J. Fluid Mech. (1982), vol. 115, pp. 493–504
Printed in Great Britain


# Experimental investigation of opposed jets discharging normally into a cross-stream

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(Received 13 February 1981)

Detailed measurements are reported of mean-flow and turbulence characteristics of opposed jets discharging normally into a cross-flowing stream. They were obtained with pitch-to-diameter ratios of two and four, and for the limiting case of single opposed jets and for a separation of four jet diameters. Results are presented at downstream distances from two diameters from the plane of the jet centres.

The results for the symmetrically arranged jets show that the jets retain their identity for a velocity ratio of unity and pitch-to-diameter ratios of four and infinity. With a velocity ratio of 1·8, the single opposed jets bifurcate about a vertical plane to form two symmetric cores of mixed jet fluid. With the pitch-to-diameter ratio of two, the individual jets retain their identity and, in contrast with the results for a pitch-to-diameter ratio of four, where each jet divides to form two cores, only one core is formed for each jet. In general, the turbulence characteristics are determined by the mean flow, which is controlled largely by pressure forces.

## 1. Introduction

The flow characteristics downstream of a single jet blowing at right angles to a free stream are well known as a result of the experimental investigations of many authors including Crabb, Durão & Whitelaw (1981), who provide a brief review of the previous work. The flows downstream of a row of jets or rows of opposed jets have received little attention, although they are of relevance to gas-turbine combustors and to many other applications. Mean-temperature distributions have been reported downstream of a row of jets by Kamotani & Greber (1973), Holdeman, Walker & Kors (1973) and Walker & Kors (1973). Mean velocity, concentrations of a passive scalar and one-point velocity correlations have been reported by Crabb (1979). Opposed jets have been investigated by Kamotani & Greber (1974), who presented mean-velocity distributions downstream of two opposed jets for a jet-to-free-stream momentum ratio of 32. A related investigation was described by Khan & Whitelaw (1980), who presented values of mean velocity and the concentration of a passive scalar for pitch-to-diameter ratios of two and four, with emphasis on the influence of hole eccentricity.

The results presented here were obtained in a two-dimensional channel downstream of the exit plane of opposed jets and correspond to pitch-to-diameter ratios of two and four, and to the limiting case of two opposed jets. They include values of mean velocity, the concentration of a passive scalar and one-point velocity correlations

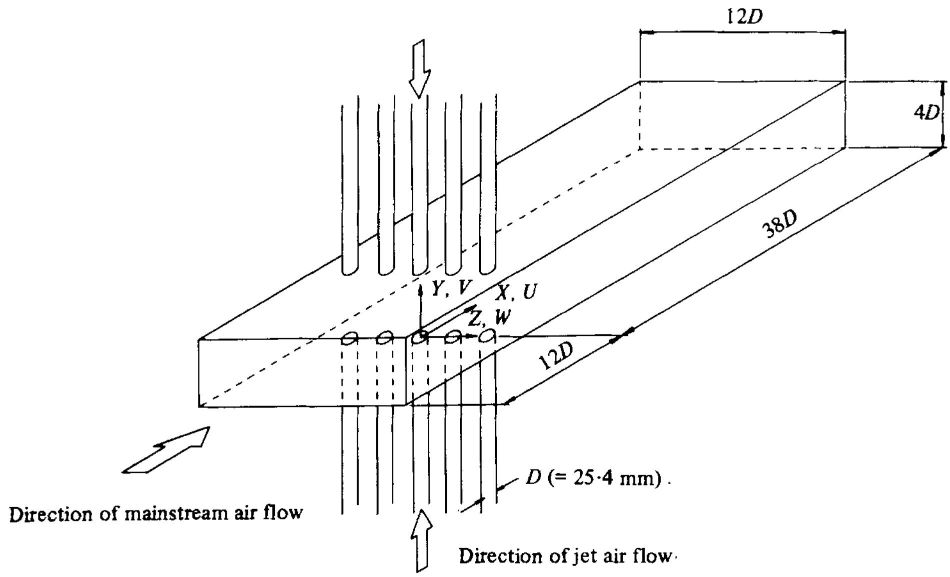


FIGURE 1. Flow configuration.

measured by hot-wire anemometry. The main purpose of the investigation was to determine the main flow features, their relationship to each other and to those of a single row of jets and a single jet in cross-flow and to do so in a manner which could provide a basis for the design methods which might be extended to gas-turbine combustion-chamber arrangements. In this context, it is useful to note that the use of turbulence models to describe single jets in cross-flow (e.g. Crabb 1979; Jones & McGuirk 1980) appears to be less important than numerical approximations; this stems partly from the large influence of pressure forces in the single-jet arrangement and may be less true with the multiple jets considered here.

