Experimental Study of a Turbulent Cross Jet

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The turbulent characteristics of a cross jet mixing flow have been measured after the geometric cross point of the centerlines of the two nozzles. The flow has been generated by two circular nozzles and the crossing angle of the jets was fixed at 45 deg with respect to each other. The flowfield is strongly influenced by the cross point stagnation region, which creates an elliptical jet region with unusual turbulence properties. The measurements have been carried out at two Reynolds numbers, $Re = 5.2$ and 6.5×10^4, and some influences of nonsimilarity have been studied. The major measurement system consisted of a two-channel hot-wire anemometer connected to an on-line computer system. The measurement of the mean velocities and the Reynolds stresses have been compared with existing semiempirical relationships for jet flows, and the comparisons have proved useful in understanding the flow structure. The general shape of the jet retained an elliptical cross section in the downstream direction and the spreading rates have been measured and curve fitted with semiempirical expressions. Also measured were the statistical distributions of the flatness factors along both the Y and Z axes, and the resulting distributions were similar to single jet flows across the central portion of the cross jet. The outer region of the flow exhibited a large amount of scatter for the majority of the statistical measurements that have been carried out.

Nomenclature

b_1, b_2	= jet half width in Y and Z directions, respectively
b_o	= mean value of b_2/b_1
$F(u'), F(v'), F(w')$	= flatness factor of u', v', and w'
$F(u')_{cl}$	= centerline flatness factor
Re	= Reynolds number
$S(u'), S(v'), S(w')$	= skewness factor of u', v', and w'
U, V, W	= mean velocities in X, Y, and Z directions
U_m, V_m, W_m	= maximum value of U, V, and W
U_o	= exit velocity of the nozzle
u, v, w	= instantaneous velocities in X, Y, and Z directions
u', v', w'	= fluctuating velocities in X, Y, and directions
$(\overline{u'^2})^{1/2}, (\overline{v'^2})^{1/2}, (\overline{w'^2})^{1/2}$	= rms values
$\overline{u'v'}, \overline{u'w'}$	= Reynolds stresses
$(\overline{u'v'})_m$, $(\overline{u'w'})$	= maximum values of the Reynolds stresses
X, Y, Z	= Cartesian coordinates in Fig. (2)
X_o	= distance between nozzle exit and geometrical jet cross point
η	= Y/b_1 or Y/b_2 = normalized coordinate

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Introduction

THE purpose of this investigation is to present the results of an experimental study of the turbulent mixing of two jets in a crossflow geometry. During the past years, there have been a large number of investigations carried out on single jets with different configurations[1-9] such as round, plane, and radial, but the amount of experiments and information on multiple cross jets has been very limited. Cross jet configurations have recently become of increased interest for the understanding of the mixing of fuel and oxidizers in combustion applicants, and the present investigation is planned to be extended into this important application area. At the present time the mixing processes in such devices as turbines and internal combustion engines are too complicated to be described by experimental or theoretical analysis, and most practical problems are solved by expensive trial-and-error development. It can be said that most devices that employ mixing between two streams are designed without a fundamental knowledge of the flow turbulence characteristics, and it is hoped that this investigation will lead to better understanding of the turbulent flow between turbulent jet streams.

A related experimental investigation on turbulent cross jets has been carried out by Andreopoulos and Rodi,[10] and Andreopoulos,[11,12] who investigated several types of flows. The typical configuration of Refs. 10–12 consisted of a low-speed secondary pipe flow jet that was injected into a high-speed main flow, but the case of cross jets of similar strengths was not investigated. Further studies of multiple jets into a crossflow have been carried out by Issac and Jakubowski,[13] and Makita et al.,[14] and Rudinger and Moon[15] investigated a two-phase cross jet under supersonic conditions for the primary flow. Additional studies on cross jets can also be found in the works of Shirkashi and Tomida[16] and Fearn and Weston.[17]

