of the local maximum mean velocity. The local maximum mean velocity increases from 0.88 $\overline{U}_o$ at the sharp edge to 0.95 $\overline{U}_o$ at x/D_o = 3.25 and decreases to 0.9 $\overline{U}_o$ before its merging with the main jet flow. This high velocity deflected flow is shearing with the ambient air behind the sharp edge, forming the wake flow. Immediately upstream of the sharp edge there seems to be a region of lower velocity between the main jet flow, the wake flow and the redirected flow. The lowest velocity measured is about 0.6 $\overline{U}_o$.

At the plane of 60° the distribution shown in Figure 2(b) also indicates the high velocity regions due to the main jet flow and to the deflected flow and its associated wake. The un-interrupted part of the main jet flow also deflects slightly towards the jet central axis for $x/D_o < 2$. For $x/D_o > 2$ the flow is deflected away from the jet central axis. The high velocity region due to the deflected and wake flow is also shown in Figure 2(b). Its local maximum mean velocity increases from 0.87 $\overline{U}_o$ at the sharp edge to 0.94 $\overline{U}_o$ at x/D_o = 3.1. At this plane the merging of the main jet flow and the wake flow seems to occur slightly further upstream than that at 90° plane and is more complete. It implies that it is not really possible to specify the proportion of individual contribution to the downstream high velocity region by these two flows.

At the plane of 30° the distribution shown in Figure 2(c) also indicates the high velocity regions due to the main jet flow and the wake flow. For the latter the extent is smaller than those of the other two planes. Similar deflection of the main jet flow towards the jet central axis for $x/D_o < 2$ and outward deflection for $x/D_o > 2$ are also observed. As the plane of 60° the merging of the main jet flow and the wake flow is more complete.

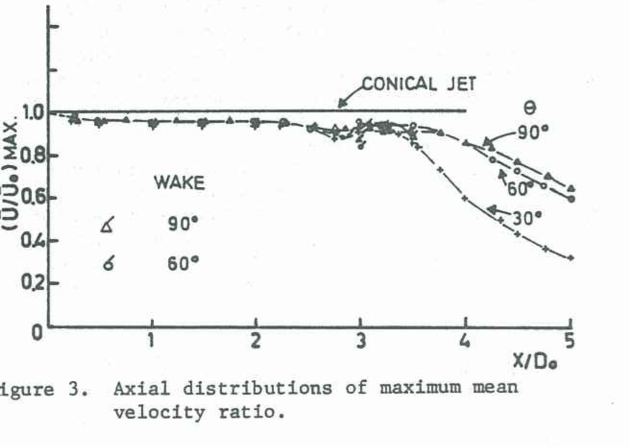


Figure 3. Axial distributions of maximum mean velocity ratio.

The axial distributions of the maximum mean velocity ratios for the main jet flow and wake flow are shown in Figure 3. The distribution of the ratios of the conical jet is also shown in the figure. For $x/D_o \leq 2.25$ the maximum mean velocity distributions of the three planes are the same. The maximum velocity ratio is nearly constant at 0.96. This axial position of $x/D_o = 2.25$ is the position where the main jet flow stops its inward deflection and starts its outward deflection (Figures 2). This suggests that before its reversal change in the deflection the main jet flow has the same maximum mean velocity distribution between the angular planes considered. Furthermore, the mean velocity distributions of the outer mixing region at the three angular planes are also nearly the same. In other words, this implies that for $\theta \geq 30^\circ$ the main jet flow is nearly independent on the angular position θ.

For $x/D_o > 2.25$ the maximum mean velocity ratios of all the three distributions experience a slight drop in value to $(\overline{U}/\overline{U}_o)_{max} \simeq 0.9$ till $x/D_o \simeq 2.8$ and then increases slightly to $(\overline{U}/\overline{U}_o)_{max} \simeq 0.92$ before its continuous reduction with axial distance. The lower maximum mean velocity at $x/Do \simeq 2.8$ may be due to the loss in momentum during its deflection away from the jet central axis. The increase in the maximum mean velocity at $x/D_o \simeq 3.3$ to $0.92\ \overline{U}_o$ seems to extend from the near constant velocity before its outward deflection. This increase may partly be due to the merging of the redirected flow by the sharp edge. For $x/D_o > 3.3$ the distributions experience drop in the maximum mean velocity and the distributions at 90° and 60° planes are nearly the same. The distributions at 30° plane experiences much more rapid drop in value.

The distributions of the maximum mean velocity of the redirected or wake flow before its merging with the main jet flow are also shown in Figure 3. The wake flow seems to have a slight increase in its maximum velocity during its passage over the sharp edge before the merging.

