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A Visual Study on Elliptical Jets in Cross Flow

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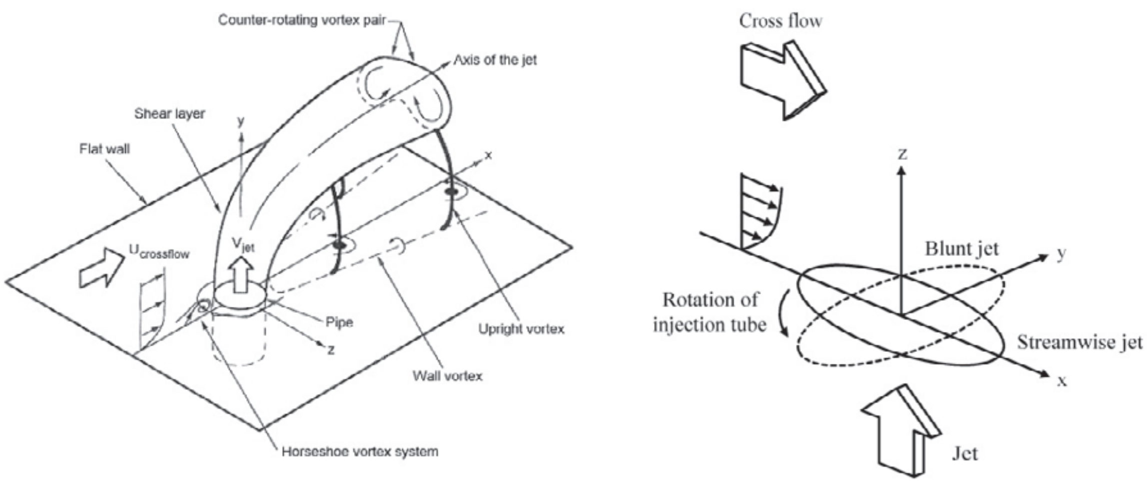
***Abstract*:** Laser-induced fluorescence technique is used to study the near-field of an elliptical jet exiting normally into a cross flow, for elliptic jet having aspect ratio of 2 and 3. Results show that the non-uniform curvature of the elliptic geometry causes the leading-edge vortices at the interface between the jet and the cross flow to behave differently from that of a circular jet. In particular, when the major-axis is aligned with the cross flow there is an intense interaction between the leading-edge vortices which culminates in the pairing of adjacent vortices. The pairing is suppressed when the major axis is perpendicular to the cross flow.

***Keywords*:** flow visualization, elliptical jet, jet in cross flow, laser-induced fluorescence, dye-injection.

1. Introduction

The understanding of the behavior of a jet in cross flow (hereinafter referred to as JICF) is important to applications such as film cooling of turbine blades, combustion process, V/STOL aircraft design, missile control system development as well as the discharge of effluent by chimneys and in waterways. Previous studies have established that a circular JICF produces a host of vortical structures interacting with one another, and the more significant ones are shown schematically in Fig. 1 (a), previously by Kelso et al. (1996).



(a) (b)

Fig. 1. (a) A schematic of large-scale vortical structures usually associated with a circular JICF, and (b) streamwise and blunt elliptical jet configuration.

Although jets of circular geometry have been studied extensively, there is a dearth of information on jets of other geometry in a cross flow environment. Recently, Haven and Kurosaka (1997) conducted a series of experiments to study the effect of jet geometry on film cooling, and one of the cases considered is an elliptical JICF. While they have uncovered certain flow differences between the elliptical and circular jet geometries, their findings are restricted to a maximum velocity ratio (*VR*) of only 2, since they are primarily interested in the situation where the deflected jets stayed close to the cooling surface. However, previous study by Kelso et al. (1996) has shown that too low a velocity ratio may not yield a global view of the jet flowfield, since the resultant flow is more wake-like than jet-like due to the dominance of the cross flow.

