Turbulence Characteristics of Swirling Jets in a Dump Combustor Model

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Abstract: The turbulence characteristics of weakly co-swirling coaxial jets exhausting into a dump combustor model has been evaluated at different velocity ratios using a single normal hot wire probe. It has been found that velocity ratio of 1.0 gives the best mixing and lateral spread of the jets in the confinement. Measurements of wall pressure distribution along the test confinement have also been reported.

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INTRODUCTION

The interaction of swirling axisymmetric jets in a confinement has been the subject of research in the last decade all over the world [1-6]. The emphasis of these investigations has been to establish the type of flame which may be formed into a confinement of expansion ratio 1.0 or a dump confinement.

Habib and Whitelaw [1] measured the flow characteristics of turbulent, confined swirling coaxial jets and quantified the effect of the confinement and the swirl on the tendency of flow reversal on the centre line. Vu and Gouldin [2] investigated co and contra swirling coaxial jets mixing into a cylindrical confinement (ER = 1.0) and observed a zone of reverse flow on the centre line. Gouldin et al. [3] have extended the work of Vu and Gouldin [2] for reacting flows using laser anemometry and found that the central recirculation zone was present for both co and contra swirl combinations. So et al. [4] in their study on jets in a large expanding confinement have shown that the presence of a confinement enhances the dissipative nature of the jet and the superimposition of the swirl further increases the rate of dissipation. Singh et al. [5-7] have done a detailed analysis of swirling coaxial jets in a confinement and have quantified the effect of swirl on the development of coaxial jets in a confinement for a number of configurations of the swirl. In most of the above studies, the changes in flow development phenomena in comparison to non-swirling unconfined jets have been attributed to the setting up of radial and axial pressure gradients due to the presence of swirl and confinement.

Literature is scanty on the turbulence characteristics for co-axial jets exhausting into a dump confinement. These have been only measured by Habib and Whitelaw [1] and Singh and Agrawal [8]. This paper presents the turbulence characteristics for co-swirling, coaxial jets exhausting into a dump confinement. These have been evaluated based on detailed measurement taken with the help of a single normal hot wire probe using the method suggested by Beer and Chigier [9]. The expansion ratio of the dump confinement was fixed at 2.10 and the swirl in both the jets was imparted in clockwise direction with the help of a 15° annular swirler and a 15° hubless swirler. With these fixed conditions, the effect of the velocity ratio (V_o/V_i) on the mixing of jets has been investigated. The velocity ratios selected were 0.55, 1 and 1.5.

EXPERIMENTAL SETUP AND PROGRAM

The schematic sketch of the experimental setup is shown in Fig. 1. It consists of two blowers, a 2-D rectangular diffuser which houses a small settling chamber for the inner jet, a settling chamber, central and annular jets and the confinement forming the measuring section. The detailed description of the test set up is given in Kesri [10].

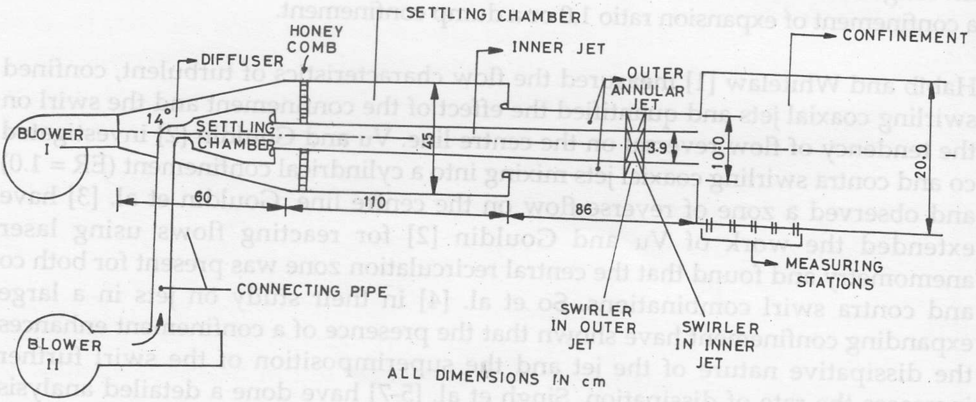


Fig. 1 : Detail of Experimental Set-up.

