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Partially Confined Multiple Jet Mixing

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Results of hot-wire measurements in an incompressible partially confined jet issuing from an array of rectangular nozzles, equally spaced with their small dimensions aligned are presented. The quantities measured include mean velocity and the Reynolds stress in the two central planes of the jet at stations covering up to 115 widths (small dimension of a nozzle) downstream of the nozzle exit. For downstream distances greater than 60 widths, the flowfield is observed to be nearly homogeneous and the turbulence appears to be quite similar to that of a grid generated turbulence.

Nomenclature

AR = aspect ratio, L/D
D = width (small dimension) of the nozzle
L = length (long dimension) of the nozzle
L_1 = spacing between the plates
S = spacing between the nozzles
U = mean velocity component in the X direction
U_c = mean velocity component along the centerline of the jet in the X direction
U_0 = mean velocity component in the exit plane of the jet in the X direction
U_s = mean velocity component of the secondary flow in the X direction
u = fluctuation velocity component in the X direction
u_{rms} = $\sqrt{u^2}$ = rms velocity fluctuations in the X direction
$\tilde{u}$ = $\sqrt{u^2}/U_c$ (normalized rms velocity fluctuation in the X direction)
v_{rms} = $\sqrt{v^2}$ = rms velocity fluctuation in the Y direction
$\tilde{v}$ = $\sqrt{v^2}/U_c$ (normalized rms velocity fluctuation in the Y direction)
w = fluctuation velocity component in the Z direction
w_{rms} = $\sqrt{w^2}$ = rms velocity fluctuation in the Z direction
$\tilde{w}$ = $\sqrt{w^2}/U_c$ (normalized rms velocity fluctuation in the Z direction)
$\overline{uv}, \overline{uw}, \overline{vw}$ = components of the turbulent shear stress tensor
X = coordinate along the jet axis
Y = coordinate along the small dimension of the nozzle
Z = coordinate along the long dimension of the nozzle
δ = gap between the plate and the nozzle

Introduction

PARTIALLY confined multiple jets are used in a wide variety of engineering applications; for example, thrust augmenting ejectors for VTOL/STOL aircraft. The configuration of interest is an array of rectangular nozzles in a line as shown in Fig. 1. Few investigations have been reported in the literature regarding the structure and development of partially confined multiple jets, such as in the present configuration. Early work on this subject was done by Corrsin,[1] who studied the flow from seven parallel slot nozzles in a common wall with emphasis on flow stabilization methods. Overall aerodynamic studies have been made by Aiken[2] on an ejector with multiple rectangular nozzles with various spacing to width ratios and nozzle dimensions. In these studies, most of the measurements were made on the mean flow rather than on the detailed turbulence structure. The purpose of the present paper is to present and discuss the results of experiments with a partially confined multiple jet configuration and thus add to the understanding of its fluid mechanical structure. The data should also provide analysts with a basis upon which a computational model can be built. This experimental investigation presented is part of a Stanford program to study the turbulent mixing of multiple rectangular jets.

The characteristics of the flowfield depend upon the aspect ratio of the nozzle, inlet geometry of each nozzle, the type of exit velocity profile for each nozzle, the magnitude of the turbulence intensity at the exit plane of each nozzle, the Reynolds number at the nozzle exit, spacing between the nozzles, configuration of confining surfaces, and condition of the ambient medium into which the jet is issuing. In the present investigation, nozzles having an aspect ratio of 16.7 were chosen. The spacing between the nozzles was $8D$ (D being the small dimension of the nozzle). These parameters were chosen to be consistent with the nozzle used by Aiken.[2] Inlet geometry of the nozzle was designed specifically to obtain a low turbulence level at the exit plane. The velocity profile at the exit plane of each nozzle was flat with a laminar boundary layer at the walls.[3] A mean velocity of 60 m/s was maintained at the exit plane of each nozzle. This results in a Reynolds number of 1.2×10^4 based on the width of the nozzle. Two parallel plates 100 widths long were placed symmetrically perpendicular to the long dimension of the nozzle as shown in Fig. 1. The spacing between the plates can be adjusted between $1.2L$ to $1.7L$ (L being the long dimension of the nozzle).

