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FLOW CHARACTERISTICS OF INCLINED ELLIPTIC NOZZLES

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ABSTRACT

A flow visualization and digital particle image velocimetry study has been carried out to investigate the resultant flow behaviour of elliptic nozzles with 30° and 60° inclined exits along the major- and minor-planes. Flow images show that regardless of incline-plane, persistently inclined vortex roll-ups are produced for 30° incline case, whereas they undergo rapid turning for the 60° incline case. Axis-switching behaviour is either distorted or suppressed in all inclined nozzles tested. Systematic differences in the vorticity distributions and magnitudes suggest that imposing inclined exits leads to dissimilar vortex-stretching, the extent of which depends on the exact nozzle configuration. Lastly, Reynolds flow stress results indicate that the resultant mixing characteristics are strongly affected by the inclined nozzle designs.

INTRODUCTION

Geometrical alterations to circular jets have been studied previously to explore techniques which may potentially aid jet-mixing and control enhancements. Investigations carried on noncircular jets have demonstrated favourable mixing behaviour in these jets resulting from the presence of the axis-switching phenomenon. Of particular interest here is the elliptic jet as it possesses smooth variation of the circumference without any sharp corners, which makes it ideal to bridge between circular and noncircular jet behaviour. Previously studies by Husain and Hussain (1983), Gutmark and Ho (1986), Ho and Gutmark (1987) and Hussain and Husain (1989) have shown persistent axis-switching to occur in elliptic jets, and found that associated jet entrainment and mixing characteristics are higher compared to circular jets. Their investigations also revealed the sensitivity of elliptic jet flow behaviour with respect to the exact nature of the initial momentum thickness, jet aspect ratio, and the presence of forcing, amongst several other flow conditions.

In addition to modifying the azimuthal geometry of the nozzles, investigations have also been performed on nozzle geometries which possessed variations in their axial extent. For example, Wlezien and Kibens (1986, 1988) observed energy redistributions within jet shear layers in circular nozzles with inclined and stepped exits. They attributed these observations to the non-uniform formation of inclined ring vortices along the jet shear layer, where they initiate along the shorter nozzle length and propagate along the jet shear layer circumferentially towards the longer nozzle length. Webster and Longmire (1997, 1998) investigated the effects of incline-angle and forcing frequency on jets and vortex-rings issuing from inclined circular nozzles. Results showed that under low forcing frequency, the resulting inclined ring-vortices move towards the shorter nozzle length regions. Similar observations were also made using discrete vortex-rings. Furthermore, large incline-angles impede successful pairing of the ring-vortices by causing them to break down shortly after they are formed. The breaking down of the ring-vortices was later clarified by Lim (1998) when the study concluded that circumferential flows along the vortex filaments cause the vortex-rings to bulge or break down, depending on the exact vortex-ring Reynolds number, incline-angle and stroke length used.

On the other hand, while inclined circular nozzles are relatively well studied, investigations on noncircular nozzles with inclined exits remain limited. Axis-switching behaviour is an important component of the mixing mechanisms associated with elliptic jets and it will be interesting to study how the use of inclined nozzle exits will affect that and other associated jet flow behaviour. Hence, an experimental study was performed using flow visualization and digital particle image velocimetry (DPIV) techniques to understand the fundamental flow characteristics associated with inclined elliptic nozzles and to shed some light on the use of inclined noncircular nozzles in general.

EXPERIMENTAL SETUP AND PROCEDURES

The study was carried out using a recirculating water tank with internal dimensions of the water tank measuring 400mm (W) x 400mm (H) x 800mm (L). Water was channelled from a small reservoir into the jet apparatus using a centrifugal pump and a Blue-White Industries Ltd F-400 rotameter was used to meter the flow rate. The