Unlike circular jets, non-circular jets usually possess large variation in the momentum thickness of the boundary layer along their jet exit perimeter, often resulting in highly three-dimensional flows even in a simple free-jet configuration. This is especially true for jets with corners such as square and rectangular jets, where resolving the highly complex three-dimensional resultant flow remained a continuing effort. Elliptical jets, however, present the smallest possible momentum thickness variation for a symmetrical non-circular jet exit due to the smooth variation in its perimeter curvature. The lack of sharp corners also meant that three-dimensionalities in the resultant flow is not as severe as in the case for square and rectangular jets. Hence, they can provide an excellent initial understanding on the behavior of non-circular JICF. The desire to obtain a deeper insight into the physics of non-circular JICF motivates us to carry out the present investigation using elliptical geometry. To obtain a more global view of the flow structures, velocity ratio of 1 to 5 are considered.

2. Equipment Setup and Techniques

The experiments were carried out in a recirculating water tunnel in the Fluid Mechanics Laboratory of the National University of Singapore. The test section, which was fabricated out of Plexiglass, measured 0.4 m by 0.4 m in cross-section and 1.83 m in length. A variable speed centrifugal pump was used to drive the water around the tunnel, and before the water entered the test section, it was passed through a honeycomb grid and three layers of fine screens to ensure low turbulence level in the test section. Two elliptical jets of aspect ratios (*AR*) 2 and 3, with the same cross-sectional areas were used, one at a time. The jet nozzles were flush-mounted to the test section floor. Small quantity of water from the water tunnel was constantly being channeled into an overhead water tank to provide the fluid for the jets, the flow rate of which could be accurately controlled by appropriate adjustment of a control valve. All flow rates were measured using electronic volume flowmeters.

For studies on JICF, it is common to employ the parameter known as the momentum ratio which is the ratio of the jet momentum flux to the cross flow momentum flux over the same cross-sectional area. However, when both jet and cross flow fluids are similar in temperature and density, the ratio can be further reduced to one of the jet mean velocity to cross flow mean velocity, known conventionally as the velocity ratio. Furthermore, an elliptical jet can assume many orientations with respect to the cross flow. However, to simplify the present study, only two orientations were considered in this study, namely the streamwise and the blunt orientations. The former is defined as the orientation when the major-axis of the elliptical jet is parallel to the cross flow and the latter is defined as the orientation when the minor-axis of the same jet is parallel to the cross flow. Fig. 1 (b) shows a pictorial representation of the streamwise and blunt configuration with respect to the cross flow. The change in the orientation was accomplished by fabricating the jet apparatus in such a way that the jet nozzles were able to rotate freely and accurately.

Laser-induced fluorescence (LIF) technique was used to obtain cross-sectional views of each elliptical JICF at different velocity ratios and orientations. The velocity ratio was varied from 1 to 5, and typical Reynolds number based on the jet mean velocity and hydraulic diameter ranged from 1000 to 5000. The corresponding Reynolds number based on cross flow velocity was 21500. Flow visualization was recorded using a 3CCD camera in conjunction with a SVHS recorder. Subsequent still images were obtained using an image grabber card in a PC.