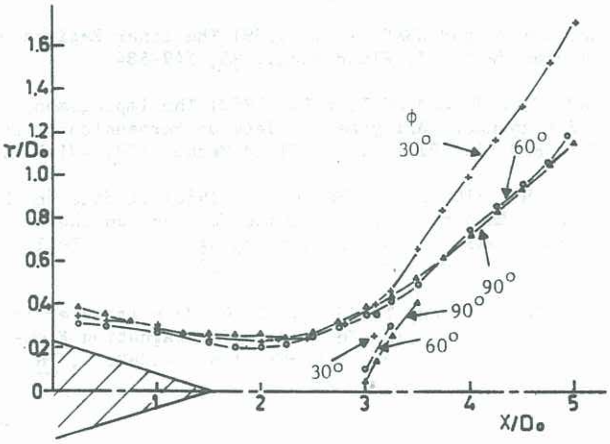


Figure 4. Loci of maximum mean velocity ratio.

The independence of the main jet flow with angular position for $x/D_o < 2.25$ is also shown in the distributions of the locii of the maximum mean velocity (Figure 4). Not only the distributions of the three planes at $x/D_o < 2.25$ are nearly the same, the distributions at 90° and 60° planes are nearly the same even after the outward deflection. Further for the 30° distribution it is only for $x/D_o > 3.1$, that is, after the sharp edge, that the distribution deviates more outwardly from those of the other two planes.

For the redirected or wake flow there seems to be a progressive outward shift of the locii of the maximum mean velocity with the decrease in angle (Figure 4). In other words, the wake flow is deflected more outwardly at 30° plane than that at 90° plane.

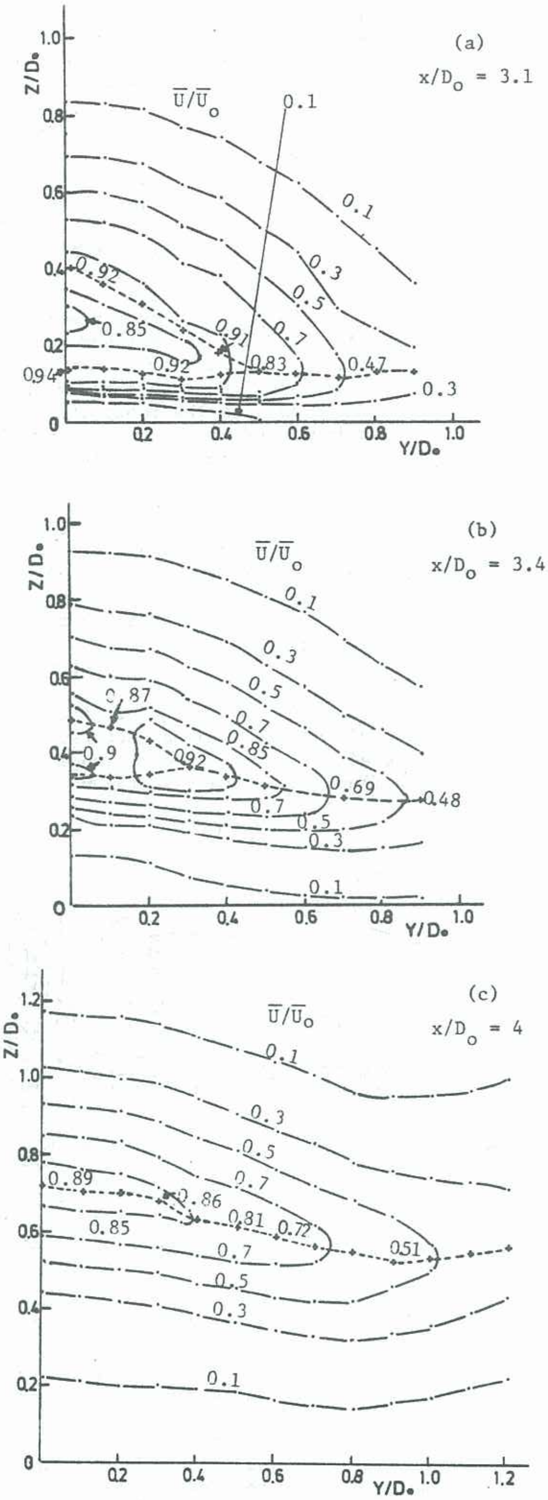


Figure 5. Distributions of mean velocity ratio.

The distributions of the mean velocity at y-z plane are shown in Figures 5(a) to (c). At $x/D_o = 3.1$, just downstream of the sharp edge, the distribution shows two high mean velocity regions (Figure 5(a)). The region, starting at $z/D_o = 0.4$, $y/D_o = 0$ and extending to $z/D_o = 0.2$, $y/D_o = 0.4$, is associated with the deflected main jet flow. The locii of the maximum mean velocity at this region still retain some axisymmetrical characteristics of an axisymmetrical jet. This near axisymmetrical characteristics seem to be present at $x/D_o = 3.4$ (Figure 5(b)) and is nearly absent at $x/D_o = 4$ (Figure 5(c)).

