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Measurements in the Flowfield of a Linear Array of Rectangular Nozzles

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An experimental study of the flowfield from an array of rectangular jets has been conducted. The measurements include the total pressure field and the streamwise component of the turbulence field using hot-wire anemometry. The mapping of these quantities is quite complete in the region within 30 jet slot widths of the nozzle exit plane. Experiments have been conducted at nominal Reynolds numbers of 22,900 and 10,000, based upon nozzle slot width. The jets first appear to develop in a fashion comparable to that for a single free rectangular jet. Eventually, at a distance which depends upon the interjet spacing, the jets merge. In the merging region, the centerline velocity decay rate is significantly reduced. Downstream of the confluence of the jets the mixing rate, based upon velocity decay, was reduced significantly.

Nomenclature

L	= length of each nozzle
P_n	= nozzle pitch: spacing normalized with nozzle width
t_p	= nozzle slot width
U	= mean velocity
u',v',w'	= fluctuating components of velocity
x,y,z	= coordinate axis (see Fig. 1)
$y^{1/2}$	= half width of jet velocity field
α	= constant in error curve for velocity distribution

Subscripts and Superscripts

0	= values at nozzle exit plane
℄	= values at centerline of flow
av	= average value of maximum velocities in a spanwise traverse
max	= local maximum of velocity for a single jet
NEP	= values at nozzle exit plane, on centerline of flow
($\overline{\ }$)	= time-averaged quantity

Introduction

THE rate at which jets mix with the surrounding fluid is an important consideration in many applications, including combustors and powered high-lift devices, and in pollutant dispersal. Thrust-augmenting ejectors for V/STOL applications require rapid mixing and methods of enhancing mixing are sought. It has been observed that some improvement is to be expected when a long slot jet is replaced by segmented jets.[1,2] Such a subdivision offers a great many possible configurations, some of which may be inefficient. The present study was undertaken to obtain some understanding of the nature of the mixing processes which take place in a particular arrangement of rectangular nozzles, i.e., a linear array, to extend the work which was reported on briefly in Ref. 3 and to expand the scope of jet flow studies described in Ref. 4. The data obtained should also be useful to numerical analysts as a basis for evaluating models of this type of flow.

While other studies[2,5-7] have examined the mixing characteristics of nozzle arrays, the majority have dealt with arrays of circular jets. Only one other paper is known which deals with a linear array of rectangular jets,[8] although Wang[7] has reported on a pair of rectangular jets.

A *confined* hexagonal array of round jets has been studied by Fabris and Fejer.[5] A uniform velocity profile was found at 76 nozzle diameters downstream. However, in view of the effects of confinement and the array geometry, the results of that study are not really comparable with the present case. Similarly, Baines and Keffer,[6] using an array of circular jets issuing into an *unconfined* region, performed a very different type of experiment. Nonetheless, some of their arguments regarding mixing rates are relevant to the present study. Although Knystautus[2] used a linear array of jets, the jets were round, and hence, in the characteristic decay region between the end of the potential core and the merging region, the decay of the centerline velocity would be expected to be different from that encountered with rectangular jets. The confining walls used by Knystautus were comparable to those used in the present work. Wang[7] examined the flowfield from two rectangular nozzles which issued into ambient air; the flow was not confined. Rather high velocities were used ($M = 0.967$) and the stagnation temperature in the jet flow was 644 K. The paper does not describe the upstream conditions, but the velocity profiles reported suggest that the jet issued from relatively long slots with almost fully developed profiles at the nozzle exit plane. Moreover, the measurements were taken at only a few stations in the near field, upstream of the merge point. Finally, the work of Krothapalli et al.,[8] concentrates attention on the development of a single jet in the array. Thus the scope is somewhat different from the present work. However, this experiment is generally comparable with the present work. Certainly the main features observed in Ref. 8 coincide with the results reported in this paper.

This paper reports on the flowfield of a linear array of rectangular jets issuing into ambient, still air. The nozzle exit plane velocities are typically quite low (about 35-40 m-s^{-1}), although a few experiments were conducted at nozzle exit plane velocities of up to 100 m-s^{-1}.