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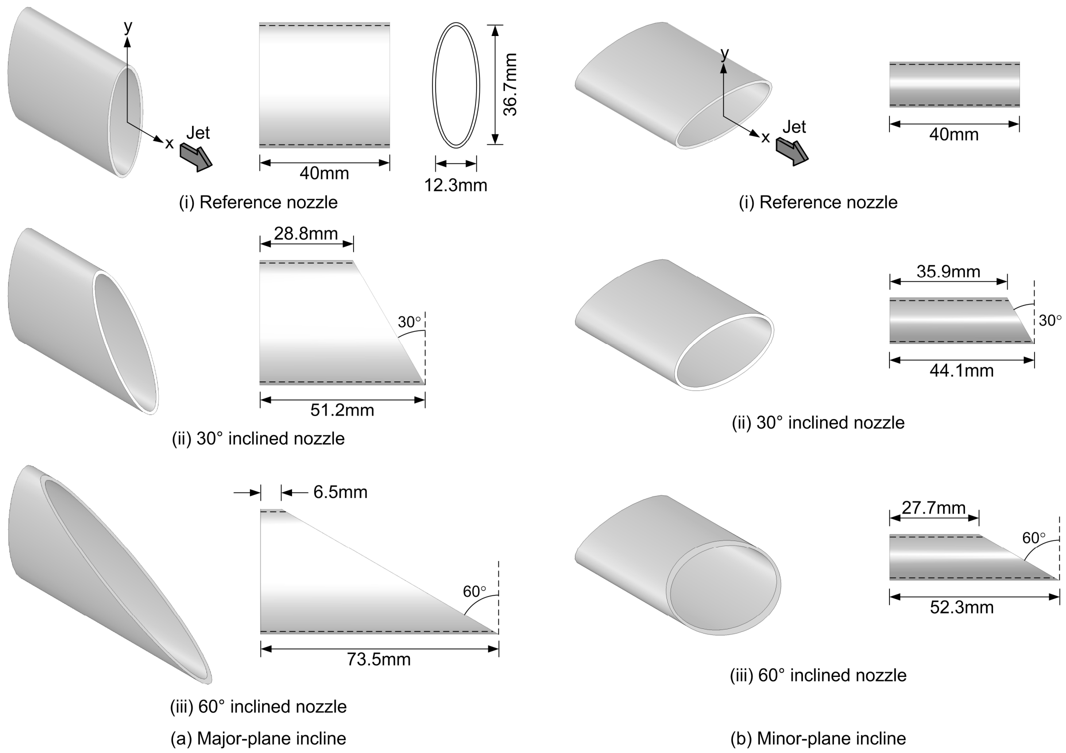

Fig. 1 Inclined elliptic nozzle designs used in the present study, which consist of inclines along the (a) major-plane and (b) minor-plane.

rotameter was calibrated against an electromagnetic flow meter prior to the study. As water passed through the jet apparatus, it would encounter a diffuser, honeycombs, three layers of fine screens and a circular-to-elliptic contraction chamber before exhausting into the water tank via the test nozzles. To capture water overflow, two outlets at the end of the water tank channelled excess water back into the small reservoir via PVC pipes. Aspect-ratio of three elliptic nozzles with major and minor diameters of D_{major}=36.7mm and D_{minor}=12.3mm respectively were used in the present study. The resultant hydraulic diameter was D_h=16.4mm. One nozzle was non-inclined while the other four nozzles were designed with 30° and 60° inclined exits along their major- and minor-planes, as shown in Fig. 1. For the sake of consistency, all nozzles were designed to have a common mean height of H=40mm, where their origins were located as well. Nozzle wall thicknesses were kept at 1mm.

Jet flow velocity was maintained at U=0.15m/s with a corresponding Reynolds number of $Re=UD_h/\nu=2500$, based on the nozzle hydraulic diameter. Additionally, the jet flows were subjected to in-line forcing at Strouhal number, $St=fD_h/U=0.5$ to ensure formation of shear layer instabilities along the entire nozzle exit contours, as well as to organize the large-scale vortex motions. The forcing was carried out via a piston driven by an electromagnetic actuator and a function generator. It was implemented such that it was just sufficient to produce distinct shear layer instabilities and the forcing amplitude was estimated to be 2% of the mean jet flow velocity. Flow visualization was carried out by releasing coloured-dye circumferentially into the jet shear layers. Coloured-dye was fed into a cylindrical port designed within the jet apparatus using gravity-feed technique. Thereafter, coloured-dye was carefully released from a 1mm circumferential slit designed into the cylindrical port. The visualized flow fields were illuminated by halogen floodlight and captured using a 3CCD colour video camera. Recorded videos were then transferred to a workstation for subsequent image-grabbing and analysis.

