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# Turbulence Measurements in Swirling Flows

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**Abstract.** Investigations have been conducted to find out the region of high turbulent intensities in a swirling jet passing through a divergent passage. A hot wire anemometer is used to measure the turbulence intensity using a four position method. It has been concluded that the jet spreads with increasing diffuser angle and the region of high turbulent intensity also spreads. The high turbulence intensity region lies around the recirculation zone and it decays rapidly along the main flow direction.

## 1. Introduction

Flame size, shape, stability and combustion intensity are often controlled by the use of swirl, which is used in gas turbine combustors and industrial burners. Swirling flows are associated with high turbulence intensities and shear stresses. The location of the region where the shear stresses are high carries significant importance in the design of gas turbine combustors since it aids the process of evaporation of the injected liquid fuel. Swirling flows are commonly used for flame stabilisation in gas turbine combustors and industrial burners. The use of a diffuser at the outlet to the swirler reduces the pressure loss of the system. Swirling recirculating flows where the magnitude of flow fluctuations are large, are very complex in nature. The location of regions of high intensity of turbulence is important in the distribution of the fuel spray.

A constant temperature hot wire anemometer has been used by Rose[1] for measuring velocities and turbulence intensities. He has concluded from his experimental results that a swirling jet spreads at a larger angle, entrains rapidly and consequently displays a more rapid reduction in mean velocity. The hot wire anemometer technique was also used by Syred *et al.*[2] for determining the distribution of various shear stress components in an open swirling jet issuing from an annular swirler. They have concluded that a significant radial variation of effective viscosity exists with considerable anisotropy of turbulence. Rao *et al.*[3] also used a four position technique for measuring turbulence in free and swirling open jets. They have concluded that the high turbulence intensity region was outside the recirculation zone. Conducting the experiments on swirling jets caused by vane swirlers in an enclosed chamber, Ganesan[4] has concluded that a region of high kinetic energy exists in the recirculation zone. He further concluded that the recirculation zone grows with increasing vane angle accompanied by an increased kinetic energy of turbulence. The measured values of three components of mean velocity and corresponding normal stresses in a swirling flow are reported by Baker *et at.*[5] who have used a laser anemometer for measurement in isothermal flows and reacting flows of air and natural gas. The turbulent kinetic energy is presented for isothermal flow and nearly isotropic regions were identified. They have concluded that the regions of recirculation are different for reacting flow and that the turbulence is far from isotropic over a large extent of the flow field. An experimental study of the flow field of turbulent swirling jets passing through a diffuser of angle of 20° has been made by Chigier and Dvorak[6] in cold and reacting flows using the laser anemometer technique. They have concluded that the recirculation zone penetrated into the diffuser at a swirl number of 0.3 and that the flow pattern underwent substantial changes once combustion set in. The kinetic energy of turbulence in the flame was higher than in cold flows in almost all regions of the flame. The values of local properties obtained by solving conservation equations using a two equation turbulence model are presented and compared with measurements by Khalil *et al.*[7]. They have concluded that the results agree with the published data.

In the present work, the principle of four position method, useful in the measurement of three dimensional, turbulent, swirling recirculating flow is discussed and measurements made in a swirling jet passing through diffusers are presented and compared with those carried out in an open swirling jet.

**Nomenclature**

| | |
|---|---|
| $A, B, C$ | Constants in the probe calibration graphs |
| $D$ | Diameter of the annular swirler |
| $E$ | Mean D. C. voltage |
| $e$ | r.m.s. voltage |
| $G, K$ | Directional sensitivity constants of hot wire probe |
| $KE$ | Kinetic energy of fluctuations |
| $R_0$ | Radius of the annular swirler |
| $r$ | Non-dimensional radial distance $(r/R_0)$ |
| $\bar{u}$ | Mean axial velocity component |
| $u'$ | Axial fluctuating component |
| $U_{max}$ | Maximum velocity |
| $U_{min}$ | Minimum velocity |
| $U_{ref}$ | Reference velocity |
| $\bar{v}$ | Mean radial velocity component |
| $v'$ | Radial fluctuating component |

| | |
|---|---|
| $\bar{w}$ | Mean tangential velocity component |
| $w'$ | Tangential fluctuating component |
| $X$ | Axial distance |
| $\bar{X}$ | Non-dimensional axial distance ($X/R_0$) |
| $\theta$ | Diffuser half angle |

## 2. Principle of Four Position Method Used for Measuring Velocity and Turbulence

A hot wire anemometer has the advantage of causing minimum disturbance to the flow, coupled with high sensitivity. Its high frequency response allows measurements of turbulence intensities and shear stresses. The accuracy of measurement is shown to be improved by using higher order polynomials of the form

$$E^2 = A + B\sqrt{U} + CU \tag{1}$$

A constant temperature system is commonly used as it minimises the thermal inertia of the probe and in this method, the heating current constitutes a measure of heat transfer and hence the velocity. In the present investigations, a single wire probe is used to measure three dimensional mean velocities and turbulence level taking advantage of the directional sensitivities of the probe. In this method, only D. C. and r.m.s. voltages are to be measured at four positions for each point of measurement at intervals of 45° from the initial orientation of the probe. From the above measurements, it is possible to calculate the three components of the mean velocities and turbulence level.

