MEAN FLOW CHARACTERISTICS IN THE NEAR FIELD OF A TURBULENT OFFSET JET

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ABSTRACT

The flow field of a turbulent offset plane jet with an offset ratio of 2.125 has been investigated using laser Doppler anemometry (LDA) for up to 20 nozzle widths downstream from the nozzle plate. Mean velocity vectors show a high turbulence recirculating flow region close to the nozzle plate between the jet and the offset plate. The spatial distributions of turbulence intensities and Reynolds shear stress of this jet are also presented.

INTRODUCTION

Offset jets have numerous technological applications. For instances, entrainment and mixing processes in boiler and gas turbine combustion chambers, heat exchangers, injection and carburettor systems are strongly governed by offset jets. As shown schematically in Fig. 1, an air jet is discharged from a plane nozzle of width (w) into quiescent ambient surroundings above a wall offset from the axis of the jet discharge by a distance h. Entrainment of the air below the jet and above the offset wall causes a sub-atmospheric pressure zone forcing the jet to deflect towards the wall in the converging region and eventually reattaching to it in the impingement region. Far downstream from the nozzle plate, in the wall jet region, the flow resembles an ordinary wall jet flow.

Some of the studies of the offset jet were conducted by Bourque & Newman (1960), Sawyer (1960 and 1963), Bourque (1967), McRee & Moses (1967), Perry (1967), Rajaratnam & Subramanya (1968), Ayukawa & Shakouchi (1976), Nozaki et al. (1979), Hoch & Jiji (1981), Nozaki et al. (1981), and Lund (1986). These studies included measurements of static pressure distributions, mean streamline velocity profiles, and the effect of offset ratio (h/w) on the streamwise distance of the impingement point from the nozzle plate (x_r) using either Pitot tube or single hot-wire for jets with offset ratios from 0.694 to 48. Nonetheless, there are discrepancies among reported experimental results. For instance, early studies of Bourque and Newman (1960) and Sawyer (1960 and 1963) had assumed a uniform pressure within the recirculation zone and hence a constant radius of curvature of the jet centreline which were examined by Bourque (1967) and Rajaratnam & Subramanya (1968) to be erroneous. More recently, Pelfrey & Liburdy (1986) used two component laser Doppler anemometry to measure velocity components and turbulence intensities of an offset jet with an offset ratio of 7. They found that the magnitude of the curvature strain rate is significant, thus implying that the flow field cannot be accurately modelled as a thin shear layer.

Previous investigations have been focussed on jets with relatively high offset ratios. Studies of low offset ratios are mainly concerned with static pressure measurements in determining reattachment length. With the exception of Pelfrey & Liburdy(1986), measurements were made with hot-wire or Pitot tube which cannot resolve the recirculation flow region with confidence. The objective of this paper is, therefore, to document the flow field of an offset jet with a small offset ratio in terms of velocity field, turbulence intensities and Reynolds shear stresses obtained with laser Doppler anemometry.

APPARATUS AND EXPERIMENTAL CONDITIONS

Experiments were conducted in a jet facility similar to that of Lai & Nasr(1995) using the same LDA measurement system. The nozzle was 180 mm long with a width of 6 mm, giving an aspect ratio of 30. The wall was offset from the centreline of the nozzle by 12.75 mm, thus yielding an offset ratio (h/w) of 2.125. Nozzle exit Reynolds number was 6600 (corresponding to a nozzle exit velocity U_O of 16 m/sec). The streamwise turbulence intensity at the centreline of the nozzle exit was less than 0.5%. Side plates were used to enhance the two-dimensionality of the flow by preventing surrounding air being entrained from the top and bottom sides of the jet.

RESULTS AND DISCUSSIONS

As shown in Fig. 2, the variation of the reattachment length (x_r/w) with offset ratio (h/w) as reported in the literature can be expressed by a power law. Mean velocity vectors, determined from simultaneous measurements of mean streamwise and lateral velocity components, for the jet with h/w=2.125 are shown in Fig.3. A sub-atmospheric pressure zone close to the nozzle plate is formed due to the entrainment of the air between the jet and the wall. As a result, the jet converges towards the wall as it proceeds downstream from the nozzle plate, forming a recirculation flow region (Fig. 3). The jet finally reattaches to the wall at about $x_r/w=5$ which is in good agreement with the experimental data depicted in Fig. 2. The maximum velocity of the reversed flow was measured to be about $-0.27U_o$ at (3.5w, 0.11w) and the standing vortex centre was found to be at (3.75w, 0.6w). Owing to the flow curvature, the maximum mean streamwise velocity U_m/U_o of the offset jet decays much faster than that of a single jet and a wall jet up to the reattachment zone (Fig. 4). Downstream of the reattachment zone, it decays much slower than a single jet and appears to approach that of a wall jet by x/w=20. For higher offset ratios such as h/w of 7 for Pelfrey and Liburdy (1986), U_m/U_o increases downstream of the reattachment zone. This is perhaps because the flow curvature is larger than the current study due to the higher h/w, thus resulting in the collision of the jet centreline with the wall and conversion of the static pressure into velocity momentum.