The measurement techniques chosen for the investigation include pressure and sampling probes and hot-wire anemometry. As a result, detailed measurements have not been attempted in the upstream region except to confirm the symmetry of the jet profiles and that the mass flow through each jet exit plane was equal. Hot-wire measurements were restricted to regions of the flow where the local intensity was less than approximately 0·25 and, as a result, were obtained at, and downstream of the plane, six diameters from the jet exit; mean-velocity results were obtained from four diameters and concentrations of the passive scalar from two.

## 2. Experimental arrangement and measurement systems

The open-circuit wind tunnel had the dimensions shown on figure 1, with five jets emerging from each of the roof and floor through one-inch diameter holes. The flow to each of the jets passed through a long straight pipe and the five roof and five floor jets were supplied by the same fan but different plenum chambers with flexible piping connecting the plenum chambers and straight pipes. The holes were arranged with a pitch-to-diameter ratio of two, and holes were blocked to achieve the pitch-to-diameter ratio of four and the two opposed-jet configurations. The present results were obtained with an initial free-stream velocity of 11·1 m/s that was constant throughout the length of the working section in the absence of the jets; the corresponding turbulence intensity, measured in the plane of the jets, was 0·007. Sandpaper trips were located on the floor and roof of the tunnel and close to the beginning of the channel, and resulted in boundary layers of momentum thickness $2{\cdot}65 \times 10^2$ at the location of the leading edge of the holes. The shape of these boundary layers conformed to a turbulent flow with identifiable logarithmic regions. Two-dimensionality of the cross-stream was confirmed to within 1 % of the free-stream value over the central 93 % of the channel; no rotation of the free stream could be detected.

The flow at the exit planes of the pipes was investigated for the two sets of jets separately and in the absence of the free stream. The long length (0·76 m) of the pipes ensured fully developed turbulent flow in the exit plane of each pipe. The flow in each pipe was adjusted to ensure that the mean flow in each was the same, within 1 %, and that the exit-plane profiles of mean velocity, measured in two orthogonal planes for each jet, did not deviate by more than 4 % from the centre-line value. The jet pipes were nominally parallel and the pitch-to-diameter ratios were equal to within 0·02 mm.

The mean-velocity measurements in the exit plane of the jets were obtained by a probe of external and internal diameters 1·1 and 0·69 mm respectively. The traversing arrangement allowed translation of the probe in two orthogonal locations with a precision of 0·05 mm. The mean velocity and concentrations of the trace of helium gas, added to the flow upstream of the straight pipes, were obtained with a probe of outside and inside diameters of 1·1 and 0·61 mm respectively. The total (and static) pressures were measured with a calibrated transducer and the concentrations with a thermal conductivity cell, previously used by Khan & Whitelaw (1980) and others. The cell was located in a constant-temperature oven and allowed the measurement of helium concentration within ±2 % of the concentation level (approximately 1 %) at the pipe exit. The calibration of the conductivity cell indicated linear response over the range of measurement.

Mean velocity and one-point velocity correlations were obtained in the downstream region by hot-wire anemometry. Cross-wire probes were used in conjunction with linearizers (DISA 55D10) and constant-temperature anemometers (DISA 55D01). The linearized voltages were passed to an analog-to-digital convertor and to a mini-computer (DEC PDP8E) and magnetic-tape arrangement. The system has been described by Ribeiro & Whitelaw (1975) and Crabb *et al.* (1981) and made use of the evaluation method of Champagne & Sleicher (1967). The errors introduced by calibration and the measurement system were small, but those due to truncation in the transform equations became increasingly important as the turbulence intensity increased above around 15 %. In addition, the transform equations assumed that the probe was aligned with the direction of mean flow at the measurement location, and it was therefore necessary to confine these measurements to the downstream region where the $V$ and $W$ velocity components were negligible. It is expected that the measurements at, and downstream of, eight diameters are within error bounds given by $\overline{U}/U_\infty$ ±5 %; $\tilde{u}/U_\infty$, $\tilde{v}/U_\infty$, $\tilde{w}/U_\infty$ ±8·6 %, and $\overline{uv}/U_\infty^2$, $\overline{uw}/U_\infty^2$ ±15·8 %.