A Dantec 2D DC-PIV system was used for DPIV measurements in the present study. It consisted of a New-Wave Research 50mJ double-pulsed Nd:YAG laser and a 1600px by 1200px FlowSense CCD camera, controlled by Dantec FlowManager on a workstation with time-synchronization and image-acquisition cards. Before commencing the experiments, 50micron polyamid seeding particles were used to seed the water. To ensure good particle distribution, the seeded water was recirculated through the flow circuit for 15mins before the actual measurements. Scattered light from the particles was captured by the CCD camera with a 60mm f2.8 lens in double-frame mode and time interval between images in each image-pair was kept at 2ms. The DPIV system was operating at the maximum 15Hz operating frequency of the PIV system for sequential measurements, as well as under triggered mode for phase-averaged measurements. 500 image-pairs were taken under each operating mode. To analyze the captured image-pairs, a two-pass multigrid cross-correlation scheme was used. The initial and final interrogation windows were 128px by 128px and 32px and 32px respectively, and the overlap was 50% in both directions. To validate the raw velocity vector maps, peak and moving-average validation schemes were used, before a 3-by-3 neighbourhood moving-average smoothing filter was used to arrive at the final velocity vectors.

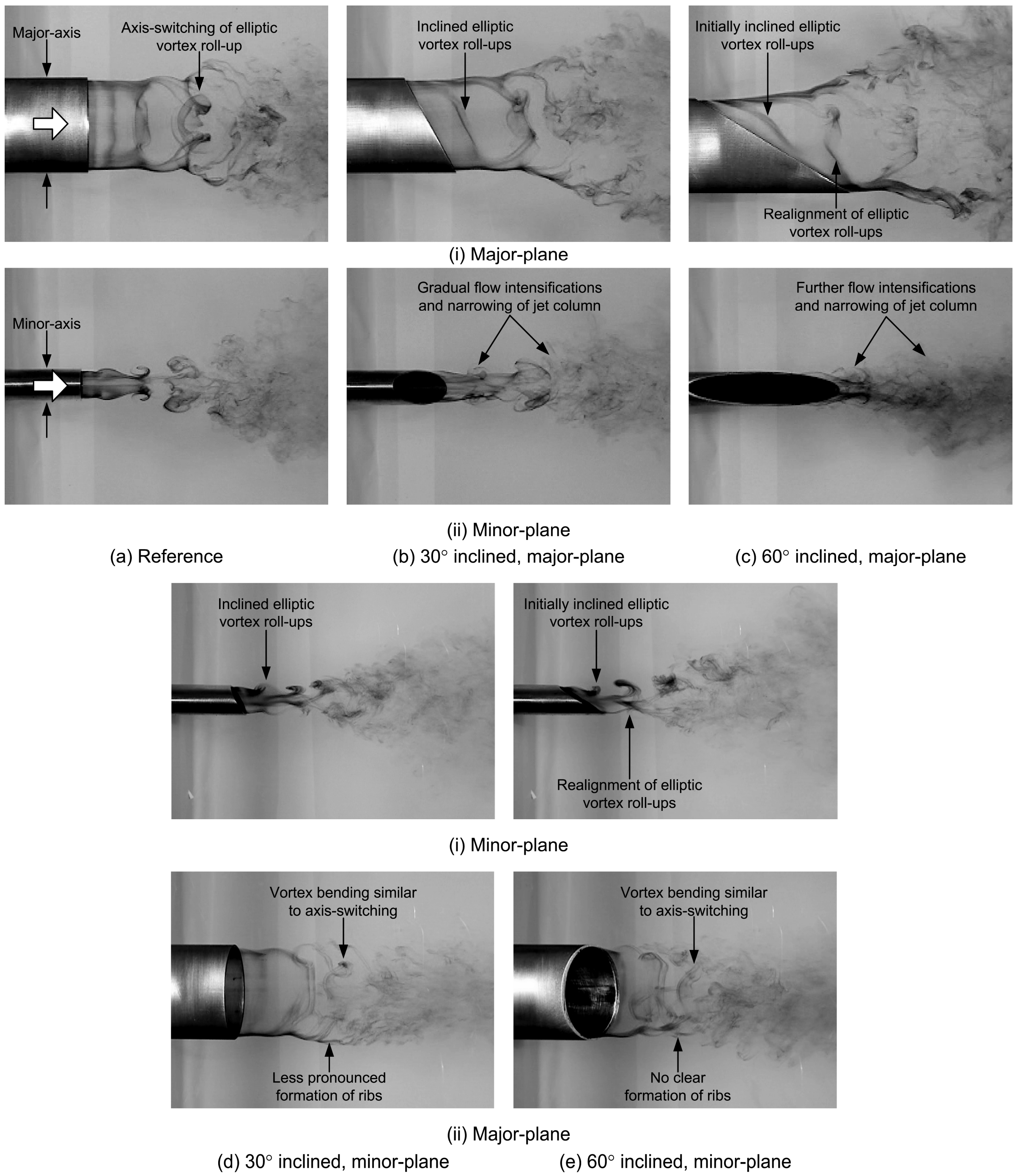

Fig. 2 Instantaneous flow visualization images for all inclined elliptic nozzles tested in the present study.

RESULTS AND DISCUSSIONS

Flow visualization

Instantaneous flow images for all test nozzles along their major- and minor-planes are shown in Fig. 2. For the reference nozzle, the presence of axis-switching behaviour can be clearly discerned. Jet shear layer instability formed under forcing rolls up along the minor-plane initially before it propagates along the instability circumference towards the major-plane. As the elliptic vortex roll-up convects away from the nozzle exit, it bends towards the downstream and upstream directions along the major- and minor-planes respectively and leads to a corresponding reduction and increase in the cross-stream extents of the vortex roll-up. At some stage of the flow, the cross-stream extent along the minor-plane exceeds that along the major-plane and thus results in the switching of the original major- and minor axes of the jet. Lastly, rib structures similar to those observed by Hussain and Husain (1989) are also formed along the major-plane as the vortex roll-up bends towards the downstream direction.

