A Relook at Jet Charcteristics using Laser Doppler Velocimeter

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Abstract: Three jet configurations, viz. single jet, annular jet and coaxial jet have been relooked with the help of LDV. It is observed that single jet behaviour established with intrusive probes agrees well with LDV measurements. It is seen that annular jet development is slow on account of suction through the central core. Velocity ratio effect on coaxial jets in unconfined space has been established.

Received: *10 December 1995*
Accepted: *26 November 1996*

Keywords: *Jets, Laser Doppler Velocimeter*

INTRODUCTION

Measurements of velocity distributions in any flow system is necessary to understand the flow mechanism and its development. These measurements in the past have been taken using intrusive probes. Development of Laser Doppler Velocimeter, a non-intrusive technique, has prompted many researchers to have a relook at the already explored fluid flow systems. An understanding of the fluid mechanics of flow development for free jet, annular jet and coaxial jets is necessary for various engineering applications.

Single round jet exhausting in an unconfined space has been thoroughly investigated and results are well documented in Abramovich [1], Rajaratnam [2] and Rodi [3]. Analytical methods have been developed by Rajaratnam [2], Tucker and Islam [3] and others for the analysis of these jets. Annular jets with no central jet have also been investigated by many researchers [2, 5, 6, 7]. It has been established from these studies that vortices are generated at the inner mixing region and not at the outer mixing region. Unconfined coaxial jets have been the subject of study of Chigier and Beer [8], Champagne and Wynanski [9] and Durao and Whitelow [10]. Their studies have shown that the coaxial configuration of jets reaches a self preserving state faster than a single axisymmetric jet and the rate at which the self preserving state is reached is a function of the interface height and the nature of the inlet velocity profile. It is important to note here that only Durao and Whitelaw [10] have used Laser Doppler Anemometer (LDA) for simple flow configuration.

The physical model of jets, single or coaxial, mixing in a confined space is complex on account of wall recirculation, interface wake and centre line vortices. Strength of LDA technique in allowing understanding the flow domain for such physical models has now been well established.

In the present study, the behaviour of a single round jet in presence of an annular confined space, an annular jet in the presence of the central space and coaxial jet configuration have been investigated using LDV technique.

EXPERIMENTAL FACILITY

The experimental facility showing the configuration of jets is shown in Fig. 1. The LDV set up is shown in Fig. 2. Figure 1 shows the flow set up designed and fabricated for the present study. The central nozzle which formed the inner or central jet had a diameter of 12.57 mm. An annular nozzle with its inner diameter of 25.9 mm formed the outer jet. The interface height between the two jets was 1.9 mm. Deducing the area occupied by the interface height, the area ratio of outer to inner jet was obtained as 2.55. Air to both the jets was supplied by two independent centrifugal blowers.

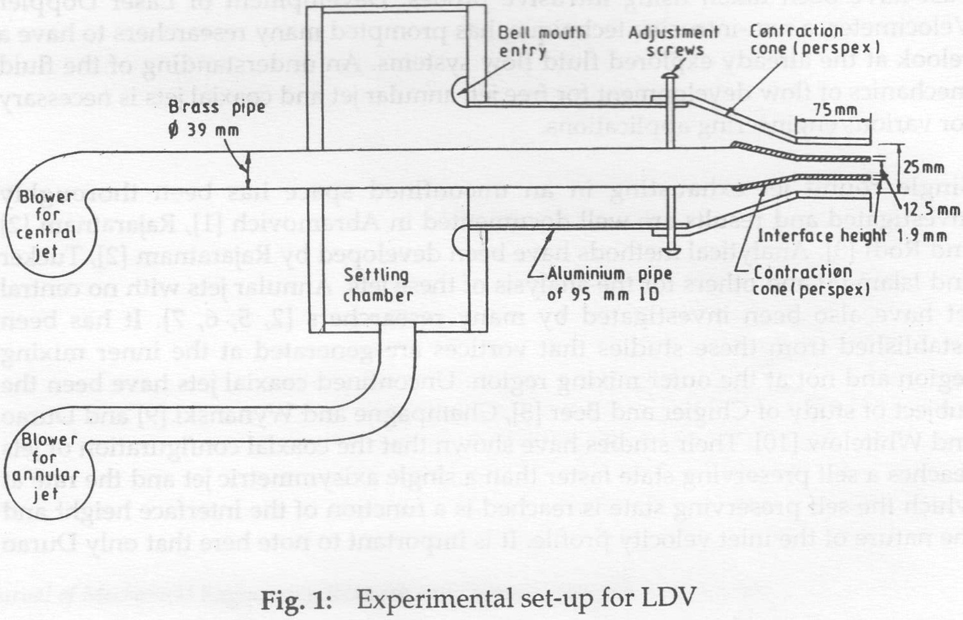

Fig. 1: Experimental set-up for LDV

The outer jet is fed by the blower through a setting chamber, along an annular passage and a contraction cone. A bell mouth is provided at the setting chamber exit to avoid corner effects penetrating into the measuring section. The contraction cone reduces the 95 mm outer diameter of the annular passage to an outer jet diameter of 25.9 mm for the annular passage. A straight length of 75 mm downstream of the contraction cone allows the annular jet to become uniform before it exhausts into the unconfined space.