The present investigation is an extension of a program of research initiated by Rho and Kim,[18] which was concerned with the interaction of 45-deg cross jets formed by two circular nozzles. This preliminary investigation concentrated on the crossflow stagnation region, and detailed statistical measure-

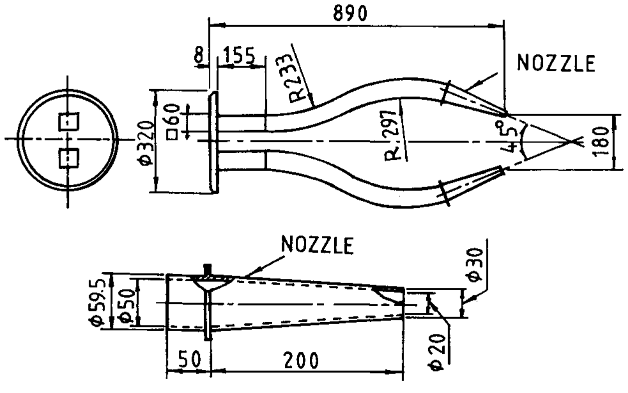

Fig. 1 Nozzle geometry.

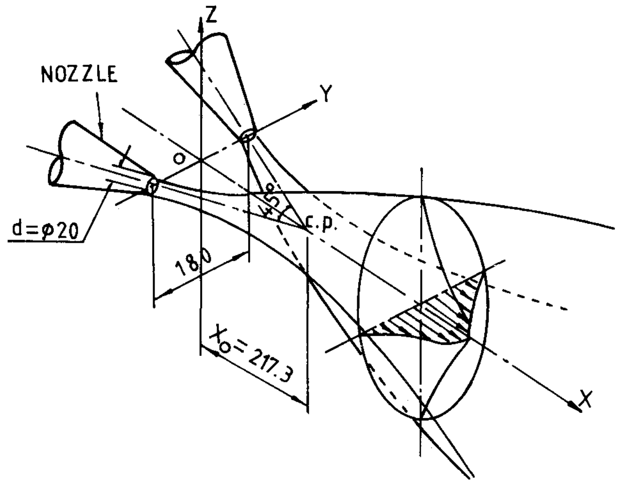

Fig. 2 Structure of cross jet mixing flows.

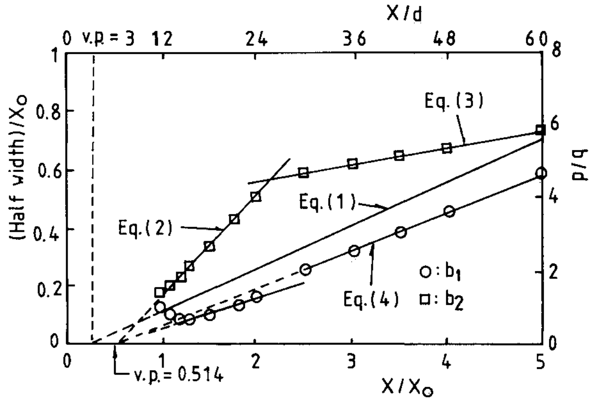

Fig. 3 Jet half-width variation.

ments were carried out in this region. Of particular interest were the measurements of one- and two-dimensional distributions of probability densities such as flatness factors, and the evolution of these distributions as the flow mixes and develops.

Problem and the Experimental System

The present investigation is concerned with the statistical turbulence characteristics and development of two cross jets at 45 deg with respect to each other. The measurements that have been carried out are extensive, and they include the detailed mean and fluctuating characteristics of the flow. The basic geometry of the system is given in Figs. 1 and 2, and it can be seen that the flow involves the partial stagnation of the crossflow velocity component, which is then followed by an elliptical jet development downstream of the stagnation region. It is hoped that the present set of measurements will serve as a data base for future modeling studies, and that eventually a complete theoretical and experimental understanding of the system will be established.