The central round jet was made from a 2.7 m long brass pipe with 39 mm ID and 42 mm OD. The flow in this jet was monitored by an orifice plate fixed downstream of the blower. Mean average velocities were fixed at 24.55 m/s, 36.8 m/s. and 66.94 m/sec. The annular jet was made of an aluminium pipe having 95.4 mm ID and 0.86 m length. The air to this jet was supplied by an independent blower via a settling chamber. A bell mouth shape was provided at the junction of the annular jet pipe with the settling to damp out the effect of disturbances in the annular jet as a result of area change. The mean average velocity in this jet was fixed at 36.8 m/sec. Thus the velocity ratios (V_o/V_i) achieved between the two jets were 0.55, 1.0 and 1.5. Swirlers with vanes inclined at 15° to the axial direction imparting circumferential velocity in clockwise direction were designed as per Mathur [11] and installed two diameters upstream of the jet exit plane. The vane thickness for the annular and hubless swirlers were 1 mm and 0.5 mm respectively. The vane wakes formed, if any, did not influence the flow development phenomena in the confinement as it is known that these wakes decay approximately over a distance of 200 times the vane thickness [13]. The 'test confinement consisted of two cylindrical pipes casted out of fibre glass and joined together with flanges. The total length of the confinement was kept 0.9 m and the internal diameter was 200 mm. Thus an expansion ratio of 2.10 was achieved.

Most of the measurements of velocity and turbulence quantities were done using a 5 µ tungsten wire normal hot wire proble using `DISA' Hot-wire Anemometer. A three hole probe in null mode was also used to measure the mean velocity for the sake of comparison with hot wire data, in high turbulence zone. A tuft probe was used for flow visualization.

Wall static pressures were obtained on the test section wall along its length with the help of wall static pressure tappings. At each axial location, three tappings were fixed at 120° to each other on the confinement circumference. These pressure tappings taps were also helpful in ascertaining the symmetry of the confinement with the jet axis.

The flow symmetry in the test section was ascertained through continuity and was found to be within ± 2%. The error in velocity measurements was of the order of 2 to 3% for velocities greater than 5 m/s. Where as for the lower velocities it increased and was as high as 25%. Other measurements had an accuracy of about 3%.

PROCEDURE FOR EVALUATION OF MEAN VELOCITY AND REYNOLD'S STRESSES

The single wire method as proposed by Beer and Chigier [9] has been adapted to measure velocity and Reynolds stresses in the test confinement. The wire was calibrated in a low speed low turbulence open circuit wind tunnel. The response of the wire was assumed to follow the modified Kings Law,

$$E^2 = A + B\,U^{1/2} + CU \quad (1)$$

Constants A, B, and C were evaluated from the calibration. The response of the hot wire to the three velocity components was taken as [9],

$$U^2 = U_x^2 + G^2 U_y^2 + K^2 U_z^2 \quad (2)$$

G and K are the yaw and pitch coefficients and were also obtained from calibration. The calibration was checked at regular intervals by measuring the cold resistance and the voltage for the zero velocity. In case of drift in the values of these parameters, the hot wire probe was recalibrated. The complete procedure of calibration was repeated in the event of hot wire breakdown with a new wire. Having calibrated the probe, the probe was fixed in the test section and traversed in the radial plane.

At any traverse point, measurements were taken at four orientations of the probe which were acheived by rotating the single wire in (z,θ) plane as shown in Fig. 2.

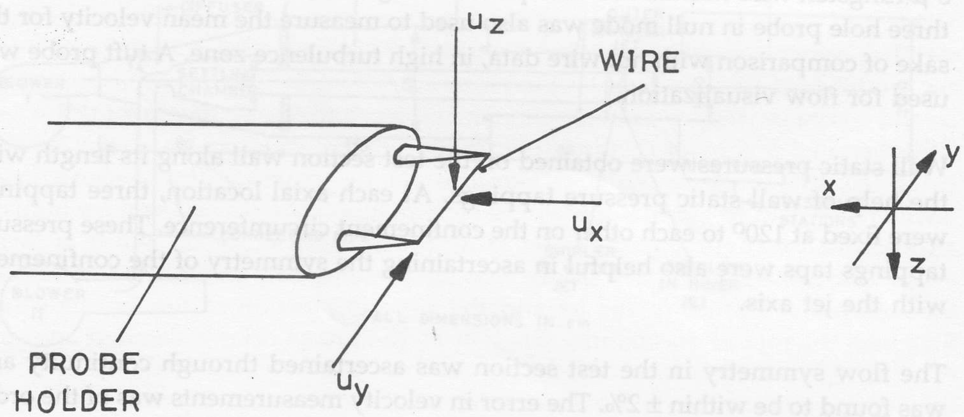


Fig. 2a: Coordinate system for directional response of a single hot-wire.

