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NEAR FIELD VORTEX STRUCTURES OF INCLINED COAXIAL JETS

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ABSTRACT

Inclined coaxial nozzles of 45° and 60° incline-angles, with area-ratio of 2.25 and velocity-ratios of 0.5 and 1, have been studied using flow visualisations to reveal the near-field vortex flow features. Streamwise and cross-stream cross-sections taken of the coaxial jets using laser-induced fluorescence technique show that unlike the case for an axisymmetric coaxial nozzle, inclined coaxial nozzles typically produce asymmetric flow fields along the inclined plane. A significant range of different flow behaviour can be observed, depending on the exact geometric and flow conditions, which will be described here. In general however, increasing either the incline-angle or velocity-ratio leads to considerable intensifications of the near-field vortex formations.

INTRODUCTION

Over the past decades, significant research efforts have been expended on the study of coaxial jets to understand the resultant vortex flow structures, in particular those in the immediate near field. In contrast to conventional single nozzle jets, coaxial jets consist of two concentrically-arranged jets exhausting together. They have strong relevance to applications where good mixing between two fluid streams are required, for instance in chemical mixing processes, combustion engines and reduction of jet noise, to name a few.

Earlier studies on coaxial jets have shown that the relative velocity-ratio of the primary main jet and secondary annular jet significantly affects their near-field flow developments. Kwan and Ko (1976, 1977) carried out a study focusing on the near-field region of a coaxial jet and they suggested that its near field behaviour can be treated similarly to a super-positioning of two single-stream jets. Their research identified three different jet flow regimes and their flow developments were analysed in detail. Research done in more recent years has proven coaxial jet flows to be more complicated than was suggested by Kwan and Ko (1976). For instance, Dahm et al. (1992) presented a detailed analysis on the near-field behaviour of a circular coaxial jet, using two-colour laser-induced fluorescence technique to identify the near-field vortex patterns and associated dynamics by varying the velocity-ratio. In addition to the velocity jump, it was observed that the jet shear layer thicknesses and the wake defect within each jet shear layer are influential towards the near-field vortex structure formation. The study also revealed a “locking” effect between the two jet shear layers, where hydrodynamic instability, vortex sheet roll-up and vortical interactions do not proceed independently for each individual jet stream.

In another study carried out by Villermaux et al. (1997), experimental evidence pointed towards the existence of two flow regimes, based on a critical velocity-ratio, above which a recirculation bubble appears and plays a significant role in the subsequent jet development. Numerical studies have also been conducted by Balarac and Metais (2005), where they carried out direct numerical simulations to investigate the influence of velocity-ratio and momentum thickness variation on coaxial jet behaviour. Similar to previous studies, their findings revealed the importance of the momentum thickness of the jet shear layers as well as the presence of the recirculation bubble upon the resultant jet flow phenomenon.

On the other hand, single-stream jets issuing from inclined nozzles have been observed to lead to redistribution of shear layer energy and enhanced mixing at specified azimuthal locations, as shown previously by Wlezien and Kibens (1986) and Webster and Longmire (1997). Furthermore, evidences gathered from flow visualization and velocity measurements by Wlezien and Kibens (1986) showed that the degree of control over jet-mixing depends not only on the nozzle geometry, but also on the ratio of jet shear layer instability wavelength to the nozzle physical scale. Their results showed that under both laminar and turbulent conditions, inclined nozzles impose azimuthal self-excitations by shear layer instabilities which propagate circumferentially. They concluded that the flow instabilities tend to produce increasingly larger-scale structures, which clearly play significant roles in the entrainment behaviour of the coaxial jet flows, and that behaviour is determined by the distance from the local separation point, regardless of the nozzle geometry. Webster and Longmire (1997) observed that single-stream inclined nozzles produce inclined vortex rings, rolling up at angles slightly smaller