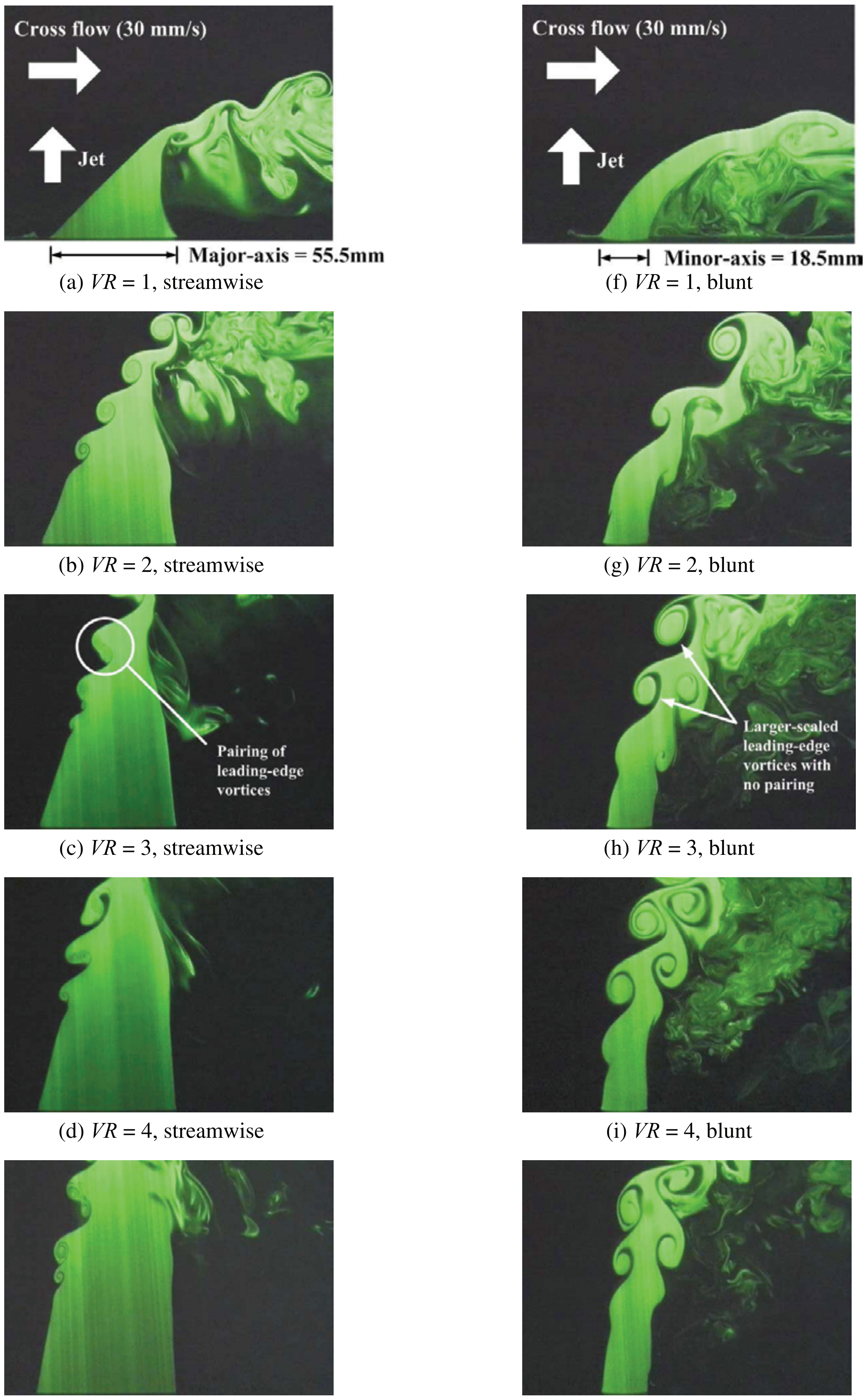
3. Experiment Results and Analysis

In Figs. 2 and 3, LIF flow visualization images for the two elliptical JICF for different velocity ratios and orientations are presented. Note that all the figures are of the same scale. It can be seen from the figures that the resultant flow for elliptical JICF shows a close qualitative resemblance to that of a circular JICF. For example, the jet penetration and hence trajectories increase with increasing velocity ratios and leading-edge vortices are observed to shed regularly along the jet leading-edge region as a result of interaction between the jet and the cross flow. On the other hand, one can also detect significant flow differences in the results between different orientations and velocity ratios, especially in the generation of leading-edge vortices.

Firstly, blunt elliptical jets tend to develop leading-edge vortices which seem to be qualitatively larger than those produced for streamwise elliptical jets throughout the range of velocity ratios studied. While this visual cue implies that blunt elliptical jets may possess a higher local mass entrainment rate than streamwise jets, it may also indicate a higher local vortex stretching on the leading-edge vortices of the streamwise elliptical jets. Due to the geometrical arrangement, a smaller positive pressure region occurs upstream of the streamwise elliptical jet with a corresponding narrower wake region downstream, whereas for the blunt elliptical jet, a larger positive pressure region exists upstream of the jet with a corresponding wider wake region. Therefore, local flow conditions for the streamwise elliptical jets are favourable with regards to vortex stretching.