The deflection of the jet towards the wall is well illustrated in Fig. 5 by the loci of the locations (y_{max}/w) of local maximum mean streamwise velocity and the locations of the inner and outer shear layer half-widths ($y_{+1/2}/w$ and $y_{-1/2}/w$ respectively). It can readily be seen that by x/w=7, the jet has reattached to the wall and begins to develop like a wall jet flow. Fig. 6 shows that upstream of the impingement region, $y_{+1/2}/w$ of the offset jet is higher than that of the wall jet and single jet. This is simply because the nozzle is offset from the wall for the offset jet. It can be seen that $y_{+1/2}/w$ decreases with x/w from the nozzle plate up to x/w=8. Downstream of the impingement zone ($x/w \approx 8$), $y_{+1/2}/w$ starts to increase with x/w but at a rate slower than that of the wall jet. This result, being consistent with the slower velocity decay of the offset jet shown in Fig. 4, is because the offset jet only starts to develop as a wall jet flow downstream of the impingement zone whereas the plane wall jet develops from x/w=0. In order to illustrate the spreading of the offset jet, the jet half-widths in the inner shear layer (b_-/w) and outer shear layer (b_+/w) are depicted in Fig. 7. The results of Pelfrey & Liburdy (1986) are also included for comparison. For both offset jets, the outer shear layer spreads faster than that the inner shear layer which is constrained by the presence of the wall. This is consistent with the results of Sawyer (1963) indicating that the spreading rate is higher on the convex side of a curved jet than that on the concave side. Fig. 7 also shows that for both offset jets, the jet width is about the same for the inner and outer shear layers at about the reattachment point. Downstream of the reattachment point, the inner shear width decreases with x/w as the jet develops to be a wall jet.

Contours of streamwise turbulence intensity (u'/U_o), lateral turbulence intensities (v'/U_o) and Reynolds shear stress ($\overline{uv}/U_o^2$) are displayed in Figs. 8-10 respectively. Upstream of the reattachment point, the turbulence intensities and Reynolds shear stress in the inner shear layer especially near the nozzle exit are much higher than those in the recirculation flow region due to the high shear there. In the neighbourhood of the reattachment point, the turbulence intensities and Reynolds shear stress have developed to comparable magnitude to those in the inner shear layer near the nozzle exit, thus indicating high momentum transfer between the main jet flow and the near wall flow in the reattachment zone. Downstream of the reattachment zone, the contours start to resemble those of a wall jet flow.

CONCLUSIONS

LDA measurements of the velocity field of a turbulent plane offset jet with a low offset ratio of 2.125 have been presented for the first time to illustrate the spatial development of this jet. The maximum mean streamwise velocity of the reversed flow was found to be about $-0.27U_o$. The reattachment length of this jet to the wall is in good agreement with the power law relationship derived from the data in the literature.

ACKNOWLEDGMENT

This project has been supported by the University College Rector Special Research Grant.

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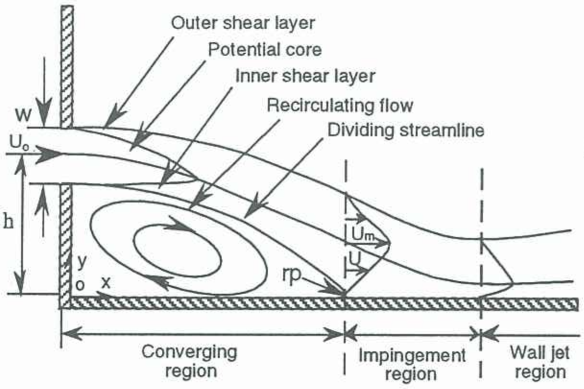

FIG. 1 SCHEMATIC OF AN OFFSET JET.