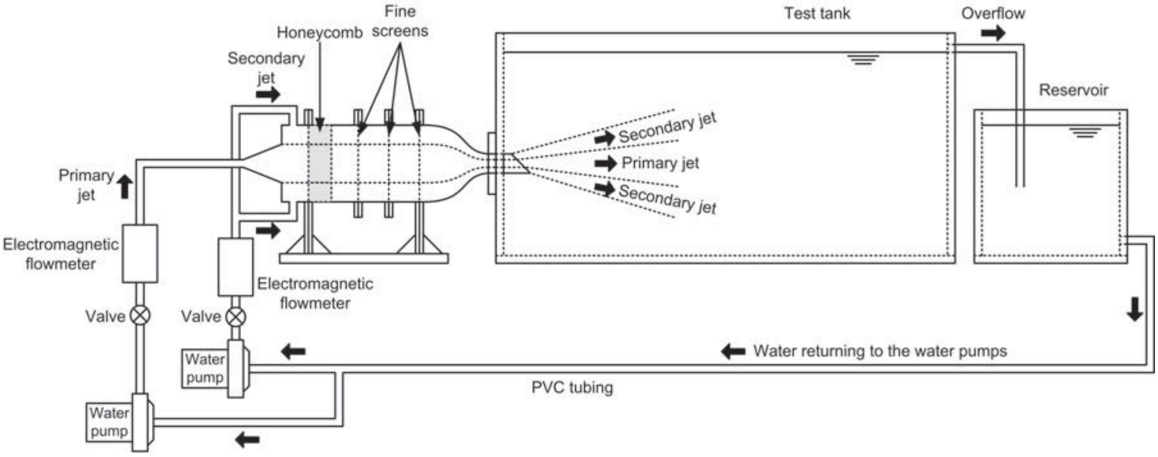
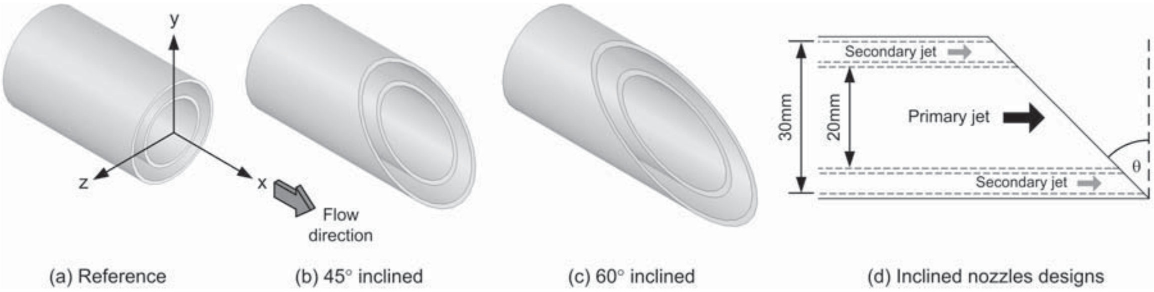


Fig.1 Schematics of the water tank, jet apparatus and equipment



(a) Reference (b) 45° inclined (c) 60° inclined (d) Inclined nozzles designs

Fig.2 Reference and inclined coaxial nozzles used in the present study

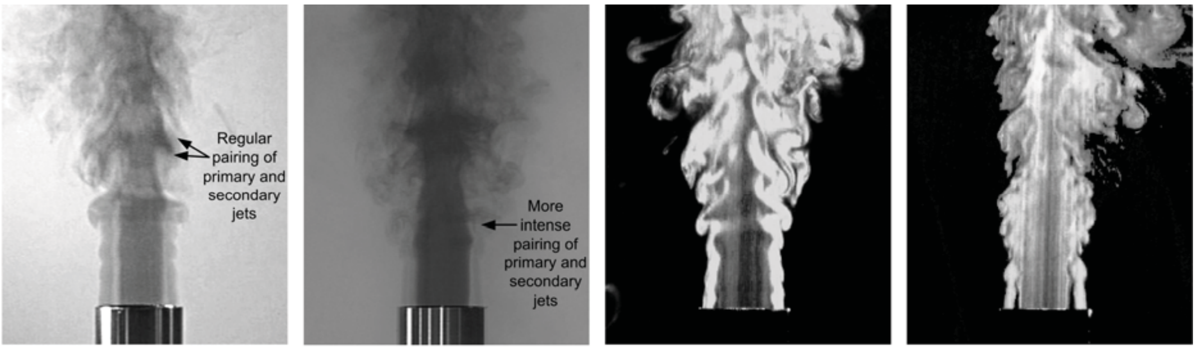
than the nozzle incline angle, which increased with downstream distance. Increase of the inclination angle resulted in dislocation of the pairing, moving closer to the nozzle lip. It was also observed that for nozzles with larger incline angles the vortex core broke down before pairing could occur.

