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An Experimental Study on Comparison of Non-circular Co-flow Jet with Co-axial Jets and Computational Verification

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ABSTRACT

The present study addressed the experimental investigation followed by computational validation of incompressible single and co-axial jet. The characteristics of non-circular co-flow jets have been analysed for different types of orifices, i.e., circular, hexagon and crusi-form. The flow field's characteristics like centerline velocity, spreading rate, velocity along radial direction and potential core length have been determined by using Pitot tube. Using FLUENT the numerical simulation has been carried out and compared with experimental results. Significant similarities have been obtained in experimental and computational data. Though the axial velocity magnitude of single jet was less than the coaxial jet, but the jet half width of single circular jet was found higher than the jet half width of coaxial jets.

Key words: Coaxial jet, computational fluid dynamics, jet half-width, co-flow, non-circular

INTRODUCTION

Coaxial jets are an integral part of many engineering systems where mixing of streams of different fluids are required. They are widely used to mix the fuel and oxidisers inside the combustors of gas turbine power plant of aircraft. A properly designed jet will be desired to mix efficiently, while providing the best overall combustion efficiencies. It has been reported that single non-circular jets have better mixing characteristics than their axi-symmetric counterparts. Combinations of such jets into coaxial configurations have promising aspect on designing the jet vane. Also, the detailed dynamics of jet entrainment and mixing have certain fundamental importance on various applications like noise suppression, combustion, lift augmentation, heat transfer, and chemical reaction in reactors, and are required a thorough analysis prior to use.

A good deal of research work on coaxial nozzle has been performed so far and reported. Cutler and White (2001) developed and tested the turbulence model in supersonic coaxial jet. Khanbabaei *et al.* (2008) presented a computational analysis of fluid flow in VVER-1000 reactor. Khodadadi and Vlachos (1989) studied the flow separation of confined coaxial turbulent jet. Moustafa (1995) investigated experimentally and numerically the interaction between multiple supersonic jets in two, three and four nozzle configurations. Nikitropoulos *et al.* (2003) investigated the turbulent characteristics of circular and square coaxial jets. Ragunathan and Reid (1981) studied the interaction between multiple supersonic jets arranged in radial configurations and found that in the five jet cases there is considerable noise reduction without significant reduction in momentum. Rehab *et al.* (1998) provided the information about the variation of velocity and potential core length of coaxial jet. Sarma *et al.* (2003) studied the flow and turbulence characteristics of incompressible jets from various orifices. Selvatti *et al.* (1996) studied the effects of inlet conditions on the dynamics of vortex structure of an axi-symmentric coaxial jet. Smoot (1976) presented the mixing co-efficient correlations for turbulent, compressible axisymmentric jets. Tang and KO (1995) investigated the coherent structure of excited coaxial jet. Vargas and Choudhuri (2004) studied the effects of an elliptic co-flow on a circular inner jet. Vijayakumar *et al.* (2002) has numerically studied the interactions of multiple supersonic jets in various configurations. Wlezien (1989) studied the effect of nozzle spacing on the coupled interaction between supersonic jets and concluded that for closely spaced nozzles. The near-field characteristic of a turbulent elliptic coaxial jet with the velocity ratio of 0.55 and 1.45. Yu *et al.* (2004) provided the information about the near field flow structure of confined coaxial square jet. The effects of tabs and its effect on mass flow rate were studied by Zamam (1999) experimentally.

In above contest, an extensive research has been carried on non-circular co-flow, and presented in this study. Here, the flow evolves into a single jet after merging into the annular and inner flows. Using the non-circular shape like hexagon and crusi-form outlet, the flow behavior and jet properties are investigated experimentally and computationally. More emphasis is given on studying the length of potential core, jet decay, jet half-width, jet shape, and structural changes at near field of the co-axial flow.