Secondly, leading-edge vortices produced for all streamwise elliptical jets demonstrate a strong pairing phenomenon at $VR = 3$ and above. However, corresponding leading-edge vortices resultant of blunt elliptical jets show very little or no signs of such pairing. Moreover, it is found that while the $AR = 2$ blunt elliptical jet does produce occasional pairing of the leading-edge vortices, the actual process is not as coherent and regular as the previous jet orientation. Also, the observation that the $AR = 3$ blunt elliptical jet does not produce any pairing of these vortices seems to indicate that the occurrence of the pairing process diminishes with the bluntness of the jet. Unfortunately, Figures 2 and 3 are not able to fully convey the dynamic nature of the pairing process. To explore the three-dimensional aspects of the pairing process, the experiments were repeated using direct injection of neutrally buoyant blue-coloured food dye at the upstream tip of the elliptical jets. Figures 4 and 5 depict the flow visualization images typical of the elliptical jets in both orientations using dye-injection. The images show a more unsteady flowfield for the blunt elliptical jets than the streamwise ones, since there are larger pressure differences between the upstream and downstream regions of the blunt elliptical jets. Other than showing regular pairing and clear entanglement of two consecutive leading-edge vortices, the filaments of leading-edge vortices for streamwise elliptical jets are also clearly observed to extend to the lee-side region before a change in direction was encountered, and the lee-side portions of the filaments entwined with a pair of counter-rotating vortex pair (CVP). Unfortunately for blunt elliptical jets, the coloured-dye seemed to be convected rapidly by the leading-edge vortices and therefore very little dye was convected along the sides of the jets. It appears that the low curvatures of the upstream regions for blunt elliptical jets does not encourage sideway convection of coloured-dye. It is believed that the blunt upstream condition results in much lower side flow velocities than would be in the case of a streamwise upstream condition. Hence, much of the coloured dye will be convected away by the leading-edge vortices.

The authors believe that these observations can be understood through a closely related phenomenon exhibited by free elliptical jets. It has been demonstrated by Hussain and Husain (1989) that free elliptical jets also exhibit similar pairing and entanglement process. They found that the higher self-induced velocities of the elliptical vortex filaments at the ends of the major-axes were higher due to the smaller radii of azimuthal curvature compared to the self-induced velocities at the larger azimuthal curvature at the ends of the minor-axes. The additional cross flow ensured that a minimum velocity ratio has to be reached before the vortex filaments were close enough to interact mutually. However, the pairing is not the kind usually associated with pairing of circular jets, where equal azimuthal curvature of the vortex filament ensures that pairing occurs for the entire vortex filaments. Unlike free elliptical jets where entanglement of the vortex filaments are at least symmetrical at both ends of the major-axes, elliptical JICF only exhibit vortex filament entanglement at the upstream portion of the jet. As to the reason why no similar process occurred at the lee-side region of the streamwise elliptical jets, one has to look at the dye-injection images (see Figs. 4 and 5) which clearly show that the formation of a CVP at the sides of the elliptical jets disrupts and distorts the development of the elliptical vortex filaments, thus preventing pairing of the vortex filaments from taking place at the lee-side region.



(a) *VR* = 1, streamwise (f) *VR* = 1, blunt

(b) *VR* = 2, streamwise (g) *VR* = 2, blunt

(c) *VR* = 3, streamwise (h) *VR* = 3, blunt

(d) *VR* = 4, streamwise (i) *VR* = 4, blunt

(e) *VR* = 5, streamwise (j) *VR* = 5, blunt

Fig. 2. Elliptical jet of *AR* = 3 with *VR* = 1 to 5.