EXPERIMENTAL PROCEDURES

The experiments were conducted using a recirculating rectangular Plexiglas water tank setup with internal dimensions of 50cm (W) x 50 cm (H) x 150cm (L), as shown in Fig. 1. The coaxial jet apparatus consisted of two separate but concentric contoured sections with the primary jet located within the secondary jet. Both primary and secondary jet sections have honeycombs in place to straighten the flow and fine screens to reduce the turbulence levels before exhausting into the water tank. Two centrifugal pumps were used to provide the water for the two jets. The flow rate of each jet was controlled by needle valves and metered by an electromagnetic flow meter. Excess water from the exhausting of jet fluid into the water tank was redirected to a reservoir where it would be channelled to the water pumps for recirculation.

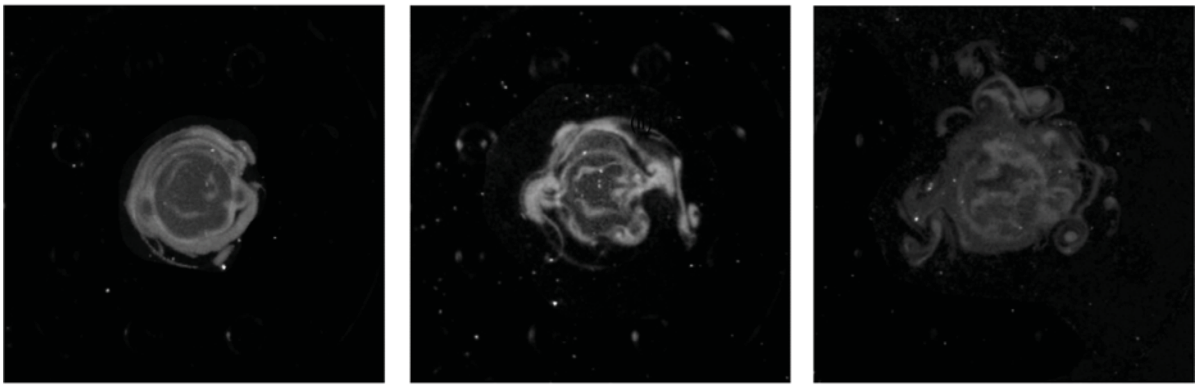
Inclined coaxial nozzles of 45° and 60° incline-angles, as well as reference circular coaxial nozzles were used for this study. All coaxial nozzles consisted of a primary nozzle with diameter D_1=20mm and a secondary nozzle with diameter D_2=30mm, hence giving an area-ratio (defined as $(D_2/D_1)^2$) of 2.25. To maintain consistency with conventional circular coaxial nozzles, the nozzle lips of the primary and secondary jets for inclined coaxial nozzles were “flushed” with each other along the incline plane, as shown in Fig. 2. The primary and secondary jet nozzle lip-thicknesses were both 1mm which produced an annular gap size of d=4mm. The primary jet velocity was kept constant at u_1=0.14m/s ($Re_1=u_1D_1/\nu=2500$) and the secondary jet velocity was altered to give a velocity ratio of r_u=0.5 ($Re_2=u_2d/\nu=500$) and r_u=1 (Re_2=1000).

