ON THE EFFECTS OF VELOCITY PROFILES ON THE TOPOLOGICAL STRUCTURE OF A JET IN CROSS FLOW

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ABSTRACT

The effect of jet exit velocity profile on the topological structure of a round jet in a cross flow is investigated experimentally using the laser induced fluorescence technique. The study is focused on two velocity profiles, namely top-hat and parabolic profiles. The jet Reynolds number considered ranges from 350 to 1750, with the corresponding velocity ratios varying from 1 to 5. The results show that the top-hat jets are more unstable and likely to shed shear layer vortices than parabolic jets. Interestingly, it is found that the parabolic jets penetrate higher into the flow, but the large- scale structures appear to be less coherent than those of the top-hat jets. These findings suggest that the characteristics of a jet in a cross flow is not only a function of the Reynolds number and the velocity ratio, but also a function of the shear layer thickness and hence velocity profile.

INTRODUCTION

The study of jets in cross flows (JICF) has immense relevance to engineering applications such as film cooling for turbine and combustors, fuel injection for burners, thrust reversers for propulsive systems as well as in the development of S/VTOL aircrafts. Its relevance in areas involving the dispersion of effluents in waterways and of pollutants in the atmosphere via chimneys and smoke stacks has long been recognized by the research community.

Early research on JICF was confined mainly to determining the mean paths of the deflected jets (Jordinson, 1956 and Margason, 1968). Later, the focus was shifted to the measurement of the axial velocity decay and turbulence intensity along the jet axis by Keffer & Baines (1963), Pratte & Baines (1967) and Andreopoulos (1982 and 1985). Their results show that fluid entrainment and hence the mixing process, is substantially more intensive for a JICF than for a

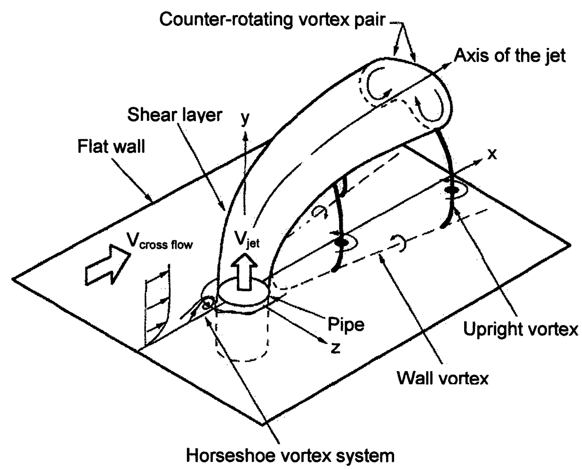


Figure 1 : Schematics of a jet in cross flow phenomenon as illustrated by Kelso et al (1996).

free jet. This resulted in a surge of research focusing on better mixing of fluids. Recent studies see a rise in the use of computational simulations to predict both the fluid entrainment and the deflected jet trajectory as well as to verify earlier experimental work (Yuan & Street, 1996 and 1998). The numerical results of Yuan & Street looked promising and hold great potential for further investigations. A more detailed review of the subject over the last fifty years can be found in Margason (1993), Fric & Roshko (1994) and Kelso et al (1996).

Earlier experimental work on JCIF has revealed a complex system of interacting vortical structures resulting from the interaction between a transverse round jet and a cross flow boundary layer (Figure 1). The main flow features can be summarised as follows:

1. The existence of horseshoe or necklace vortices in the cross flow boundary layer upstream of the exiting jet.

2. The formation of ring vortices due to the rolling-up of the deflected jet shear layer. These vortices are similar to those which occur in a free jet, but strongly distorted by the cross flow.

3. The formation of a pair of kidney-shaped counter-rotating vortex pair (CVP) downstream of the deflected jet.

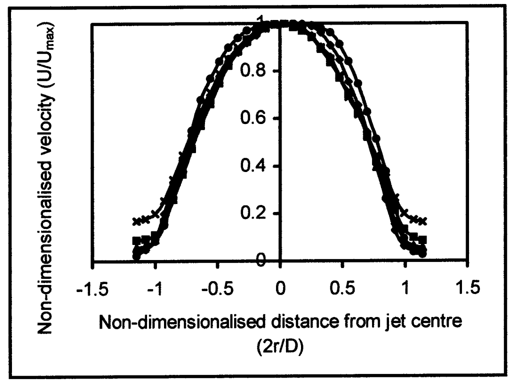
4. The formation of wake vortices comparable to the Karman vortex street in the wake behind a circular cylinder in an uniform cross flow.