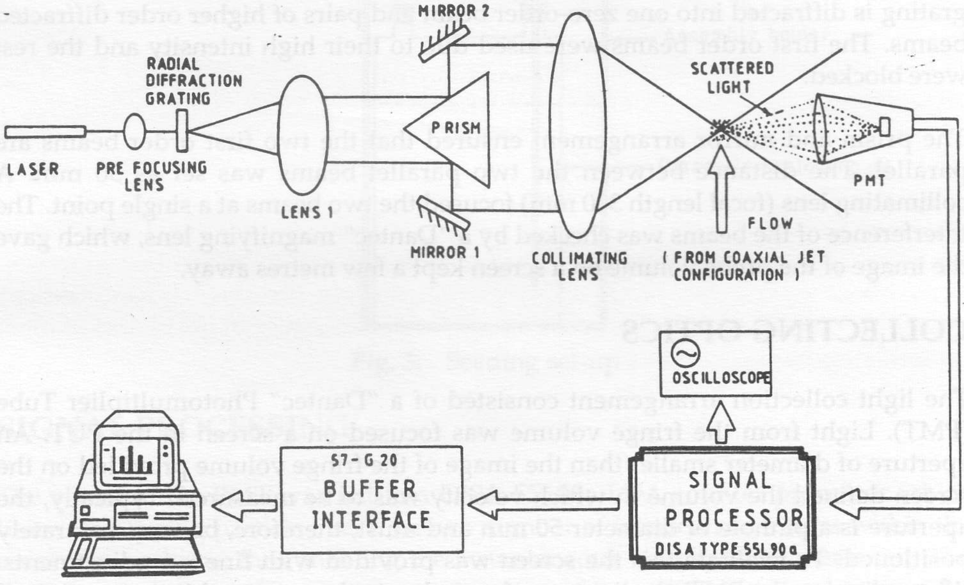

Fig. 2: Optical set-up

The central jet was formed from a long pipe of 39 mm diameter, one end of which was connected to a centrifugal blower. At the other end, a contraction cone was provided to reduce the pipe diameter from 39 mm to 12.75 mm, the actual diameter of the central jet. A straight length of 75 mm was also provided to achieve uniform flow in the central jet. Both the blowers had a facility for controlling the RPM and hence the velocity of the jets. The interface height between the jets at the exit was 1.9 mm.

LASER DOPPLER ANEMOMETER SET-UP

The Laser Doppler Anemometer was operated in the dual or real fringe mode with light collection in forward direction. The beam splitting was achieved by means of a radial diffraction grating. A schematic representation is shown in Fig. 2. The LDA set up was mounted on a milling table which allowed motion to it in all the three orthogonal directions.

TRANSMITTING OPTICS

It comprised a light source (35 mW He-Ne Laser), a predensity filter, a radial diffraction grating for beam splitting and a prism with two mirrors and a focusing lens. The laser light used had a wavelength of 632.7 nm. The predensity filter was used to focus the Laser beam to minimum waist diameter having Gaussian distribution of light intensity. The light while passing through the high efficiency grating is diffracted into one zero-order beam and pairs of higher order diffracted beams. The first order beams were used due to their high intensity and the rest were blocked.

The prism and mirror arrangement ensured that the two first order beams are parallel. The distance between the two parallel beams was set as 50 mm. A collimating lens (focal length 300 mm) focused the two beams at a single point. The interference of the beams was checked by a "Dantec" magnifying lens, which gave the image of the probe volume on a screen kept a few metres away.

COLLECTING OPTICS

The light collection arrangement consisted of a "Dantec" Photomultiplier Tube (PMT). Light from the fringe volume was focused on a screen in the PUT. An aperture of diameter smaller than the image of the fringe volume provided on the screen defined the volume in which velocity was to be measured. Typically, the aperture is a pinhole of diameter 50 mm and must, therefore, be very accurately positioned. To facilitate this the screen was provided with fine x-y adjustments. When aligning the PMT, the light was focused onto the screen while being viewed through a port. A sheet of white or tissue paper was kept at the fringe volume and the light scattered from it was accurately focused on a small black spot in the centre of the screen. The PMT was mounted about 10^{o} upwards of the plane of the beams, to prevent any extraneous light entering the receiver. The PMT was operated at 1.5-2 kV and its maximum mean anode current was limited to 100 mA.