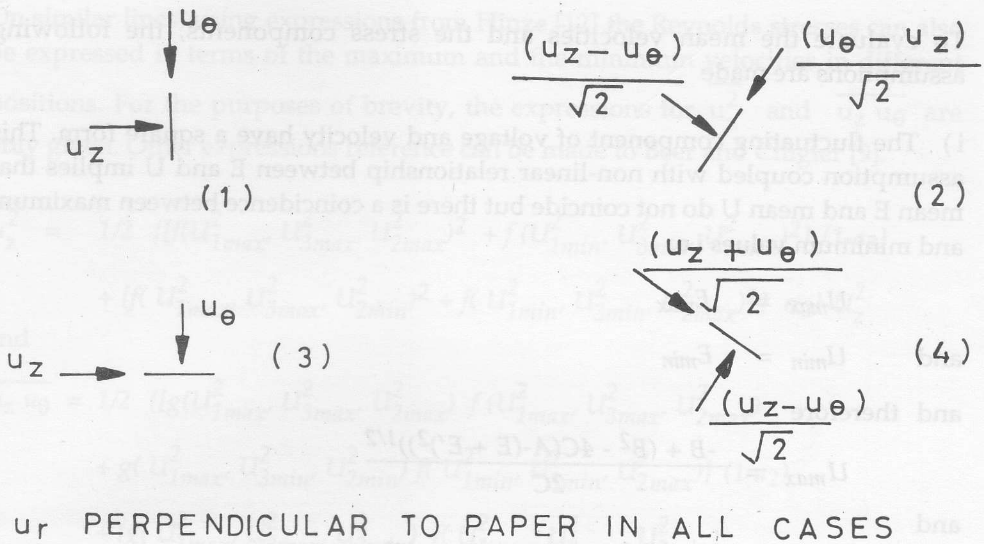


Fig. 2b : Velocity diagrams for various probe positions.

For the four positions, the response of the hot wire to the instantaneous velocity can be expressed as,

$$U_1^2 = U_r^2 + G^2 U_z^2 + K^2 U_\theta^2 \tag{3}$$

$$U_2^2 = U_r^2 + \frac{G^2}{2}(U_\theta + U_z)^2 + \frac{K^2}{2}(U_\theta - U_z)^2 \tag{4}$$

$$U_3^2 = U_r^2 + G^2 U_\theta^2 + K^2 U_z^2 \tag{5}$$

$$U_4^2 = U_r^2 + \frac{G^2}{2}(U_\theta - U_z) + \frac{K^2}{2}(U_\theta + U_z)^2 \tag{6}$$

Four equations can be taken and simplified to give U_r, U_z and U_θ. Choosing the first three equations, the three velocity components are expressed as,

$$U_z^2 = f(U_1^2, U_2^2, U_3^2) \tag{7}$$

$$U_\theta^2 = g(U_1^2, U_3^2, U_z^2) \tag{8}$$

$$U_r^2 = h(U_3^2, U_z^2, U_\theta^2) \tag{9}$$

To evaluate the mean velocities and the stress components, the following assumptions are made

i) The fluctuating component of voltage and velocity have a square form. This assumption coupled with non-linear relationship between E and U implies that mean E and mean U do not coincide but there is a coincidence between maximum and minimum values i.e.

$$U_{max} = E_{max}$$

and

$$U_{min} = E_{min}$$

and therefore

$$U_{max} = \frac{-B + (B^2 - 4C(A-(E + E')^2))^{1/2}}{2C}$$

and

$$U_{min} = \frac{-B + (B^2 - 4C(A-(E - E')))^{1/2}}{2C}$$

then $\bar{U} = 1/2\,[U_{max} + U_{min}]$

ii) The three voltages are of similar shape (E_1, E_2 and E_3) and same frequency but could be out of phase. E_1 and E_3 are in phase because U_θ, U_z have comparable magnitudes [9]. The phase difference can be derived by making use of the additional equation and can be expressed as,

$$\alpha_2 = \frac{[2U_4-(U_{1max}^2 + U_{3max}^2 - U_{2max}^2)^{1/2}-(U_{1min}^2 + U_{3min}^2 - U_{2min}^2)^{1/2}]}{[[(U_{1max}^2 + U_{3max}^2 - U_{2min}^2)^{1/2} + (U_{1min}^2 + U_{3min}^2 - U_{2max}^2)^{1/2} - (U_{1max}^2 + U_{3max}^2 - U_{2max}^2)^{1/2} - (U_{1min}^2 + U_{3min}^2 - U_{2min}^2)^{1/2}]]}$$

With the above assumptions, mean velocity in z-direction can be expressed as,

$$U_z = 1/T \int_o^T f(U_1^2, U_3^2, U_2^2)\,dt$$

$$U_z = 1/2\,\{[f(U_{1max}^2, U_{3max}^2, U_{2max}^2) + f(U_{1min}^2, U_{3min}^2, U_{2min}^2)]\,(1-a_2) + [f(U_{1max}^2, U_{3max}^2, U_{2min}^2) + f(U_{1min}^2, U_{3min}^2, U_{2max}^2)] + \alpha_2\}$$

Similar expressions can be found for U_θ and U_r.