Measurements were made using hot-wire anemometry and include the mean velocities, turbulent intensities for the three

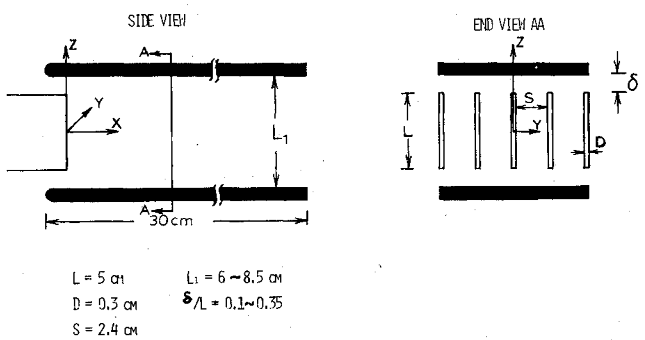

Fig. 1 Schematic of the model and dimensions.

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components of velocity, and the turbulent shear stresses $\overline{uv}$ and $\overline{uw}$. All the detailed measurements were made in the two perpendicular central planes of the center nozzle.

Apparatus, Instrumentation, and Procedure

A blowdown air supply system was used to provide the air flow to the nozzles. The experimental facility and the model are the same as that used in earlier experiments[3,4]; thus, the details are not furnished here. The long L and short D dimensions of the rectangular nozzle exit are 50 mm and 3 mm, respectively. The spacing between the nozzle is 24 mm. Each nozzle exit is preceded by a 40 mm long rectangular (50 × 3 mm) channel. Two parallel plates of 9.5 mm thick and 30 cm long are placed symmetrically perpendicular to the long dimension of the nozzles as shown in Fig. 1. The leading edges of the plates are rounded with no fairing added. The spacing L_l between the plates can be varied from 6 to 8.5 cm. The exit velocity of the jet was maintained at 60 m/s to an accuracy better than 1%. The centerline turbulence intensity at the exit of the nozzle was 0.3% at a mean velocity of 60 m/s.

Measurements were made with DISA 55M01 constant temperature anemometers using DISA 55D10 linearizers. Most of the measurements were made using either an x wire or a single wire. These wires were manufactured by DISA and constructed from 5μ platinum coated tungsten wire with an active length of 1.2 mm. The details of the instrumentation, calibration procedures, and the error estimation are discussed by Krothapalli et al.[4]

A Cartesian coordinate system (X, Y, Z) is chosen with its origin located at the center of the center nozzle as shown in Fig. 1, with the X axis directed along the centerline of the jet. Hot wire traverses were made in the two central X, Y and X, Z planes at various streamwise X locations covering up to $115D$. Unless otherwise stated, all the data presented here were taken with the x wire probe. The experiment was conducted in three parts. In the first part, measurements were made on the center nozzle with all the other nozzles blocked and the results are presented in Ref. 3. In the second part, measurements were made on the center nozzle with all five nozzles blowing, and the results are presented in Ref. 4. In the third part, measurements were again made on the center nozzle with all five nozzles blowing and with confining surfaces in place. All the measurements in all the three cases were made on the two central planes of the center nozzle. Mean velocity measurements were made across the center three jets in order to establish the symmetry of the flow about their central planes; however, only the data for each half plane of the center nozzle will be presented.