On the other hand, imposing inclined exits on elliptic nozzles along either the major- or minor-plane can be seen to distort the underlying vortex dynamics and associated axis-switching behaviour. For exits inclined along the major-plane, shear layer instabilities formed under forcing can be seen to be initially parallel to the inclined nozzle exits. While the vortex roll-ups for the 30° inclined nozzle proceed to undergo visibly distorted bending reminiscent of axis-switching previously observed in the reference nozzle case, those produced by the 60° inclined nozzle turn rapidly such that they become perpendicular to the jet flow. The turning of the vortex roll-up initiates along the vortex roll-up section nearer to the shorter nozzle length, where it accelerates downstream even before the entire vortex roll-up is fully formed circumferentially. Rib structures remain detectable in these two nozzles, although they appear to spread further laterally. It is worth noting that axis-switching is absent in this nozzle with the vortex dynamics more complex than those of the reference and 30° inclined nozzles. In view of this, it is not surprising that the views along minor-planes show significant flow intensifications as the incline-angle increases. However, rapid diffusion of the coloured-dye due to flow intensifications prevents any further meaningful analysis. Nonetheless, these observations are in good agreement with the study by Wlezien and Kibens (1986), despite the different nozzle geometry used in their investigation.

As for inclined exits imposed along the minor-plane, the resulting flow fields are relatively similar to those associated with inclined exits along the major-plane using the same incline-angle. For instance, inclined vortex roll-ups are initially formed parallel to the nozzle exits at the early stages of the flows. However, those produced by the 30° inclined nozzle remain inclined as they convect downstream, while those produced by the 60° inclined nozzle experienced rapid turning. However, it is difficult to discern from the flow image in this case whether the turned vortex roll-up is perpendicular to the jet flow due to the rapid diffusion of the coloured-dye. Interestingly, the flow images along the major-plane for these nozzles reveal increased flow unsteadiness with observable vortex bending, though it is not clear at this point whether it is associated with typical axis-switching behaviour. Furthermore, the formation of rib structures also shows persistent reductions in intensity when the incline-angle increases. In general, the above results show that the main flow features and effects of imposing inclined exits along the major- and minor-planes share some similarities. In particular, the increasingly distortive effects on the axis-switching behaviour due to the use of progressively larger incline-angle can be clearly discerned.

