THE EFFECTS OF WALL INCLINATION ON AN INCLINED OFFSET JET

by

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ABSTRACT

There are numerous technological applications in which offset jets play an important role, such as entrainment and mixing processes in boiler and gas turbine combustion chambers, fuel injection systems, and thrust-augmenting ejectors for V/STOL aircraft. Although studies of both offset jets with zero angle of wall inclination and inclined wall jets (with no offset) using primarily pressure measurements and hot-wire anemometry have been reported in the literature, the flow field of an offset jet with an inclined wall has remained largely unexplored.

In this paper, the mean velocity field and turbulence field of an inclined plane offset jet with an offset ratio of 2.125 has been determined using a two-component Laser Doppler Anemometer (LDA) for a nozzle exit Reynolds number of 6100. The effects of the wall inclination angle (β) on the spatial development of the flow field in the converging region of the jet are assessed for β = 0°, 15° and 30°. Results obtained indicate that when compared with the 0° jet, the reattachment length measured along the plate is 51% and 160% longer for β = 15° and 30° respectively. Even when the spatial coordinates are nondimensionalized using the reatachment length, the size of the recirculation flow region increases as β increases. Furthermore, the maximum mean velocity decay is faster and the turbulence field is stronger as β increases. These data are hitherto not available in the literature and will provide a useful database for validating turbulence models for complex shear flows.

1 INTRODUCTION

There are numerous technological applications in which offset jets play an important role, such as entrainment and mixing processes in boiler and gas turbine combustion chambers, fuel injection systems and thrust-augmenting ejectors for V/STOL aircraft. The flow patterns of an inclined offset jet with a wall inclination angle β are shown schematically in Fig. 1. Two Cartesian coordinate systems (X-Y and x-y) can be used to describe the flow. The X-Y system is based on the centre-line of the jet at the nozzle exit plane whereas the x-y system is based at the wall. As shown in Fig.1, a plane, incompressible, turbulent air jet is discharged from a plane nozzle with width *w* and offset from the wall by a ratio of *h/w*. Entrainment of the air between the jet and the wall in the converging region causes a negative pressure zone, thus forcing the jet to deflect towards the wall and eventually to reattach to it at some downstream location. Part of the inner shear layer fluid is deflected back upstream from the reattachment point (rp) into the recirculation zone by an adverse pressure gradient. Downstream from the reattachment point, in the reattachment region, the flow is subjected to the effects of stabilizing curvature, adverse pressure gradient and the interaction with the wall. Far downstream from the nozzle plate, in the wall jet region, the flow starts to develop as an ordinary wall jet.

Turbulent wall jets have been extensively studied both theoretically and experimentally. However, a review by Launder (1983) on turbulent wall jets has revealed that despite over two hundred publications on the topic, accurate data particularly on the distribution of turbulence stresses are lacking and the physics of the flow is still not well understood. With very few exceptions, all the measurements so far were conducted in the fully-developed region of the jet where self preservation is being approached or has already been attained. Some of the more recent studies, such as Matsuda et al (1990), Katz et al (1992), Hsiao & Sheu (1994), Schneider & Goldstein (1994) and Zhou et al (1996) have been directed at studying the flow structures in plane wall jets. Forthmann (1934) conducted the first experimental study of an inclined wall jet and the Coanda effect (in which a jet reattaches to a nearby solid surface) has attracted considerable attention. Based on surface pressure measurements, Newman (1961) proposed a flow model that provides an estimate of the reattachment distance. His results were in fair agreement with experimental data for $\beta < 45°$ and for jet exit Reynolds number > 8000. While pressure measurements in an inclined wall jet were reported by Newman (1961) and several attempts in modelling the flow to predict the jet reattachment distance were made such as by Bourque (1967) and Perry (1967), the velocity field of an inclined wall jet, particularly in the near field, has not been fully explored. The effect of the wall angle (β) on the development of the velocity field of an inclined wall jet was first investigated using constant temperature hot-wire anemometry by Lai & Lu (1996) for $\beta = 0°$, 15°, 30° and 45° and a nozzle exit Reynolds number of 10,000. Although surface pressure measurements and flow visualisation results as documented by Lai & Lu (1992) seem to correlate quite well with the hot-wire measurements, the hot-wire data cannot discriminate against reversed flow in the recirculation flow region between the main jet flow and the wall. A detailed study of an inclined wall jet with $\beta = 30°$ has been conducted by Lai & Lu (2000) using a two component laser Doppler anemometer (LDA).

Offset jets with zero angle of inclination have been studied by many researchers including Bourque & Newman (1960), Sawyer (1960 and 1963), Bourque (1967), McRee & Moses (1967), Perry (1967), Rajaratnam & Subramanya (1976), Ayukawa & Shakouchi (1976) and Lund (1986). With the exception of Pelfrey & Liburdy (1986) who used one component LDA for an offset jet with large h/w, these studies were conducted using, to a large extent, intrusive techniques such as hot-wire and Pitot tube probes which are subject to severe measuring errors due to the presence of recirculation zone and high flow curvature in the near field. More recently, Nasr and Lai (1998) reported the velocity field of an offset jet with a low offset ratio of 2.125 obtained using a two-component LDA system. In the case of an inclined offset jet, with the exception of the analytical work of Bourque (1967), there seems to be no experimental work published in the literature.

