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A STUDY OF A ROUND JET IN CROSS-FLOW AT DIFFERENT VELOCITY RATIOS

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ABSTRACT

An experimental study has been carried out to investigate the effect of the velocity ratio on the structure of a round jet in cross-flow. The experiments were conducted in a water channel using dye visualization techniques. The study revealed that as the velocity ratio was increased from about 1 to about 5.5 the flow changed from a wake-like structure to a jet-like structure. At a velocity ratio of 4, the vortex roll-ups at the sides of the jet appeared to undergo vortex breakdown.

INTRODUCTION

The study of jets in cross-flow is of great practical relevance to many engineering applications such as V/STOL aircraft exhaust flows, the roll-control of missiles and chimney flows. The characteristics of a jet in cross-flow are primarily dependent on the ratio of the momentum flux from the jet orifice to the momentum flux of the cross-flow over equal areas. It is conventional to define the "effective velocity ratio" R as the square root of this ratio. When the jet and cross-flow densities are equal, then

$$R = \frac{V_{jet}}{U_\infty}$$

where V_{jet} is the mean (RMS) velocity of the jet and U_∞ is the cross-flow free-stream velocity.

It is well known that when a jet discharges normal to a cross-flow, the jet deflects in the direction of the cross-flow and the flow structure near the pipe exit is dominated by ring-like vortices (Andreopoulos (1985), Fric & Roshko (1989)). The flow far downstream is dominated by a pair of streamwise vortices, commonly referred to as the Counter-Rotating Vortex Pair (CVP), which seem to originate near the pipe exit (Moussa et al. (1977), Sykes et al. (1986)). Even though these phenomena have been observed by many workers and advances have been made (Fric (1990), Kelso (1991), Kelso et al. (1992)), very little is understood about the topology of the flow. The aim of this paper is to study how the flow structure is affected by the change in velocity ratio. This work forms part of an ongoing research program into the structure of jets in cross-flow.

APPARATUS

The flow visualization experiments were carried out in the closed-return water channel at the University of Melbourne. Figure 1 shows a schematic diagram of the jet apparatus. The plexiglass working section measured 0.3 m x 0.3 m in cross-section and operated at a typical cross-flow velocity of 60 mms^{-1}.

The jet was constructed from plexiglass tubing with an internal diameter of 25 mm, giving a Reynolds number of 1,600, based on the cross-flow velocity and the jet diameter. The pipe was very short with the fluid entering it from an axisymmetric 36:1 contraction, thus giving a top-hat velocity profile in the case of no cross-flow.

A narrow circumferential slot in the pipe wall allowed dye to be injected directly into the pipe to mark the boundary layer (hence the jet shear layer). A small dye injection port was also located within the pipe immediately upstream of the pipe exit. Moveable dye injection tubes were also used to introduce dye into the cross-flow from points away from the wall. Dyes with specific gravity $\cong 1$ were used to visualize the flow. No deliberate forcing was applied to any of the flow cases described here.

RESULTS & DISCUSSION

The flow structures in transverse jets with velocity ratios ranging from 1 to 5.5 share many common features. The main features will be discussed with reference to R=4, as shown in figure 2, because the flow structures are more clearly defined than at other velocity ratios.

When dye is released from the injection port as seen in figure 2(a), it seems to fill a small separation region which occurs just below the upstream lip of the pipe exit.

Consequently, all the dye seen in this photograph originates from this small separation region. This dye marks the upstream side of the "cylindrical" shear layer issuing from the pipe and this shear layer rolls-up to produce vortex loops which bear a striking resemblance to the positively buoyant co-flowing jet structures discussed in Perry & Lim (1978). The sides of the vortex loops appear to tilt with the bending of the jet and these loops also appear to pair regularly downstream. The Strouhal number (in terms of the roll-up frequency, jet diameter and jet velocity) of the initial shear layer roll-up was 0.43. However, in figure 2(b) where dye is injected from the circumferential slot as well, the shear layer on the lee-side of the jet is also shown to roll-up. This roll up does not appear to be connected to that on the upstream side. Figure 3 depicts the authors' interpretation of the instantaneous streamline pattern showing the separation and the rolling up of the shear layer from the upstream side of the pipe. The horse shoe vortex system system has also been included to complete the picture. This pattern has been inferred from experimental observation.