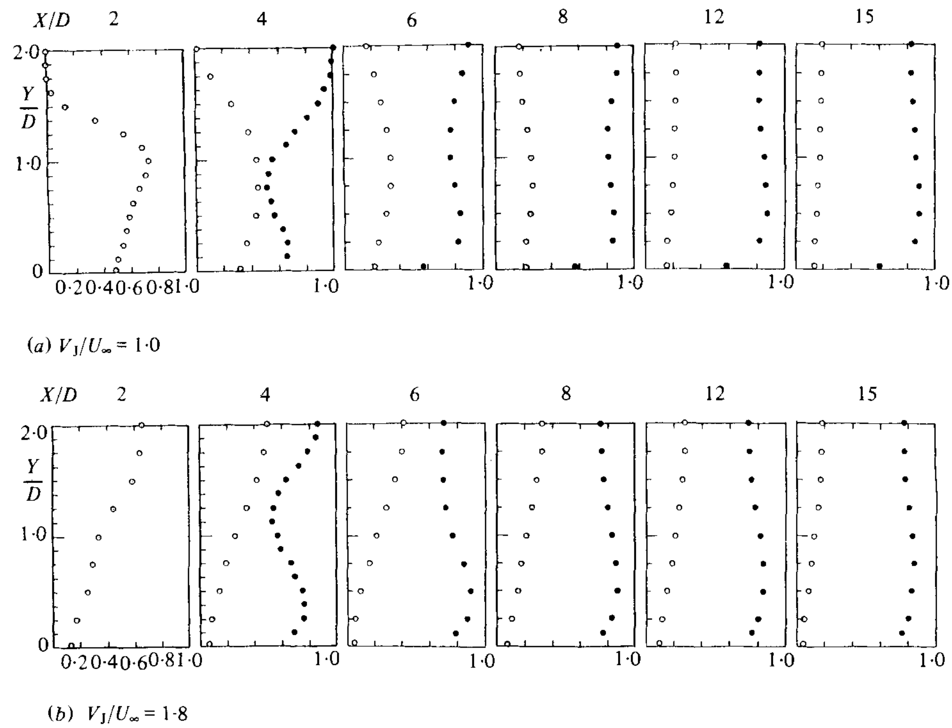


FIGURE 2. Centre-plane ($Z/D = 0$) profiles of mean velocity and scalar concentration: ●, $\bar{U}/U_{\infty}$; ○, $\bar{\theta}/\theta_J$.

## 3. Results and discussion

The results are presented in a sequence of decreasing pitch-to-diameter ratio so that §§ 3.1, 3.2 and 3.3 are concerned, respectively, with pitch-to-diameter ratios of infinity, four and two. A brief discussion follows in § 3.4, and brings together the results of §§ 3.1–3.3, together with those mentioned in § 1. In all cases, only a sample of the measurements is reported, and has been chosen to demonstrate the more important flow features.

### 3.1. *Two opposed jets*

Measurements with two opposed jets were obtained from $X/D = 2$–$15$ and, as an example of spacing of the measured points, profiles of mean velocity and concentration are presented in figure 2 for velocity ratios of unity and 1·8. As can be seen with the lower velocity ratio, the jets create a wake and the free-stream flow is forced to accelerate about the mid-plane and (as shown in figure 3) around the jets. With the higher velocity ratio and increased jet penetration, the free stream is prevented from passing between the opposed jets by $X/D = 6$. For both velocity ratios, the flow is comparatively uneventful beyond 12 diameters. The concentration profiles show the trajectory of the jet fluid: at $X/D = 4$ and the lower velocity ratio, for example, the jet fluid is much closer to the wall from which it emerged than with the higher velocity ratio; this property is maintained up to $X/D \simeq 8$. Thus it is clear that the jet fluid is distributed in very different ways for the two velocity ratios.

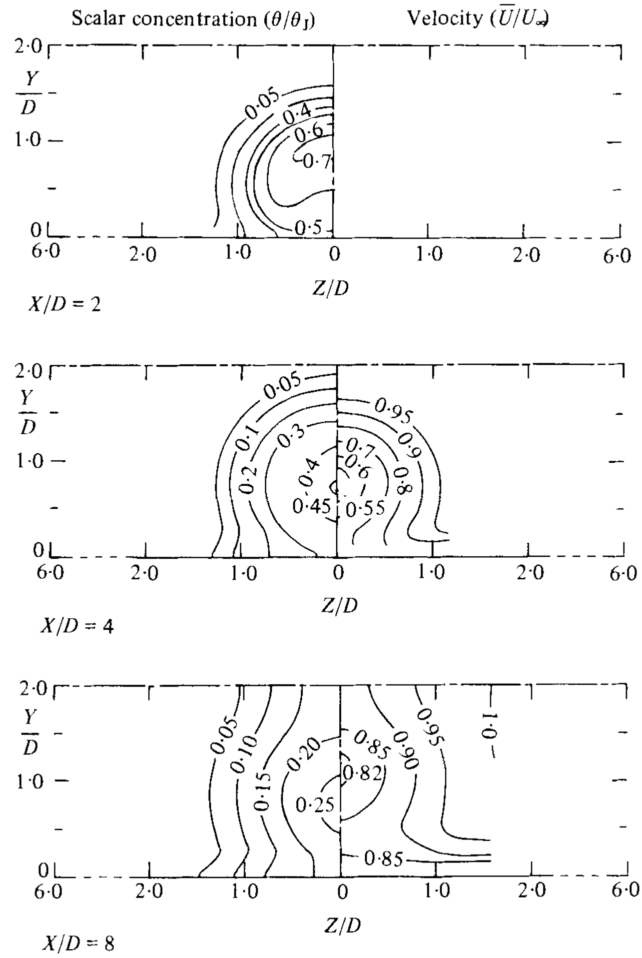


FIGURE 3. Normalized contours of mean velocity and scalar concentration for $V_J/U_\infty = 1{\cdot}0$.