In order to generate the airflow for this cross jet experiment, a subsonic wind tunnel was utilized. This wind tunnel was controlled by a variable speed motor and the stability of the mean flow system was found to be excellent. The crossflow nozzles were designed to insure a uniform flow from the exits, and the exit velocities of the two nozzles were the same. The primary measurement system for the experiment was a pair of constant-temperature hot-wire anemometer systems (TSI 1050 series). The measurement system consisted of the following: 1) an anemometer; 2) a signal conditioner; 3) a linearizer; and 4) a signal correlator. The data-acquisition system was completed with an rms voltmeter, an oscilloscope, a dynamic analyzer, and an Apple II computer system. The calibration of the system was carried out with a TSI calibration system and an electric micromanometer, which insured an accuracy of 1 mm of water for the velocity measurements. The hot wires were of the tungsten I type and had an X geometry, and several pitot tubes were employed to check the analog system continuously.

A schematic of the flow system is shown in Fig. 2, and the geometry of the flow and the coordinate system is presented in this figure. From the distance of separation of the jets, 180 mm, and an angle of 45 deg, the geometrical cross point (c.p.) can be defined as $X_o = 217.3$ mm. The majority of the measurements have been carried out for Reynolds numbers of $Re = 5.2$ and 6.5×10^4, and it will be seen that the appropriately normalized results exhibit a degree of self-similarity. Measurements were carried out in the range of $X/X_0 = 1.1$ to 8.0, but the range of 1.1 to 2.0 has been emphasized, because of the strong turbulent mixing that occurred in this region. At the majority of measurement locations, the probes were moved laterally to cover both the Y and Z directions and to measure both the mean and the fluctuating components of the flow.

Results and Discussions

The study will begin with a presentation of the mean flow quantities. The flow has been normalized with the initial jet velocity U_0, and the c.p. location X_0 has been used to define a normalized flow direction. Figure 3 shows the longitudinal development of the jet half-widths along the Y and Z axes, which are perpendicular to the flow. It can be seen that the Z half-width b_2 develops or diffuses at a much larger rate than the Y half-width b_1 in the initial region after the collision of the two jets. Away from the collision region, $X/X_0 > 2$, the spreading of the Z half-width decreases rapidly as the overall jet development begins to change over to that of a more conventional round jet flow.

The development of the centerline mean velocity profile is shown in Fig. 4, and it is marked by an unusual flow pattern before the collision point of the cross jets. Before the collision point, the centerline velocity increases as the two jets approach, and then decreases rapidly in a fashion that resembles a single round jet. This behavior is not typical of simple jet flows, and is caused primarily by the converging/diverging geometry formed by the approach jets with respect to the flow centerline. The present flow with the aspects of partial flow stagnation, acceleration, and deceleration is much different than previous jet studies, and its measurement offers the possibility of extending turbulence modeling studies into this important jet mixing regime.

The data in Fig. 4 have been described with semiempirical correlations for both the approaching and the downstream flow; these correlations are

$$U_{cl}/U_o = 1.5(X/X_o) - 0.9 \quad \text{for} \quad X/X_o < 1 \tag{1}$$

$$U_{cl}/U_o = 0.39/\{(X/X_o) - 0.55\} + 0.023 \quad \text{for} \quad X/X_0 > 1 \tag{2}$$

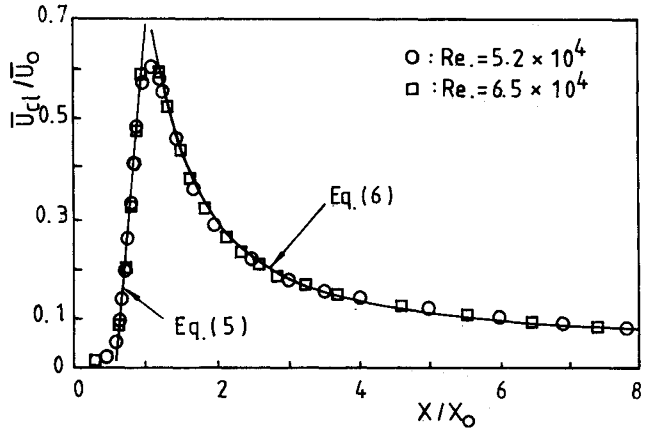

Fig. 4 Centerline mean velocity variation.