Results and Discussion

General Features of the Flowfield

Detailed discussion of the flow structure from a single rectangular nozzle is given by Krothapalli et al.[3]

A schematic of the flowfield of a multiple rectangular freejet is shown in Fig. 2. Mean velocity profiles in the two central planes for the center three nozzles are shown in the figure. For the configuration tested ($S = 8D$, $\mathcal{R} = 16.7$), the flows from the nozzles do not exhibit any mutual interaction for X less than $15D$. Complete merging of the jets (i.e., individual jets lose their identity) is observed for X greater than or equal to $60D$, as indicated by a flat velocity profile across the nozzles. The mean velocity profile in the central X, Z plane at different downstream locations exhibits characteristics similar to that of a single freejet. The shaded region is an attempt to show the pseudopotential core region, after which the jet acts like a single two-dimensional jet with its minor axis along the Z axis. Detailed discussion of the flow structure with supporting measurements is given in Ref. 4.

The profiles in the central X, Z plane for the confined multiple jet show marked differences when compared with a

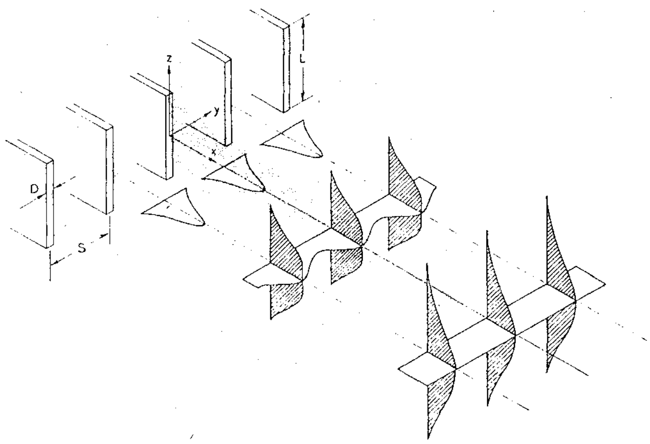

Fig. 2 Schematic representation of flowfield of a multiple freejet.

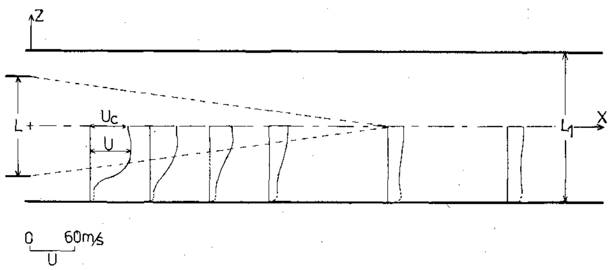

Fig. 3 Schematic of axial mean velocity profiles in the X, Z plane of a multiple confined jet.

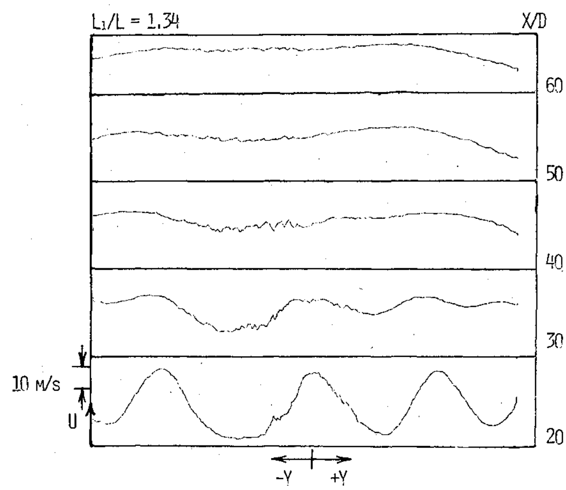

Fig. 4 Axial mean velocity profiles in the X, Y plane for $L_l/L = 1.34$.

multiple freejet configuration, and a schematic of this flowfield is shown in Fig. 3. The profiles are plotted to scale. The dotted lines in the figure correspond to a pseudopotential core where the jet acts like a single jet (see also Fig. 2). The end of this pseudopotential core occurs at X equal to $60D$. For X greater than $60D$, the mean velocity profiles are almost flat across the jet. This observation along with previous discussion (regarding profiles in the X, Y plane) suggest that the mean velocity for X greater than $60D$ is nearly homogeneous in the two lateral planes.