Figures 3 and 4 present contours of constant mean velocity and concentration for velocity ratios of unity and 1·8 and at values of $X/D = 2$, 4 and 8; as with related results for the other pitch-to-diameter ratios a lower (symmetric) quadrant of the flow is presented in each case with velocity on the right and concentration on the left. The concentration results were obtained with only the central, lower jet containing the helium tracer; the measured values in the upper half were added to those in the lower half to give the results of figures 3 and 4. Thus the contours are equivalent to a situation where the upper and lower jets contained the tracer. With the lower velocity ratio, there is clearly little interaction between the two jets. The minimum velocity, corresponding to the wake shown on figure 2(*a*), is nearly coincident with the region of maximum concentration that represents the jet fluid. Thus the two jets have turned and, with a small degree of mixing, have retained their identities as two single jets. This is in contrast to the higher velocity ratio, figure 4, where the two jets have interacted to form two cores, separated by the centre plane ($Z/D = 0$), which are likely to become one at a further downstream location. In the first case, the free stream has

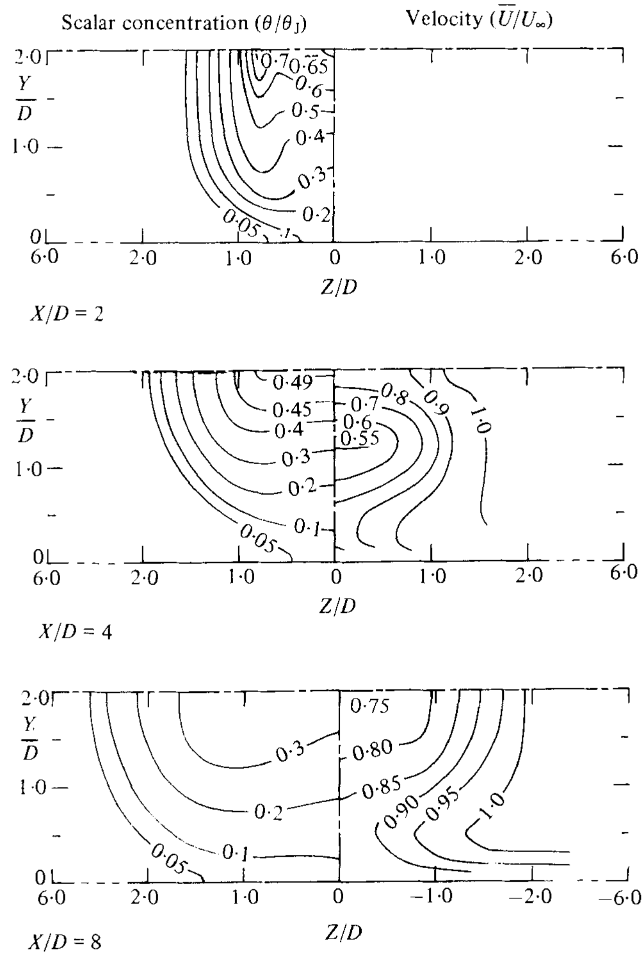


FIGURE 4. Normalized contours of mean velocity and scalar concentration for $V_J/U_\infty = 1{\cdot}8$.

accelerated around and between the jets; in the second, it has accelerated only around the jets. The trajectories of the jet flow, for the two velocity ratios, correspond to those of figure 2. For the lower velocity ratio, the jet has clearly turned between $X/D = 2$ and 4 and maintained a similar core position between $X/D = 4$ and 8 but, as expected, with considerable spreading between those locations. With the higher velocity ratio, the jet core has reached the mid-plane ($Y/D = 2$) at $X/D = 2$ and remains there, with concentration maxima on either side of $Z/D = 0$.