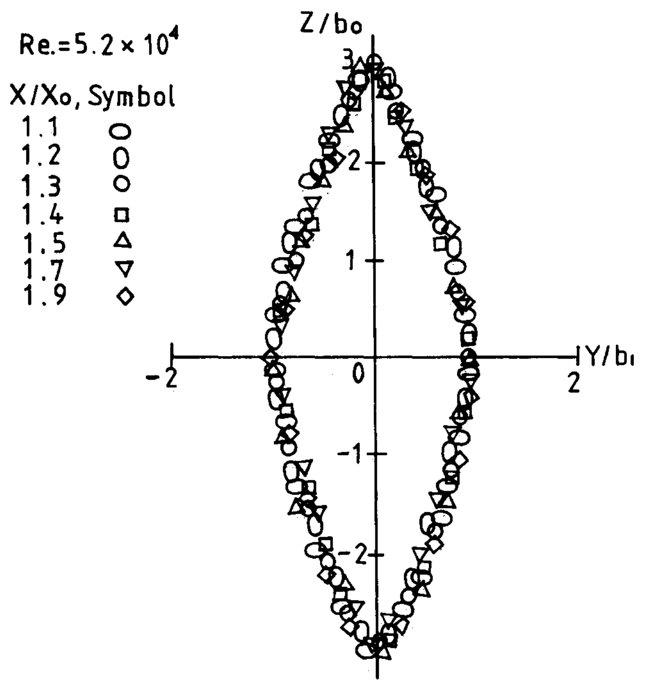

Fig. 5 Formation of mixing flow cross section.

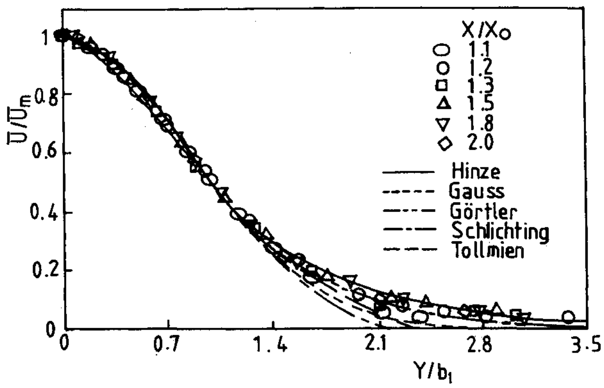

Fig. 6 Mean velocity distribution U-Y axis ($Re = 5.2 \times 10^4$).

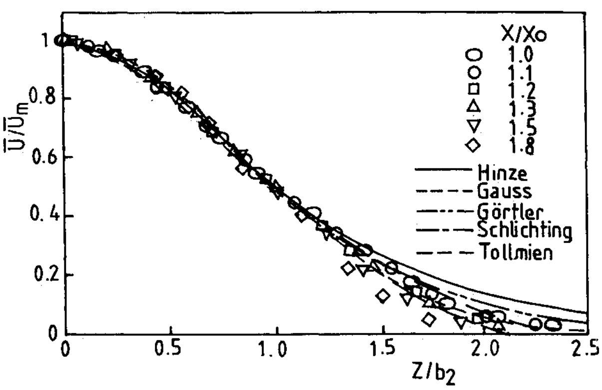

Fig. 7 Mean velocity distribution U-Z axis ($Re = 5.2 \times 10^4$).

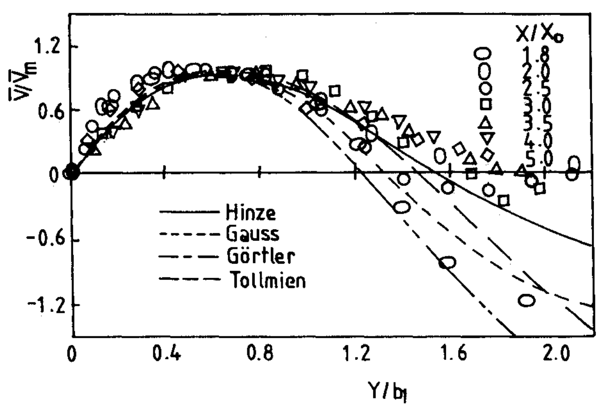

Fig. 8 Mean velocity distribution V-Y axis ($Re = 5.2 \times 10^4$).