### *Calibration of Hot Wire Probe*

The hot wire probe is usually calibrated in a uniform low turbulence air stream using a voltage-velocity relationship of the form given in Eqn. (1). Fig. 1a shows a hot wire probe along with the three components of the velocity vector acting in directions parallel to three axis. The calibration curves obtained for the three directions are shown in Fig. 1b. The response of the hot wire to the three velocity components can be written as

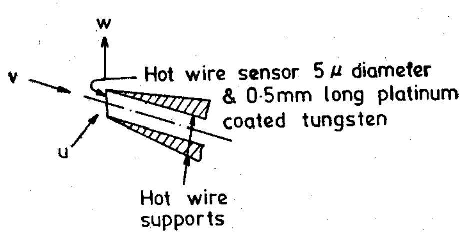


**Figure 1a.** Hot wire probe and velocity components.

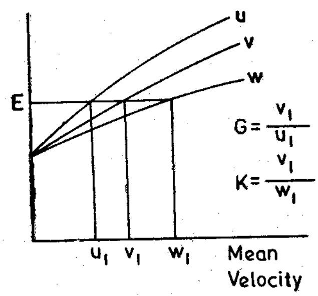


**Figure 1b.** Calibration curves for three different directions.

$$U^2 = v^2 + G^2u^2 + K^2w^2 \tag{2}$$

where $G = v/u$ and $K = v/w$ and $G$ and $K$ are known as directional sensitivity constants.

From Eqn. (1), $U_{max}$ and $U_{min}$ can be obtained as noted below if values of D. C. and r.m.s. voltages are known.

$$U_{max} = \left[\frac{-B + \sqrt{B^2 - 4C\{A - (E + e)^2\}}}{2C}\right]^2 \tag{3}$$

$$U_{min} = \left[\frac{-B + \sqrt{B^2 - 4C\{A - (E - e)^2\}}}{2C}\right]^2 \tag{4}$$

*Response Equations*

Considering the hot wire probe to be mounted parallel to the $v$-axis in the given co-ordinate system as shown in Fig. 2a, the probe may be rotated about its axis of symmetry and measurement of D.C. and r.m.s. voltages can be made at four positions at intervals of 45°. The response equations corresponding to each position of the probe can be derived from the velocity components as shown in Fig. 2b.

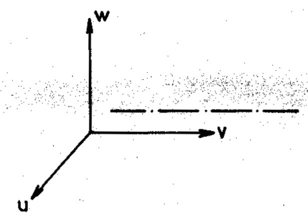


**Figure 2a.** Co-ordinate system—probe parallel to $v$-axis.

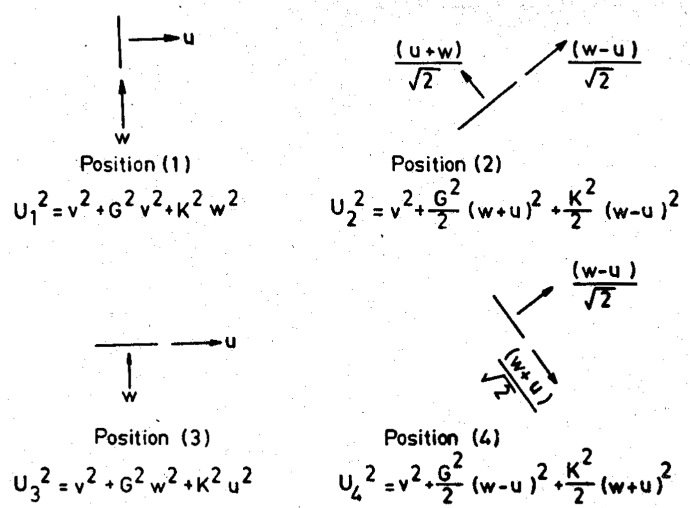


**Figure 2b.** Velocity components at various probe positions.

$$U_1^2 = v^2 + G^2u^2 + K^2w^2 \tag{5}$$

$$U_2^2 = v^2 + \frac{G^2}{2}(w+u)^2 + \frac{K^2}{2}(w-u)^2 \tag{6}$$

$$U_3^2 = v^2 + G^2w^2 + K^2u^2 \tag{7}$$

$$U_4^2 = v^2 + \frac{G^2}{2}(w-u)^2 + \frac{K^2}{2}(w+u)^2 \tag{8}$$

Three equations from the above set of four equations are sufficient for evaluating $u$, $v$ and $w$. Principally any three equations. can be used. However, the choice is mainly dependent upon the probe sensitivity and its orientation. For solving the set of Eqns. (6), (7) and (8), it is assumed that the wave form of the velocities $U_2$ and $U_3$ is in phase because of the nature of the Eqns. (6) and (7). If $\alpha_3$ is the phase difference between $U_2$ and $U_3$ and $U_2$ and $U_4$, it can be determined in terms of maxima and minima of the velocities at the four positions.

By solving the set of Eqns. (6), (7) and (8)

$$u = \left[\frac{(U_2^2 + U_4^2 - 2U_3^2) + \sqrt{(U_2^2 + U_4^2 - 2U_3^2)^2 + (U_2^2 - U_4^2)^2}}{2(G^2 - K^2)}\right]^{\frac{1}{2}} \tag{9}$$

$$= f(U_2^2, U_3^2, U_4^2)$$

$$v = \left[\frac{(U_2^2 + U_4^2)}{2} - \frac{(G^2 + K^2)\sqrt{(U_2^2 + U_4^2 - 2U_3^2)^2 + (U_2^2 - U_4^2)^2}}{2(G^2 - K^2)}\right]^{\frac{1}{2}} \tag{10}$$