Flow-visualisation using gravity-feed dye-injection was carried out by releasing two different coloured-dyes into the primary (red) and secondary (blue) jet streams prior to their entry into their respective jet apparatus sections. Laser-induced fluorescence (LIF) technique was also used to study the resultant flow features, where pre-mixed Rhodamine B and fluorescein disodium fluorescent dyes were injected into the primary and secondary jets respectively via gravity-feed method. A 5W Laser Quantum diode-pumped solid state laser illuminating at 532 nm was used. Beam-steering optics and a rotating mirror were used to produce laser sheets to illuminate the fluorescent dye along the desired visualisation planes. For both visualization techniques, both primary and secondary jet fluids were fully seeded with the dyes prior exhausting into the water tank. A 3CCD Panasonic colour video camera with a 17X TV zoom lens and digital video recorder were then used to capture and record all flow visualisations for subsequent playback analysis on a workstation.



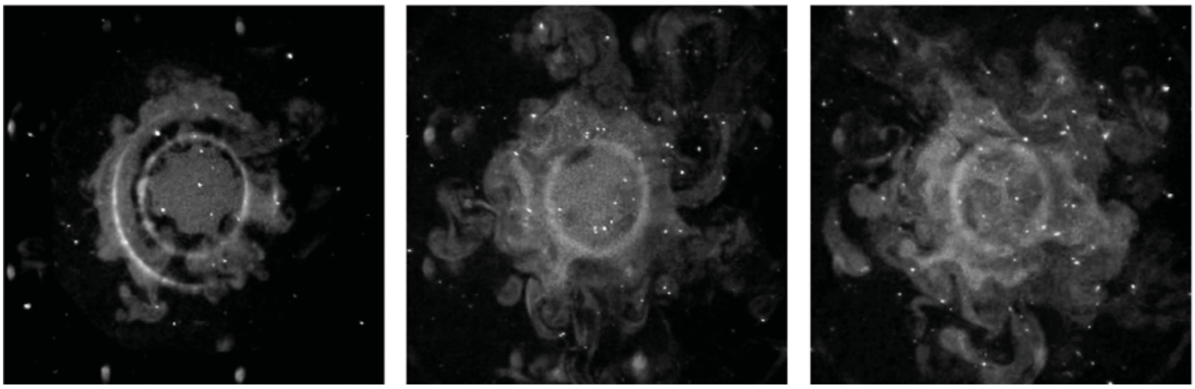
(i) r_u=0.5 (ii) r_u=1 (i) r_u=0.5 (ii) r_u=1

(a) Dye-visualisation images (b) Streamwise LIF images



(i) x/D_1=3 (ii) x/D_1=4 (iii) x/D_1=5

(c) Cross-stream LIF images for r_u=0.5



(i) x/D_1=3 (ii) x/D_1=4 (iii) x/D_1=5

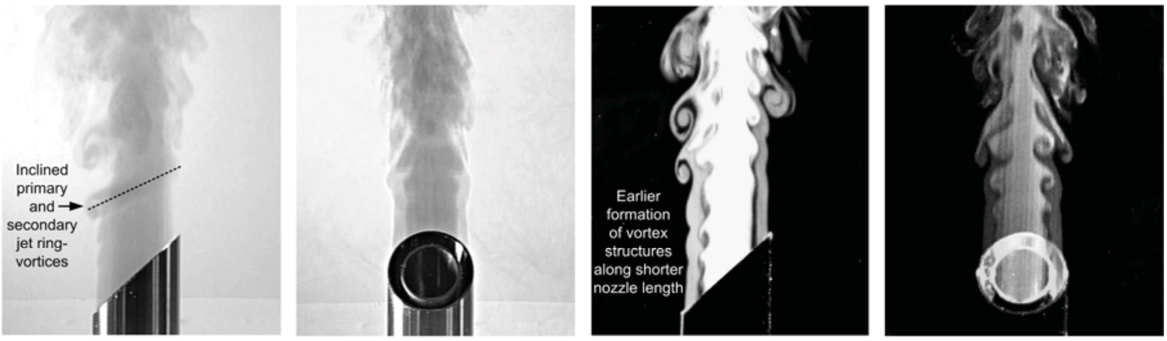
(d) Cross-stream LIF images for r_u=1

Fig.3 Dye-visualization and LIF flow images for the reference circular coaxial nozzles