To date, most of the experimental and numerical research on JICF is restricted mainly to jets with the "top-hat" exit velocity profiles. This is because most engineering applications are confined to using short entrance lengths for the jets. In addition, the elimination of the jet boundary layers simplifies both theoretical and computational analyses. However, the authors believe that jet exit velocity profiles also play a part in determining the overall topology of JICF because related studies have shown that a thin shear layer is inherently unstable, and more likely to roll up than a thick shear layer. This may have profound influence on the mixing processes. However, the extent to which the velocity profiles affect JICF is presently not known because, to the best of our knowledge, there is no experimental or numerical work conducted in this area. The lack of understanding in this area motivated us to carry out the present investigation. Our attention is focused on two exit velocity profiles, namely top-hat profile (i.e. thin shear layer) and parabolic profile (i.e. thick shear layer), but over a range of Reynolds number and velocity ratios.

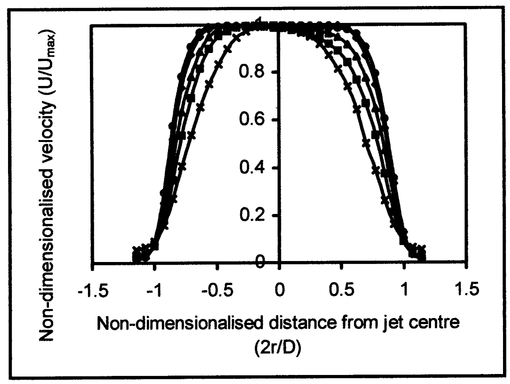
EXPERIMENTAL APPARATUS AND METHODS

The experiments are carried out in a re-circulating water channel in the Fluid Mechanics Laboratory at the National University of Singapore. The test-section of the channel measures 45cm × 45cm x 183cm long, and is fabricated entirely out of plexiglass sheet, hence allowing easy optical access for flow visualization purposes. The velocity in the test-section is controlled by a variable speed centrifugal pump. Before the flow enters the test-section, it passes through a honeycomb, followed by three fine screens. This is to ensure that the turbulence level of the cross flow remains low throughout. Jet fluid is supplied by a constant head water tank, to which a small portion of water is diverted from the water channel and exhausted as jets. The purpose of the constant-head tank is to provide a constant flow rate through the jet nozzle.

In this study, three jet nozzles of different diameters (i.e. 9.47mm, 13.53mm and 32.47mm) are used. They are mounted flushed with the bottom surface of the test section.



(a) Parabolic



(b) Top-hat

Figure 2 : Typical experimental jet velocity profiles for (a) parabolic jets and (b) top-hat jets. × : VR=1, □ : VR=2, △ : VR=3, ◇ : VR=4, ○ : VR=5.

To ascertain that the jet exit velocity profiles are indeed top-hat and parabolic, a Dantec hot-film probe and a constant temperature anemometer are used to measure the mean exit velocity profiles (without the cross flow) for all the Reynolds numbers considered. The results are sampled using a data acquisition board in a Pentium based PC, after passing through a signal conditioner.

To obtain the top-hat velocity profiles at the jet exit, the flow from the overhead tank is allowed to pass through a contraction section prior to exiting from the jet nozzle. The contraction is modeled after a fifth-order polynomial equation. To obtain fully-developed parabolic velocity profiles, the flow is allowed to pass through long length of hoses while keeping the curvature of the hoses to a minimum. Figure 2 shows typical jet profiles obtained in this experiment. To visualize the flow, the jet fluid is seeded with fluorescein disodium salt at the exit of the overhead tank, and illuminated with a thin sheet of laser. To capture the flow structures, a SONY CCD DXC-930P color video camera is used in conjunction with a SONY SVO-9620 S-

VHS Recorder. The camera is fitted with a Fujinon Aspheric 16X TV zoom lens, which enables a close-up view of the flowfield to be captured. All recorded images are subsequently replayed for analyses.