$$= g(U_2^2, U_3^2, U_4^2)$$

$$w = \left[\frac{-(U_2^2 + U_4^2 - 2U_3^2) + \sqrt{(U_2^2 + U_4^2 - 2U_3^2)^2 + (U_2^2 - U_4^2)^2}}{2(G^2 - K^2)}\right]^{\frac{1}{2}} \tag{11}$$

$$= h(U_2^2, U_3^2, U_4^2)$$

The mean velocity component can be evaluated as

$$\bar{u} = \frac{1}{t}\int_0^t f(U_2^2, U_3^2, U_4^2)$$

$$= \tfrac{1}{2}[\{f(U_{2\max}^2, U_{3\max}^2, U_{4\max}^2) + f(U_{2\min}^2, U_{3\min}^2, U_{4\min}^2)\}(1 - \alpha_3)$$

$$+ \{f(U_{2\max}^2, U_{3\min}^2, U_{4\max}^2) + f(U_{2\min}^2, U_{3\max}^2, U_{4\min}^2)\}\alpha_3] \tag{12}$$

Similarly, $\bar{v}$ and $\bar{w}$ can be calculated.

$$\alpha_3 = \frac{2\bar{U}_1 - (\sqrt{A} + \sqrt{B})}{(\sqrt{C} + \sqrt{D})(\sqrt{A} + \sqrt{B})} \tag{13}$$

where

$$\bar{U}_1 = (U_{1max} + U_{1min})/2$$

$$A = U^2_{2max} + U^2_{4max} - U^2_{3max}$$

$$B = U^2_{2min} + U^2_{4min} - U^2_{3min}$$

$$C = U^2_{2max} + U^2_{4max} - U^2_{3min}$$

$$D = U^2_{2min} + U^2_{4min} - U^2_{3max}$$

The fluctuating velocity $u'$ can be determined as

$$\overline{u^2} = \overline{(u + u')^2} = \bar{u}^2 + \overline{u'^2}$$

Therefore $\overline{u'^2} = \overline{u^2} - \bar{u}^2$

$$= [f(\overline{U_2^2, U_3^2, U_4^2})]^2 - \bar{u}^2$$

$$u'^2 = \tfrac{1}{2}[\{f(U^2_{2max}, U^2_{3max}, U^2_{4max})^2 + f(U^2_{2min}, U^2_{3min}, U^2_{4min})^2\}(1 - \alpha_3) + \{f(U^2_{2max}, U^2_{3min}, U^2_{4max})^2 + f(U^2_{2min}, U^2_{3max}, U^2_{4min})^2\}\alpha_3] - \bar{u}^2 \quad (14)$$

Similarly, the expressions for $\overline{v'^2}$ and $\overline{w'^2}$ can also be derived. From $\overline{u'^2}$, the turbulence level can be obtained using the relation of the form $[(\overline{u'^2})^{1/2}/U_{ref}] \times 100$. The kinetic energy of turbulence ($KE$) is given by

$$KE = \overline{u'^2} + \overline{v'^2} + \overline{w'^2}$$

and percentage $KE$ can be expressed as $(KE/U^2_{ref}) \times 100$.

A computer programme has been developed for solving all four possible sets of equations and the choice of the results is based on probe orientation, its sensitivity and the mean velocity measurements compared with mean velocity measurements made by using a pitot sphere probe. The flow chart of the computer programme used for calculating the mean and fluctuating velocities and kinetic energy is shown in Fig. 3.

## 3. Experimentation

The schematic arrangement of the test rig is shown in Fig. 4. The annular swirler is 70 mm in diameter (inner) and 380 mm long and four tangential slots, 5 mm wide nad 300 mm long, are cut on the periphery of the swirler. Three diffusers of half