SEEDER

Corn oil was used to seed the flow with the help of seeder shown in Fig. 3. A fine jet produced by the passage of air through a small opening draws up oil from the reservoir by the venturi effect and disintegrates the oil droplet into a fine spray to be carried by the air flow. Compressed air from a reciprocating compressor was supplied to the atomiser. A pressure valve was installed at the compressor outlet to minimise fluctuations in the flow rate of compressed air, thereby ensuring a uniform seeding rate. A separator was also provided in between the atomiser and the seeding point which helped in preventing larger particles from entering the system.

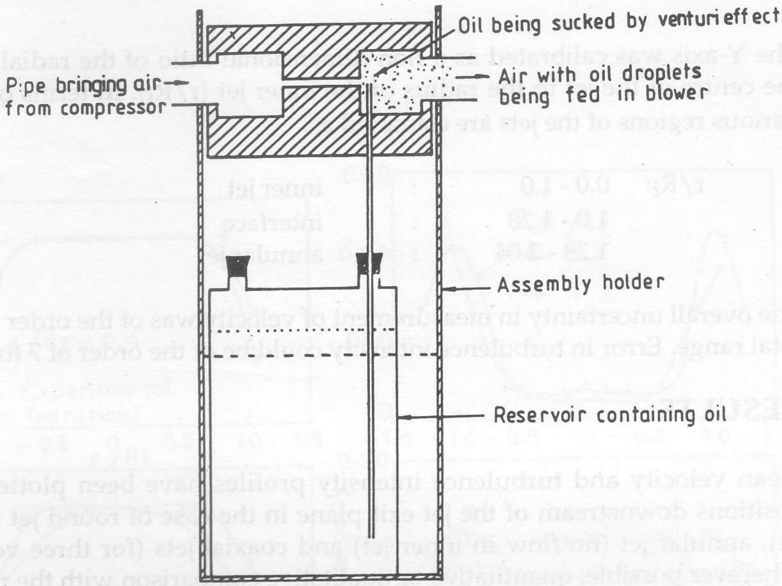

Fig. 3: Seeding set-up

SIGNAL PROCESSING

The signal of the PMT was fed to a DISA 55L90a LDA counter processor which times a scattering particle over a known number of interference fringes within the measuring volume, thus enabling the instantaneous velocity to be measured. The digital output from the counter was transferred to a 57G20 buffer interface for communication with a PC.

For proper analysis of the signal it was important to have a high Data Rate (the number of validated pulses) and a high Validation Rate (ratio of validated pulses to the total pulses). This was achieved by properly controlling the seeding rate, focusing the scattered light on the PMT and by adjusting the filter settings. The operation of the counter processor was always in the optimised mode. "EnCOUNTER", a Dantec software was used to perform the data analysis. An online display allowed optimisation of different instrument settings.

EXPERIMENTAL PROGRAM

The mean and rms velocities have been measured along the jet cross section at various axial locations. The measurements were carried out all the way through the jet to regions at the edge of the jet, where the turbulence intensity reached a very high value. The measurements were extremely stable as long as sufficiently long averaging time was used.

The Y-axis was calibrated as a non-dimensional ratio of the radial distance from the centre of the jet to the radius of the inner jet (r/R_i). In terms of this ratio the various regions of the jets are classified as:

r/R_i:	0.0 - 1.0	:	inner jet
	1.0 - 1.28	:	interface
	1.28 - 2.04	:	annular jet

The overall uncertainty in measurement of velocity was of the order of ± 3% for the total range. Error in turbulence intensity could be of the order of 7 to 10%.

RESULTS

Mean velocity and turbulence intensity profiles have been plotted at different positions downstream of the jet exit plane in the case of round jet (axisymmetric jet), annular jet (no flow in inner jet) and coaxial jets (for three velocity ratios). Wherever possible, quantitative or qualitative comparison with the results of other investigators has been carried out.

Round Jet

When an incompressible turbulent jet discharges into still air, the shear layer grows continuously with the entrainment of the ambient surrounding air. The characteristics of the turbulent jet can be divided into three principle regions. The initial region has uniform velocity or potential core (Fig. 4a) which extends up to $x/D_i \sim 8$). Further downstream, there exists a developed region where the eddy structure becomes such that the flow quantities, i.e., mean velocity, turbulent intensity etc., become self-preserving. Due to shearing at the interface between the jet and the surrounding ambient air the turbulent intensities are higher in that region (Fig. 4b). Even by $x/D_i = 9.55$, the intensities in the shear layer are high.