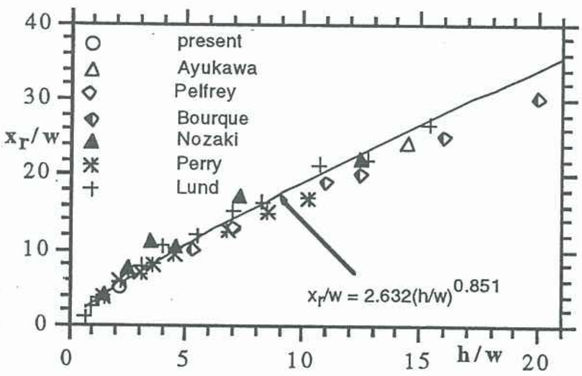

FIG. 2 VARIATION OF x_r/w WITH h/w.

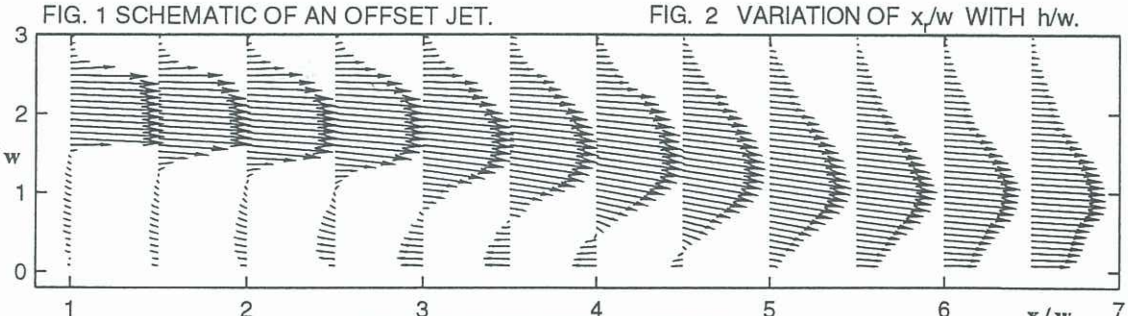

FIG. 3 MEAN VELOCITY VECTORS.

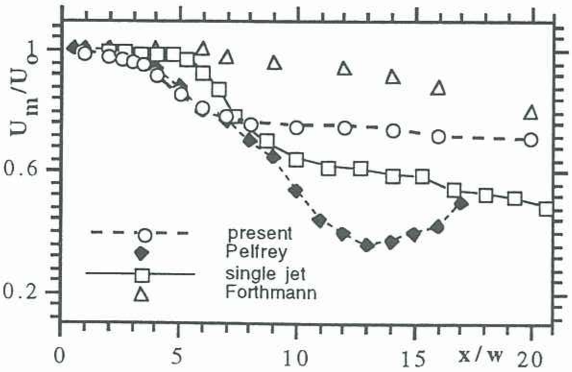

FIG.4 JET CENTRE- LINE VELOCITY DECAY.

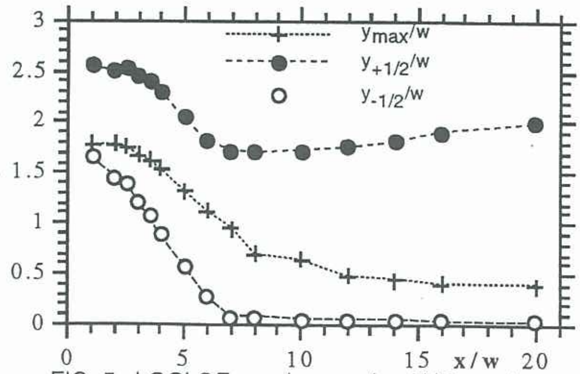

FIG. 5 LOCI OF y_{max}/w, $y_{+1/2}/w$, AND $y_{-1/2}/w$.

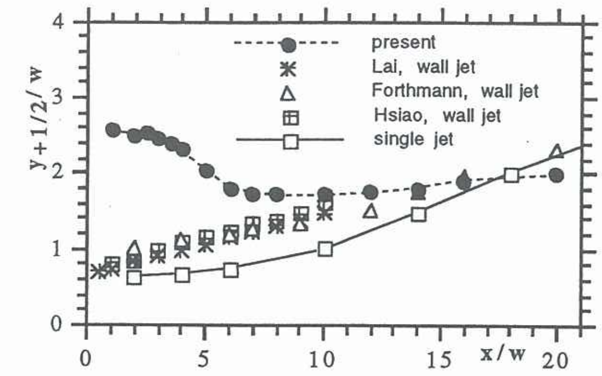

FIG.6 LOCI OF $y_{+1/2}$/w FOR VARIOUS JETS.