The other high mean velocity region is found to be closer to the sharp edge. At the axial position of $x/D_o = 3.1$ it is at $z/D_o \simeq 0.13$, at $x/D_o = 3.4$ it is at $z/D_o \simeq 0.35$ and $x/D_o = 4$, it is at $z/D_o \simeq 0.6$ (Figures 5(a) to (c)). The extent of the region, where the maximum mean velocity is found nearly parallel, occurs right across the flow, $0 \leq y/D_o \leq 1.2$. This suggests that it is associated with the redirected jet flowing over the sharp edge, forming the wake flow. Because the redirected jet flow flows over the sharp edge, the wake flow formed may inherit the basic characteristics of the sharp edge. This may result in the flow being nearly parallel to the edge of the sharp edge or the y axis. For $x/D_o \leq 3.4$ the extent of the main jet flow, as discussed above, is found mainly at $y/D_o < 0.5$ and diminishes further downstream. Further, the absence of the main jet flow downstream of $x/D_o > 3.4$ suggests that after merging the redirected or wake flow may be more dominant and may be more responsible for the flow in the region behind the sharp edge.

The mean velocity distribution upstream of the sharp edge is shown in Figure 6. The plane is at $\theta = 270^\circ$, that is, along the central axis of the sharp edge. In compared with the mean velocity contours of the main jet flow at $\theta = 90^\circ$, 60° and 30°, the contours at this angular plane, up to $x/D_o = 2.5$ are more diverged. This indicates that the flow is being redirected, resulting in more diverged pattern.

For the axial position of $2.5 \leq x/D_o \leq 2.95$ the mean velocity ratios could not be obtained accurately. It is because of the effect of the severe change of direction of the flow. Nevertheless, the velocity contours indicate that the jet flow is roughly divided into two portions. The dividing contour seems to be at $\overline{U}/\overline{U}_o \simeq 0.55$. The top or higher velocity portion seems to be redirected towards the jet central axis and over the sharp edge. It may result in the high velocity region found behind the sharp edge observed above. During its passage, it sets up a low velocity region on the sharp edge surface. The mean velocity gradient of this low velocity is fairly high and the mean velocity reduces from $0.6\ \overline{U}_o$ at $x/D_o = 2.8$ to $0.075\ \overline{U}_o$ at $x/D_o = 2.95$. The extent of this low velocity region occurs at $-0.45 < z/D_o < 0$.

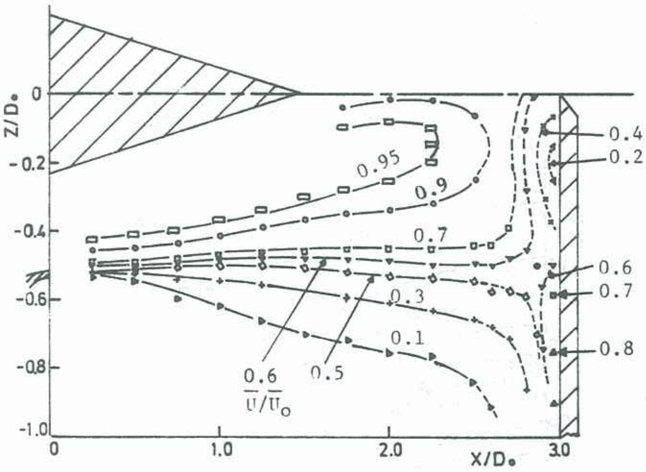


Figure 6. Distributions of mean velocity ratio.

The bottom or low velocity portion seems to be redirected away from the jet central axis. After its redirection, the flow in this portion seems to induce a small region of higher velocity next to the sharp edge surface. Within this region the mean velocity seems to increase from the velocity of $0.6\ \overline{U}_o$ at $z/D = -0.5$ to $0.7\ \overline{U}_o$ at $z/D_o = -0.68$ to $0.8\ \overline{U}_o$ at $z/D_o = -0.75$ and to $0.83\ \overline{U}_o$ at $z/D_o = -0.9$. It is not yet known the cause for this high velocity and accelerating region on the sharp edge surface.

5 CONCLUSION

The detailed measurements of the mean velocity distributions of an interrupted jet, which is interrupted by an 180° sharp edge, isolate the three distinct flows: the main jet flow, the wake flow behind the sharp edge and the redirected flow on the surface of the sharp edge.

The main jet flow is divided into two regimes: the one before interruption and the one after interruption. The flow within the regime before interruption is independent on angular position while that within the regime after interruption is dependent on angular position.

The wake flow is formed by the deflection of the high velocity portion of the jet flow impinging on the sharp edge and its passage over it. This flows then shears with the stationary air outside. During its passage there seems to be an increase in velocity, approaching that of the deflected main jet flow, before their merging.

The redirected flow on the surface of the sharp edge consists of two basic portions. The top or high velocity portion flows towards the jet central axis, forming the wake flow. When it flows over the surface, it seems to induce acceleration.

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