The primary objective of this paper is, therefore, to present the velocity field of an inclined offset jet with an offset ratio of 2.125 using a two-component laser Doppler anemometer for β = 15° and 30°. These results are compared to those obtained for a non-inclined offset jet of the same offset ratio, that is, β = 0°. These data which cover the whole flow field including the recirculation zone are hitherto not available in the literature and will provide a useful database for validating turbulence models for complex shear flows.

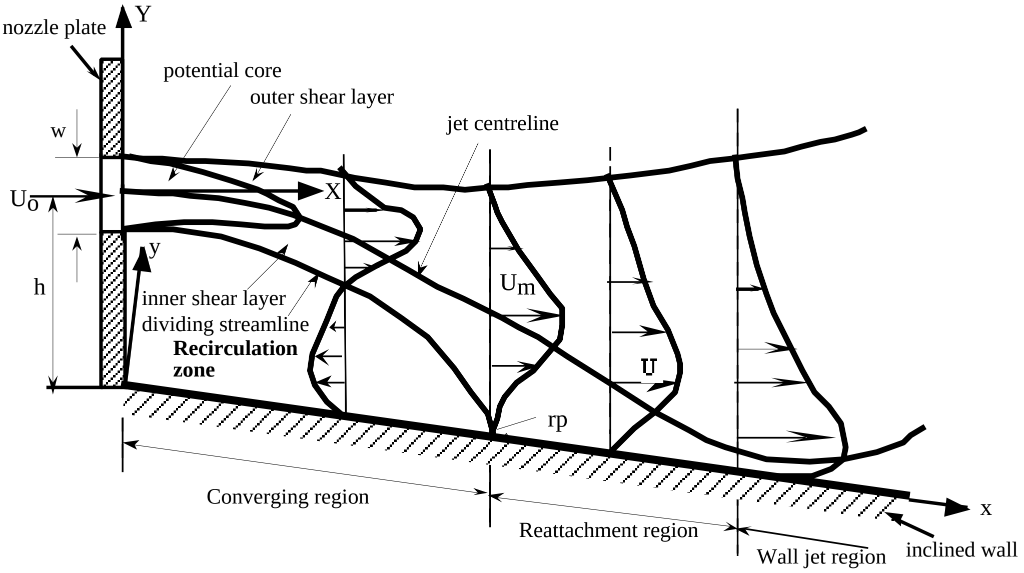


Fig. 1 Schematic diagram of an inclined offset jet.

2 APPARATUS AND EXPERIMENTAL CONDITIONS

The two-dimensional experimental jet rig comprised a perspex jet settling chamber 770 mm long, 150 mm wide and 350 mm high. The air flow rate was controlled with a frequency invertor and grids were used in the settling chamber to reduce the turbulence intensity. The streamwise turbulence intensity at the centreline of the nozzle exit was less than 0.5%. A two-dimensional nozzle with width (*w*) of 6 mm and an aspect ratio of 30 was made of an aluminium plate with thickness 7.5 mm. Side plates were placed horizontally at the top (ceiling) and bottom (floor) sides of the nozzle in order to enhance the two-dimensionality of the flow.

Mean velocity and turbulence measurements were made in the midplane between the top and bottom sides of the nozzle by a two component LDA system. The jet Reynolds number at the nozzle exit was 6100, corresponding to an averaged nozzle exit velocity of 15.35 m/s. The LDA system comprised a DANTEC Coherent's *INNOVA 70* series Argon ion laser as the light source and two DANTEC 57N10 Burst Spectrum Analysers operated in burst mode. Two blue and green laser beams each of 75 mW were used and the flow field was seeded using Rosco Fog Fluid. The number of burst samples for each measurement was set at 3000 and raw data was processed by applying the transit time weighting function to reduce velocity bias errors. LDA measurements were validated by theoretical results and hot wire data made in a single free jet. Analysis of the LDA data indicated that the uncertainties in the measured mean velocities (U,V), rms velocity fluctuations (u',v') and velocity correlation $\overline{uv}$ were within ±0.085 m/s, ±0.09 m/s and ±0.4 $\mathrm{m^2/s^2}$. Details of the experimental set-up and instrumentation are given by Nasr and Lai (1998).