MATERIALS AND METHODS

A block diagram of coaxial jet experimental set-up is shown in Fig. 1. It has consisted of a Blower, Coaxial jet assembly, three-dimensional traversing platform, Pitot tube and a U-tube manometer. Figure 2 shows the coaxial jet assembly used for the experimental investigations has been presented. It has consisted of two concentric nozzles made of copper tube. The inner nozzle's placed concentrically with the outer nozzle with the help of three setscrews. It has arranged at equi-angle (120 degree) position. A 3HP motor and blower (flow rate 5 m^{3-1} sec, U= 30 m^{-1} sec and head rise 200 mm of water gauge) are used. The Reynolds number based on the diameter and inlet velocity of the jet has been found to the range of 4.34×10^4. Three nozzle configurations like circle, hexagon and crusi-form have been fabricated with the equivalent inner and outer diameter of 10 and 20 mm, respectively and are also shown in Fig. 3. Table 1 has shown the different combination of coaxial flow.

Numerical simulation: Initially, the grid dependency of computational domain was checked and a selected grid size was adopted for simulation. The domain for the jet simulation was taken as rectangular with a radial dimension of 10 equivalent outer diameters and axial dimensions of 20

Table 1: The different combination of coaxial flow

Name	Outer jet shape	Inner jet shape
Set 'A'	Circle	---
Set 'B'	Circle	Circle
Set 'C'	Hexagon	Circle
Set 'D'	Crusi-form	Circle

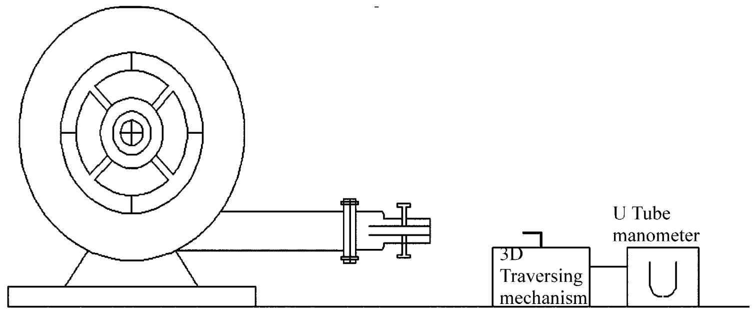

Fig. 1: Block diagram of experimental setup

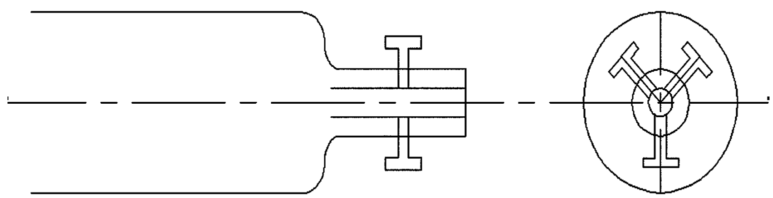

Fig. 2: Coaxial jet setup

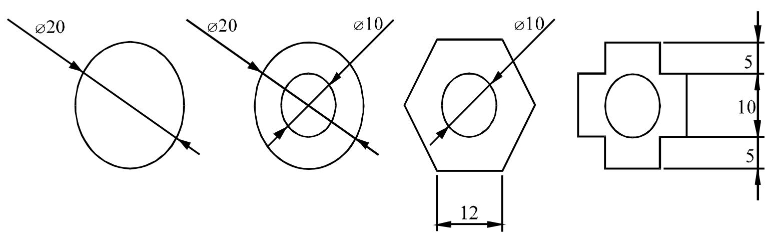

Fig. 3: Co-axial jet flow configurations

equivalent outer diameters. The 3-D grids with 30x30x100, 40x40x100, and 50x50x100 Cells have been considered in present study. The result of grid independence study is shown in Fig. 4 in terms of total pressure variation in the axial direction. It did not execute any marked variations for different grids considered. Hence, a grid of 40x40x100 has been used for all subsequent computations.

RESULTS AND DISCUSSION

Number of experiments has been carried out for an incompressible coaxial jet. The co-flow orifices of different geometries like circle hexagon and crusi-form have been used during the experimentation with constant velocity ratio. Data procured at different axial locations by experiment for various flow properties are compared with computational value and presented in the form of Fig. 4-11.