Mean Velocities

Mean axial velocity profiles in the central X, Y plane for the center three nozzles at various downstream locations for L_l equal to $1.34L$ and $1.5L$ are shown in Figs. 4 and 5, respectively. These profiles were plotted with an X-Y recorder with the output of the averaged, linearized single normal wire

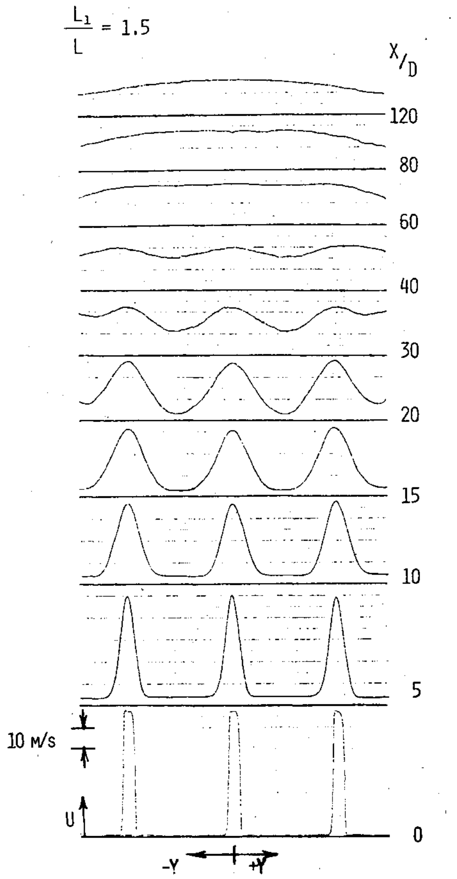

Fig. 5 Axial mean velocity profiles in the X, Y plane for $L_l/L = 1.5$

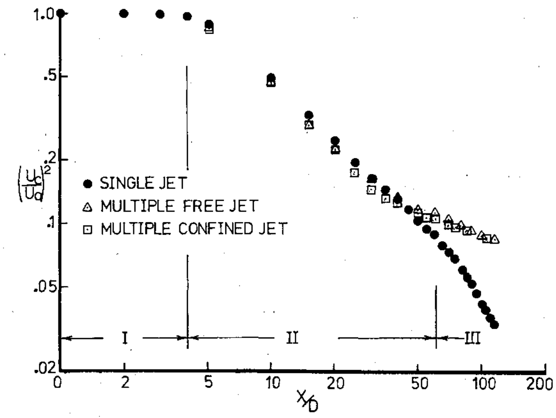

Fig. 6 The decay of the axial mean velocity along the centerline of the jet.

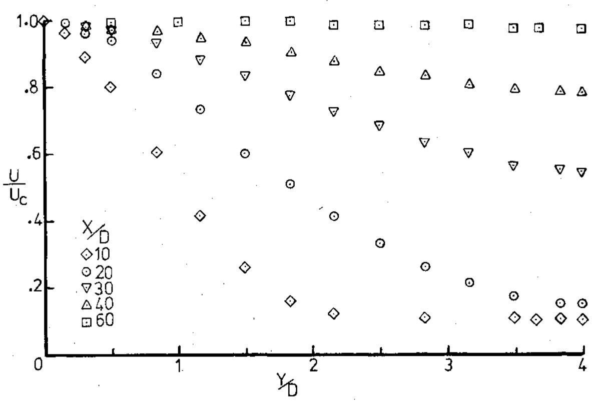

Fig. 7 Axial mean velocity profiles in the X, Y plane.