The study is purely experimental, with the objective of attempting to provide a data base from which predictive theories for complex three-dimensional mixing might emerge. The experimental techniques are relatively unsophisticated, since the quantities to be observed at this stage are fairly primitive. It seems unproductive to carry out highly detailed measurements at one or two points when the first need is a basic understanding of the gross features of the flow.

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Index categories: Nozzle and Channel Flow; Jets, Wakes and Viscid-Inviscid Flow Interactions; Subsonic Flow.

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Table 1 Data summary

Array configuration	Nominal velocity, m-s^{-1}	Spacing	3-D plots	centerline decay	Diagnostics and data available Rake data	Normal hot wire	Crossed hot wire
Single nozzle	100	...	✓	✓	...	...	...
3 nozzles	100	×1	✓	✓	...	...	...
	100	×2	✓	✓	...	...	...
5 nozzles	100	×1	✓	✓	...	...	...
	100	×2	✓	✓	...	...	...
Full array (with sidewalls)							
20 nozzles	35-40	×1	...	...	$x/t_p = 5,10,16,30$	5,7.5,16	...
10 nozzles	35-40	×2	...	...	$x/t_p = 5,10,16,30$	5,12	5,10

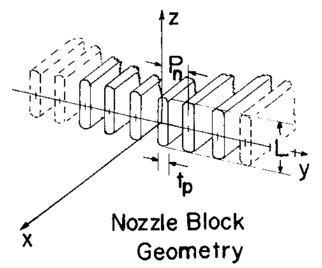

Fig. 1 Schematic diagram of nozzle array showing geometry: $t_p = 3.96$ mm, $L \simeq 38$ mm, $P_n = 4.7\,t_p$.

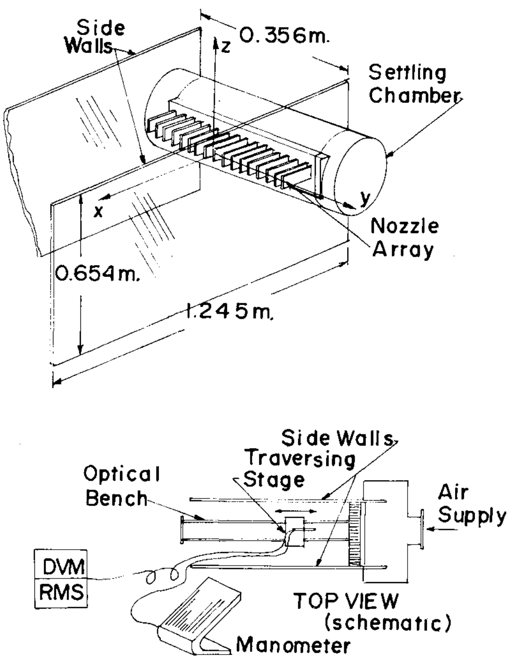

Fig. 2 Schematic diagrams of experimental setup.

Experimental

The flowfield for a particular configuration of jet nozzles has been extensively mapped by means of observation of the total pressure field, while detailed anemometric measurements using crossed and normal hot wires have been carried out at a few locations.

The nozzle configuration is shown in Fig. 1. The principal nozzle dimensions are given in the figure caption. The general arrangement of nozzles, settling chamber, and sidewalls is shown schematically in Fig. 2. The nozzles were supplied with air either by a low-mass flow rate compressor (for high-velocity runs with a few nozzles) or by a small blower which could supply all nozzles but at lower velocity. The two flow rates provided nominal Reynolds numbers of 22,900 and 10,000, where Reynolds number is based upon slot width t_p. Tests were carried out with the supply air within about 2°C of normal temperature. Velocity profiles at the nozzle exit plane were quite flat; within the limits of experimental error, one might correctly assume "top hat" profiles.