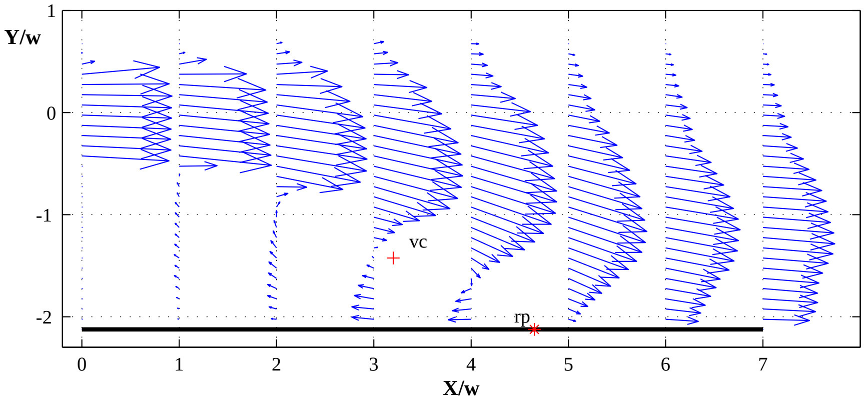
3 RESULTS AND DISCUSSIONS

3.1 Mean velocity field

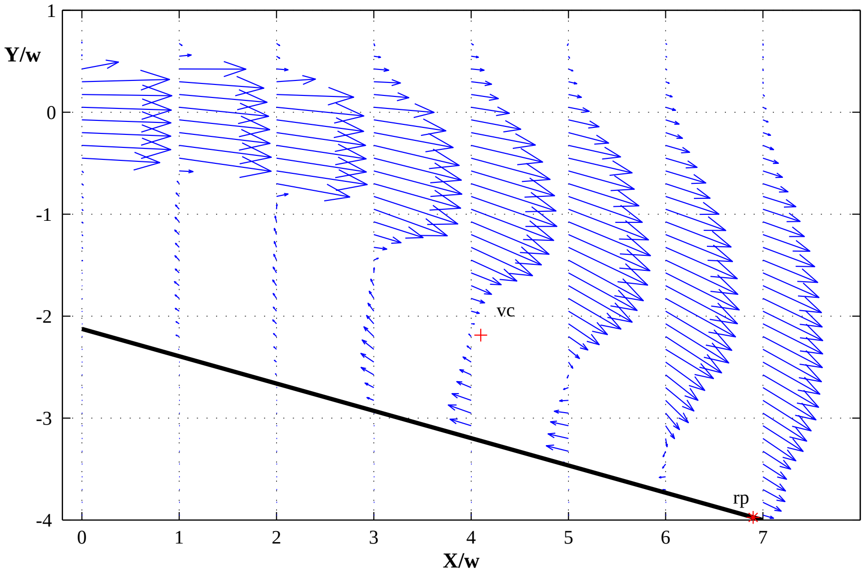
Figures 2(a)-(c) display the mean velocity vectors in the converging region of an inclined offset jet for $\beta = 0°$, 15° and 30° respectively in the X-Y coordinate system. These velocity vectors were determined from simultaneous measurements of mean streamwise (U) and lateral (V) velocity components. It can be seen that for all three cases, owing to the entrainment of air between the jet and the wall, a sub-atmospheric pressure zone is formed close to the nozzle plate. The jet converges towards the wall as it proceeds downstream from the nozzle plate and finally reattaches to it at some downstream location. The mean velocity vectors in the reattachment/wall jet region for $\beta = 0°$, 15° and 30° are shown in Figs. 3(a)-(c) respectively in the x-y coordinate system. Here the streamwise distance x along the wall is nondimensionalized by the reattachment length x_r. It is quite clear that for all three cases, the jet has developed into a plane wall jet by $x/x_r = 2$.

As shown in Fig. 2(a), for a simple offset jet ($\beta = 0°$), the reattachment length X_{rp}/w was determined to be 4.65 compared with 6.8 and 10.5 for $\beta = 15°$ and 30° respectively. When measured along the wall, these reattachment lengths x_{rp}/w correspond to 4.65, 7.04 and 12.12 respectively, thus indicating that it is longer than $\beta = 0°$ by 51% for $\beta = 15°$ and 160% for $\beta = 30°$. For $\beta = 0°$, the standing vortex centre (X_{vc}/w, Y_{vc}/w) is located at (3.2, 0.7), compared with (4.75, 0.85) and (7, 2.2) for β = 15° and 30° respectively. On the other hand, the maximum velocity of the reversed flow is rather similar for all three cases, being $-0.27U_o$ at X=3.5w and Y=0.11w for $\beta = 0°$, $-0.26U_o$ at X=5w and Y=0.2w for $\beta = 15°$, and $-0.23U_o$ at X=7w and Y=0..2w for $\beta = 30°$.

The variation of the maximum velocity Q_m/U_o with streamwise distance X/w has been determined and is shown in Fig. 4(a). These results indicate that the 0° offset jet decays faster than the 15° and 30° offset jets. However, when the streamwise distance X is nondimensionalized by the reattachment length X_r, Fig. 4(b) shows that the 30° jet decays fastest, followed by the 15° and then the 0° jets. The locus of the locations of maximum velocity, plotted in Fig. 5, show that they are pretty similar for all three jets if the distances are nondimensionalised by the reattachment length.