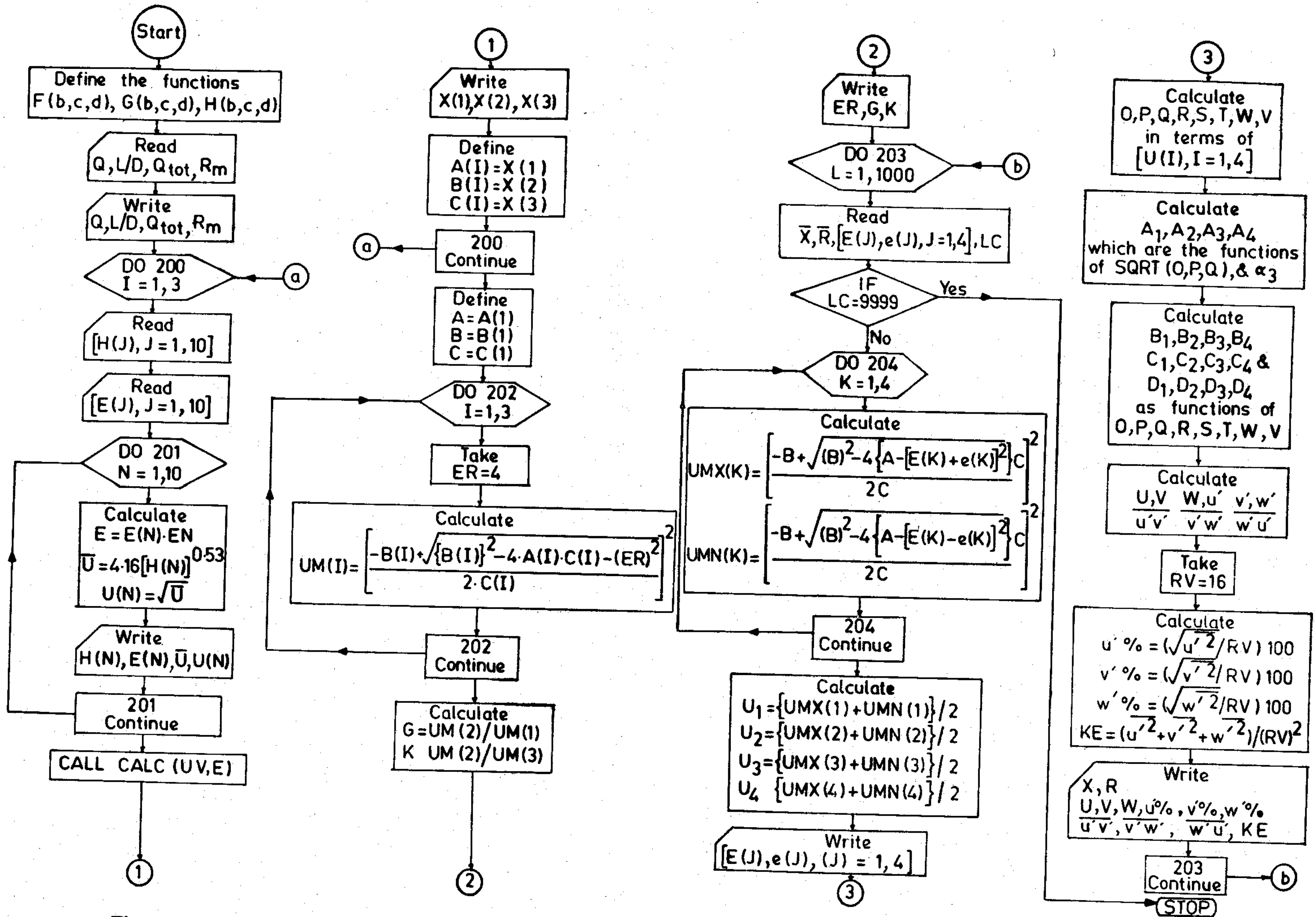


**Figure 3.** Flow chart for finding the turbulence characteristics [CALC (*UV*, *E*) is a sub-routine for finding the calibration constants A, B, C].

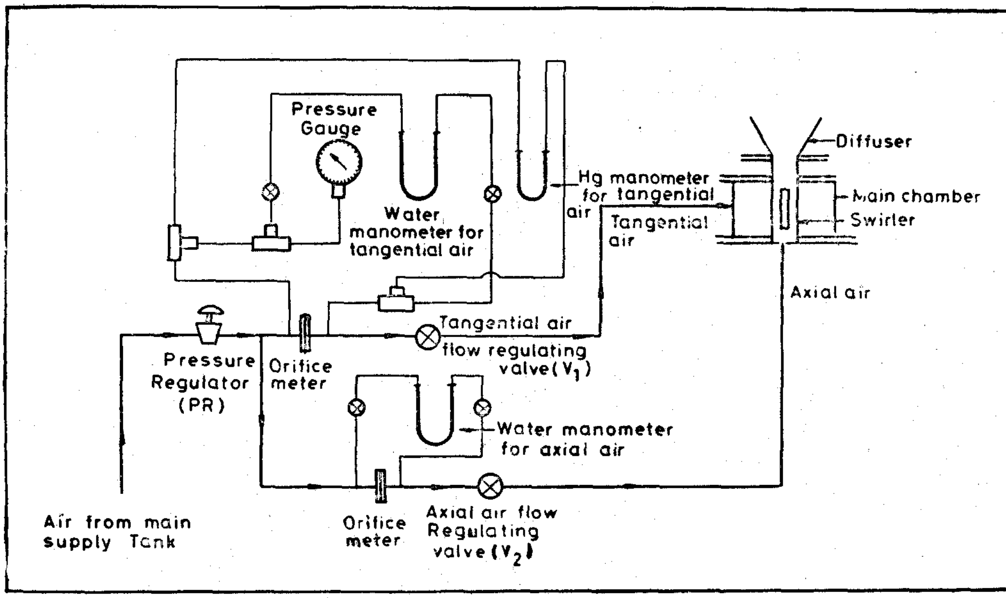


**Figure 4.** The schematic arrangement of test ring.

angles 15°, 20° and 25° whose height is equal to the diameter of the swirler are used in the present investigations. Holes provided in the diffuser enabled traversing a 5 hole probe and hot wire probe radially at different axial stations.

A DISA 55 MOl constant temperature hot wire anemometer is used in the present investigations. For accurate measurements of D.C. and r.m.s. voltages DISA 55D, 31 digital voltmeter and 55D, 35 r.m.s. voltmeter were used. A tungsten wire of diameter 5$\mu$ and 0.5 mm long is used as the sensor. Measurements have been carried out for a mass flow of 200 $m^3$/hr through the swirler. The hot wire sensor mounted on a three dimensional traversing mechanism is used for mapping the velocity and turbulence field. The probe is traversed radially at six different axial stations, three inside the diffuser and three outside the diffuser. Measurements were carried out at six points along the radius at each axial station.

The four position measuring technique described earlier is used for measuring the velocity and fluctuating components. At each point, the probe was directed first towards the direction of maximum velocity as indicated by the maximum D.C. voltage and the values of. D.C. and r.m.s. voltages were noted. Then the probe was rotated by 45° from its original position and again the values of D.C. and r.m.s. voltages were noted. This is repeated at four positions including the original one of the probe. The velocity distribution is determined with the help of a 5-hole spherical probe for locating the recirculation zone.