RESULTS AND DISCUSSIONS

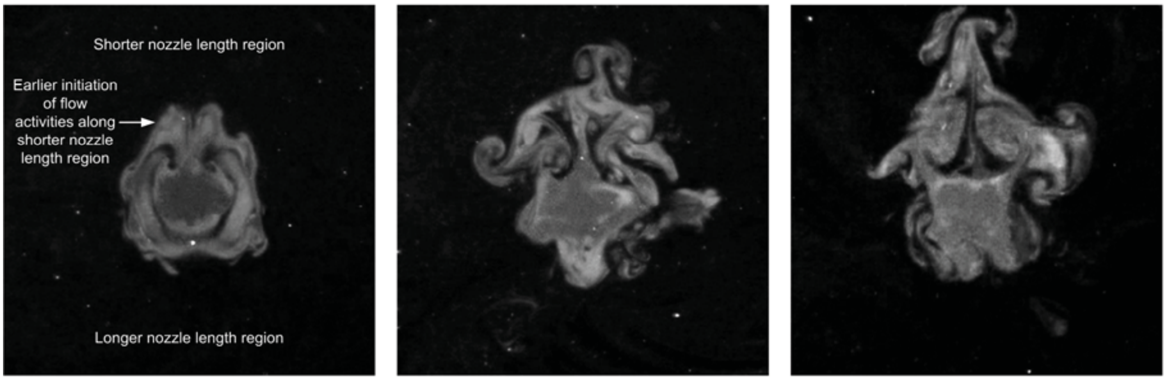
Dye injection flow visualisation results for all three coaxial nozzle configurations taken from the side- and end-views are presented in Fig. 3. On the other hand, Figs. 4 and 5 show instantaneous LIF flow images captured from the side- and end-views in the streamwise direction, as well as in the cross-stream directions at downstream locations of x/D_1=3, 4 and 5. For the reference circular coaxial nozzles, it can be observed that regardless of the velocity-ratio used, the resultant vortex structures forming along the inner and outer shear layers are practically symmetric. As the velocity ratio increases, the formation of shear layer instabilities and vortex roll-ups increase in intensity and frequency along both the inner and outer shear layers.

For 45° inclined coaxial nozzles (Fig. 4), the resultant flow begins to be dominated by the inclined nature of the nozzles. In particular, inclined ring-vortices are formed for both primary and secondary jets, with their incline-angle slightly less than that of the nozzles. Their formation mechanism is similar to that of single-stream jets issuing from inclined nozzles, where vortex roll-ups occur first along the shorter nozzle length before propagating towards the longer nozzle length. Furthermore, they pair up together as they convect towards the downstream direction, regardless of the velocity-ratio. However, as the velocity-



(i) Side-view (ii) End-view (i) Side-view (ii) End-view

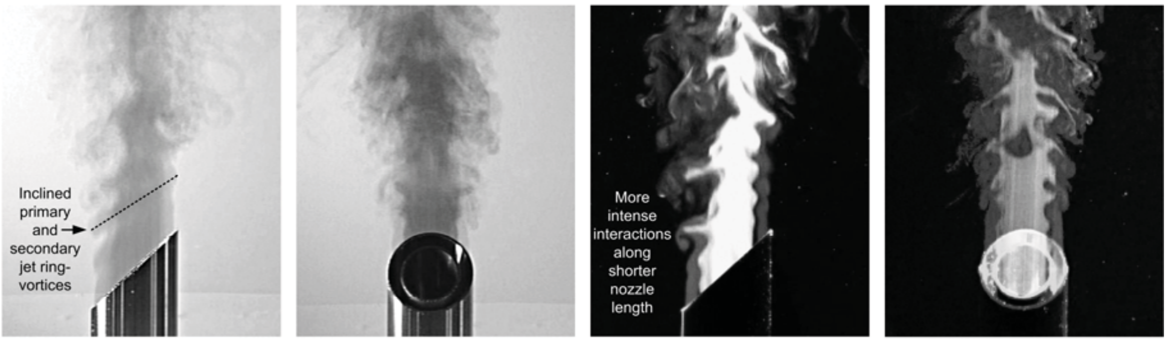
(a) Dye-visualisation images (b) Streamwise LIF images