Validation of total pressure variation and jet half width along jet centerline: Using Pitot tube, along radial direction of the circular and coaxial jet with 20 mm O.D and 10 mm I.D, the flow

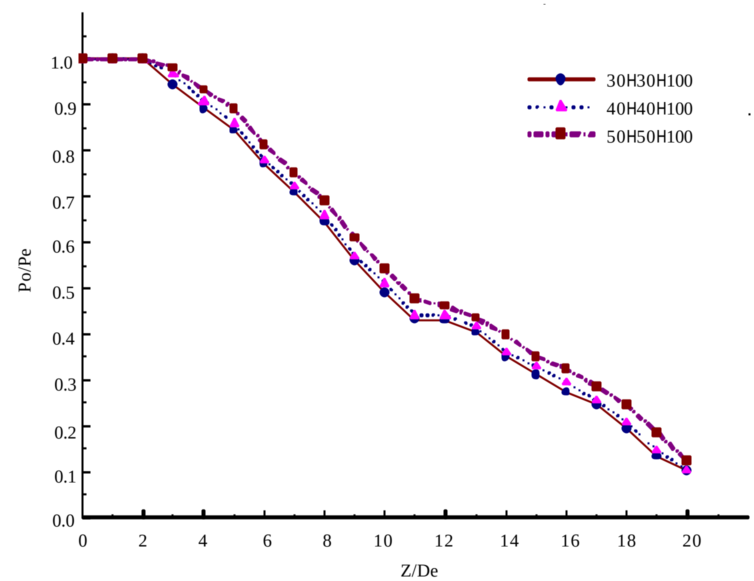

Fig. 4: Grid sensitivity study

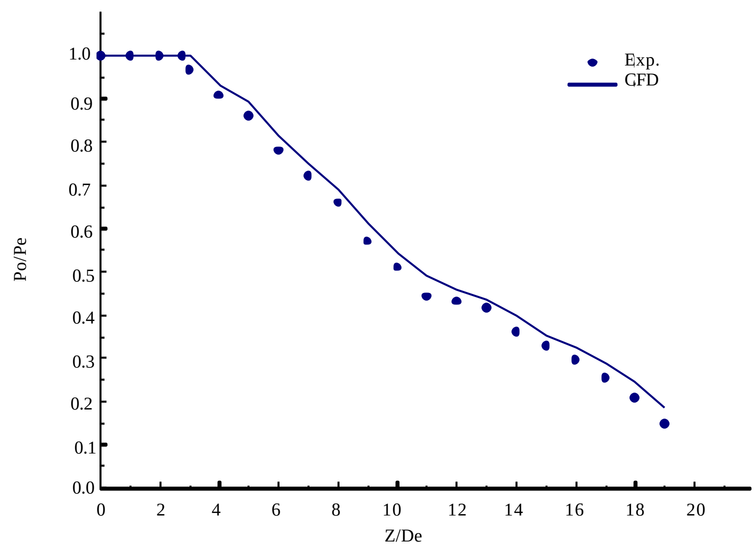

Fig. 5: Comparison of experimental and CFD results for total pressure variation along the jet centerline (SET-B)

properties like total pressure, jet half-width and velocity have been measured. In Fig. 5, the total pressure variation along the jet axis has been presented. The variation of Jet half-width as a function of Z/D_e has been measured and shown in Fig. 6. The velocity variation as a function of R/D_e along the radial direction was presented in Fig. 7 for ready references. It is evident from the results the numerical predictions have in excellent agreement with the experimental results.