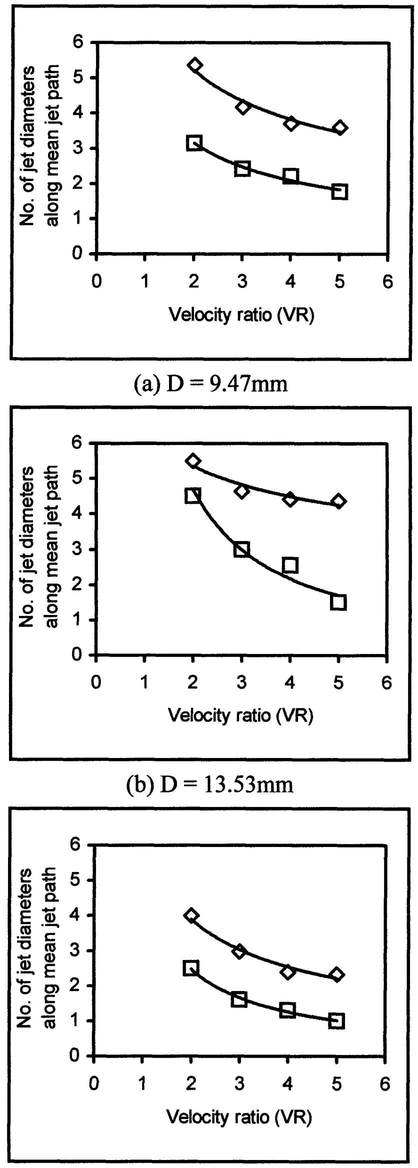
RESULTS AND DISCUSSION

Figures 4, 5 and 6 show the cross-sectional views of the flow structures obtained by imposing parabolic and top-hat profiles at the jet exits. Close examination of the pictures show that the shear layer from the top-hat profile rolls up more readily, and the vortices extend for a greater streamwise distance than those from the parabolic profile. For all the three diameters considered, the initiation of the shear layer vortices occurs substantially earlier (i.e. closer to the jet exit) especially as VR increases. For better comparison, Figure 3 shows the non-dimensionalised distances measured along the mean jet axes where shear layer vortices are first initiated for all diameters. It can be seen that the shear layer vortices from the top-hat jets, on an average, are initiated 2 to 3 diameters earlier than for the parabolic jets at the corresponding VR except for VR=1, where no shear layer vortices can be observed for both cases.

The above observation can be attributed to the fact that parabolic jets have thicker shear layers than top-hat jets. As a result, the cylindrical vortex sheet of a parabolic jet leaving the jet exit is inherently more stable, and therefore can withstand the instability introduced by the cross flow more effectively than top-hat jets'. Hence, by virtue of having thicker jet shear layers, parabolic jets can delay the initiation of shear layer vortices.

Also, the formation of shear layer vortices for the parabolic jets are profoundly influenced by the bending caused by the cross flow, as can be seen in Figures 7, 8 and 9. Interestingly, up to VR=3, the shear layer vortices appear to form very close to the region of maximum jet-bending for parabolic jets. The authors conjecture that this is probably caused by shear layer thinning due to stretching by the cross flow. This, coupled with the disturbance from the crossflow, causes the jet to breakdown, thus leading to entrainment of cross flow fluid into the shear layer.

Another distinct feature of the parabolic jets is the randomness of the shear layer vortices compared to those from the top-hat profile which are more regular, at least initially. The authors suspect that the randomness is due to the uneven shear layer thickness caused by the complex interaction between the cross flow and the jet. With the top-hat profile, the shear layer thickness is more uniform on exiting the jet nozzle, whereas with the parabolic profile, the shear layer is thick to start with. But as the parabolic jet shear layer interacts with the cross flow, uneven vortex stretching may cause an uneven thickness in the cylindrical vortex sheet, thus leading to the observed behaviour. These findings suggest that the mixing processes in JICF may be profoundly affected by the jet exit profile.



(a) D = 9.47mm

(b) D = 13.53mm

(c) D = 32.47mm

Figure 3 : Number of jet diameters along the mean jet axis where shear vortices first initiate. ◇ : Parabolic jets, □ : Top-hat jets.

Interestingly, it also seems that parabolic jets have a greater penetration into the cross flow than the top-hat jets. This can be clearly seen from the far-view images depicted in Figures 7, 8 and 9. The higher penetration could be due to the higher lift associated with the CVP. This implies that the strength of CVP resulting from the parabolic jet is higher than that from the top-hat jet. This is consistent with the well-established fact that the strength of the CVP affects the lift of the plume.

Related studies have shown that the stronger the CVP, the higher the lift will be and the higher the plume would be from the jet exit plane.