The contours of the mean velocity at a value of one-half the centerline value and at various cross sections downstream are given in Fig. 5. The normalized values in Fig. 5 show a strong similarity in the downstream direction for the range of the data, $1.5 \leq X/X_o \leq 1.9$; however, it will be necessary to extend both the Reynolds number range and the values of the cross angle to obtain a complete understanding of the flow.

Another appropriate study is to apply the semiempirical correlations that have been developed for simple jet flows to the present complex flow. Some of the correlations of interest are the following:

Hinze:

$$U/U_m = (1 + 0.414\eta^2)^{-2} \tag{3}$$

Tollmien:

$$U/U_m = [1 - 0.202\,(1.225\eta)^{1.5} - 0.00204\,(1.225\eta)^3 + 0.0041\,(1.225\eta)^{4.5} + \ldots] + \exp[-0.026937\,(1.225\eta)^{1.5} - 0.00136\,(1.225\eta)^3 + 0.00018\,(1.225\eta)^{4.5} + \ldots] \tag{4}$$

Görtler:

$$U/U_m = 1 - \tanh^2(0.881\eta) \tag{5}$$

Schlichting:

$$U/U_m = \{1 - (0.441\eta)^{1.5}\}^2 \tag{6}$$

Gaussian:

$$U/U_m = \exp(-0.693\eta^2) \tag{7}$$

The correlations have been used extensively in the past to correlate the results of plane and round jet flows, and it would be of practical interest to investigate if they can be extended to the components of the cross jet flow. Shown in Figs. 6 and 7 are the measured and correlated mean velocity profiles in both the Y and Z directions at various downstream locations.

(Note: Two different half-widths have been used in the two figures.) In general, the agreement with both round and plane jet correlations is very good near the centerline of the flow, but the outer region of the cross jet seems to have a different behavior along the Y and Z axes.

The mean crossflow velocity components V and W are presented in Figs. 8 and 9, along with values derived from the semiempirical correlations. The correlations utilized are

$$V/V_m = (U/V_m)\, \mathrm{d}b_1/\mathrm{d}x\, \{\eta f(\eta) - \tfrac{1}{2} \textstyle\int_0^\eta f(\eta)\, \mathrm{d}\eta\} \quad (8)$$

$$W/W_m = (U/W_m)\, \mathrm{d}b_2/\mathrm{d}x\, \{\eta f(\eta) - \tfrac{1}{2} \textstyle\int_0^\eta f(\eta)\, \mathrm{d}\eta\} \quad (9)$$

In general, the agreement with the round jet results of Hinze seems to be the best, but all of the semiempirical results overpredict the velocities in the entrainment region, as is typical for jet flows in finite experimental laboratories. However, we again see that the correlations may have considerable value for engineering calculations. The final observation that can be made from these results is that the V mean velocity component is less self-similar than the W component, and the reasons for this result are believed to be the interactions caused by the two different spreading rates along the two axes.

The distributions of the turbulent intensities along the centerline of two flows are given in Figs. 10 and 11 for a round jet and cross jet flow, respectively. From a comparison of Figs. 10 (round jet) and 11 (cross jet), it is seen the initial region of the cross jet has a much different turbulent structure than the round jet. All three components of the intensity in the cross jet geometry exhibit a maximum at an X/X_o location of approximately two, and this indicates a very strong generation of turbulence after the cross point of the jets. The maximum in the intensities is larger than those for the round jet, but the maximums are followed by a decrease that appears to go slightly below the round jet values. Since measurements for the cross jet have not been taken for larger values of X/X_o, it is not possible to observe the transition to round jet values in the present results.