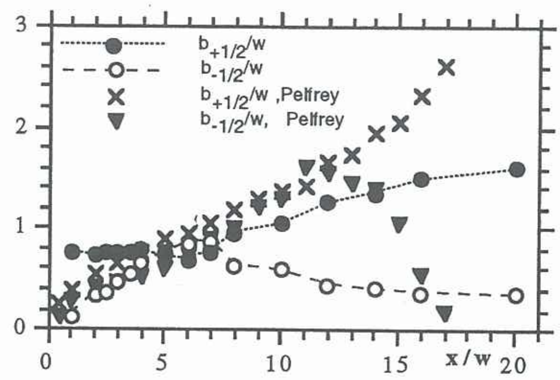

FIG.7 VARIATION OF JET WIDTH WITH x/w.

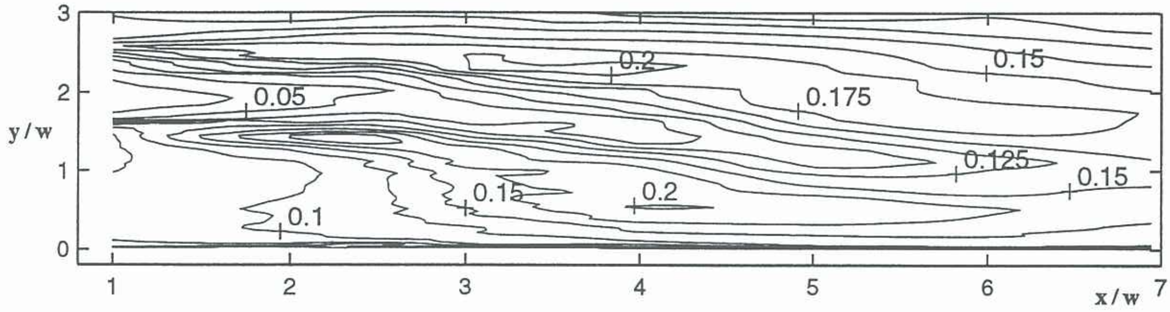

FIG. 8 STREAMWISE TURBULENCE INTENSITY CONTOURS.

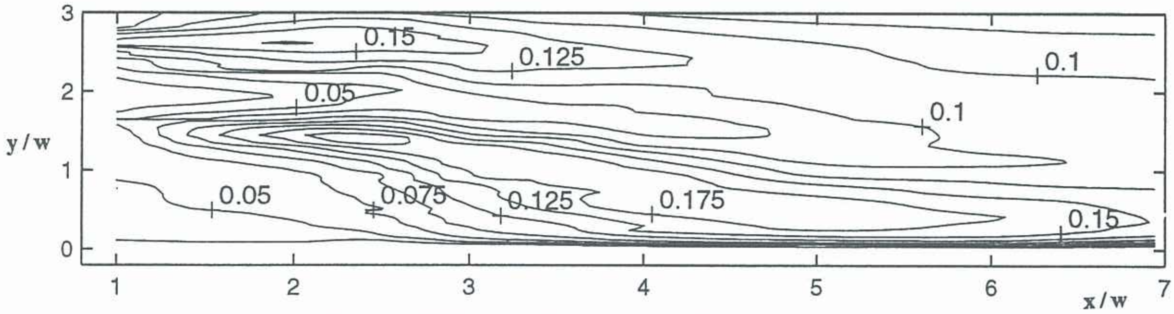

FIG. 9 LATERAL TURBULENCE INTENSITY CONTOURS.

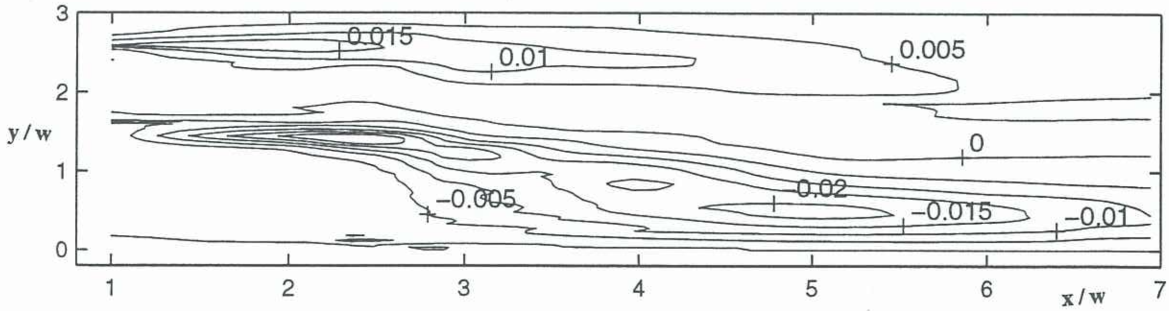

FIG. 10 REYNOLDS SHEAR STRESS CONTOURS.