CONCLUSION

Experimental investigation on the effects of exit velocity profiles on the flow structure of a jet in a cross flow has been conducted using the laser-induced fluorescence technique. The results clearly show that the exit velocity profile has a profound effect on the overall structure of the flowfield. For the top-hat jets, the formation of shear layer vortices and vortex-pairing further downstream are observed to occur much closer to the jet exits for all the VR investigated. These observations are consistent with the results previous published. However, with the parabolic jets, similar flow structures are found, but they occur significantly later into the flow, usually at a scale of 2 to 3 jet diameters downstream. In addition, shear layer vortices and their subsequent pairing are less coherent compared with their top-hat counterparts. Moreover, the resultant plumes downstream are noticeably higher from the test-section floor for parabolic jets than for top-hat jets, thus indicating the possibility of higher lift. The increase in the lift could be attributed to an increase in the strength of the resultant CVPs of parabolic jets. However, no quantitative data is available yet to justify this postulation. This work is continuing.

ACKNOWLEDGEMENT

This work is motivated partly by the conversation that the second author (T.T. Lim) had with Dr M.R. Khorrami many years ago.

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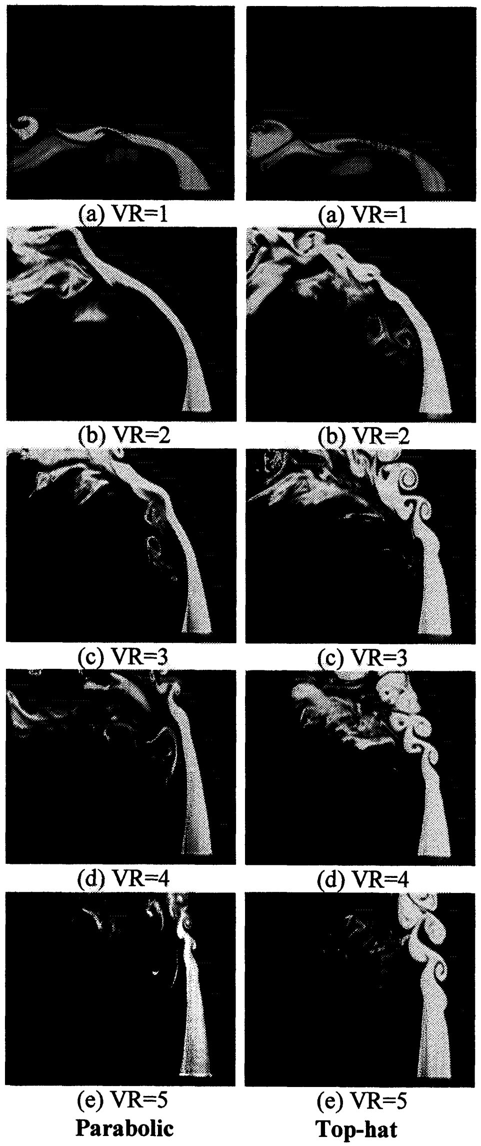

Figure 4 : Near-view LIF images of 9.47mm jet shear layer from VR=1 to 5. Left : Parabolic jets, right : Top-hat jets.