A theoretical model developed by Tucker and Islam [4], based on their experimental work, has been used in the present investigation to validate LDV results. The theoretical profiles obtained have been plotted along with the experimental profile and the two were found to be in good agreement in general. In the downstream region the deviations between the theoretical profile and the experimental profile increased. This discrepancy can be explained by the fact that the relation used by Tucker and Islam was empirical and hence is prone to errors.

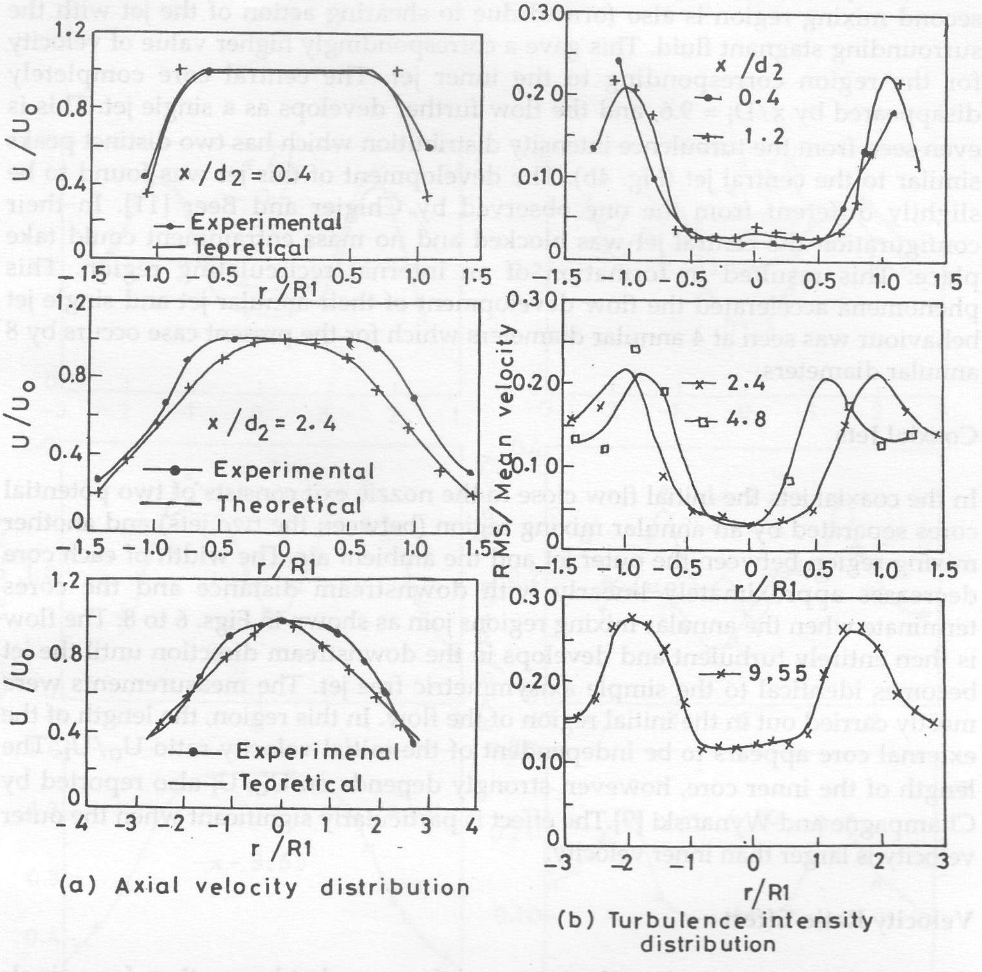

Fig. 4: Flow characteristics of axisymmetric central jet

Annular Jet

For the annular jet, two distinct peaks were observed in the annular region near the jet exit (Fig. 5a). Since the inner jet was not blocked, air was drawn in from the inner jet by the shearing action of the annular jet, forming a mixing region. A second mixing region is also formed due to shearing action of the jet with the surrounding stagnant fluid. This gave a correspondingly higher value of velocity for the region corresponding to the inner jet. The central core completely disappeared by $x/D_i = 9.6$, and the flow further develops as a single jet. This is even seen from the turbulence intensity distribution which has two distinct peaks similar to the central jet (Fig. 4b). The development of this jet was found to be slightly different from the one observed by Chigier and Beer [11]. In their configuration the central jet was blocked and no mass entrainment could take place. This resulted in formation of an internal recirculating region. This phenomena accelerated the flow development of their annular jet and single jet behaviour was seen at 4 annular diameters which for the present case occurs by 8 annular diameters.