On similar lines, using expressions from Hinze [12] the Reynolds stresses can also be expressed in terms of the maximum and the minimum velocities in different positions. For the purposes of brevity, the expressions for $\overline{u_z^2}$ and $\overline{u_z u_\theta}$ are only given. Other expressions reference can be made to Beer and Chigier [9].

$$\overline{u_z^2} = 1/2 \;\{[f(U_{1max}^2, U_{3max}^2, U_{2max}^2)^2 + f(U_{1min}^2, U_{3min}^2, U_{2min}^2)^2] (1\text{-}a_2)$$

$$+ [f(U_{1max}^2, U_{3max}^2, U_{2min}^2)^2 + f(U_{1min}^2, U_{3min}^2, U_{2max}^2)^2] \; \alpha_2\} \text{-} U_z^2$$

and

$$\overline{u_z u_\theta} = 1/2 \;\{[g(U_{1max}^2, U_{3max}^2, U_{2max}^2) \; f(U_{1max}^2, U_{3max}^2, U_{2max}^2)$$

$$+ g(U_{1max}^2, U_{3min}^2, U_{2min}^2) f(U_{1min}^2, U_{3min}^2, U_{2max}^2)] (1\text{-}a_2)$$

$$+ [g(U_{1max}^2, U_{3max}^2, U_{2min}^2) \; f(U_{1max}^2, U_{3max}^2, U_{2min}^2)$$

$$+ g(U_{1min}^2, U_{3min}^2, U_{2max}^2) \; f(U_{1min}^2, U_{3min}^2, U_{2max}^2)] \; \alpha_2\}$$

$$- \; \overline{U}_\theta \overline{U}_z$$

It is worthwhile to mention here that square wave form has been selected for the present analysis as it is easy. Any other wave form such as a triangular or a sine wave could have been selected [9], the results obtained should have been very similar.

RESULTS AND DISCUSSION

Flow symmetry was established by measuring the velocity field from wall to wall. Hence the results are presented in one half of the confinement only.

Flow Characteristics for Velocity Ratio = 0.55

Fig. 3 gives the flow characteristics for V_o/V_i = 0.55. The axial velocity profile is shown in Fig. 3a. Initially, there is a clear demarcation between the two jets. A strong recirculatiion zone, along the wall, is present. The demarcation between the two jets disappears beyond x/d_o = 0.77 and a central maximum is obtained. The recirculation zone attached to the confinement wall disappears beyond x/d_o = 3.88 and the flow beyond this position becomes uniform.