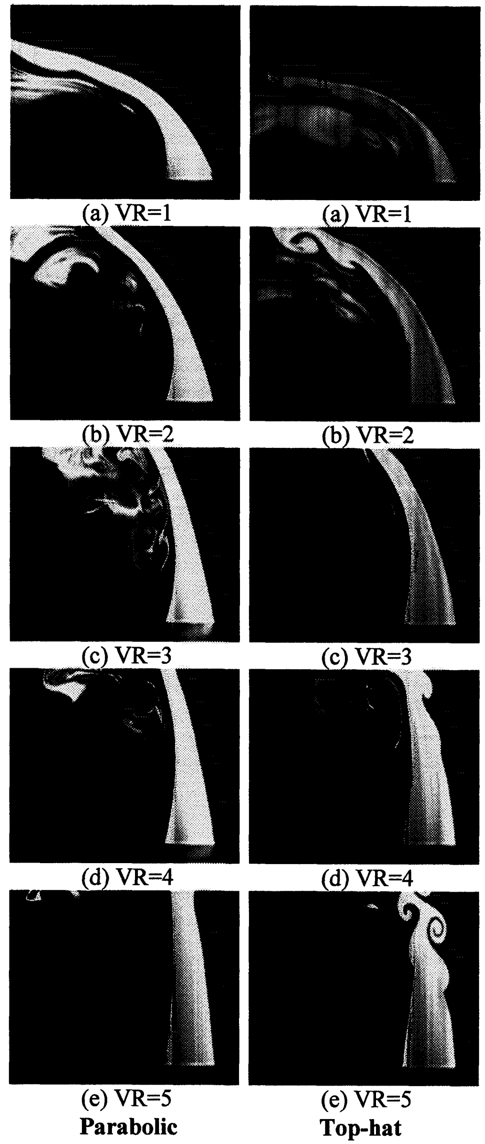

Figure 5 : Near-view LIF images of 13.53mm jet shear layer from VR=1 to 5. Left : Parabolic jets, right : Top-hat jets.

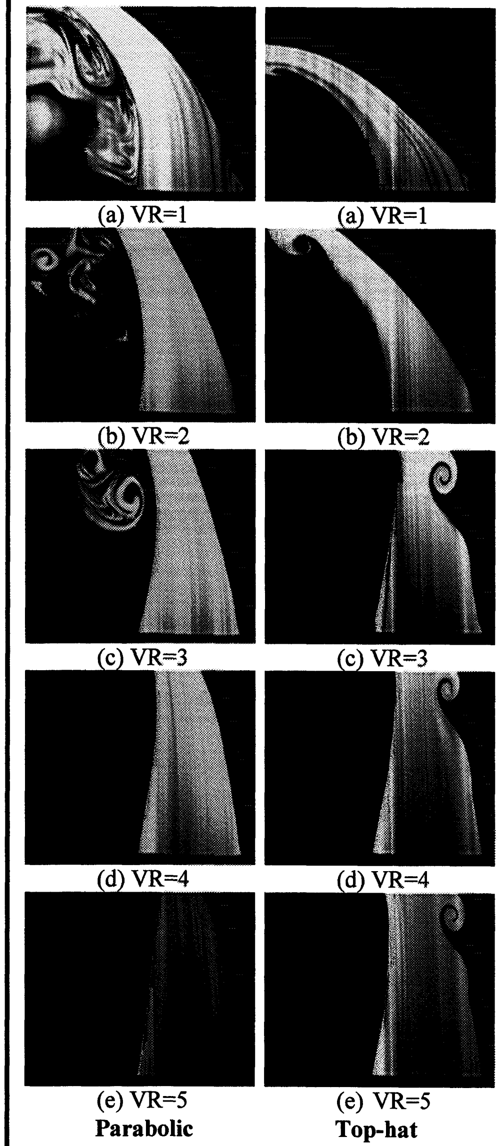

Figure 6 : Near-view LIF images of 32.47mm jet shear layer from VR=1 to 5. Left : Parabolic jets, right : Top-hat jets.

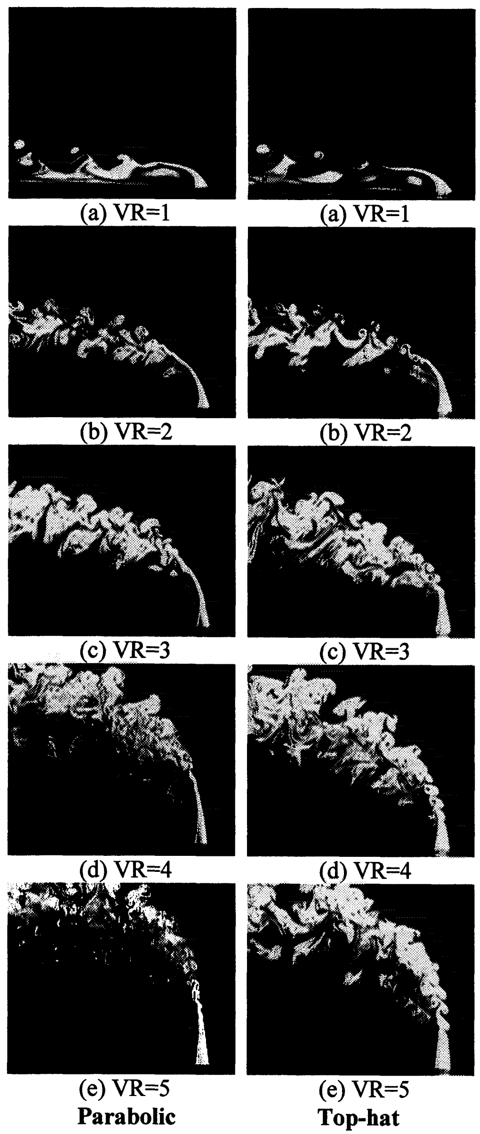

Figure 7 : Far-view LIF images of 9.47mm jet shear layer from VR=1 to 5. Left : Parabolic jets, right : Top-hat jets.