Coaxial Jets

In the coaxial jets the initial flow close to the nozzle exit consists of two potential cores separated by an annular mixing region (between the two jets) and another mixing region between the outer jet and the ambient air. The width of each core decreases approximately linearly with downstream distance and the cores terminate when the annular mixing regions join as shown in Figs. 6 to 8. The flow is then entirely turbulent and develops in the downstream direction until the jet becomes identical to the simple axisymmetric free jet. The measurements were mostly carried out in the initial region of the flow. In this region, the length of the external core appears to be independent of the initial velocity ratio U_o/U_i. The length of the inner core, however, strongly depends on U_o/U_i also reported by Champagne and Wynanski [9].The effect is particularly significant when the outer velocity is larger than inner velocity.

Velocity Ratio Effect

When $U_o/U_i = 0.5$, length of the inner core is somewhat longer than for a single jet, and this may result primarily from the decreased shear between the inner jet and its surroundings. A clear decrease in the mean velocity is observed in the interface region near the jet exit (Fig. 6). The turbulence levels are correspondingly high. The effect of the interface is to act as a buffer between the two jet streams thereby delaying the merging point of the jets. This increases the turbulence level and gives better mixing. The flow becomes developed at around a distance equal to thirteen inner jet diameters. The effect of the interface is visible till $x/D_i = 5.57$.

The two jets are separate and distinct peaks corresponding to shearing between the annular and inner jets and annular and ambient fluid are clearly visible. The turbulence intensity level at the axis is only 1%, which is lower than the corresponding levels for a single jet ($x/D_i = 5.6$).