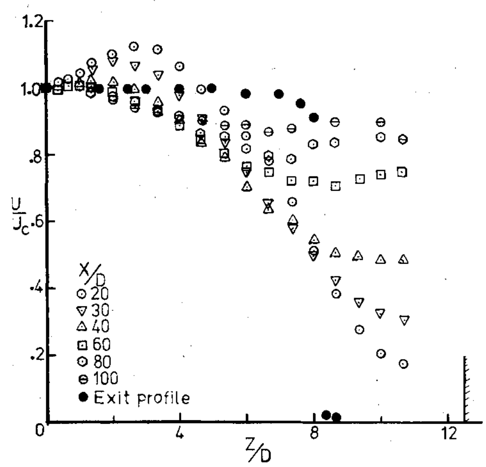

Fig. 8 Axial mean velocity profiles in the X,Z plane.

connected to the Y axis while the position of the probe was displayed on the X axis. The integration time on the digital voltmeter was held at 1 s for both cases. For L_l less than $1.5L$, low-frequency disturbances (characteristic time greater than 1 s) were present, and mean axial velocity profiles in the X, Y plane were found to be asymmetrical about their axes. Profiles typical of such a situation at L_l equal to $1.34L$ are shown in Fig. 4. Even at large downstream distances, for example, at X equal to $80D$, low-frequency disturbances were observed. Similar observations were made by Corrsin[1] in an investigation of the behavior of parallel two-dimensional air jets. In his case, asymmetry of the profiles was more pronounced than in the present case, and can be attributed to his jets being unventilated.

For L_l greater than or equal to $1.5L$ fewer low frequencies were present, and the profiles looked very similar to those of a multiple freejet (see Ref. 4) with some secondary flow induced between the jets. Profiles typical of such a situation at L_l equal to $1.5L$ are shown in Fig. 5. Top-hat profiles with equal magnitudes are found at the exit plane. At X equal to $5D$, a noticeable amount of secondary flow is induced between the jets. The ratio of U_s (secondary flow velocity) to U_0 (exit velocity) is about 0.08. Marsters[5] reports a ratio of 0.125 for two ventilated plane parallel jets at the corresponding spacing and Reynolds number ($Re_D = 12{,}000$). A nearly flat profile, corresponding to a complete mixing of the jets, occurs downstream at a location of approximately $60D$. The effect of the finite number (5) of jets is indicated by the drop in the magnitude of the velocity at the tips of the profile, which first appears at X equal to $60D$. Most of the measurements described hereinafter are for the case of a separation distance of 7.5 cm ($1.5L$).

The decay of the square of the mean axial velocity with downstream distance for the three cases (single freejet, multiple freejet and confined multiple jet) is shown in Fig. 6. The decay for the case of the multiple confined jet is almost identical to that of a multiple freejet. Judging from this, it seems that the effect of the confining surfaces on the centerline velocity of the jet is minimal. The decay of the single jet follows multiple jet data closely in the first region and most of the second region.

The normalized mean velocity profiles in the X, Y plane for the center jet from $y=0$ to $y=4D$ are shown in Fig. 7. The secondary flow induced between the jets is seen in the profile at X equal to $10D$. For X greater than or equal to $60D$, the mean velocity is uniform across the nozzles.

The normalized mean velocity profiles in the X,Z plane are shown in Fig. 8. The abscissa Z is normalized with respect to the nozzle width D, while as before the mean velocity is normalized with respect to the centerline mean velocity at the

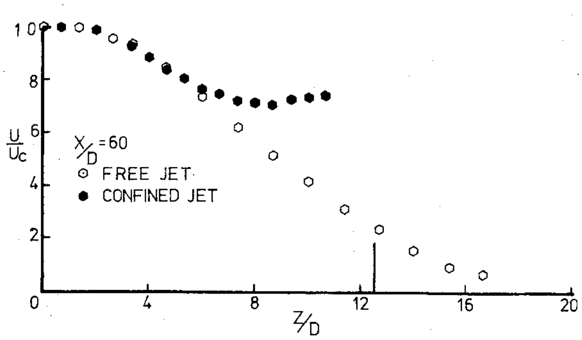

Fig. 9 A comparison of the mean velocity profiles in the X,Z plane.