Turbulence information is presented in figure 5, with figure 5(*a*) showing the development of the r.m.s. values of the three velocity components and one shear stress along the centre plane of the flow and figure 5(*b*) showing the axial mean velocity, the r.m.s. values of the fluctuations and two shear stresses at $X/D = 8$ and various cross-stream locations. As can be seen, the fluctuations of the vertical velocity component decay less rapidly on the mid-plane, probably because of the larger scales associated with the $y$-direction in this region. Closer to the walls, and in accord with the single-jet measurements of Crabb, Durão & Whitelaw, the fluctuations of the cross-stream

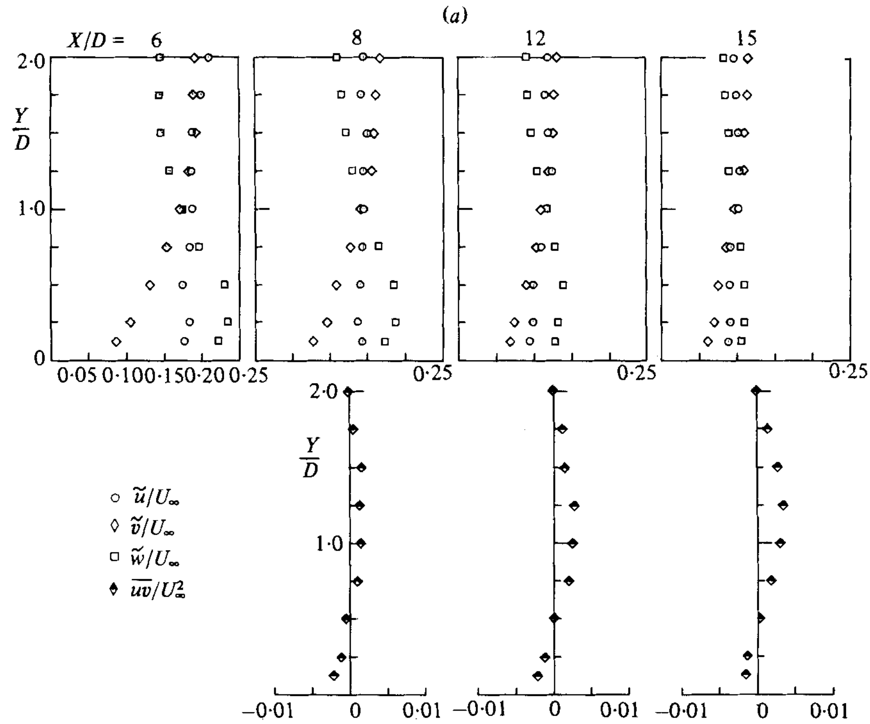


FIGURE 5. (*a*) Normalized Reynolds-stress profiles in the plane, $Z/D = 0$; $V_J/U_\infty = 1{\cdot}8$. (*b*) Normalized mean-velocity and Reynolds-stress profiles in the plane $X/D = 8$; $V_J/U_\infty = 1{\cdot}8$.

velocity are largest, and this characteristic remains throughout the range of measurements. The large values of $\tilde{w}$ are associated with the free-stream velocity dividing around the jet and meeting again. The Reynolds stresses are in accord with the gradients of the mean-velocity profile, except that the location of zero stress is further from the wall than that of the velocity maximum.

The mean-velocity values of figure 5(*b*) show that, at 8 diameters downstream, there is a substantial wake at the mid-plane, $Y/D = 2$. The highest velocity values at $X/D = 8$ are found below $y/D = 1$ and are associated with the free-stream fluid dividing and accelerating around the jet cores. The r.m.s. of the velocity fluctuations, normalized with the free-stream velocity, correspond to a normal turbulent boundary layer at $Z/D = 3{\cdot}2$, but show increasing influence of the jets with decreasing $Z/D$. It is clear from the concentration contours of figure 4 that the jet at $X/D = 8$ has spread to values of $Z/D$ greater than 2, and this is reflected in the fluctuations of figure 5(*b*) which, unlike the shear stresses, show a large effect of the jet at $Z/D = 2{\cdot}4$. The values of $\tilde{w}$ exceed those of $\tilde{u}$ and $\tilde{v}$ at the edge of the jet, with $\tilde{v}$ becoming dominant on the centre-line and close to the mid-plane. The cross-stream component $\tilde{w}$ is also dominant on the centre-line, but close to the wall where the free-stream flow has come around and under the jet fluid, as indicated in the previous paragraph.

The $\overline{uv}$ and $\overline{uw}$ shear stresses are particularly dissimilar at $Z/D = 0{\cdot}8$ and $1{\cdot}6$, where the corresponding mean-velocity gradients are consistent with the differences in sign except close to the zero-stress locations. The zero-stress and zero-mean-