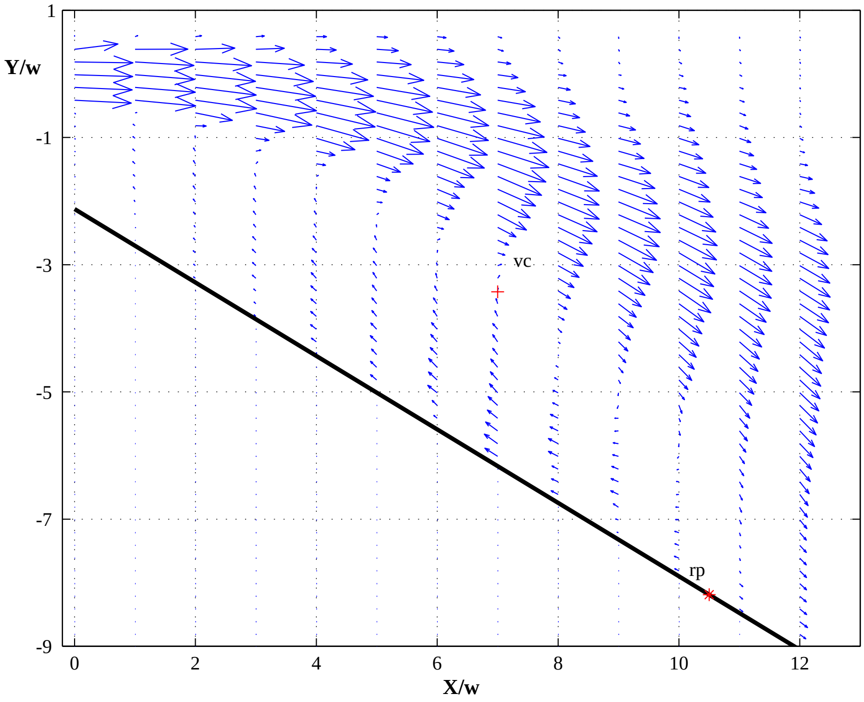


(a) β = 0°



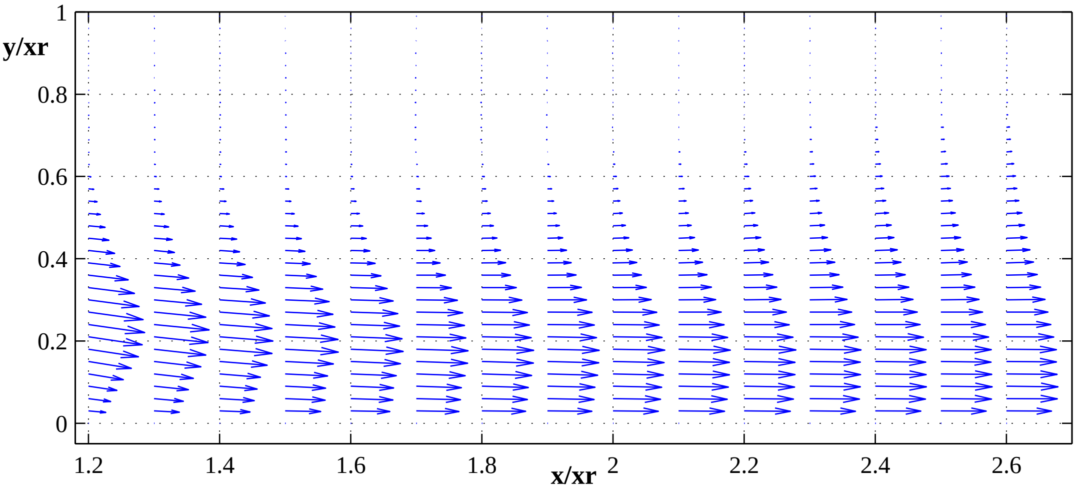
(b) β = 15°

Fig. 2 Mean velocity vectors in the converging region of an inclined offset jet.



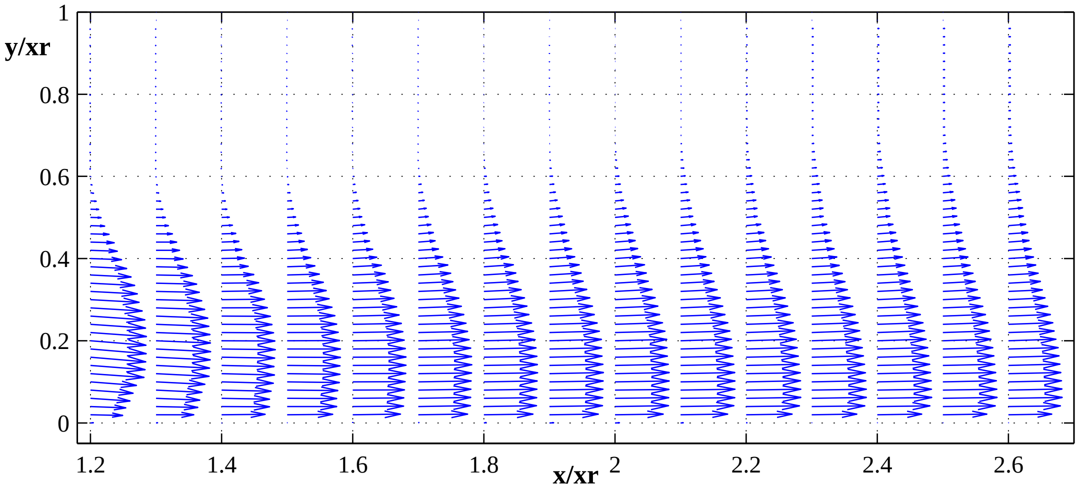
(c) β = 30°

Fig. 2 Mean velocity vectors in the converging region of an inclined offset jet.