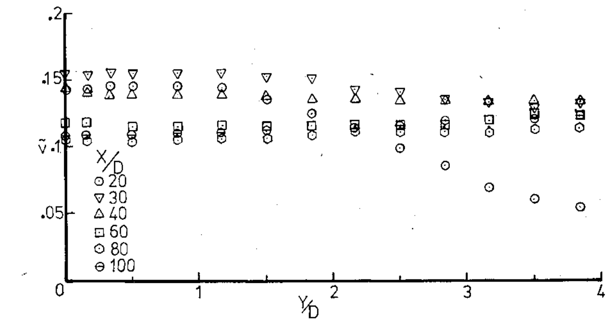

Fig. 12 The distribution of the lateral velocity fluctuations in the X, Y plane.

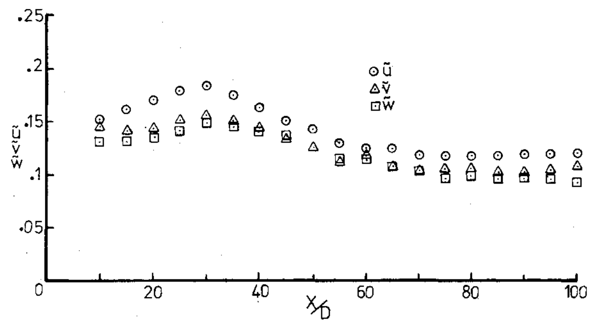

Fig. 10 Variation of turbulent intensities along the centerline of the jet.

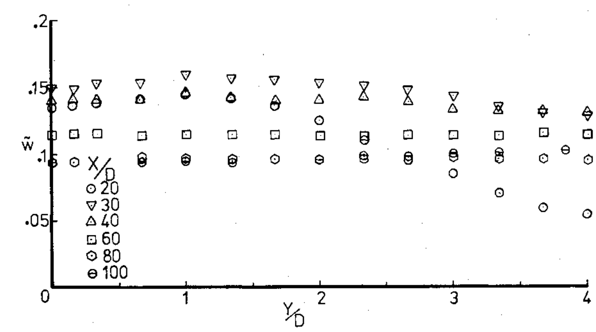

Fig. 13 The distribution of the transverse velocity fluctuations in the X, Y plane.

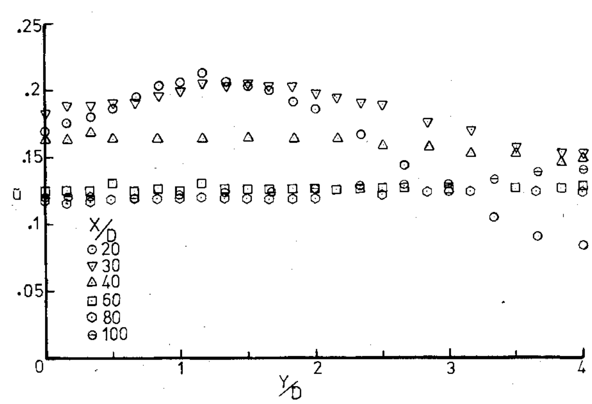

Fig. 11 The distribution of the axial velocity fluctuations in the X, Y plane.

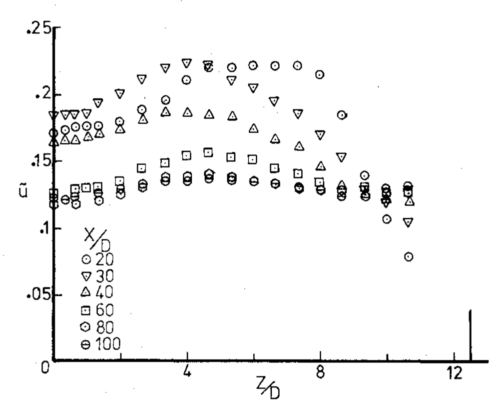

Fig. 14 The distribution of the axial velocity fluctuations in the X, Z plane.

corresponding station. The figure also locates the position of the plate. For X less than or equal to $40D$, the profiles exhibit a saddle shape. For locations X greater than or equal to $60D$, the profiles are more nearly uniform across the jet, and have a local minimum as shown in the figure.