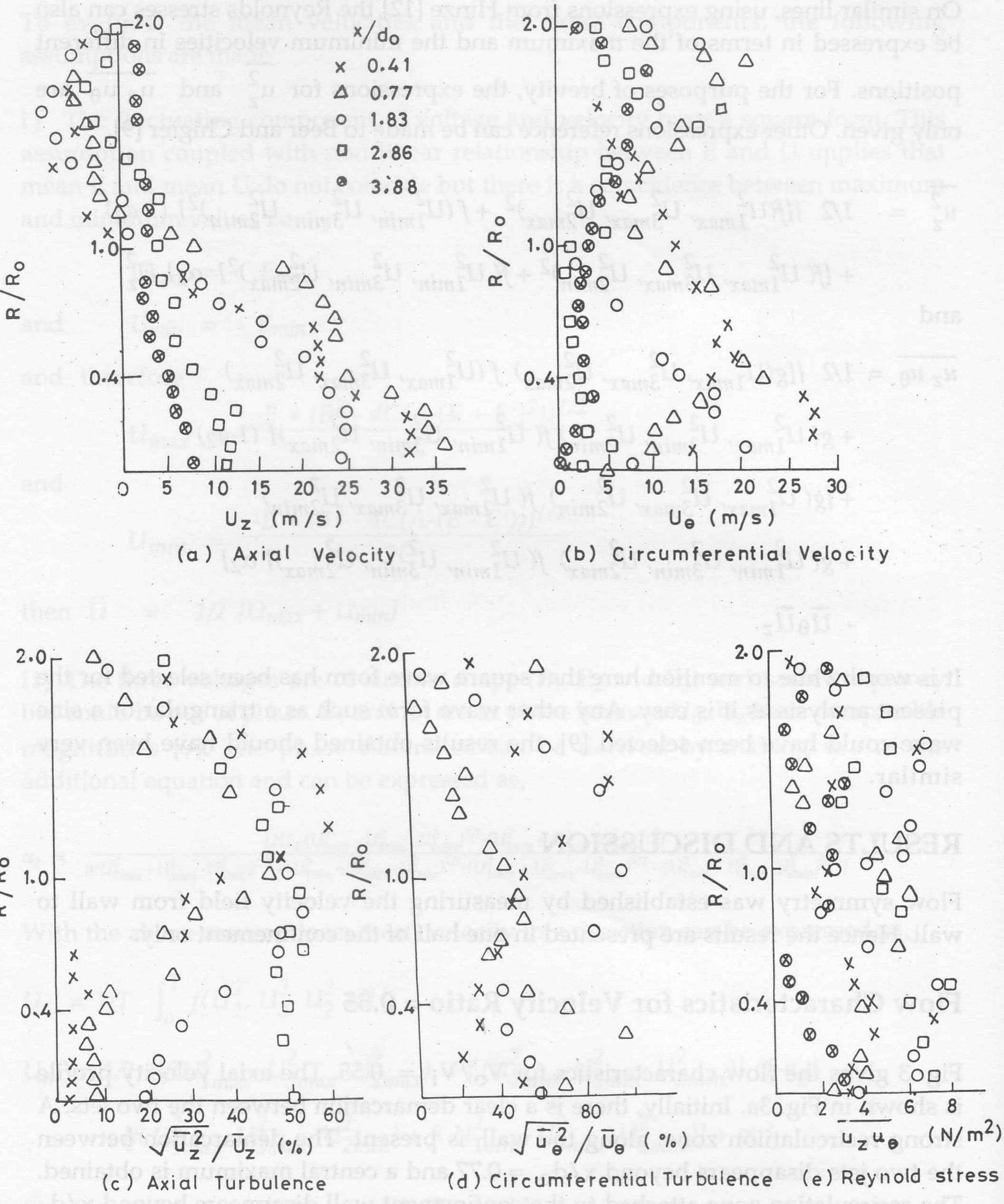


Fig. 3 : Flow characteristics in a Dump Confinement in (z-θ) plane for velocity ratio = 0.55.

The tangential velocity profiles are ploted in Fig. 3b. It is seen that initially the tangential velocity is confined in front of the jet on which it has been imposed. But, as the flow moves away from the jet exit plane, the tangential velocity reduces in the area of the jet where it was imposed but spreads in the outer part of the confinement. Thus the angular momentum is being transferred from the coaxial jets to the fluid outside it.

Axial turbulence intensity (Fig. 3c is very low for flow coming out of the jets. At $x/d_o = 0.41$, the turbulence level is seen to be very high in the recirculation zone. As flow moves along the confinement, it is seen that the maximum turbulence point shifts towards the centre line of the confinement, and the flow has nearly uniform axial turbulence at $x/d_o = 3.37$.

The tangential turbulence intensity (Fig. 3d), does not show a very definite pattern, although the peak values were very high and were generally found close to the interfaces or in the wall recirculation zone. The values beyond $x/d_o = 2.88$ were not very realistic (values greater than 100%) and hence have not been presented.

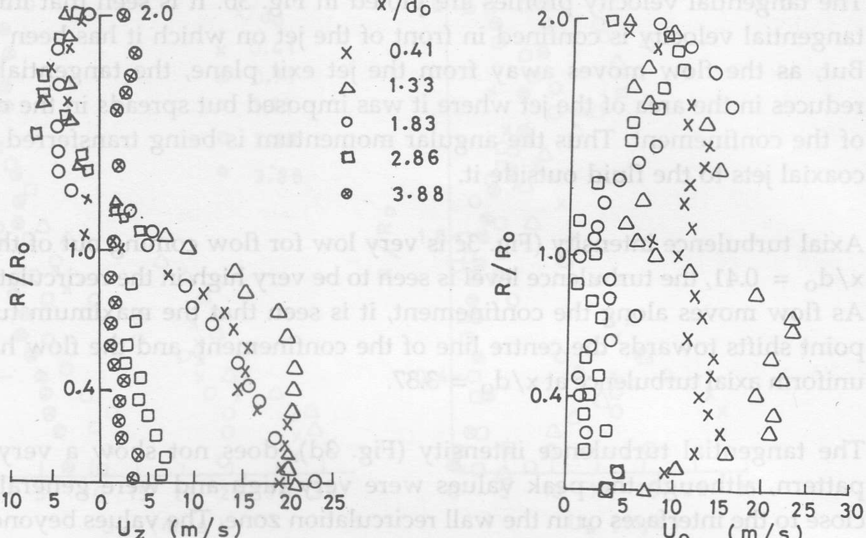
The Reynolds stress distribution, in the z - θ plane shown in Fig. 3e, depict peaks at the jet interface and these are also visible inside the recirculation specially at the boundary of the recirculation zone.