DPIV measurements

Phase-averaged vorticity maps taken for all the test nozzles along the major- and minor-planes are shown in Fig. 3. The behaviour of the large-scale concentrated vortices agrees well with the vortex roll-up behaviour observed in the flow images earlier. Regardless of incline-plane used, as the incline-angle increases from 0° (i.e. reference nozzle) to 30°, the formation of the vortex roll-ups becomes inclined and remain approximately parallel to the inclined nozzle exit. This can be seen in the downstream shift of the vortex roll-ups along the longer nozzle length (i.e. A', B' and C'), as compared to those along the shorter nozzle length (i.e. A, B and C). When the incline-angle increases to 60°, the turning of the vortex roll-ups and faster development of the vortex roll-ups along the shorter nozzle lengths can be clearly detected. On the other hand, vorticity maps along planes orthogonal to the incline-planes do not exhibit significant flow structural changes. They remain relatively symmetric about the jet centerline with no significant changes to the streamwise locations of the vortex roll-ups.

Maximum vorticity levels associated with the vortex structures however, reveal discernible variations with changes in the incline-angle. For exits inclined along the major-plane, it can be observed that along both major- and minor-planes, maximum vorticity levels along both shorter and longer nozzle lengths decrease gradually as the incline-angle increases. It is worthwhile to note that the maximum vorticity levels along the minor-planes are consistently higher than those along corresponding major-planes which indicate relatively thinner momentum thickness than that along the major-plane, which in turn are related to earlier initiation of vortex roll-up formation. Hence, flow images shown earlier are in good agreement with the flow measurements, as they indicate earlier rolling-up of the jet shear layer along the minor-planes. Lastly, it can also be observed that the overall discrepancy between the maximum vorticity levels between the minor- and major-planes reduces as the incline-angle increases.

As for exits inclined along the minor-planes, the maximum vorticity levels along the shorter nozzle lengths remain relatively invariant. However, those associated with the longer nozzle lengths increases significantly with increase in the incline-angle, which suggests increased vortex-stretching. On the other hand, maximum vorticity levels along the major-planes increases with increment in incline-angle. While this observation suggests that axis-switching behaviour remains in these nozzles, it exact nature of the flow field cannot be ascertained at this stage. Lastly, similar to exits inclined along the major-plane, the difference in the maximum vorticity levels reduces with increase in incline-angle.

To evaluate the long-term mixing characteristics, time-averaged normalized Reynolds flow stress distributions (i.e. $\overline{u'v'}/U^2$) are shown in Fig. 4. For the reference nozzle, the flow stress distribution is clearly dominated by the presence of axis-switching behaviour where higher flow stress levels are concentrated in regions where the vortex roll-ups are in the intermediate stages of vortex-bending. When inclined nozzles are used (regardless of whether the exits are inclined along the major- or minor-planes), the flow stress distributions become increasingly asymmetric when taken along the incline-plane. When the exits are inclined along the major-plane, the maximum stress levels along both shorter and longer nozzle lengths decrease as the incline-angle increases. Similar trend can be observed along the minor-planes for these nozzles, though the reductions are much smaller. On the other hand, when the exits are inclined along the minor-planes, maximum stress levels