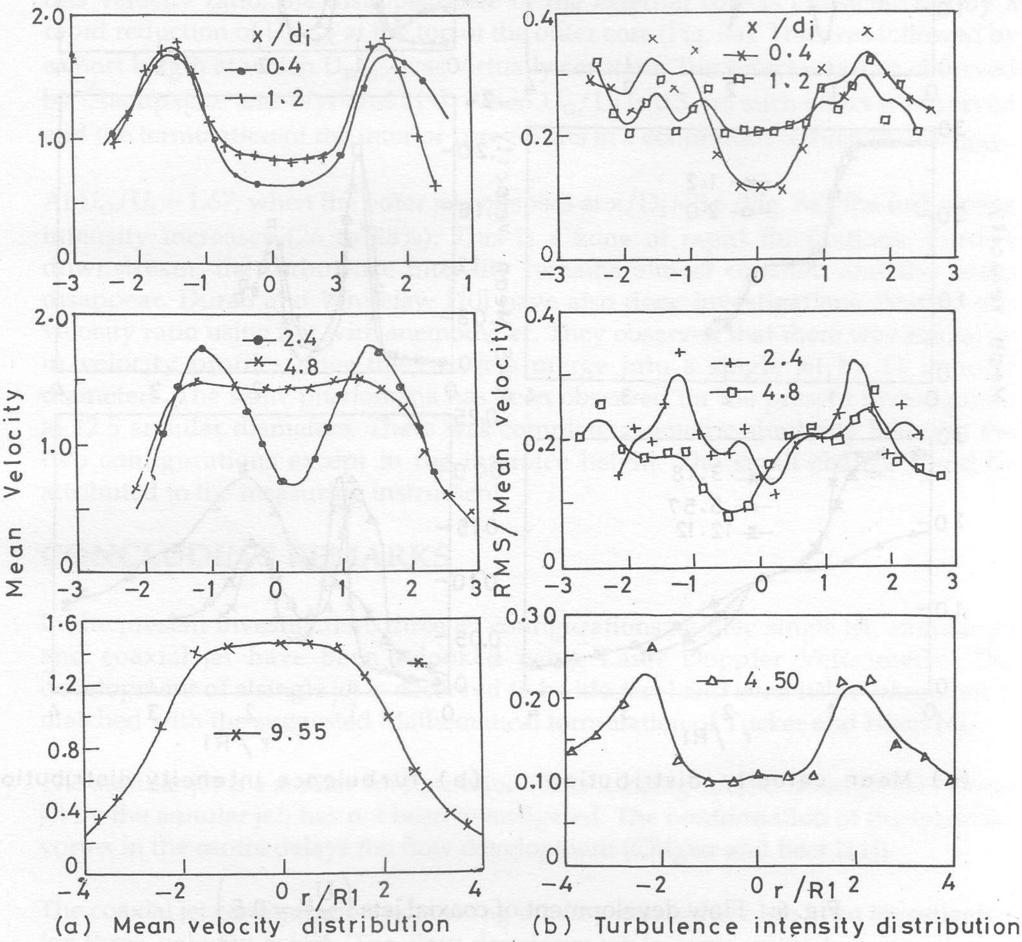

Fig. 5: Flow characteristics of axisymmetric annular jet

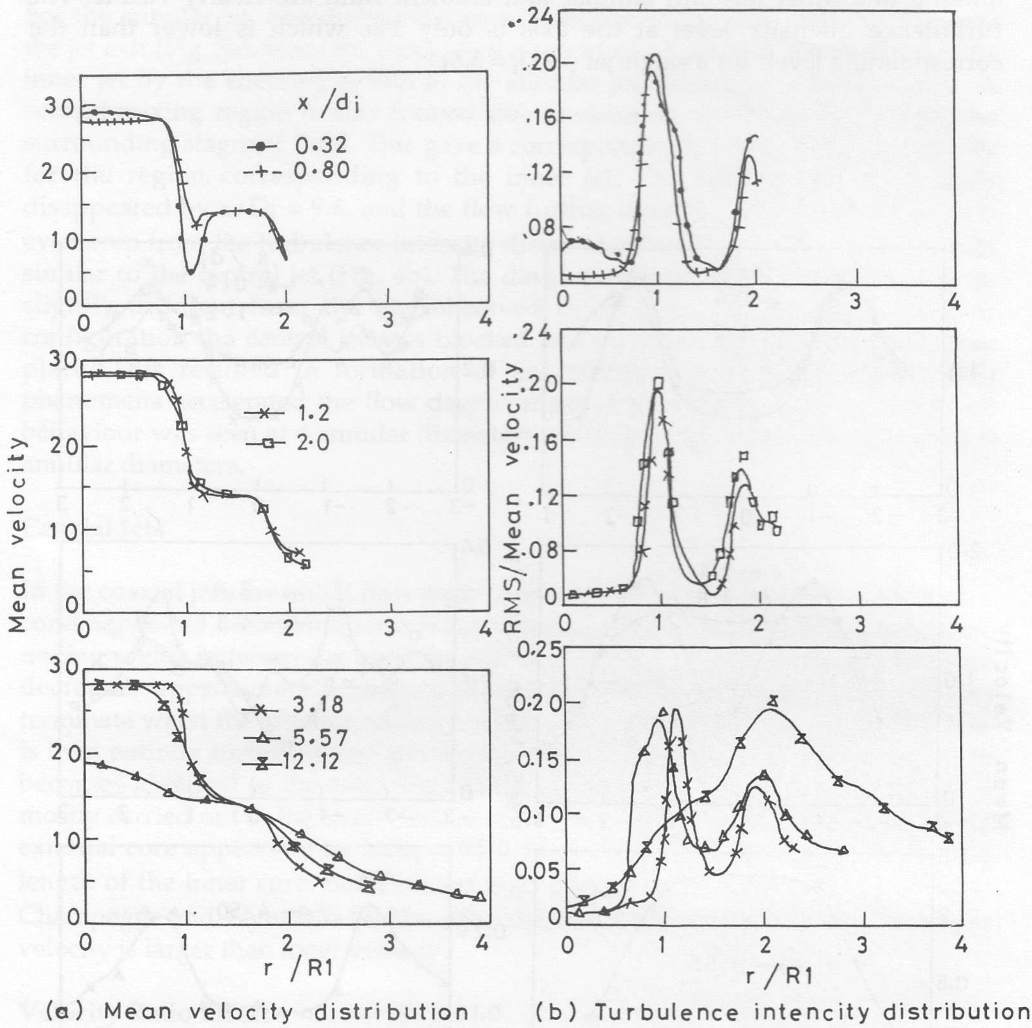

Fig. 6: Flow development of coaxial jets $\left(\frac{U_o}{U_i} = 0.5\right)$

For $U_O/U_i = 1$, the remnants of the upstream boundary layers quickly disappear and the two cores merge into one by $x/D_i = 2$ (Fig. 7a). The turbulence intensity which shows two peaks before the merging of the two jets, now has only one peak corresponding to the shearing of the outer jet with the ambient fluid (Fig. 7b).

Though the mean velocity profile becomes almost parabolic at $x/D_i = 12.7$, the turbulence intensity shows a peak corresponding to $r/R_i = 1.7$. This shows that the two jets have not mixed completely even at this position.