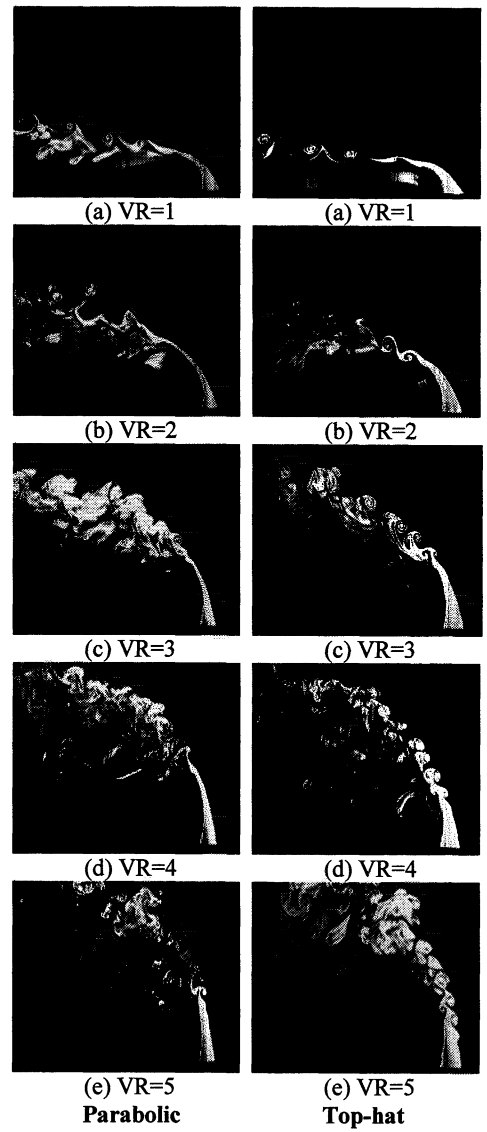

Figure 8 : Far-view LIF images of 13.53mm jet shear layer from VR=1 to 5. Left : Parabolic jets, right : Top-hat jets.

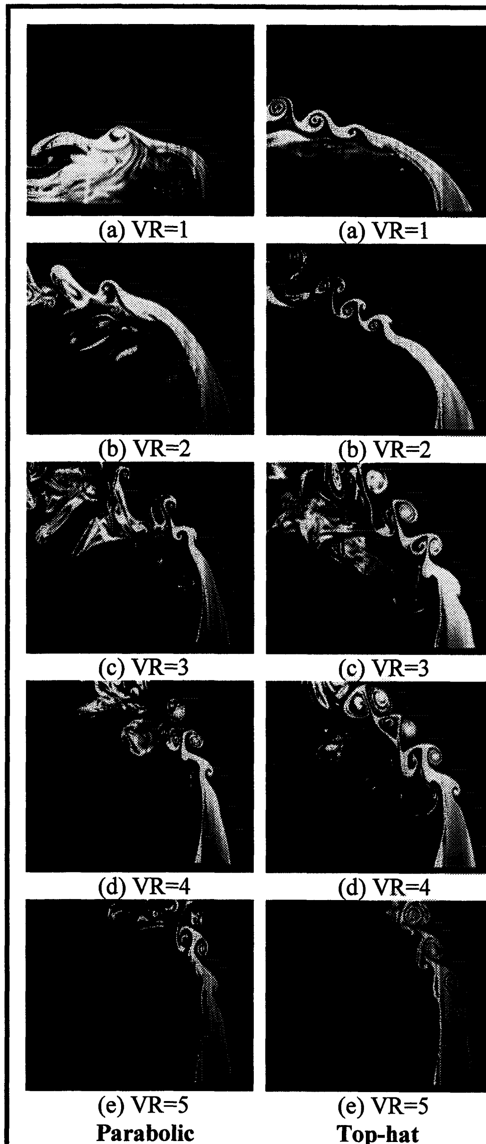

Figure 9 : Far-view LIF images of 32.47mm jet shear layer from VR=1 to 5. Left : Parabolic jets, right : Top-hat jets.