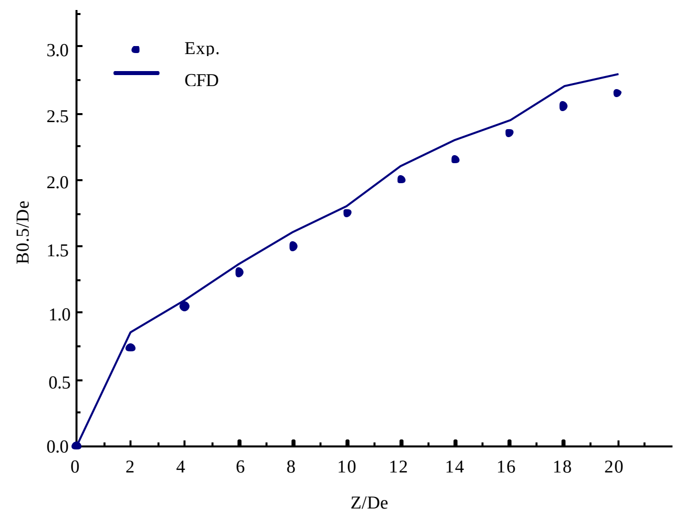

Fig. 6: Comparison of experimental and CFD results for Jet half-width (SET-B)

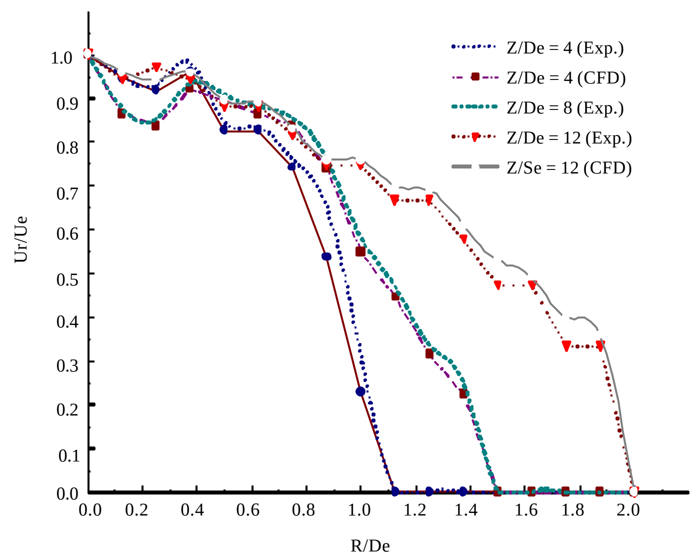

Fig. 7: Comparison of experimental and CFD results for velocity along the radial direction (SET-B)

Table 2: The potential core length of all the sets

SET	Z/De
Set 'A'	1.5
Set 'B'	2.75
Set 'C'	2.6
Set 'D'	2.25

Jet Decay studies-using centerline velocity profiles: The centerline velocity decay of all the experiments is shown in Fig. 8. The velocity decay of single jet was comparatively less than the co-axial jet as observed in all the cases. The inner jet of coaxial jet was circular and to change the co-flow jet as a non-circular shape like hexagon and crusi-form. In Fig. 8, there was no variation of velocity along the centerline upto the distance of 9 D_e has been presented. In co-flow jets, the velocity decay of crusi-form jet (SET D) was more than the circular jet (SET B).

Length of potential core: The jet centerline velocity is relatively constant inside the potential core of the jet as noted from experiments. The potential core length of all the sets are presented in

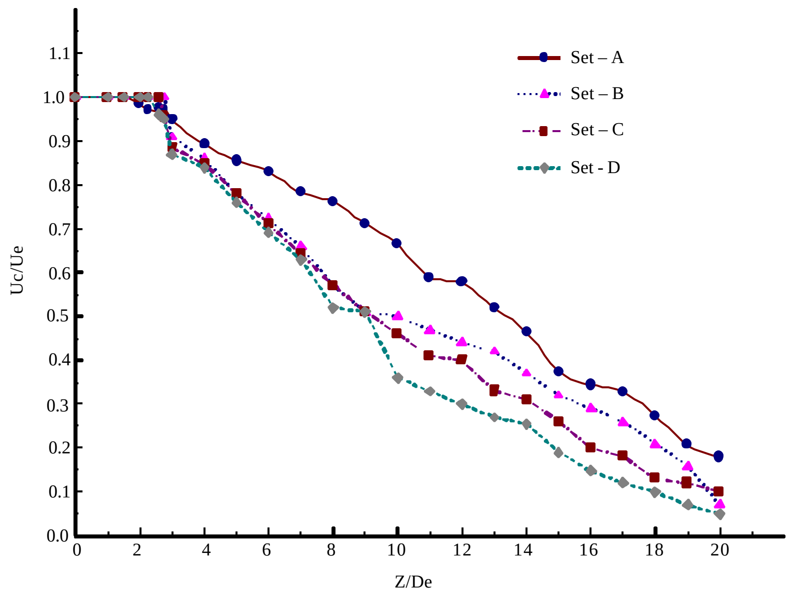

Fig. 8: Effect of non-circular co-flow jet of velocity variation along the jet centerline