Flow Characteristics for Velocity Ratio = 1.0

The axial velocity profile shown in Fig. 4a depicts the demarcation between the two jets to exist only at the first axial location and by $x/d_o = 1.33$ the flow in the two jets develops as a single jet. Beyond this point only a central maximum exists, and the flow starts achieving uniformity earlier than $x/d_o = 3.38$ but the wall recirculation zone exists upto $x/d_o = 3.88$.

The tangential velocity profile presented in Fig. 4b, shows that the jets quickly spread out into the confinement initially, but further beyond the jet exit plane, the tangential velocity only reduces in front of the jets. In other words the decay of the swirl is slow.

Initial turbulence level in the jet area has a very small percentage of axial turbulence (Fig. 4c). In this case although the maximum point of the turbulence



(a) Axial velocity (b) Circumferential velocity

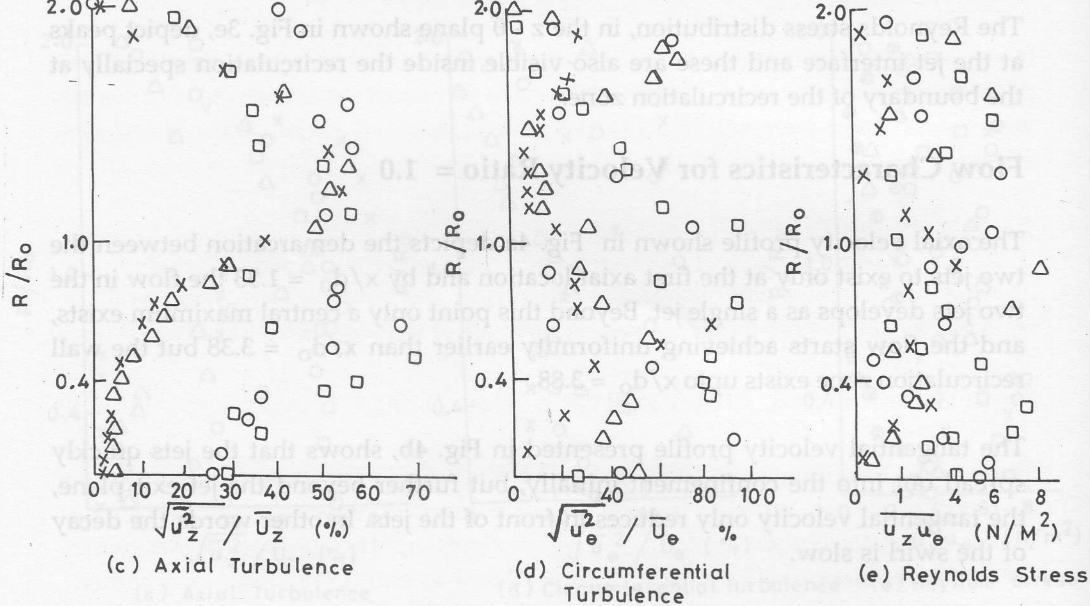


Fig. 4: Flow characteristics in a Dump Confinement for velocity ratio = 1.0

shifts towards the centre line, the level of turbulence does not become as uniform as in the previous case, although the average level of the turbulence is higher.

For this velocity ratio (Fig. 4d) the inlet tangential turbulence levels are quite high and those in the wall recirculation zones very low. The turbulence level in the wall recirculation zone increases and passes through a maxima and goes to a very low value where the recirculation zone ends. The turbulence levels in the jet area remain quite high and show two peaks which are not at the interfaces but do represent the shearing action between the two adjacent jets.

Figure 4e shows the Reynolds stresses in the z-θ plane and it is seen that the stresses are maximum at the interfaces of the jets except for $x/d_o = 1.83$. Peaks are also obtained at the shearing between the recirculating flow and the developing flow.