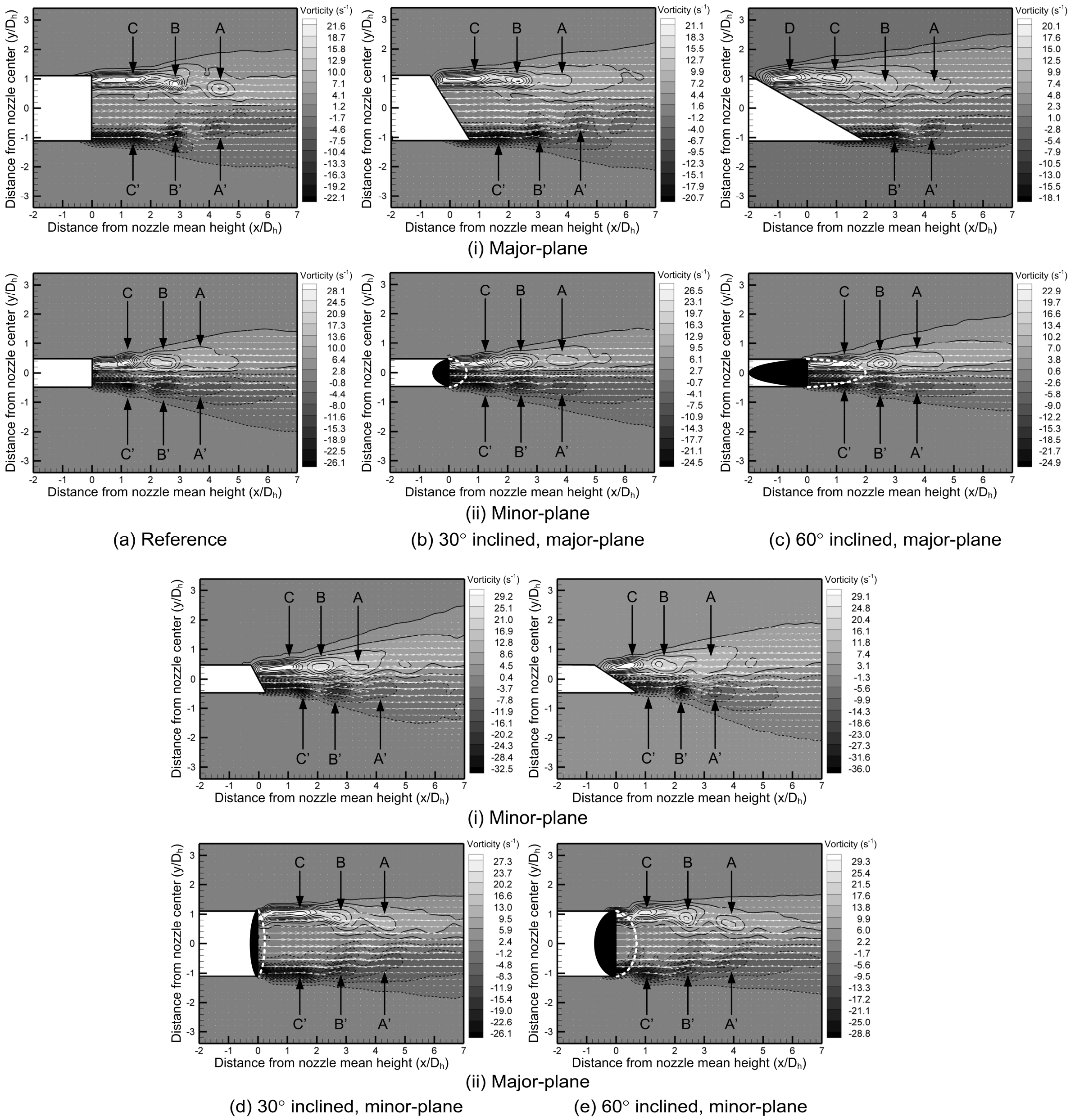

Fig. 3 Time-averaged vorticity field distributions for all inclined elliptic nozzles tested in the present study.

increase and decrease along the shorter and longer nozzle lengths respectively, when the incline-angle increases. Lastly, maximum stress levels along the major-planes of these nozzles are reduced with an increase in the incline-angle, which is similar to corresponding cases when the exits are inclined along the major-plane.

CONCLUSIONS

An experimental study has been carried out on the use of 30° and 60° inclined exits on AR=3 elliptic nozzles along the major- and minor-planes. Results show that regardless of the exact incline-plane, inclined vortex roll-ups are formed parallel to the exit contour. At 30° incline, the inclined vortex roll-ups remain approximately parallel to the inclined exits as they convect downstream. In contrast, the use of 60° incline produces significantly inclined vortex roll-ups which turning rapidly to align themselves perpendicular to the jet flow. The effects of such flow behaviour are shown to produce significant differences in the distributions of the vorticity field and Reynolds flow stress determined using PIV technique. Preliminary analysis here suggests that imposing inclined exits leads to different rates of vortex-stretching, the extent of which depends on the exact nozzle configuration, and in turn affects the overall mixing characteristics of the inclined jets.