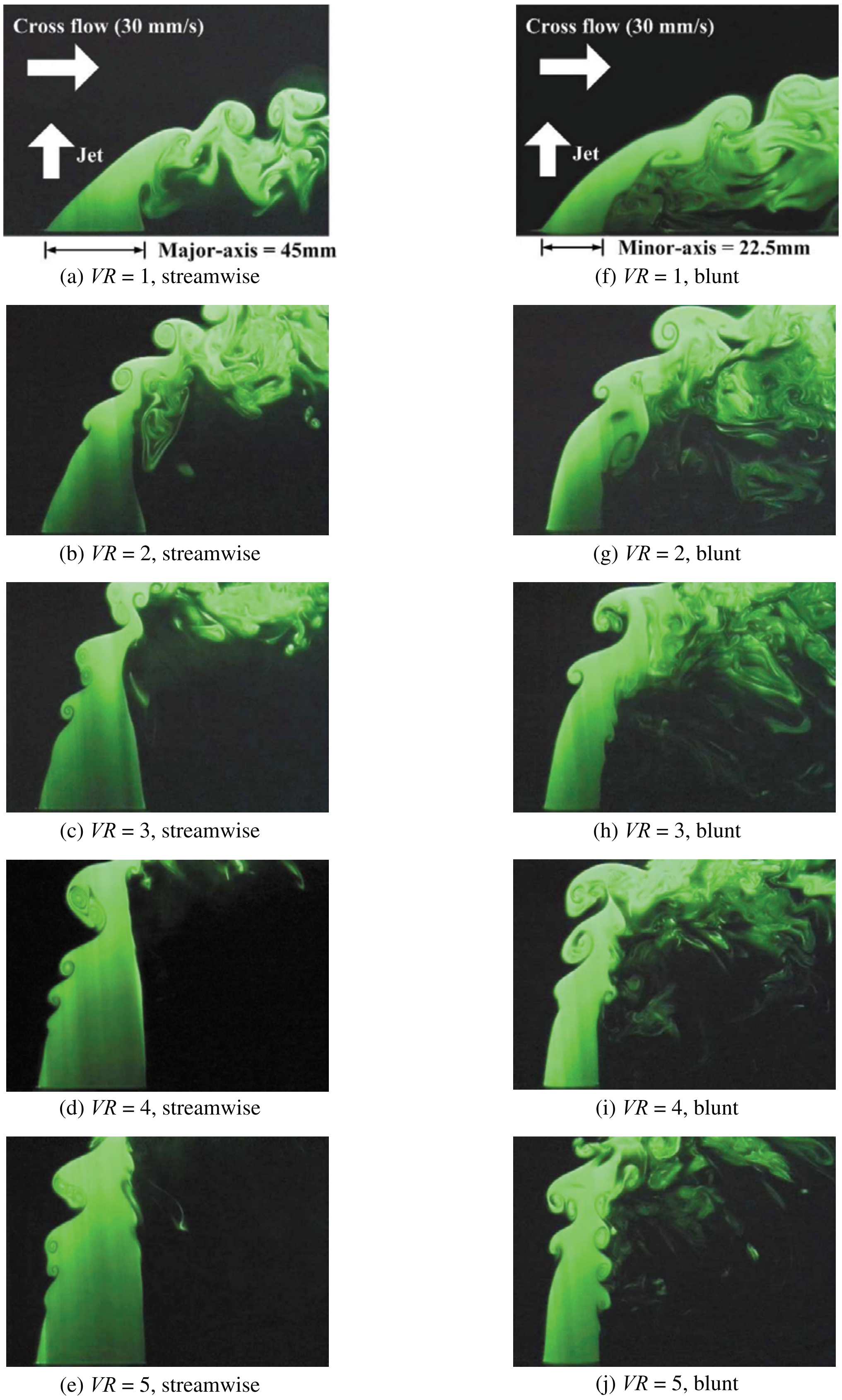
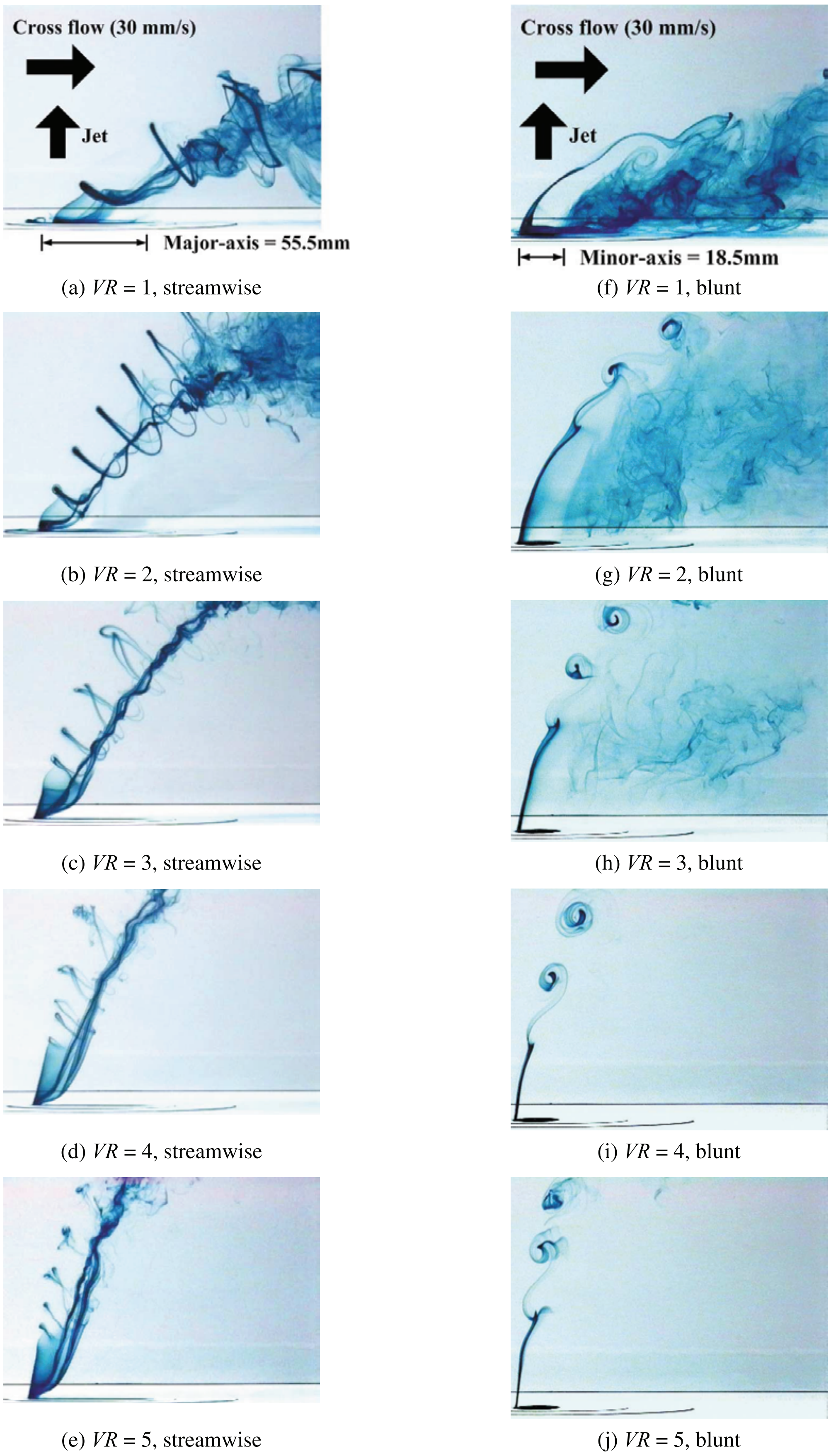