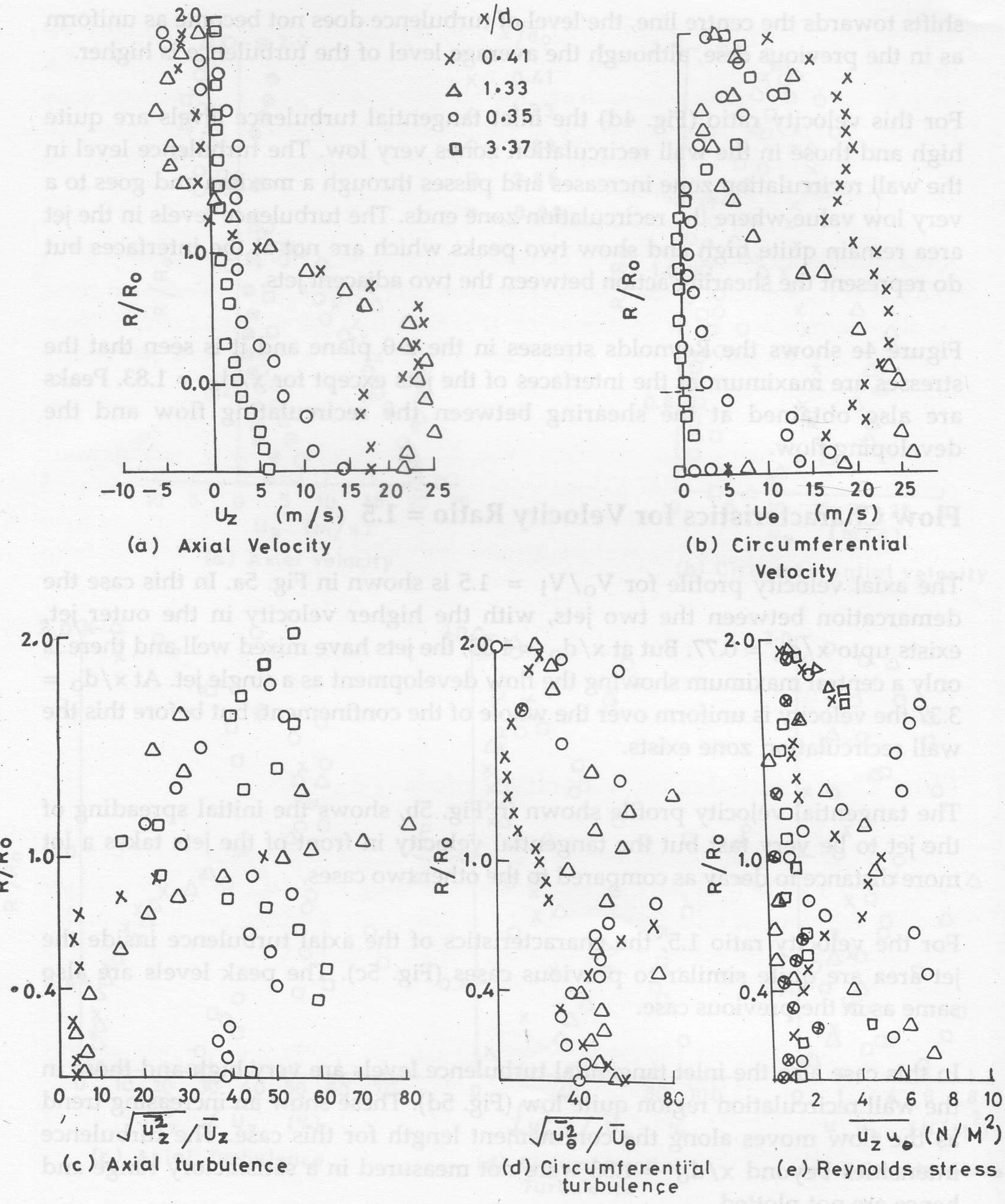
Flow Characteristics for Velocity Ratio = 1.5

The axial velocity profile for $V_o/V_i = 1.5$ is shown in Fig. 5a. In this case the demarcation between the two jets, with the higher velocity in the outer jet, exists upto $x/d_o = 0.77$. But at $x/d_o = 1.33$, the jets have mixed well and there is only a central maximum showing the flow development as a single jet. At $x/d_o = 3.37$ the velocity is uniform over the whole of the confinement, but before this the wall recirculation zone exists.

The tangential velocity profile shown in Fig. 5b, shows the initial spreading of the jet to be very fast but the tangential velocity in front of the jets takes a lot more distance to decay as compared to the other two cases.