## 4. Results and Discussions

The turbulence characteristics of swirling flows exercise a profound influence on the evaporation of a liquid fuel and process of flame stabilization. The performance of

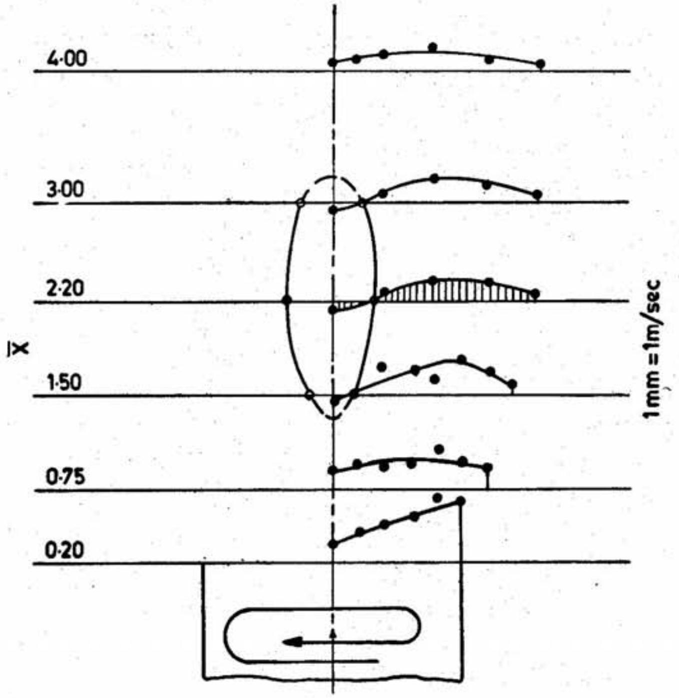


**Figure 5.** Axial velocity distribution without a diffuser.

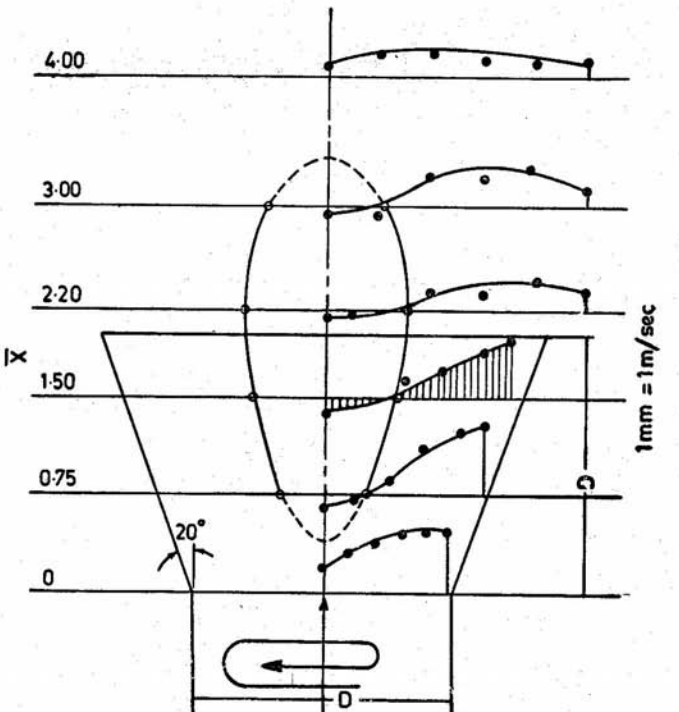


**Figure 6.** Axial velocity distribution with a diffuser ($\theta = 20°$).

a diffuser at the outlet to the swirler depends upon the inlet flow conditions and on how the momentum decays and wake develops along the flow direction.

Although some information is available, as mentioned earlier, for swirl combustors, surprisingly no data has been reported when diffusers are used. A diverging passage at the outlet to the swirler confers a number of advantages on combustor performance[8]. The present work focuses attention on turbulence intensity and kinetic energy of turbulence variation in swirling flows passing through diffusers and they are compared with the distributions in swirling flows without diffuser.

The Figs. 5 and 6 show axial velocity distributions without a diffuser and with a diffuser of 20° half angle. The recirculation region is identified by considering the variation of axial velocity distributions along the radius at different axial stations. It is obvious that the recirculation zone with diffuser is much bigger in size compared with the recirculation zone without diffuser for identical input flow conditions. The Fig. 7 shows the effect of diffuser angle on the recirculation size. It is evident that recirculation grows rapidly with increasing diffuser angle.

Figs. 8 and 9 show respectively the axial velocity fluctuations without a diffuser and with a diffuser of 15° half angle. The maximum turbulence level is found to lie outside the recirculation zone in both the cases. The turbulence intensity increases along the radius and then decreases. It is also evident that with increased axial distance, the axial turbulence level shows the tendency of decrease in magnitude indicating the decay of turbulence. The decay of turbulence is also more marked in the case of a diffuser compared with a swirler without a diffuser. Expansion of flow