(i) $x/D_1=3$ (ii) $x/D_1=4$ (iii) $x/D_1=5$

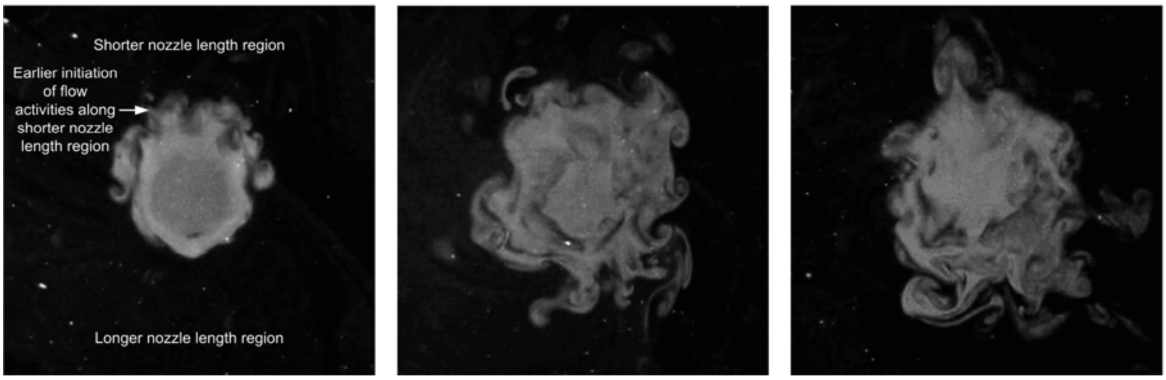
(c) Cross-stream LIF images

Fig.4 Dye-visualization and LIF flow images for the 45° inclined coaxial nozzles at $r_u=0.5$



(i) Side-view (ii) End-view (i) Side-view (ii) End-view

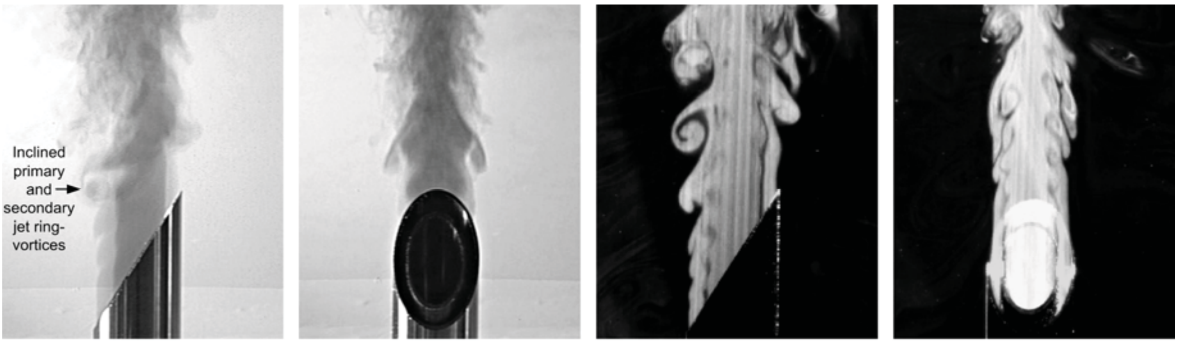
(a) Dye-visualisation images (b) Streamwise LIF images