Fig. 3. Elliptical jet of AR = 2 with VR = 1 to 5.



(a) *VR* = 1, streamwise (f) *VR* = 1, blunt

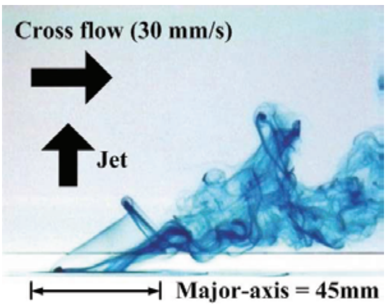
(b) *VR* = 2, streamwise (g) *VR* = 2, blunt

(c) *VR* = 3, streamwise (h) *VR* = 3, blunt

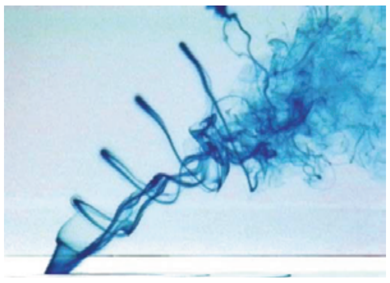
(d) *VR* = 4, streamwise (i) *VR* = 4, blunt

(e) *VR* = 5, streamwise (j) *VR* = 5, blunt

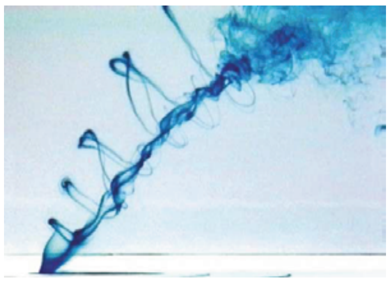
Fig. 4. Elliptical jet of *AR* = 3 with *VR* = 1 to 5.