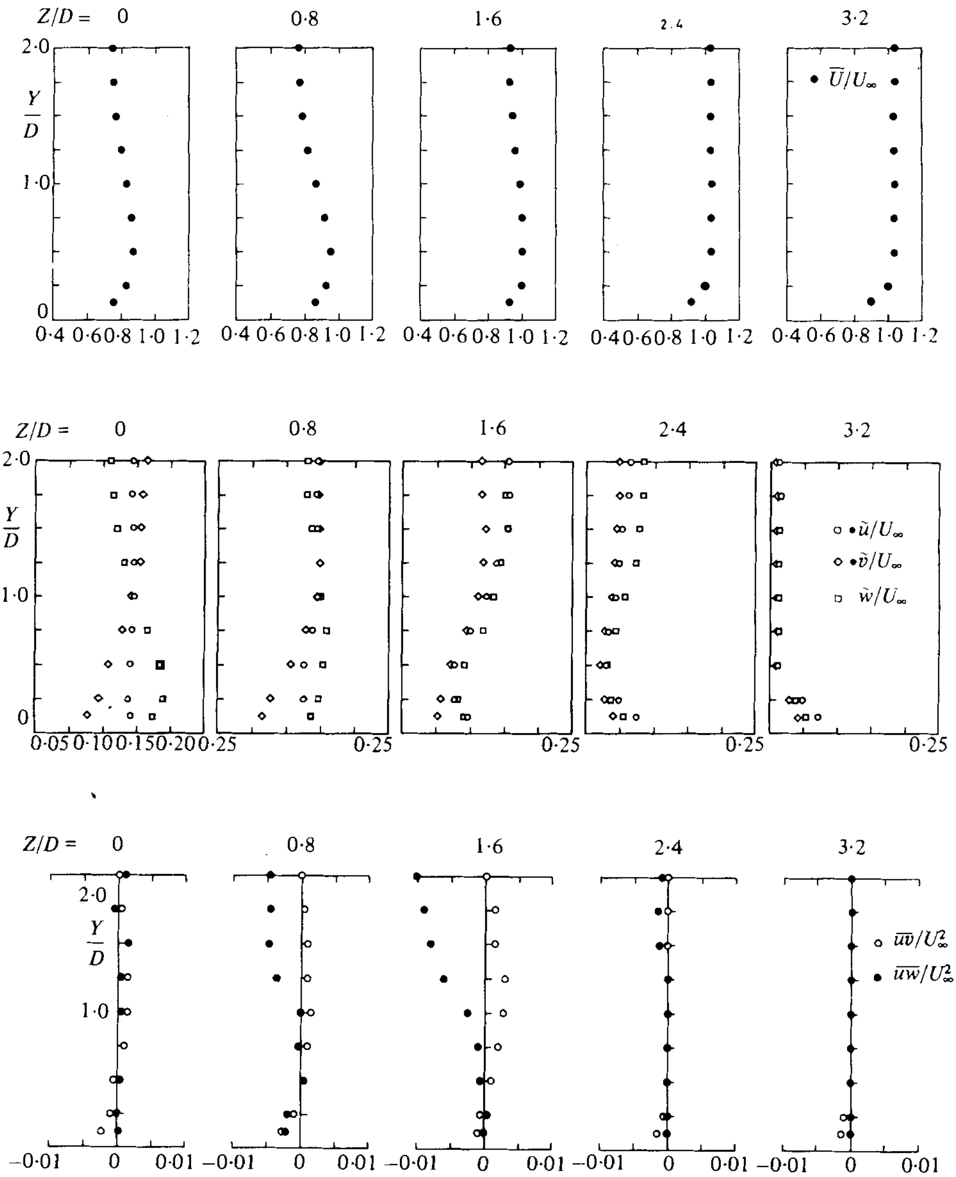


Figure 5*b*. For legend see p. 499.

velocity-gradient locations are indicated on the figure and confirm that the zero-stress location is closer to the wall in both cases.

### 3.2. *Pitch-to-diameter ratio of four*

This flow was formed by blocking two of the five jets on each side, and it is to be expected that the flow around the central jet is a good approximation to the title of this subsection. Indeed, measurements with the lower velocity ratio yielded contours similar to those of figure 3 with the same velocity ratio and are not presented. Instead,