In addition to this, the sides of the cylindrical shear layer emanating from the pipe quickly become folded into a scroll resulting in a pair of streamwise vortices. These vortices are often referred to as the Counter-rotating Vortex Pair or CVP. A short distance away from the pipe exit these vortices give the appearance of "vortex breakdown". Although this is not entirely certain, the flow appears to exhibit many of the characteristics of "spiral breakdown" as illustrated by figure 4. Figure 5 is the authors' interpretation showing how the folding of the cylindrical shear layer can lead to the formation of CVP. For clarity, the front and lee-side roll-ups have not been shown.

Figure 6 shows that the flow structure for the velocity ratio of 5.5 is generally similar to that for the case of R=4.0 except that the strength of the CVP appears to be greater. In addition there is no clear evidence of vortex breakdown. As expected, the mean curvature of the jet is smaller at the higher velocity ratio. Here the Strouhal number of the loop-like shear layer roll-up was 0.83.

As shown in figure 7, the flow structure for R=2.2 is also generally similar to that at R=4.0. The CVP is, however, barely obvious and vortex breakdown does not seem to occur. The Strouhal number of the shear layer roll-up was 0.34. A helical instability appears to occur in the upstream shear layer roll-up. This is also apparent at the higher velocity ratios.

At a velocity ratio of 1 there is a drastic change in the flow structure as shown in figure 8. The roll-up of the shear layer on the upstream side of the jet, which occurs at the higher velocity ratios, does not appear to occur here. This was confirmed by viewing slow-motion images of the flow. However, the roll-up on the lee-side of the shear layer still occurs and at approximately two diameters downstream the flow appears to have become wake-like, giving the appearance of the co-flowing wake structures of Perry & Lim (1978). The Strouhal number of this roll-up is 0.43.

CONCLUSIONS

The present study reveals that when the velocity ratio is varied from 1 to 5.5 while keeping the Reynolds number constant at 1,600, the flow structure changes from wake-like to jet-like. The main features of the flow structure include the upstream separation within the pipe, the loop- or ring-like roll-up of the shear layer and the folding of the shear layer. This study also shows that the folding of the cylindrical shear layer may be the mechanism responsible for the formation of the CVP. As anticipated, the strength of the CVP increases with the velocity ratio. Moreover, at velocity ratios close to 4, the CVP gives the appearance of vortex breakdown at a location close to the jet exit. Interestingly, there is no clear evidence of vortex breakdown at any other velocity ratios under study. This observation may be significant to the understanding of mixing processes and further work on this is needed.

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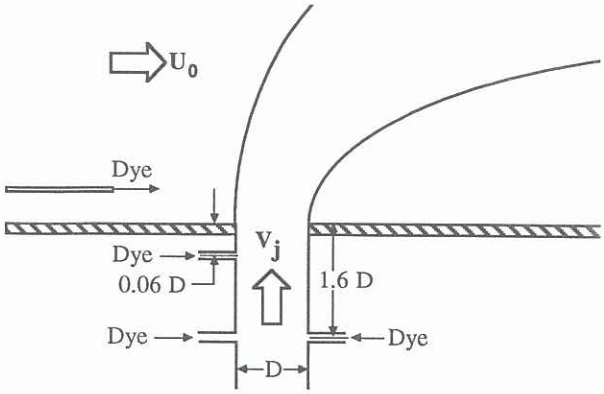
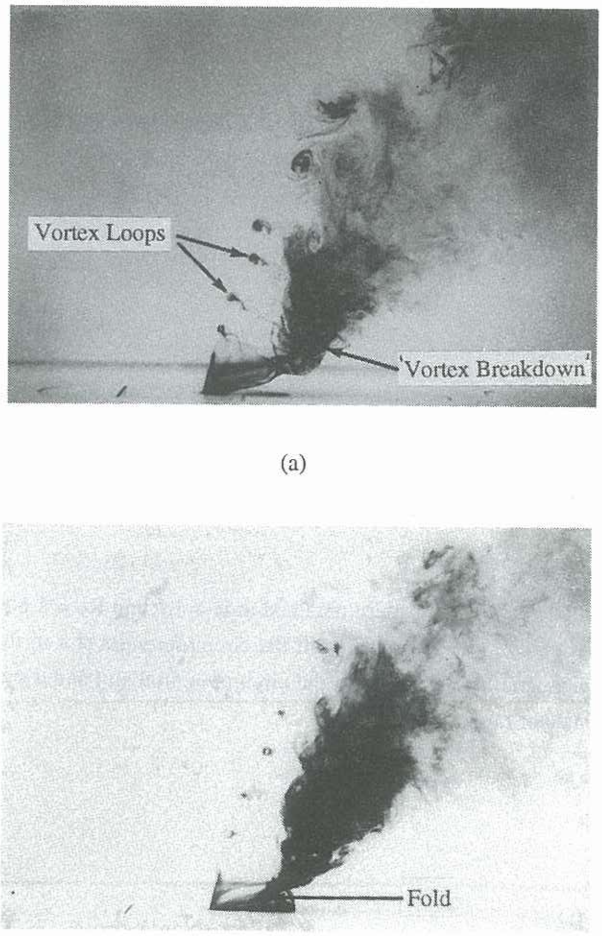