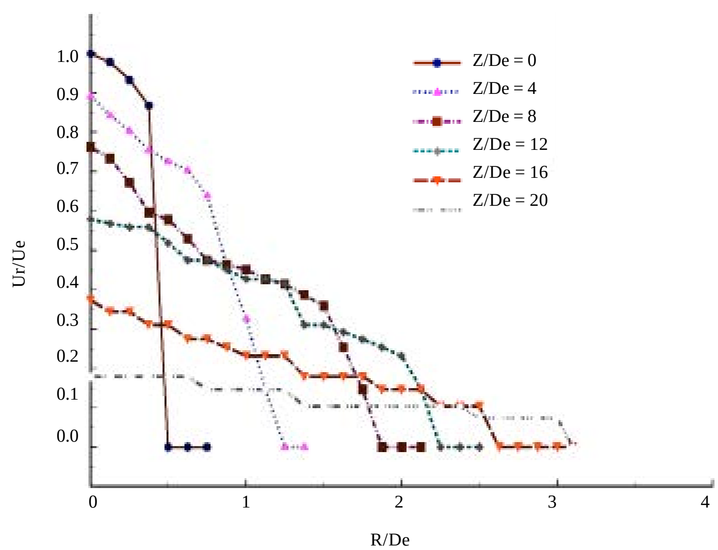

Fig. 9: Experimental results for Velocity distribution along radial direction at different axial locations of set-A

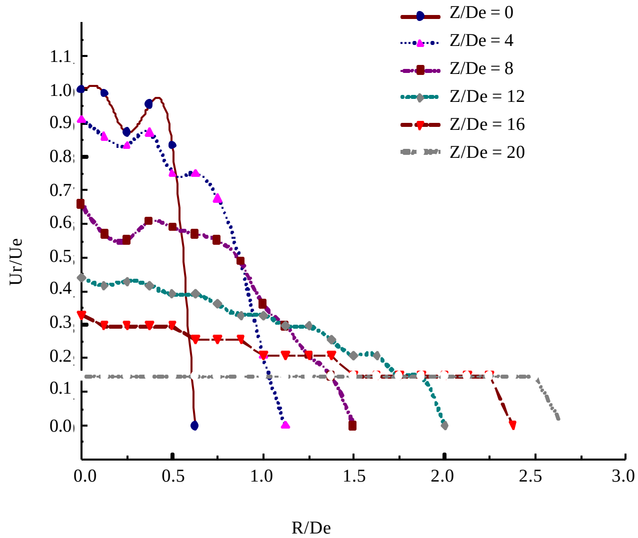

Fig. 10: Experimental results for velocity distribution along radial direction at different axial locations of Set-B

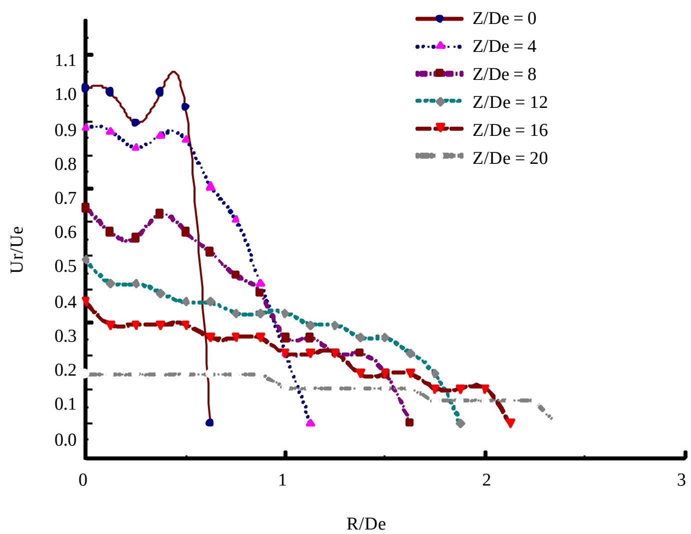

Fig. 11: Experimental results for velocity distribution along radial direction at different axial locations of Set-C