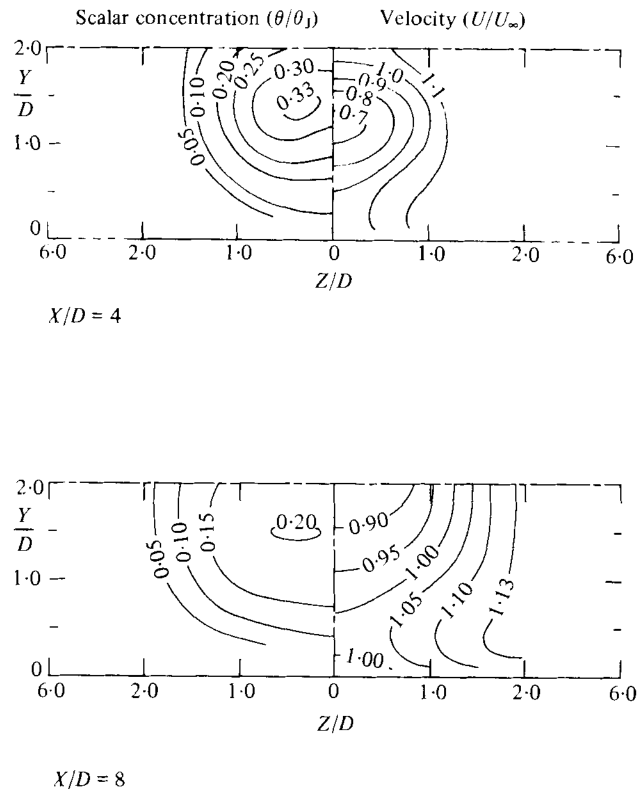


FIGURE 6. Normalized contours of mean velocity and scalar concentration for pitch-to-diameter ratio $S/D = 4$; $V_J/U_\infty = 1{\cdot}8$.

figure 6 presents velocity and concentration contours for the higher velocity ratio and for $X/D = 4$ and 8. In this case, and as confirmed by their finite gradients at the mid-plane ($Y/D = 2$), the concentration contours are based on measurements obtained in the lower half of the tunnel. Measurements were obtained throughout the flow and separately with the central top and bottom jet containing a trace of helium to confirm symmetry. Comparison of the two methods of presentation confirmed that the amount of jet fluid that crosses the mid-plane is small and affects only very slightly the location of maximum concentration. If the results of figure 6 were presented in the same manner as those of figure 4, the jet core represented at $X/D = 4$ and 8 by 0·33 and 0·20 contours, respectively, would be represented by contours of 0·38 and 0·25 that would be displaced towards the mid-plane by less than $0{\cdot}1D$.

The contours at $X/D = 8$ show that the opposing jets have not mixed to the same extent as those of figure 4 but that they have each bifurcated about the centre plane to form four core regions of jet fluid which were already recognizable at $X/D = 4$ and do not appear to have moved closer to either the mid-plane or the centre plane. The velocity contours do show a development of the flow over this distance in that the wake region has moved from half-way between the mid-plane and the wall at $X/D = 4$ to the mid-plane at $X/D = 8$. This is in accord with the acceleration of free-stream fluid between the jets at 4 diameters and its tendency to move away from the jet fluid with downstream distance. Thus, we now have three general flow

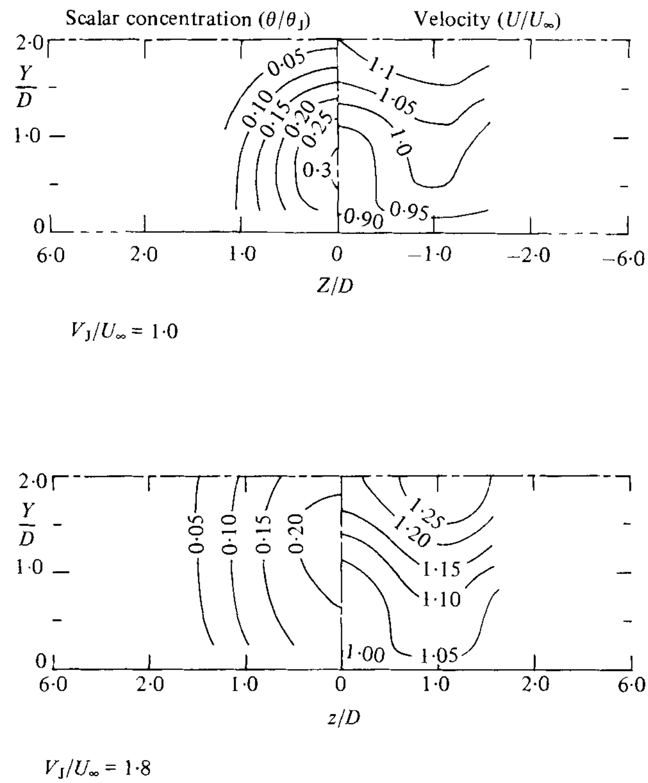


FIGURE 7. Normalized contours of mean velocity and scalar concentrations in the plane $X/D = 8$; $S/D = 2$.

configurations that arise from jets in cross-flow: (i) the situation obtained with the velocity ratio of unity and shown on figure 3 for two opposed jets (the same features were observed with this velocity ratio and a pitch-to-diameter ratio of 4) where the two opposed jets retain their identities as individual jets and bend away from each other; (ii) the two jet cores found with two opposed jets and the 1·8 velocity ratio and shown on figure 4; (iii) the four cores implied by figure 6 for the 1·8 velocity ratio and $S/D$ of 4.