Figure 1. Schematic diagram of the jet apparatus.



(a)

(b)

Figure 2. Flow pattern obtained at R = 4.0 and Re = 1,600 when dye is a) injected from the dye injection port, and b) injected from the dye injection port and the circumferential slot in the pipe.

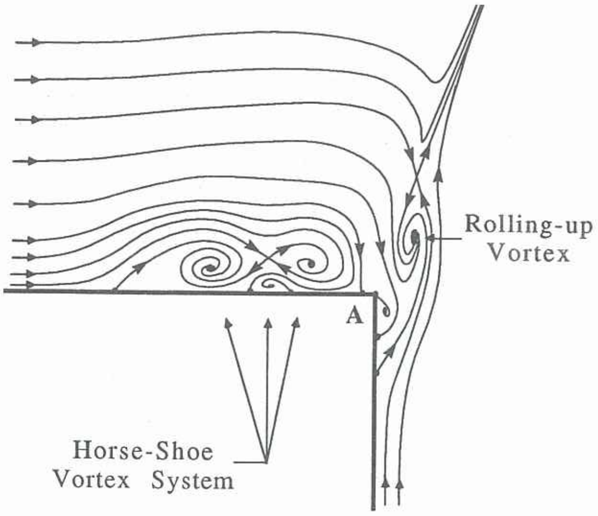


Figure 3. Authors' interpretation of the instantaneous flow pattern in the centreplane as seen by a stationary observer.

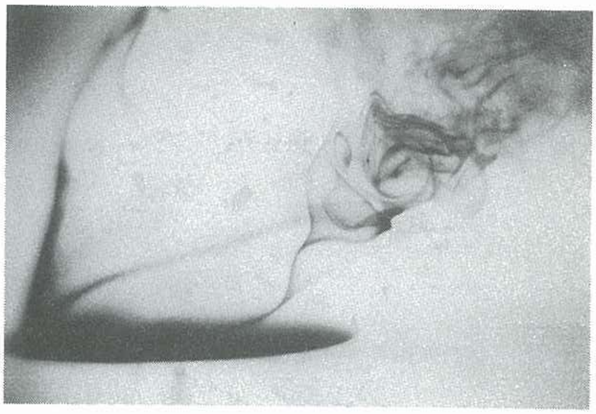


Figure 4. Close-up view of vortex breakdown in the scroll-like roll-up of the shear layer at R = 4.0 and Re = 1,600.

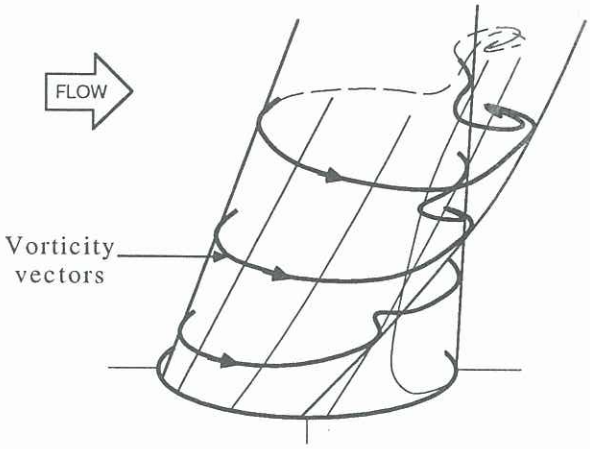


Figure 5. Authors' interpretation of the folding of the shear layer close to the pipe exit.