the Table 2. The length of potential core of Single Circular jet and Non-circular co-flow cases was shown in Fig. 8. The potential core length of the single circular jet is less than the co-axial jets. By penetration of the inner jet the potential core length was increased. The non-circular co-flow jet have longer inner potential core than the circular co-flow. In the non-circular co-flow condition, there was no considerable variation in the core length.

Effect of jet shapes on velocity distributions along the radial direction: The velocity distributions along the radial direction of all the sets were illustrated in Fig. 9-12. Decay of single circular jet velocity along the radial direction was lesser than the Co-axial jet. The velocity decay along the radial direction was faster for Crusi-form co-flow jet when compare to Circular co-flow jet due to the corner vortices.

Effect of jet shapes in Jet half width: The Fig. 13 shows the jet half width of all the Sets that has gone through experimentations. These profiles have represented the radial velocity component

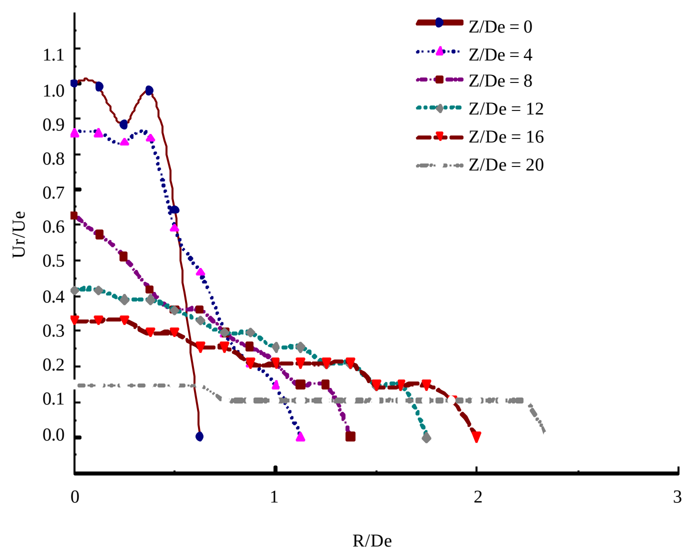

Fig. 12: Experimental results for velocity distribution along radial direction at different axial locations of Set-D

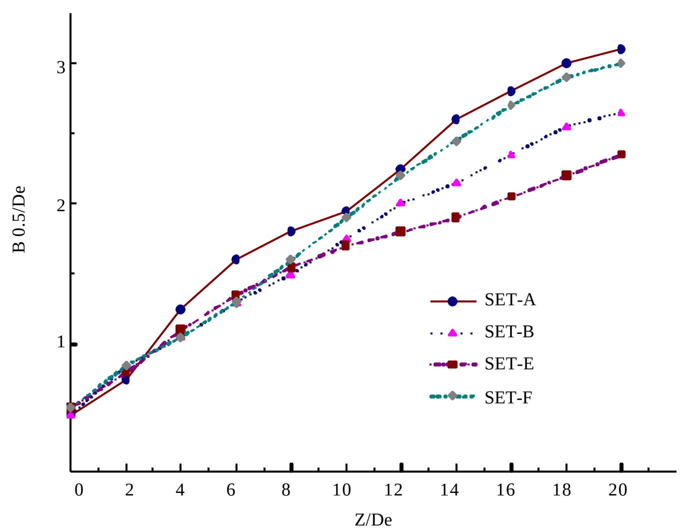

Fig. 13: Effect of non-circular co-flow jet shape on half width variation from the inner jet centerline