A particularly important quantity for the development of turbulence models for complex flows in a Reynolds stress and measurements of the Reynolds stresses are shown in Figs. 12 and 13. The development of the Reynolds stresses along both the Y and Z axes exhibits a more self-similar pattern than the turbulent intensities, and it is well described by estimates from the semiempirical correlations.

$$\overline{u'v'}/(\overline{u'v'})_m = \tfrac{1}{2} U_m/(\overline{u'v'})_m\, \mathrm{d}b_1/\mathrm{d}x f(\eta) \textstyle\int_0^\eta f(\eta)\, \mathrm{d}\eta \quad (10)$$

$$\overline{u'w'}/(\overline{u'w'})_m = \tfrac{1}{2} U_m/(\overline{u'w'})_m\, \mathrm{d}b_2/\mathrm{d}x f(\eta) \textstyle\int_0^\eta f(\eta)\, \mathrm{d}\eta \quad (11)$$

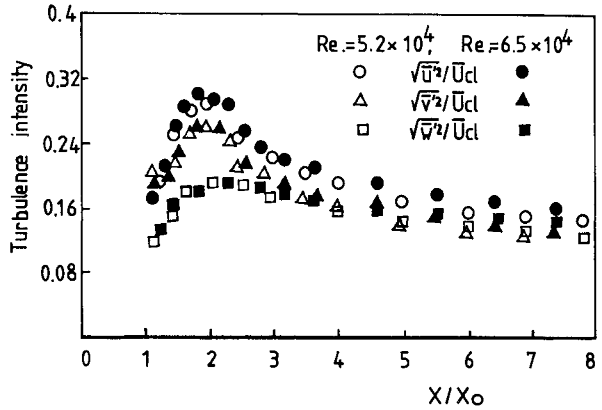

Fig. 11 Centerline intensity of turbulence distributions (cross jet).

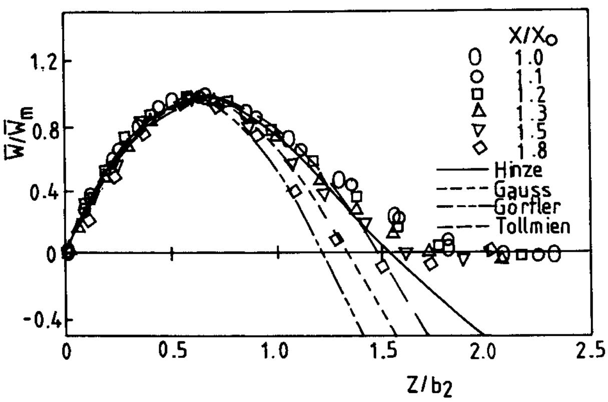

Fig. 9 Mean velocity distribution W-Z axis ($Re = 5.2 \times 10^4$).

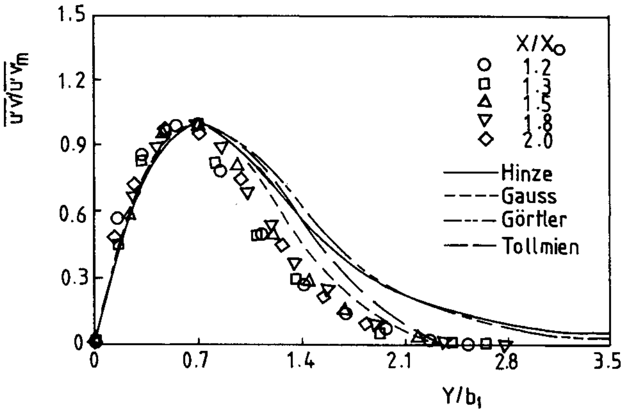

Fig. 12 Reynolds stress distributions (Y axis).