(i) $x/D_1=3$ (ii) $x/D_1=4$ (iii) $x/D_1=5$

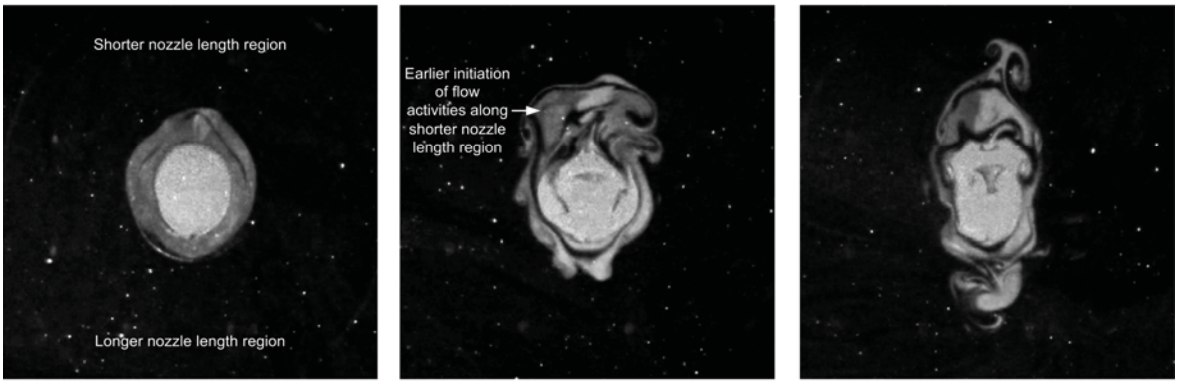
(c) Cross-stream LIF images

Fig.5 Dye-visualization and LIF flow images for the 45° inclined coaxial nozzles at $r_u=1$



(i) Side-view (ii) End-view (i) Side-view (ii) End-view

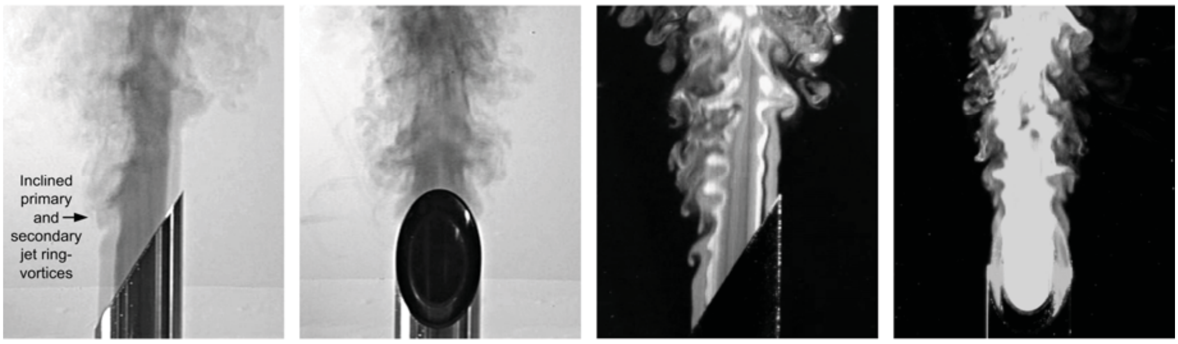
(a) Dye-visualisation images (b) Streamwise LIF images