When U_o/U_i is 1.67, the length of the inner core is reduced. This is due to the relatively low pressures created in the inner core (under these flow conditions) which allows the external jet to spread faster and thus shorten the inner core. At this velocity ratio, the disappearance of the external core is characterized by a rapid reduction of U_{max} at the top of the outer core (Fig. 8a). This was followed by a short length at which U_{max} was virtually constant. This effect was also observed by Champagne and Wynanski [9]. When U_o/U_i is 0.5, no such effect is observed and the termination of the interior core results in a continuous reduction of U_{max}.

At $U_o/U_i = 1.67$, when the outer jet collapses at $x/D_i = 5.6$ (Fig. 8a), the turbulence intensity increases (26 to 28%). This is a zone of rapid fluctuations. Further downstream, the turbulence intensity remains almost constant and the peaks disappear. Durao and Whitelaw [10] have also done investigations close to this velocity ratio using hot wire anemometer. They observed that there was similarity in velocity profiles after the two jets merge into a single jet by 11 annular diameters. The same phenomena has been observed for the present investigation at 12.5 annular diameters. There was complete geometric similarity between the two configurations except in the interface height. The small change could be attributed to the measuring instrument.

CONCLUDING REMARKS

In the present investigation, three jet configurations namely single jet, annular jet and coaxial jet have been relooked using Laser Doppler Velocimeter. The development of a single jet is observed to be identical and even its development is matched with the suggested Mathematical formulation of Tucker and Islam [4].

The annular jet is a similar configuration (flow is being sucked through the central jet by the annular jet) has not been investigated. The nonformation of the torroidal vortex in the centre delays the flow development (Chigier and Beer [11]).

The coaxial jet configuration exhausting into the atmosphere has been investigated for three velocity ratios. The flow development is comparatively faster than a single jet but the difference seen by Durao and Whitelaw [10] seems to be biased due to intrusive probe. It is seen that velocity ratio to one gives the best flow development in terms of flow uniformity and mixing. The present investigation done by LDV shows slightly delayed similarity region in comparison to Durao and Whitelaw [10]. The turbulence intensities measured are identical.