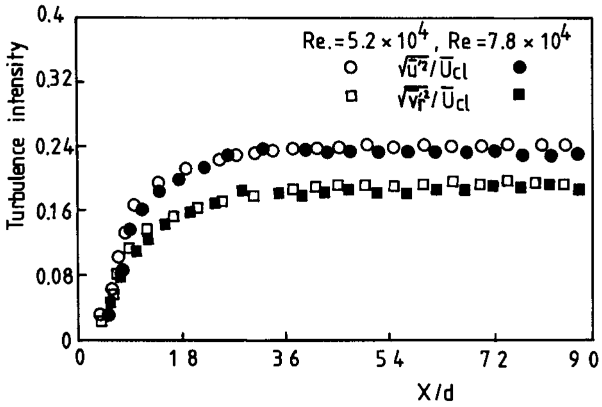

Fig. 10 Centerline intensity of turbulence distributions (round jet).

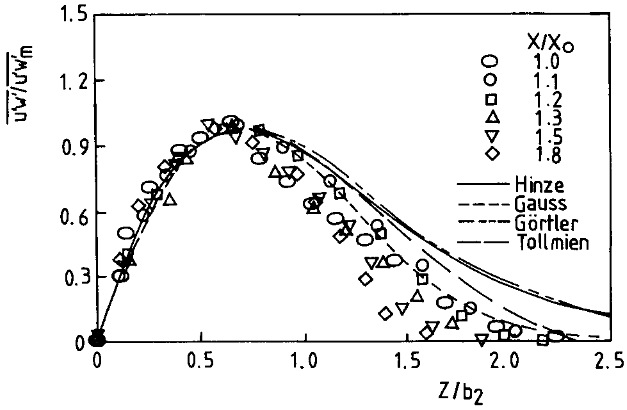

Fig. 13 Reynolds stress distributions (Z axis).

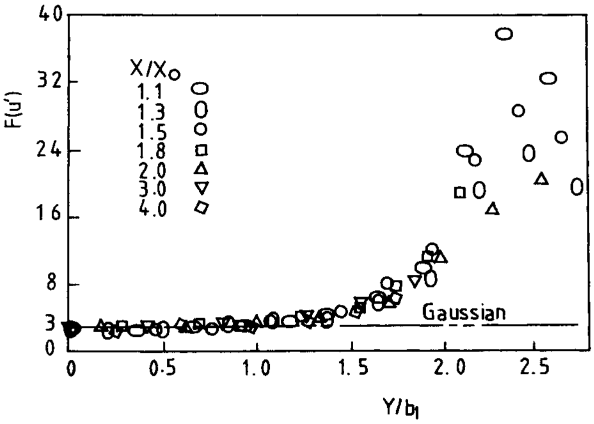

Fig. 14 Flatness factor distributions (Y axis) u'.

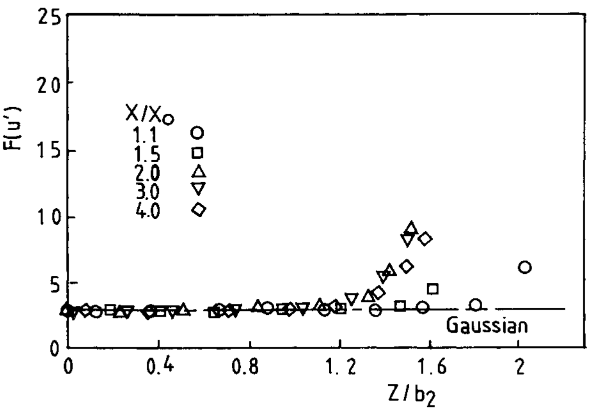

Fig. 15 Flatness factor distributions (Z axis) u'.

These correlations have been evaluated with the mean velocity profiles given in Eqs. (8) and (9), and the agreement with experimental stress distributions for the cross jet is relatively good. This good agreement with the correlations may imply that models such as the k-ϵ model will work well. However, it should be observed that there are some problems with present-day models for predicting the spreading rate of round and plane jets wth the same "universal constants." The cross jet can be considered as a hybrid between the two basic configurations, particularly in the collision region and the region far downstream. It should be pointed out again that the present cross jet flow has a very strong history effect in the turbulence caused by the partial stagnation region near the jet cross point. Any modeling attempts will have to treat this elliptic region in order to carry out a complete simulation of this flow, and it is believed the cross point region is the key to the downstream development of the flow.