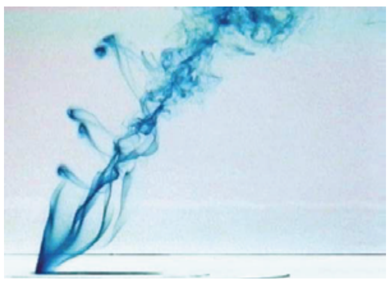
(a) VR = 1, streamwise



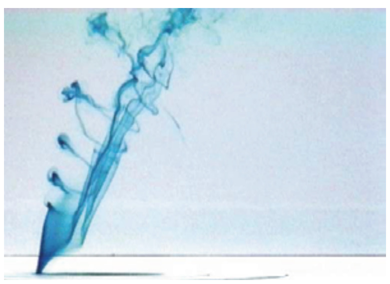
(b) VR = 2, streamwise



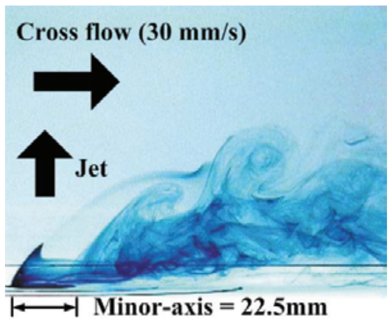
(c) VR = 3, streamwise



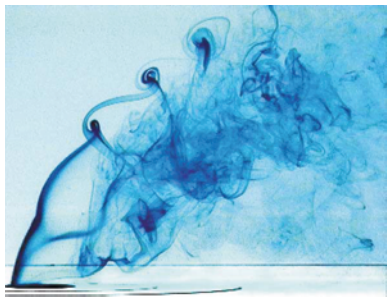
(d) VR = 4, streamwise



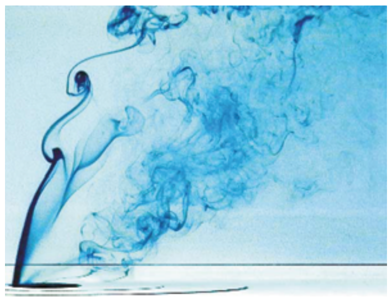
(e) VR = 5, streamwise



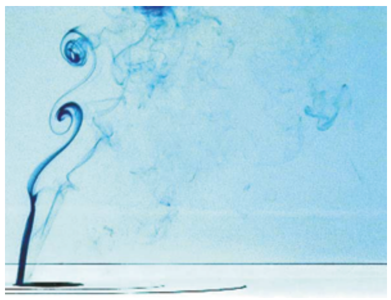
(f) VR = 1, blunt



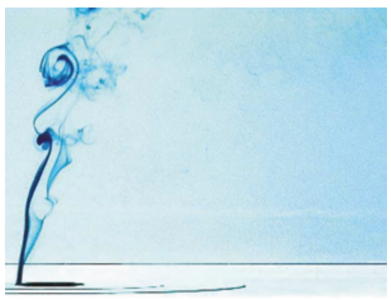
(g) VR = 2, blunt



(h) VR = 3, blunt



(i) VR = 4, blunt



(j) VR = 5, blunt

Fig. 5. Elliptical jet of AR = 2 with VR = 1 to 5.

4. Conclusion

Laser-induced fluorescence and dye injection techniques were used to study the near-field of an elliptical JICF, and the results showed that the jet structures behave differently from that of a circular JICF. With the major-axis aligned with the cross flow, regular pairings of the leading-edge vortices are found to occur, probably due to higher self-induced velocities caused by the smaller radii of azimuthal curvature. For the blunt elliptical jets, the pairing process is suppressed, for the reason which is opposite to that of the streamwise elliptical jets.

References

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Luo Siao Chung: He is an Associate Professor in the Department of Mechanical Engineering, National University of Singapore. He obtained his Ph.D from Imperial College, University of London in 1985. His research interest is mainly in the area of aerodynamics, which includes problems related to 2- and 3-D flow past single or multiple cylinder(s), flow-induced vibrations of structures and jet in cross flow etc.