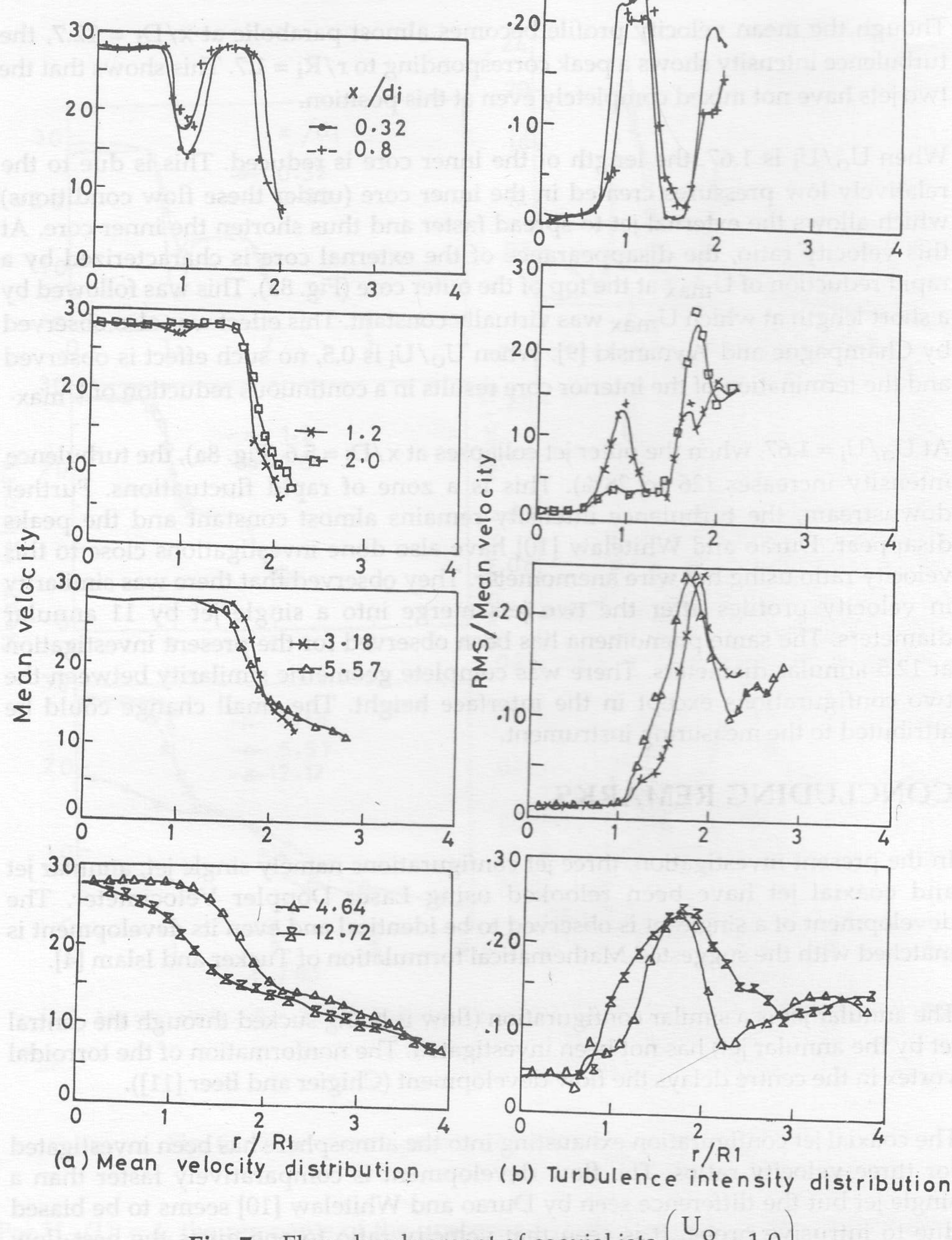

Fig. 7: Flow development of coaxial jets $\left(\frac{U_o}{U_i} = 1.0\right)$

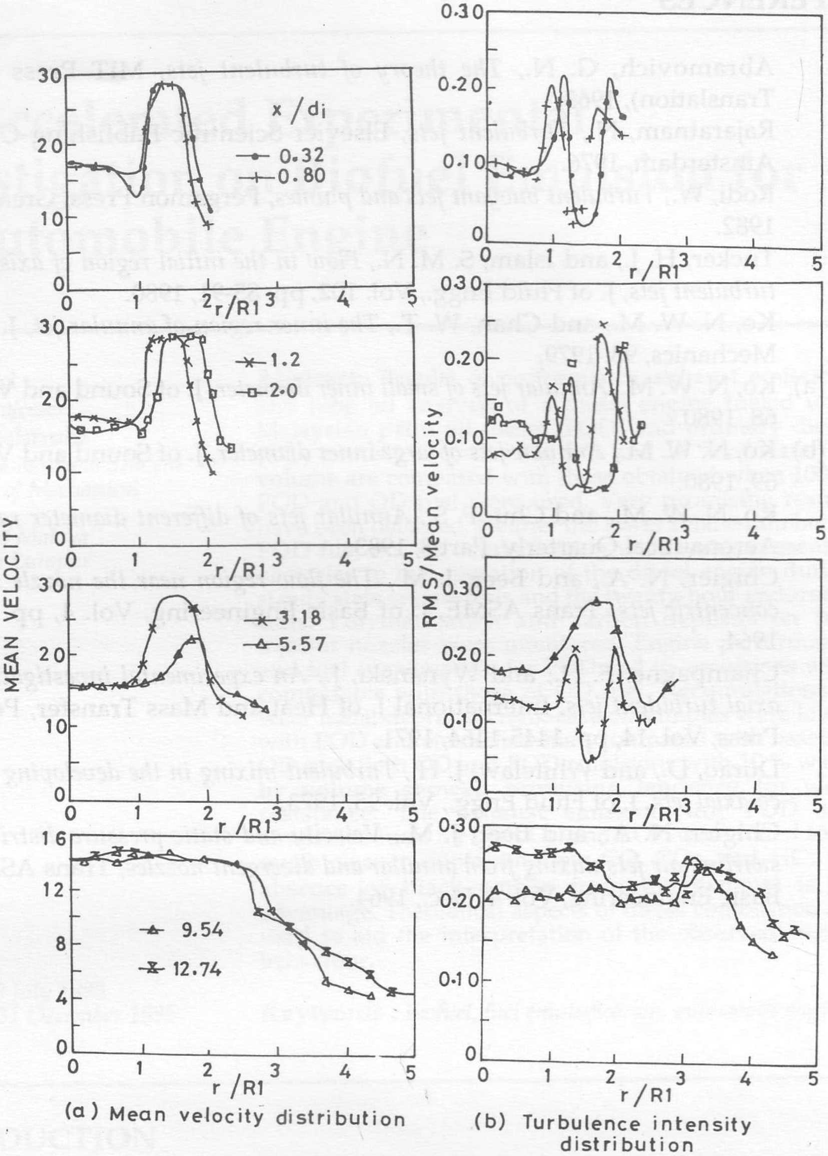

Fig. 8: Flow development of coaxial jets $\left(\frac{U_o}{U_i} = 1.67\right)$

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