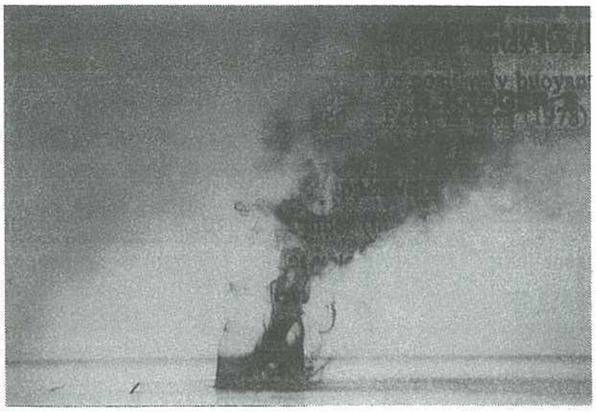


Figure 6. Flow pattern obtained when dye is injected from the circumferential slot at R = 5.5 and Re = 1,600.

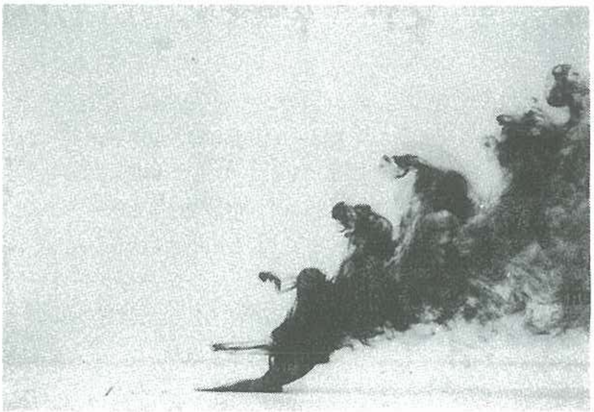
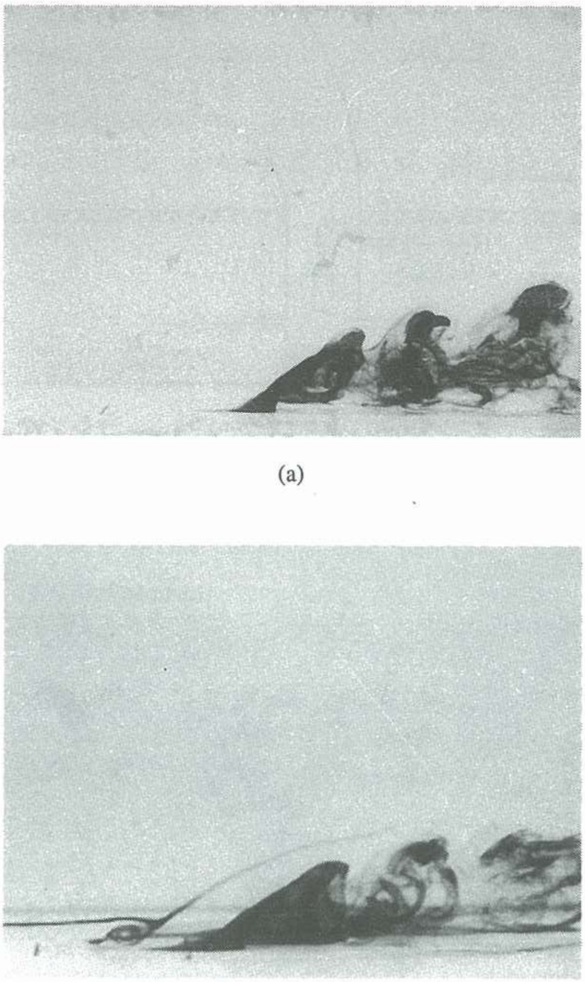


Figure 7. Flow pattern obtained when dye is injected from the circumferential slot and the dye injection port at R = 2.2 and Re = 1,600.



(a)

(b)

Figure 8. Flow pattern obtained at R = 1.0 and Re = 1,600 when dye is a) injected from the circumferential slot in the pipe, and b) injected from the circumferential slot and a dye injector far upstream.