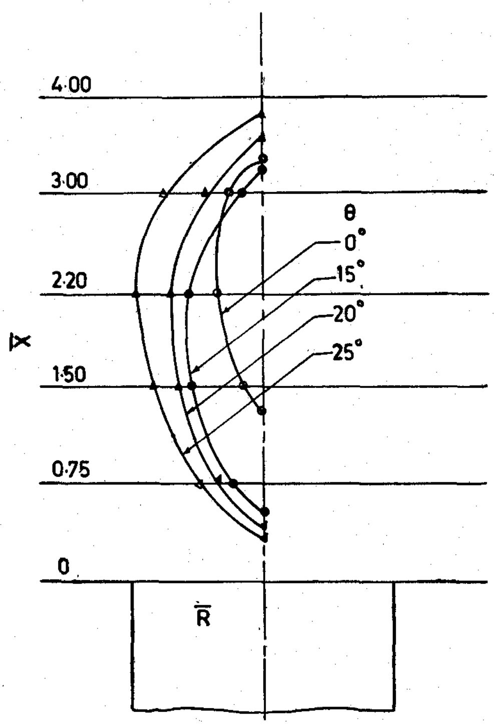


**Figure 7.** Effect of diffuser angle on recirculation zone.

passing through the diffuser may be responsible for rapid decay of turbulence. The variations of axial velocity fluctuations with a diffuser half angle of 20° and 25° are shown in Figs. 10 and 11. The trend is similar except the region of turbulence is widened and decay along axial direction is enhanced. This is due to the rapid expansion of the jet with increasing diffuser angle. The decay of $v'$ and $w'$ also showed similar trends as $u'$.

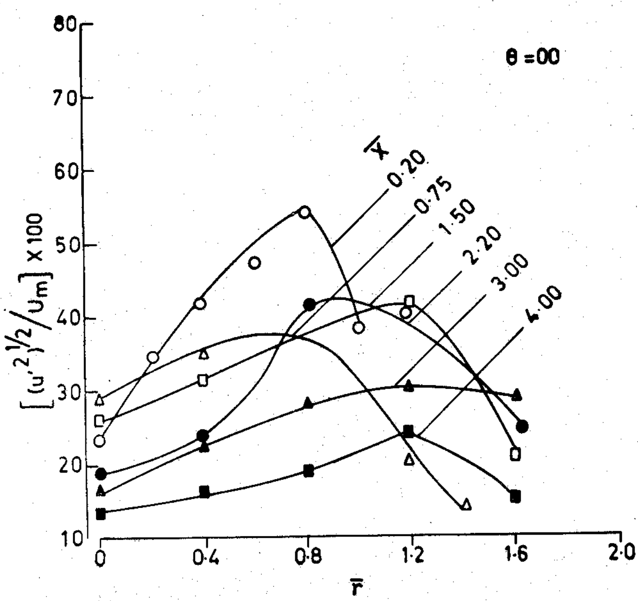


**Figure 8.** Radial distribution of axial velocity fluctuation.

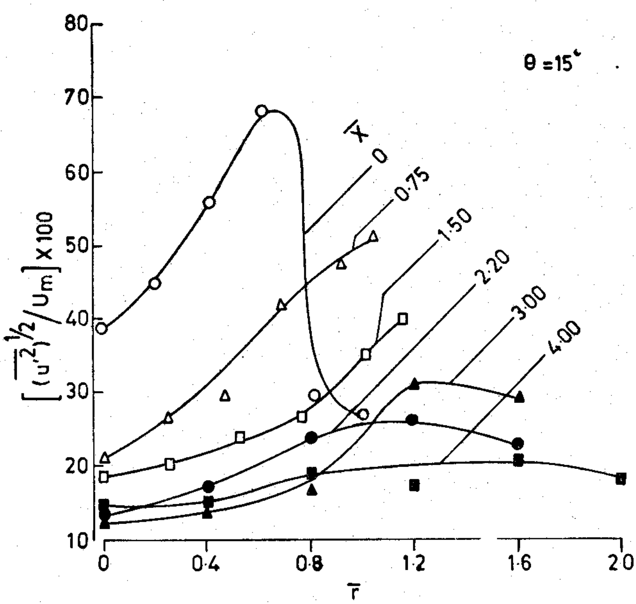


**Figure 9.** Radial distribution of axial velocity fluctuation.

The contours of constant intensity turbulence ($\sqrt{\overline{u'^2}}/U_{ref} \times 100$) in the flow field for the swirler without diffuser and with diffuser are show in Figs. 12 and 13. The