For the velocity ratio 1.5, the characteristics of the axial turbulence inside the jet area are quite similar to previous cases (Fig. 5c). The peak levels are also same as in the previous case.

In this case also the inlet tangential turbulence levels are very high and those in the wall recirculation region quite low (Fig. 5d). These show an increasing trend as the flow moves along the confinement length for this case. The turbulence intensities beyond $x/d_o = 1.83$ were not measured in a satisfactory range and hence are not plotted.


x/d
0.41
1.33
0.35
3.37
R/Ro
Uz (m/s)
(a) Axial Velocity
Uθ (m/s)
(b) Circumferential Velocity
(c) Axial turbulence
(d) Circumferential turbulence
(e) Reynolds stress
(N/M²)

The Reynolds stress profile in the z - θ plane in Fig. 5e shows the peaks to occur generally at the interfaces of the jets and at the boundary of the recirculating flow. The profile becomes quite uniform beyond $x/d_o = 3.37$.

WALL PRESSURE DISTRIBUTION

Figure 6 shows the wall static pressure distribution along the confinement length. The negative pressure along the wall shows the existence of the wall recirculation zone. The point of attachment of the flow to the wall is nearly the same for all the cases. But higher pressure for velocity ratio of 0.55 shows that the recirculation is the strongest in this case, as compared to the other two cases.

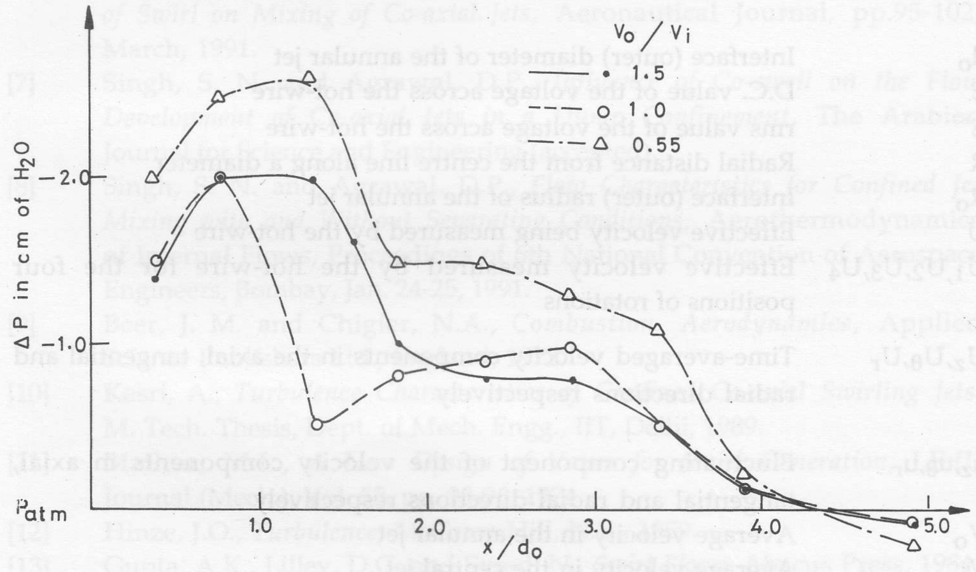


Fig. 6 Wall pressure distribution.

CONCLUSIONS

Based on the study the following important conclusions can be drawn,

(1) For the given swirl combination, best mixing is achieved for a velocity ratio of 1.0. The lateral spread is also maximum for this velocity ratio.

(2) The Reynolds stress distribution in the z-θ plane shows a maximum at the jet interfaces and the wall recirculation boundary. The transfer of fluctuating momentum is also found to be maximum at these layers.

(3) The wall pressure distribution very clearly establishes the point of flow attachment with the boundaries of the test geometry.

NOMENCLATURE

d_o	Interface (outer) diameter of the annular jet
E	D.C. value of the voltage across the hot-wire
E′	rms value of the voltage across the hot-wire
R	Radial distance from the centre line along a diameter
R_o	Interface (outer) radius of the annular jet
U	Effective velocity being measured by the hot-wire
U_1,U_2,U_3,U_4	Effective velocity measured by the hot-wire for the four positions of rotations
U_z,U_θ,U_r	Time-averaged velocity components in the axial, tangential and radial directions respectively
u_z,u_θ,u_r	Fluctuating component of the velocity components in axial, tangential and radial directions respectively
V_o	Average velocity in the annular jet
V_i	Average velocity in the central jet
x	Distance of axial location from jet exit plane

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