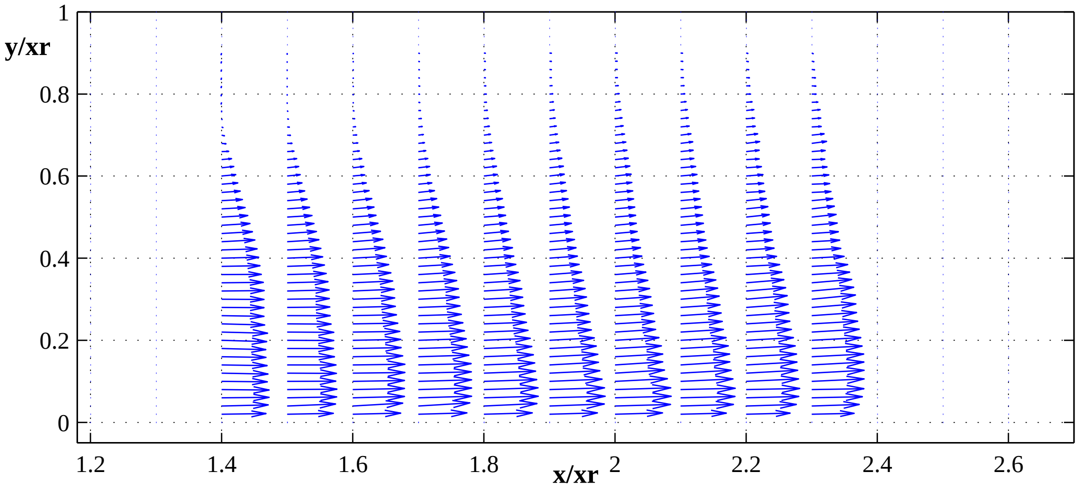


(a) β = 0°

Fig. 3 Mean velocity vectors in the wall jet region of an inclined offset jet.



(b) β = 15°



(c) β = 30°

Fig. 3 Mean velocity vectors in the wall jet region of an inclined offset jet.

Contours of the non-dimensional mean streamwise velocity U/U_o are displayed in Figs. 6(a)-(c) respectively. Here the streamwise (X) and lateral (Y) distances are nondimensionalized by the rattachment length (X_r). For all three jets, the recirculation flow region can be easily identified by the reversed flow (negative U/U_o). In terms of the number of reattachment lengths, the recirculation flow region is far more elongated for β = 30° than for β = 15° which in turn is more elongated than for β = 0°. Furthermore, the potential core is longer for β = 0° than for β = 15° and 30°. These results are fairly consistent with those presented in Fig. 4. Contours of the non-dimensional mean lateral velocity V/U_o are displayed in Figs. 7(a)-(c) respectively. For all three jet configurations, except in the recirculation zone where the lateral velocity is positive indicating the upward motion of the recirculating flow close to the wall, it is negative everywhere indicating that the jet is attracted towards the wall. The magnitude of the negative lateral velocity appears to increase with the wall angle β, thus indicating a stronger deflection of the jet towards the wall for large β than for low β. This is consistent with a faster decay of the maximum velocity for large as shown in Fig. 4.

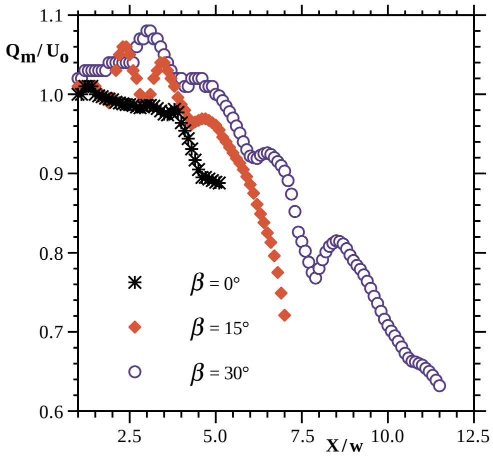


Fig. 4(a) Variation of maximum velocity Q$_m$ with X/w.

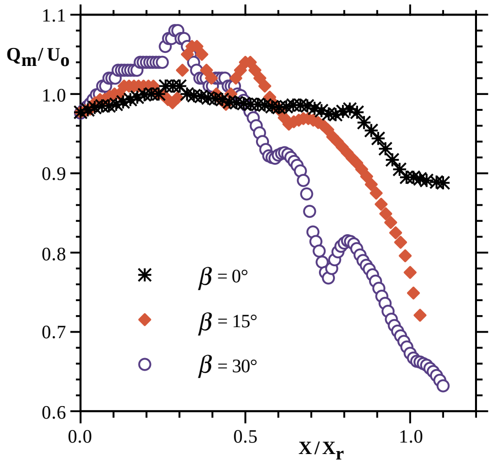


Fig. 4(b) Variation of maximum velocity Q_m with X/X_r.