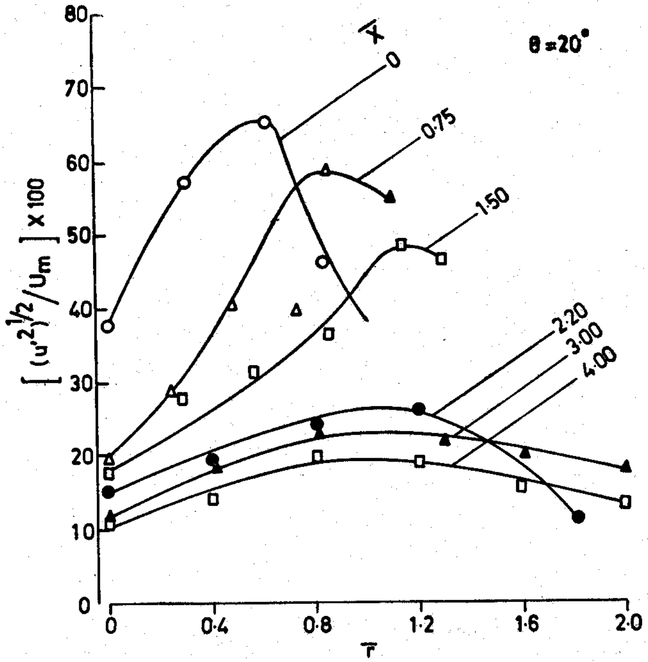


**Figure 10.** Radial distribution of axial velocity fluctuation.

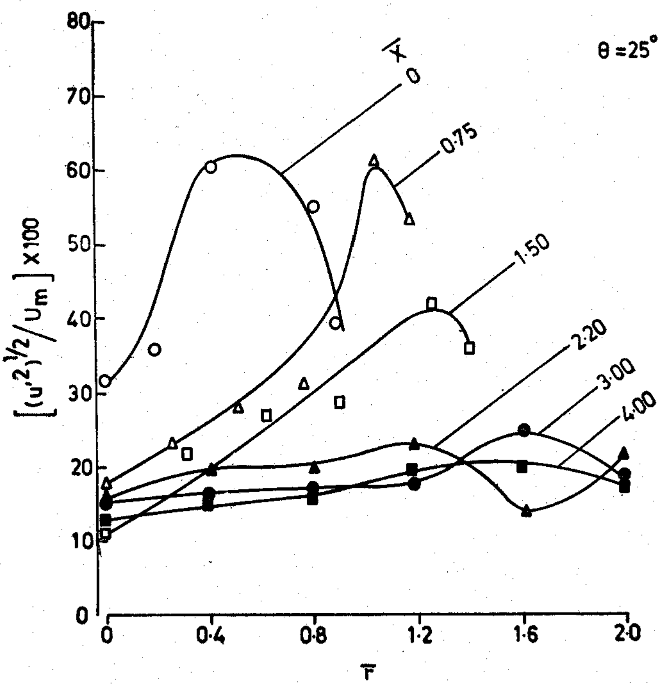


**Figure 11.** Radial distribution of axial velocity fluctuation.

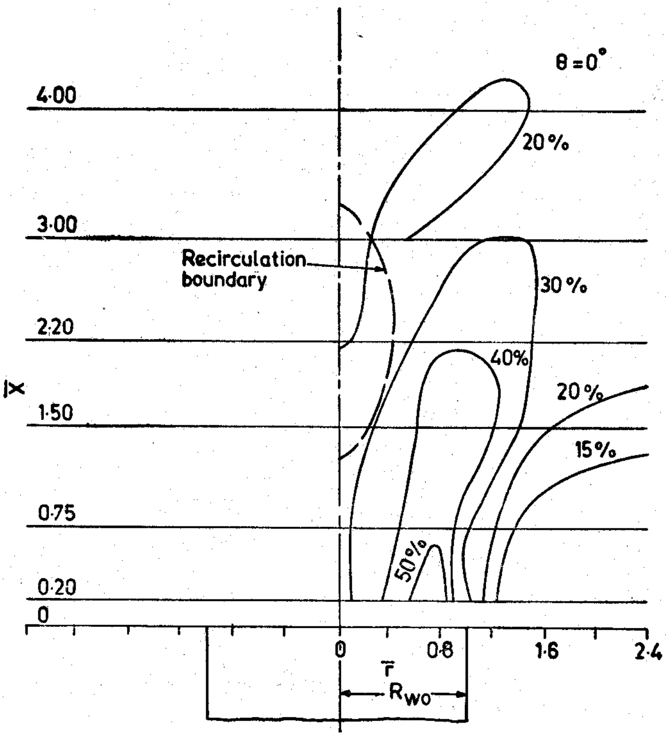


**Figure 12.** Contours of axial velocity fluctuation

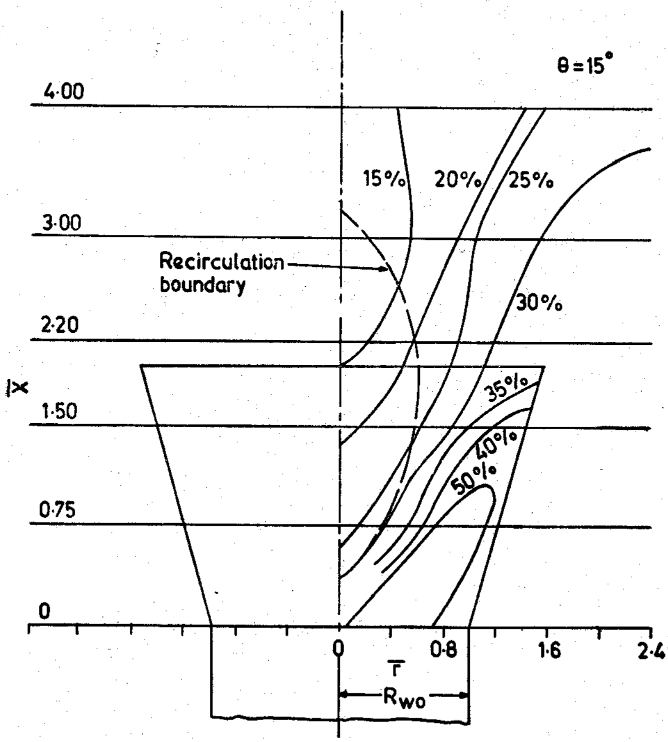


**Figure 13.** Contours of axial velocity fluctuation.

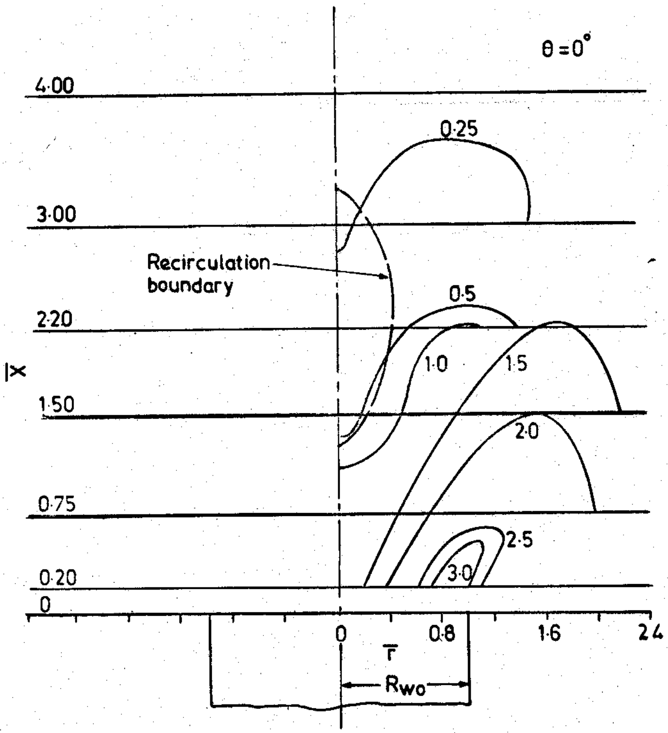


Figure 14. Contours of kinetic energy of fluctuation.

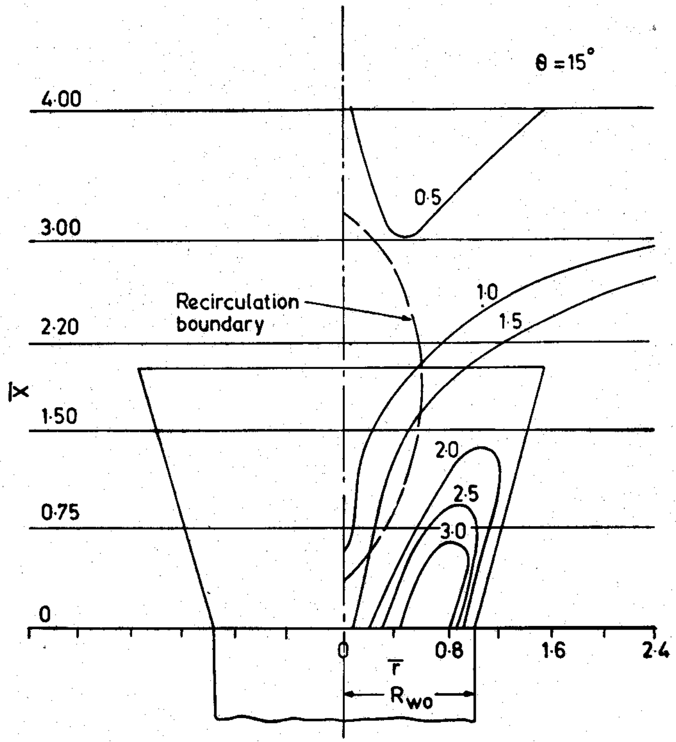


Figure 15. Contours of kinetic energy of fluctuation.

dotted lines show the recirculation zones set up in the flow which is drawn from the axial velocity profiles as discussed earlier. The recirculation size is much greater in the case of 15° diffuser compared with a swirler without the diffuser. The region of high turbulence intensity is also larger with the diffuser compared with the region without the diffuser. The common trend in both the cases is that the region of high intensity is located mostly outside the recirculation zone. It is also observed that with an increase in diffuser angle, the recirculation region grows and high turbulence intensities are observed in regions situated closer to the wall. The variations of $v'$ and $w'$ also showed a similar trend.

The constant turbulence kinetic energy contours for the swirler without a diffuser and with a diffuser of 15° are shown in Figs. 14 and 15. The nature of the distribution is very much similar to the one reported in reference 2 except that the region is widened when the diffuser is present. This distribution shows that it is desirable to inject the fuel around the recirculation zone as the high kinetic energy region facilitates the rapid evaporation of the liquid fuel.