For the purposes of clarity, a typical exit profile in the central X,Z plane is included in Fig. 8. The profile is flat across the nozzle except for the boundary layers near the wall. This profile along with the top-hat profile at the exit in the central X,Y plane suggests that the mean flow is uniform at the exit with laminar boundary layers at the walls.[3] This constitutes the mean velocity initial conditions for numerical simulation.

To exhibit the influence of the plates on the flowfield, the profiles in the X,Z plane for the two cases of the multiple freejet and the multiple confined jet at a typical location of X equal to $60D$ are shown in Fig. 9. The profiles in the center portion of the jet ($Z \leq 6D$) are almost identical. The area under the profile of the confined multiple jet is greater than that of a freejet, while the areas in the X,Y plane for both cases are nearly identical at this location ($X=60D$). This suggests a greater mean flow through the channel than for the case of a multiple freejet.

Turbulent Intensities and Shear Stresses

The rms intensities for the three components of velocity along the centerline of the jet are shown in Fig. 10. The rms intensities are normalized with respect to the local mean centerline axial velocity. For X greater than $60D$, $\tilde{u}$ reaches a constant value of about 0.12. The ratio of the intensities in the axial direction $\tilde{u}$ to that of $\tilde{v}$ or $\tilde{w}$ is approximately 1.15 and does not change significantly with downstream distance. The degree of anisotropy present in these measurements is quite similar to that of grid generated turbulence[6] where the ratio $\tilde{u}/\tilde{v}$ is found to be about 1.09 for biplane grids.

The $\tilde{u}$ profiles in the central X,Y plane for different downstream locations are shown in Fig. 11. For X greater than or equal to $60D$, the profiles become flat just as mean velocity profiles. Profiles for all downstream locations are almost identical to those of a multiple freejet[4] when compared at their corresponding locations. Similar observations are also made from $\tilde{v}$ and $\tilde{w}$ profiles in the X,Y plane, which are shown in Figs. 12 and 13, respectively.

The profiles of $\tilde{u}$ in the central X,Z plane for different downstream locations are shown in Fig. 14. The distance Z along the Z axis is normalized with respect to the width D.

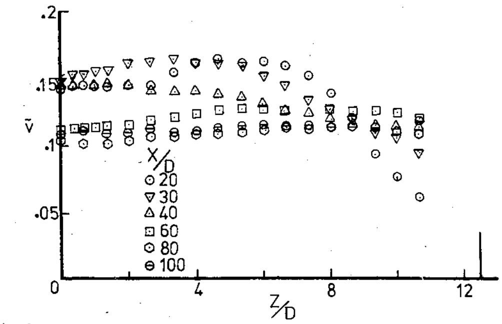

Fig. 15 The distribution of the lateral velocity fluctuations in the *X*, *Z* plane.

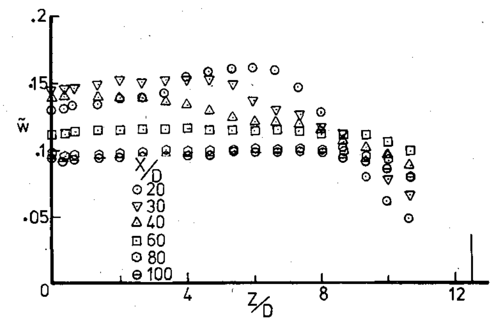

Fig. 16 The distribution of the transverse velocity fluctuations in the *X,Z* plane.

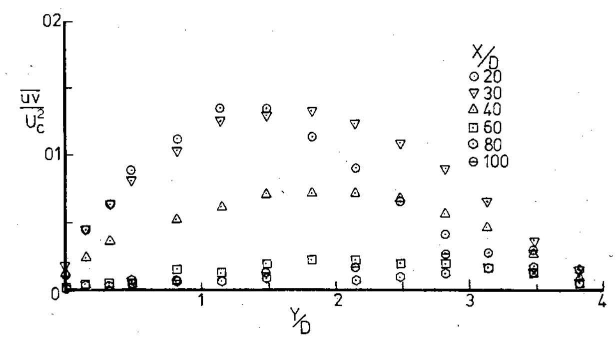

Fig. 17 The distribution of the turbulent shear stress in the *X,Y* plane.