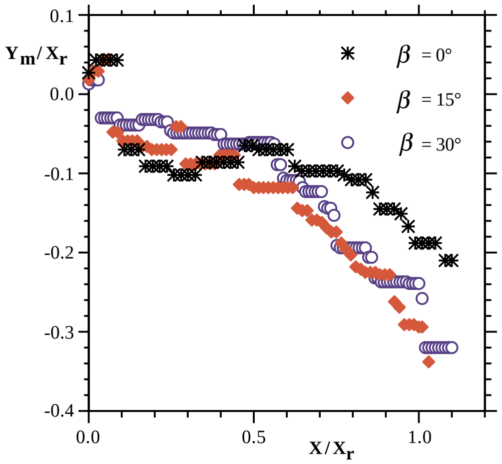
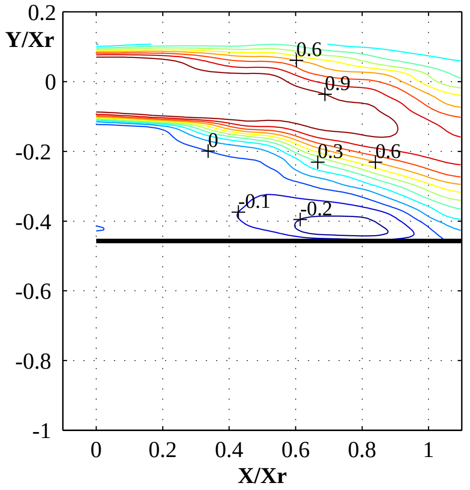
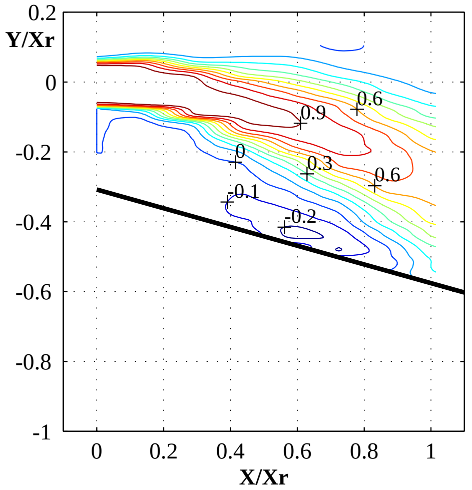


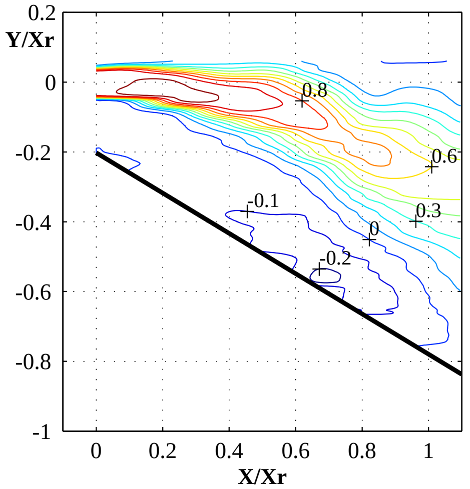
Fig. 5 Variation of maximum velocity Y_m/X_r with X/X_r.



(a) β = 0°

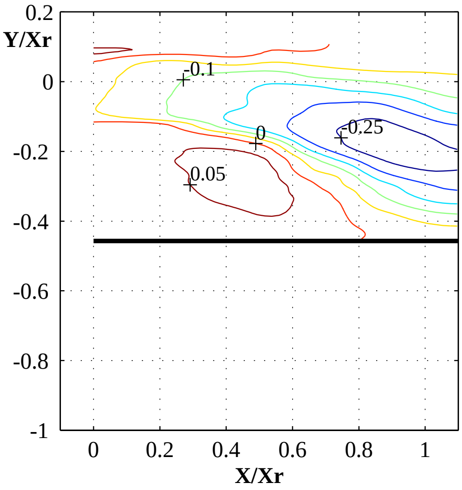


(b) β = 15°

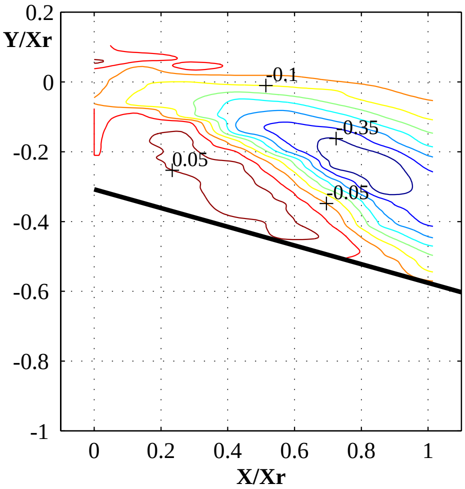


(c) β = 30°

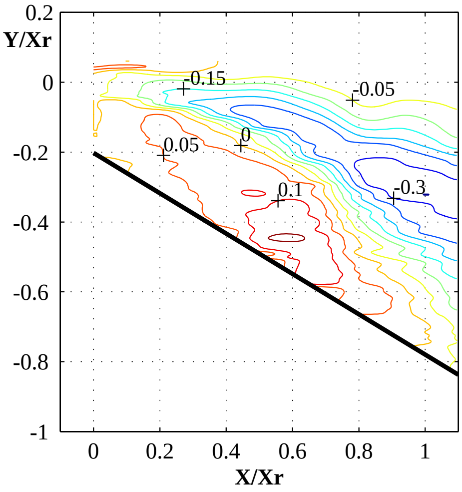
Fig. 6 Contours of U/U_o.