(i) $x/D_1=3$ (ii) $x/D_1=4$ (iii) $x/D_1=5$

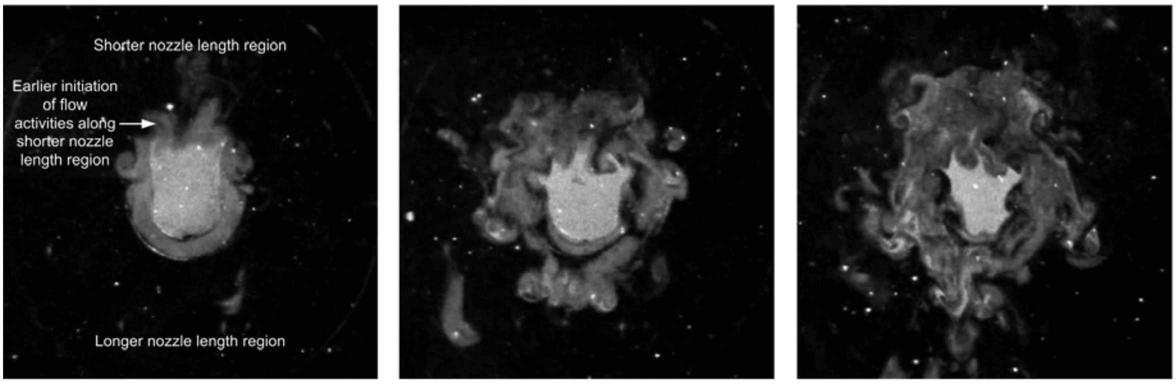
(c) Cross-stream LIF images

Fig.6 Dye-visualization and LIF flow images for the 60° inclined coaxial nozzles at $r_u=0.5$



(i) Side-view (ii) End-view (i) Side-view (ii) End-view

(a) Dye-visualisation images (b) Streamwise LIF images



(i) $x/D_1=3$ (ii) $x/D_1=4$ (iii) $x/D_1=5$

(c) Cross-stream LIF images

Fig.7 Dye-visualization and LIF flow images for the 60° inclined coaxial nozzles at $r_u=1$

ratio increases to r_u=1 (Fig. 5), the flow field can also be seen to intensify significantly and large scale structures are no longer apparent. Vortex pairing along the shorter nozzle length is more intense and the paired vortices penetrate deeper into the primary jet stream. As such, entrainment of the ambient fluid into the resultant jet flow is likely to increase due to the vortex-pairing events along the outer shear layer.

As the incline-angle increases to 60° (Figs. 6 and 7), inclined ring-vortices are similarly observed though it is clear from the images that the flow has intensified further. Their formation along the shorter and longer nozzle lengths is not directly correlated and results suggest that the vortex roll-ups evolve independently along the two nozzle lengths. Vortex-pairing events are prevalent for this nozzle configuration, similar to the case when the incline-angle is 45°. At ru=0.5 (Fig. 6), there is evidence that the inclined ring-vortices undergo realignment as they convect downstream, such that they eventually resemble those observed in the reference circular coaxial nozzles. Further downstream, the ring-vortices appear to take on symmetric forms before transition to turbulence. Increasing the velocity ratio to ru=1 (Fig. 7) will see significant intensifications of vortical formation and subsequent interactions along the shorter nozzle length. In contrast, the flow developments along the longer nozzle length do not change appreciably with the increase in velocity-ratio. While there remain occasional pairings between the primary and secondary jet ring-vortices, the extent is less than the case for the 45° inclined nozzles at similar velocity-ratio.

Cross-stream results taken for the two inclined nozzles agree well with the above flow descriptions. Due to the earlier formation of and interactions between primary and secondary jet ring-vortices along the shorter nozzle lengths, vortical activities are typically initiated near the top of the cross-stream flow images, which are associated with the shorter nozzle lengths. Particularly interesting is the significant deformation of the jet cross-sectional shape at r_u=0.5, regardless of either inclined coaxial nozzles. In contrast, no such observations were made at r_u=1. This reinforces earlier observations made for the realignment of ring-vortices in the 60° inclined nozzles, since the realignment process essentially changes the cross-section outline of the initially inclined jet flow into one which would closely resemble that associated with the reference coaxial nozzles.

CONCLUSIONS

An experimental flow visualisation study has been carried out for inclined and non-inclined coaxial nozzles to investigate the effects of varying the incline-angle and velocity-ratio. Results of the reference non-inclined coaxial nozzles agree well with earlier studies, where vortex formation and pairing behaviour increases with velocity-ratio increment. In the case of inclined coaxial nozzles, vortex formation and pairing events occur significantly earlier along the shorter nozzle length than along the longer nozzle length. As velocity-ratio increases, intensified vortex pairings along the primary and secondary jet shear layers along the shorter nozzle lengths leads to significant higher levels of interactions between the two jet streams as well as entrainment into the coaxial jet flows.

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