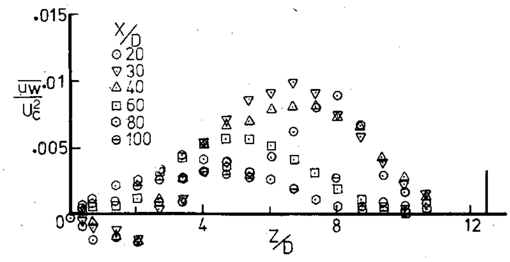

Fig. 18 The distribution of the turbulent shear stress in the *X,Z* plane.

Profiles for X less than $20D$ are almost identical to those of a multiple freejet[4] at corresponding locations. A very mild saddle shape profile is developed at X equal to $60D$, and the profile is nearly uniform. Further flattening occurs for locations greater than $60D$. The profiles of $\tilde{v}$ and $\tilde{w}$ are also uniform for X greater than $60D$ as shown in Figs. 15 and 16, respectively. This observation along with the corresponding profiles in the X, Y plane suggests that the turbulent motion for X greater than 60 widths downstream is almost statistically homogeneous (in two lateral planes) within the accuracy of measurements.

The normalized turbulent shear stress $\overline{uv}$ for different downstream locations are plotted in Fig. 17. The profiles are almost identical to those of a multiple freejet[4] when compared at corresponding locations. For X greater than $60D$, the normalized stress is quite small. The normalized turbulent shear stress $\overline{uw}$ in the X, Y plane is found to be negligible for all downstream stations measured.

The normalized turbulent shear stress $\overline{uw}$ in the X,Z plane for various downstream locations are shown in Fig. 18. The values of $\overline{uw}$ in the present case are lower than those for the multiple freejet at corresponding locations. The values of $\overline{uw}$ across the jet for X equal to $100D$ are very small (of the order of 0.003). Likewise, the magnitudes of $\overline{uv}$ in the X,Z plane are found to be very small.

As indicated from these measurements, the value of the Reynolds stress for X greater than $60D$ is quite small. This observation along with Boussineq hypothesis ($-\overline{uv}=\epsilon \mathrm{d}U/\mathrm{d}y$, where ϵ is the eddy viscosity, which can be taken to be a function of only the axial distance in free shear flows), suggest that the mean shear in the two lateral planes is quite small, and is also depicted by the mean velocity profiles as shown in Figs. 7 and 8. This being the case, there is no continuous source of turbulent energy and the turbulence decays with downstream distance. The inhomogeneity in the mean flow due to the decay in the axial direction may limit the degree of isotropy. As noted by Comte-Bellot and Corrsin,[6] a slight contraction of the channel may bring the turbulence to isotropy.

Conclusions

For the case of partially confined multiple jet with a separation distance between the plates of $1.5L$ (or $\delta/L=0.25$), the following observations are made. The flowfield in the plane of the array of nozzles (X, Y plane) was affected slightly by the presence of the plates and the mean velocity profiles are quite similar to that of a multiple freejet at corresponding locations. In spite of the strongly inhomogeneous character of the flowfield in the initial region of the jet ($X<15D$), the flowfield for X greater than $60D$ is nearly homogeneous in the two lateral planes (X, Y and X,Z). The degree of anisotropy present in the rms intensities is comparable with that of grid generated turbulence.

The present investigation, as described, furnishes detailed experimental data for the configuration studied. Owing to the limitation on the dimensions of the probe, with respect to the nozzle, measurements were made for X greater than $10D$. Adequate knowledge of the flow conditions at the nozzle exit such as the velocity profiles, nature of the boundary layer, and the initial turbulence intensity are provided in the present study. Further detailed investigations are still needed to clarify the importance of the flow details at the nozzle exit and the flow structure close to it.

Acknowledgment

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