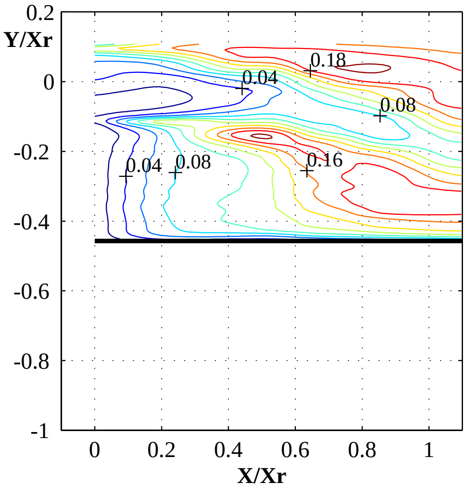
(a) β = 0°



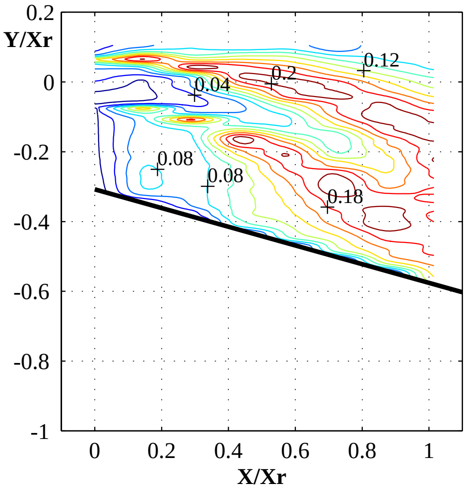
(b) β = 15°



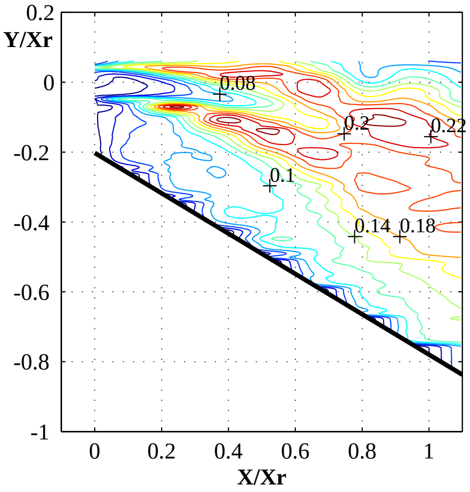
(c) β = 30°
Fig. 7 Contours of V/U_o.



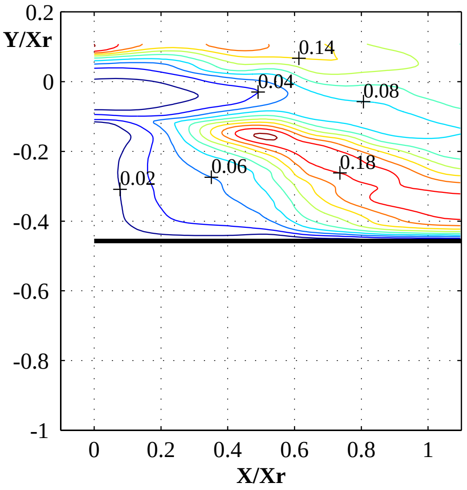
(a) β = 0°



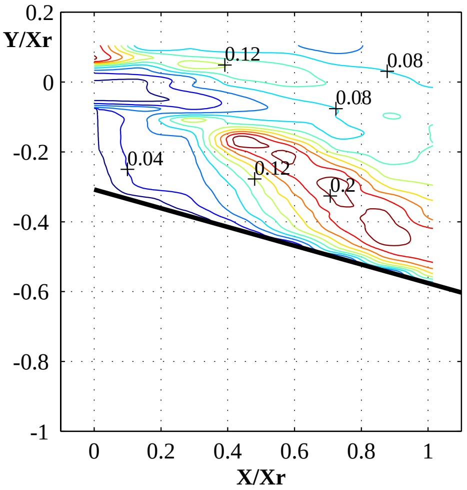
(b) β = 15°



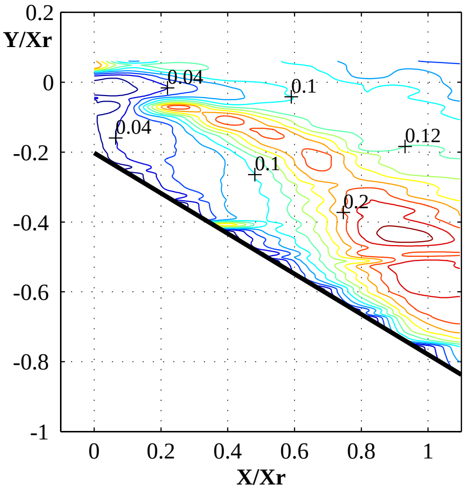
(c) β = 30°
Fig. 8 Contours of u'/U_o.