Table 3: Effect of jet shapes in the spreading rate along the radial direction

Name	(R/De)
SET 'A'	3.10
SET 'B'	2.65
SET 'C'	2.35
SET 'D'	2.50

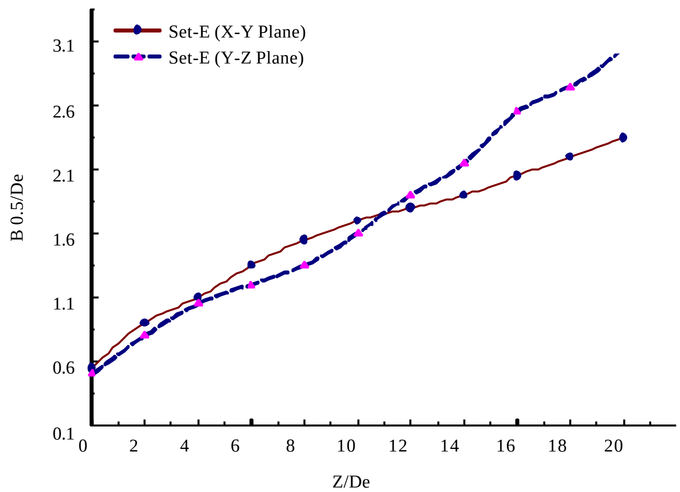

Fig. 14: Jet Half width variation of SET-C (Hexagon-Circle) at different plane

of different configurations. A comparison is done between the single circular jet and circular and non-circular co-flow jets.

The single circular jet half width was more than the circular co-flow jet. In a single jet, it expands freely without any interaction of flow. But in the case of co-axial jet, as the jet expands, the annular flow moves into the center of the jet. So the half width of the jet was decreased.

Non-circular co-flow jet; the jet half width of crusi-form co-flow was more than the hexagonal co-flow. In the case of Hexagon shape, the jet half width of (X-Z) and (Y-Z) planes of Set-C were shown in Fig. 14. In Set-C (Hexagon-Circle) the axis switching was taken at a distance of $Z/D_e = 11$. The jet half width of (Y-Z) (Flat-Flat) plane was more than the (X-Z) (Corner-Corner) plane.

Effect of jet shapes in spreading rate: The effect of jet shapes in the spreading rate along the radial direction was shown in Table 3. From the Table 3 it can be easily noted that the single circular jet has larger spreading rate when compare to the circular co-flow jet. In case of non-circular co-flow jet, the hexagonal co-flow jet have less spreading rate than the other configurations due to the concave corners attached.

CONCLUSION

Based on experimental and numerical investigations of an incompressible circular and non-circular co-flow jet using hexagon and crusi-form geometries, the following conclusions have been drawn:

- The velocity decay of single jet was less than the Co-axial jet. It was significant in size for crusi form jet when compared with circular jet and related to vortices generated at the corner of jetting. Also, it has been observed that the centerline velocity has changed at a distance of 9De
- The potential core length of Single circular jet was less than the Co-axial jet and it was longer for circular co-flow jet when compared to the non-circular co-flow
- The velocity decay along the radial direction of single circular jet was lesser than the Co-axial circular jet, and it was faster for non-circular co-flow jet when compare to circular co-flow jet
- The jet half width of single circular jet was more than the coaxial jets. In case of circular co-flow jet has more jet half width than the non-circular co-flow
- In the hexagonal shape, the spreading rate of (Y-Z) (Flat-Flat) plane was more than the (X-Z) (Corner-Corner) plane. Here the axis switching of the Set-C (Hexagon-Circle) was taken at a distance of $Z/D_e=11$

NOMENCLATURE

D	=	Inner diameter of outer nozzled
D_e	=	Equivalent diameter of the outer jet
d_e	=	Equivalent diameter of the inner jet
U_r	=	Velocity of the jet at radial direction
U_c	=	Axial Velocity of the jet at the axis
λ	=	Velocity ratio $(U_0/U_{i)}$ P - Pressure
X,Y	=	Coordinates in the lateral direction
Z	=	Axial coordinate in the flow direction
ρ	=	Density of fluid
P_{atmo}	=	Atmospheric pressure
P_t	=	Total Pressure

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