The flatness distributions for this flow have been measured and analyzed for the Y and Z axes. The definition used to form the flatness is

$$\text{flatness} - F(u') = u'^4/(u'^2)^2$$

The flatness factor distributions are shown in Figs. 14–17. They also exhibit a typical jet behavior with a Gaussian value close to three near the centerline, and large increases are observed as the jet boundary is approached. As has been the case for most of the other measurements that have been made, the quantities along the Z axis exhibit the most scatter and the most nonsimilar behavior. Also, it is clear that the data sets are extensive and consistent, and that they should provide a data base for modeling and practical applications.

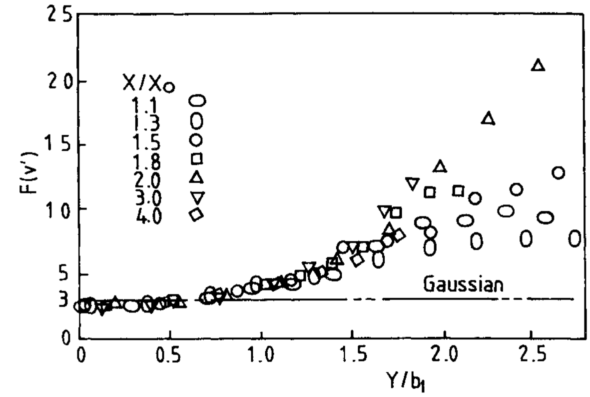

Fig. 16 Flatness factor distributions (Y axis) v'.

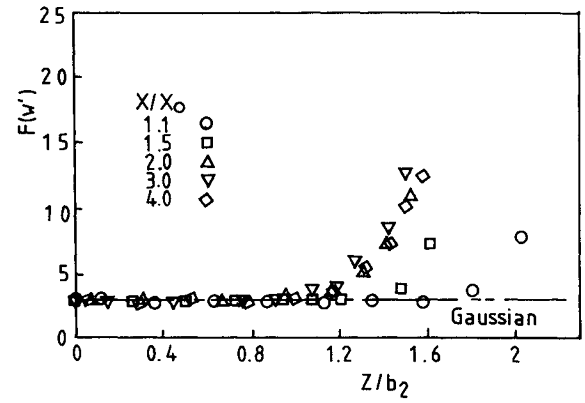

Fig. 17 Flatness factor distributions (Z axis) w'.

Conclusions

A turbulent cross jet formed by two circular jets at 45 deg angles has been measured in detail to determine its structure. The resulting jet of elliptical cross section developed strongly after the cross flow stagnation point, and there are significant differences between the two axes of a typical cross section. In general, the mean velocity profiles can be correlated with semiempirical equations based on the local half-widths of the jet, but there are significant differences between the two axes of the flow. As the jet changes from its elliptical shape to a circular shape downstream, the intermittancy factors increase in the outer regions of the flow.

The developments of the intensity of turbulence distributions is the most unusual aspect of the flow. A large maximum in these quantities has been observed after the jet cross point. The Reynolds stress distributions do not exhibit this unusual behavior, and they can be correlated well with semiempirical relationships in the central region of the jet.

For the majority of the quantities measured, the Z axis exhibited the most nonsimilarity and the largest variation from classical jet behavior. The results measured have been very extensive and include the skewness, flatness, and intermittency factors. At the present time, the analysis of the data is not complete, but the results do serve as a data base for the formulation of both analytical and numerical models to predict complex flows of this type.

The present data set offers a good possibility to test the validity of present-day turbulence models for three-dimensional flow problems. The cross jet flow problem contains a partial stagnation region followed by three-dimensional jet flow. Both regions contain unusual turbulence properties, and a theoretical understanding of this flow structure will be important for further developments in this field.

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