## Conclusions

From the present investigations, the following conclusions are drawn :

1. The four position measurement technique discussed in the present paper is a convenient method for the measurement of high turbulence level in three dimensional flow fields.
2. The turbulence intensity decays along the direction of flow. The decay is faster with a diffuser compared with the performance of a swirler without a diffuser.
3. The recirculation size increases with an increase in diffuser angle.
4. The high intensity turbulence region lies outside the recirculation zone.
5. The high kinetic energy region also exists outside the recirculation zone.

## References

1. Rose, W. G., *Journal of Applied Mechanics.*, December (1962), 615.
2. Syred, N., Beer, J. M. & Chigier, N. A., 'Thirteenth Symposium (International) on Combustion', (International Combustion Institute) 1970, p. 563.
3. Rao, A. N., Ganesan, V., Natarajan, R., Gopalakrishnan, K. V. & Murthy, B. S., 'Fourth National Conference on I. C. Engines and Combustion.' India. (Madras Combustion Institute, India), 9–11 December 1977, C2-61.
4. Ganesan, V., 'Ph.D. Thesis' (IIT Madras, India) 1975, 178.
5. Baker, R. J., Hutchinson, P., Khalil, E.E. & Whitelaw, J. H., 'Fifteenth Symposium, (International) on Combustion' (International Combustion Institute) 1974, p. 553.
6. Chigier, N. A. & Dvorak, K., 'Fifteenth Symposium (International) on Combustion', (International Combustion Institute) 1974, p 573.
7. Khalil, E. E., Spalding, D. B., Whitelaw, J. H., *J. Heat Mass Transfer.*, **18** (1975), 775.
8. Domkundwar, V. M., Sriramulu, V. & Gupta, M. C., 'Fourth National Conference on I. C. Engines and Combustion' India, (Madras Combustion Institute) 9–11 December 1977, C2-41.