Detailed turbulence measurements were not made for the $S/D$ of 4 configuration, since preliminary results did not reveal characteristics which appeared to have special significance. As for the results of figure 5, the $\tilde{w}$-fluctuations predominated where the free stream met, after dividing to pass around the jets, and the shear stresses displayed greatly different magnitudes between $Z/D = 0$ and 1, with a zero value which did not coincide with values of zero mean-velocity gradients.

### 3.3. *Pitch-to-diameter ratio of two*

In the mean-flow measurements of Khan & Whitelaw (1980), considerable difficulty was experienced in achieving a symmetric flow with $S/D = 2$ and a velocity ratio of 2·3 and, although great care was exercised to achieve equal mass-flow rates through the individual pipes, it was always worse than the figure quoted earlier with this velocity ratio. At velocity ratios of unity and 1·8, however, symmetry similar to that of the previous two cases was readily achieved, and figure 7 presents contours of velocity and concentration for these velocity ratios. It should be noted that this problem of achieving symmetric flow from apparently symmetric geometric boundary conditions is likely to be magnified in practical situations, such as annular combustors, where engineering tolerances are worse and velocity (and momentum) ratios higher.

The velocity contours of figure 7 show that the free-stream flow passes between neighbouring jets and also accelerates between the impinging jets. The opposing jets retain their identity, as for the previous two cases with unit velocity ratio, although substantial mixing has taken place to reduce the core concentrations to 0·23 since the jets cannot spread laterally to the same extent as in the previous flows. The identity of the jets is even more marked with the lower velocity ratio; for which it appears that the jet has turned even further towards the surface from which it came, with reduced mixing of the opposed jets. These same characteristics were observed at $X/D = 4$, where, in the higher-velocity case, concentrations in excess of 0·5 were observed. It appears, therefore, that the jet trajectories with unit velocity ratio are not strongly dependent upon the pitch-to-diameter ratio, although the mean velocity distributions are quite different. With the higher velocity ratio and impingement, however, the jet fluid is transported to provide very different concentration contours at $X/D = 8$. With the highest velocity ratio that could be achieved with the present arrangement (2·3), and allowing for small asymmetries which could not be removed, the concentration and velocity contours were similar to those of figure 7 for the 1·8 velocity ratio.

Measurements of the three normal stresses at $X/D = 6$, the furthest upstream station at which the mid-plane intensities were less than about 0·25, are in contrast to the decaying cross-stream values of figure 5(*b*). The differences stem from the greater mean-velocity gradients and lateral mixing associated with the reduced pitch-to-diameter ratio. In spite of this increased turbulent mixing, the jets have retained their identities as revealed by the mean-flow results of figure 7. The mid-plane distribution of the $\overline{uv}$ shear stress was finite in the plane of the jet centre lines and shows that the $\partial u/\partial x$ gradient is finite and reasonably large at this location. The $\overline{uw}$ shear stress was close to zero at the same location, which implies slowly varying gradients of the $U$ and $W$ velocities in the $z$- and $x$-directions, respectively.

### 3.4. *Discussion and concluding remarks*

The major result from the present measurements is that, for all three values of pitch-to-diameter ratio and for velocity ratios of unity and less, the jets do not impinge to any serious extent and, as a result, the jets retain their identities at downstream stations with a single concentration maximum for each jet. The dominance of the pressure forces and of the resulting acceleration of the free stream between opposing jets is responsible for the situation. The mean-velocity and turbulence characteristics do depend on the pitch-to-diameter ratio, again largely because of the pressure forces, but the effects are small compared to that resulting from the separating effect of the free stream. This situation is likely to exist for larger values of jet separation but, as the separation is decreased or the jet momentum increased, impingement of opposing jets will occur, with results which may be similar to those observed with the velocity ratio of 1·8.

The results obtained with the higher velocity ratio indicate that the jets can bifurcate in three different ways; i.e. retaining their identities with single jet cores as for

$S/D = 2$, with two jet cores per jet as for $S/D = 4$, or mixing to form two mixed-jet cores as for $S/D \rightarrow \infty$. Again the dominant forces are likely to stem from local pressure gradients, which are largest with the smallest pitch-to-diameter ratio. With $S/D = 4$ and $\infty$, the free stream accelerates between the centre-lines of the jets or around the jets, with mixing between the opposed jet fluids in both cases upstream of $X/D = 8$. With $S/D = 2$, and, as with the lower velocity ratio, the free stream accelerates between opposed jets and inhibits mixing.

In engineering practice where values of velocity ratio are high with pitch-to-diameter ratio between 2 and 4 – a combination present in some combustor arrangements – the multiple maxima in scalar concentrations will correspond to cold or hot streaks, with consequent implications for design. These 'streaks' are persistent, as is witnessed by their presence in results obtained with higher velocity ratios (up to 2·3) even though significant asymmetries were present.

The authors are glad to acknowledge financial support from the Ministry of Defence and the Science Research Council.

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