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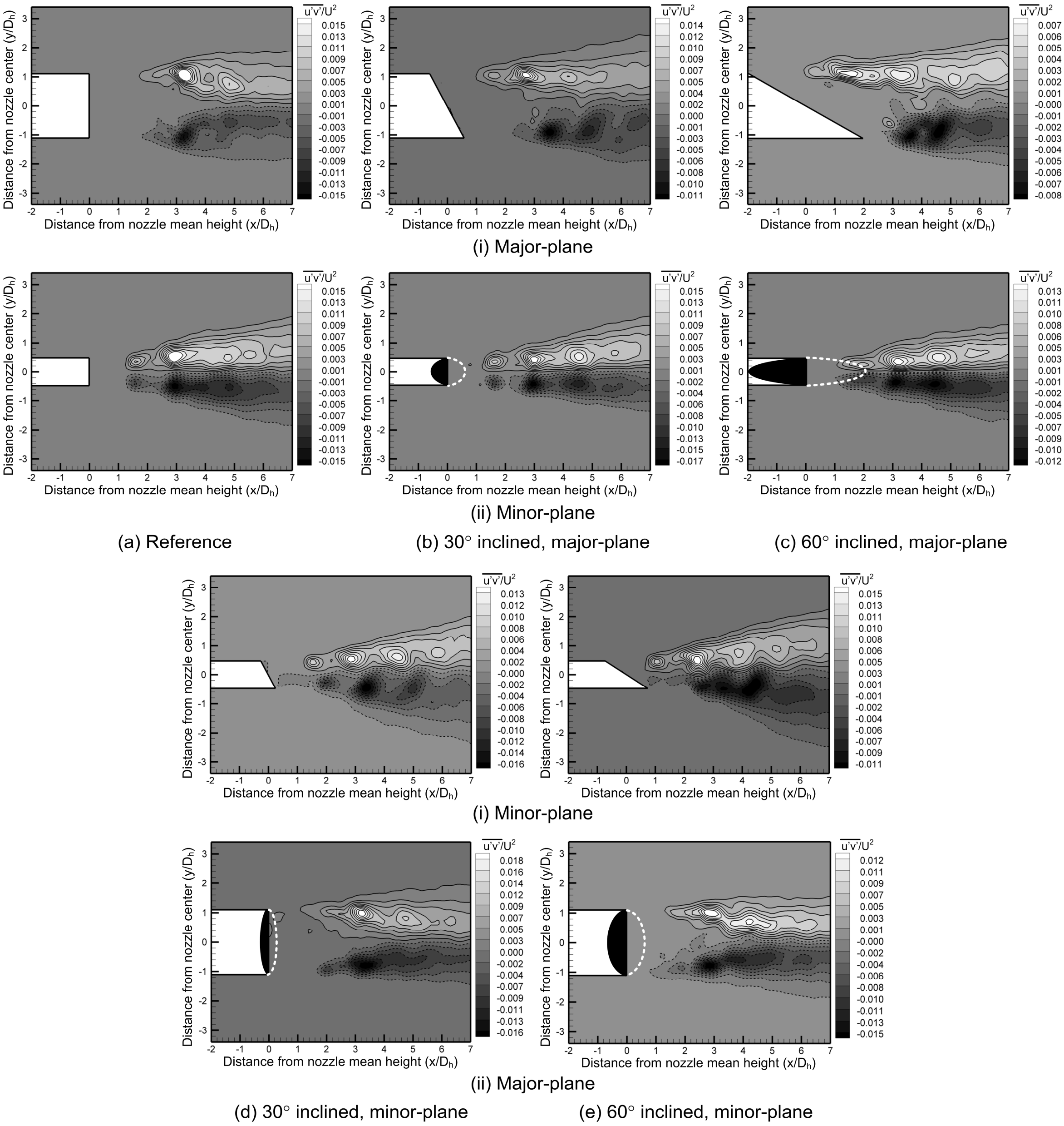

Fig. 4 Time-averaged Reynolds flow stress distributions for all inclined elliptic nozzles tested in the present study.

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