(a) β = 0°

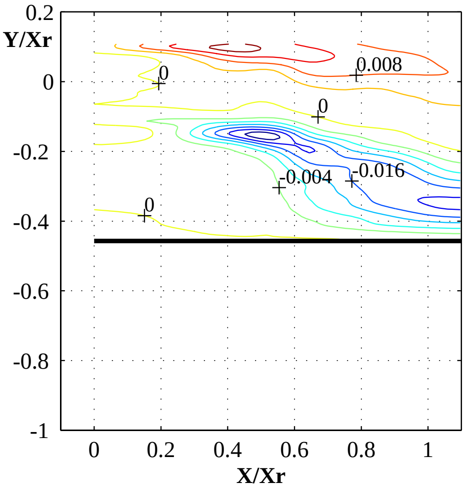


(b) β = 15°

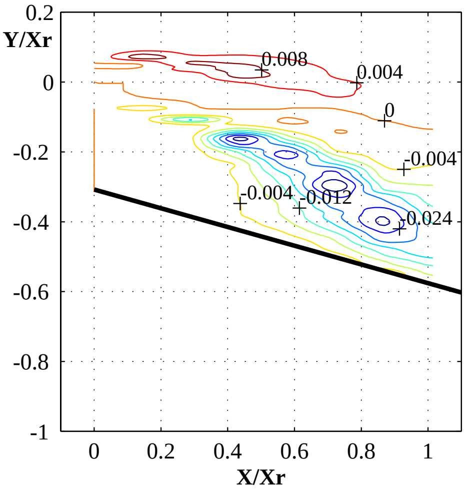


(c) β = 30°

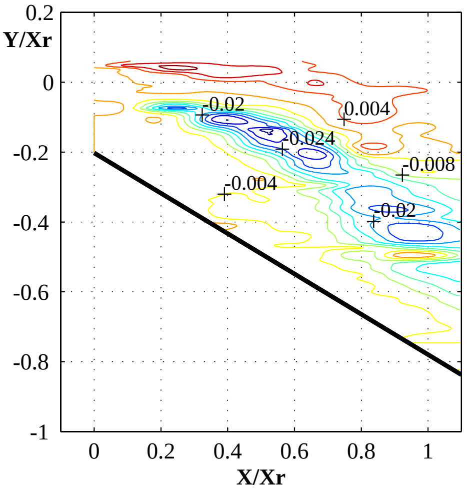
Fig. 9 Contours of v'/U_o.



(a) β = 0°



(b) β = 15°



(c) β = 30°

Fig. 10 Contours of $-\overline{uv}/U_o^2$.

3.2 Turbulence Field

The spatial development of the streamwise and lateral turbulence intensities (u'/U_o and v'/U_o) in the X and Y directions is displayed as contours in Figs. 8 and 9 respectively. For all three jet configurations, the inner and outer shear layers of the jet are clearly identified by the contour maxima in u' and v'. The magnitudes of the streamwise and lateral turbulence intensities in the inner and outer shear layers are comparable for all three cases, although they would be higher for β = 30° than for β = 0° if the local mean streamwise velocity is used as the length scale instead of the jet exit velocity U_o to normalize u' and v'.

The spatial development of the Reynolds shear stress $-\overline{uv}/U_o^2$ is displayed as contours in Figs. 10(a)-(c) for β = 0°, 15° and 30° respectively. Similar to the streamwise and lateral turbulence intensities shown in Figs. 8 and (9), the inner and outer shear layers can be identified by the contour maxima in $-\overline{uv}/U_o^2$. As the jet curves towards the wall, large negative values of $-\overline{uv}/U_o^2$ can be identified near the wall, characterising the momentum transfer between the inner shear layer and the recirculating flow region. The Reynolds shear stress reaches a maximum value in the vicinity of the reattachment point, indicating high momentum transfer due to the jet impinging on the wall.

4 CONCLUSIONS

LDA measurements of the velocity field of a plane offset jet with a small offset ratio of 2.125 and various wall inclination angles (β) have been presented. The maximum mean streamwise velocity of the reversed flow was found to be 0.27, 0.26 and 0.23U_o for β = 0°, 15° and 30° wall inclination angles respectively. Compared to the non-inclined jet (β = 0°), the spatial location of the standing vortex was found to be farther from the nozzle exit and from the offset wall as the inclined wall angle increases. The size of the recirculation flow region increases and becomes more elongated as β increases from 0° to 30°. When compared with the 0° offset jet, the reattachment length measured along the plate is 51% and 160% longer for β = 15° and 30° repsectively. This increase in size of the recirculating flow region is far in excess of that to be expected from the consideration of the primary geometrical parameter, β. Mean streamwise and lateral velocity results indicate that the maximum velocity decays faster with streamwise distance when nondimensionalised by the reattachment length. While the mean turbulence intensities and Reynolds shear stress are similar in magnitude for all three jets when these parameters are nondimensionalised using the nozzle exit velocity as the length scale, they would be significantly higher for β = 30° than for β = 0° if the local maximum streamwise velocity is used as the length scale.

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