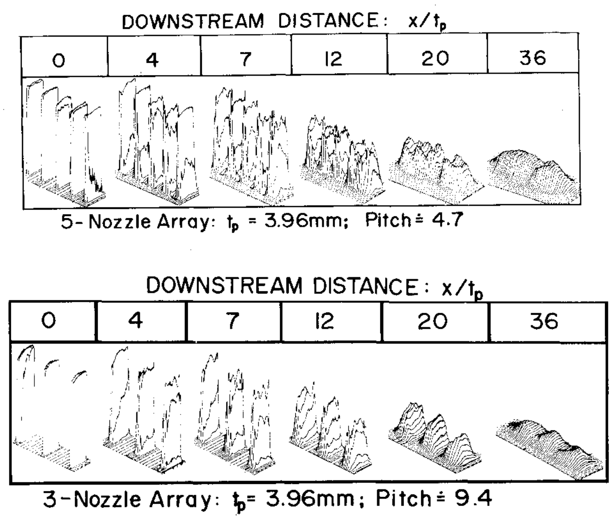

Fig. 3 Three-dimensional plots for three- and five-nozzle arrays at several downstream stations. (Vertical deflections are proportional to the total pressure; no confining walls.)

Several observational techniques were used. Table 1 lists the various configurations, diagnostic techniques used, and data available. First, single total head tube traverses were carried out yielding three-dimensional plots of the total pressure field. These studies were primarily qualitative and indicated the main features of the flow. At the same time transverse traverses were done. Subsequently, traverses using a total head tube rake (10 tubes) were carried out. These were at fixed x stations, providing total pressure data at a large number of grid points in the y-z planes. Typically, the grid dimensions were 2.5×2.5 mm, but in some cases the data in the regions between nozzles were suppressed. The data were recorded from a sloping multitube manometer bank.

The flowfield was again probed using normal and inclined (crossed) hot-wire anemometer probes. Limitations in the accuracy of the traversing gear have made interpretation of the crossed-wire signals difficult. Nonetheless the main features of the turbulence field have been investigated satisfactorily, and regions of high turbulence have been clearly identified. These main features were quite reproducible. No attempt has been made to obtain correlations other than for Reynold's shear stresses, and spectra have not been obtained. The turbulence measurements utilized standard (DISA) anemometry, and the unlinearized data were reduced using the method of Wilson.[9]

Two different nozzle spacings were observed by the simple expedient of blanking off alternate nozzles to obtain "×2 spacing." Although some interference effects from the inoperative nozzles could be expected, this appears to be small, probably because of the fairly long (25 t_p) nozzles

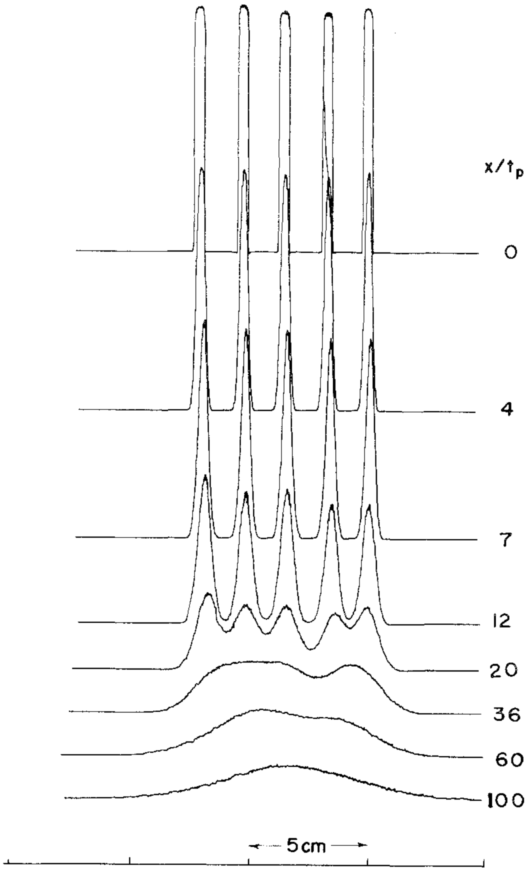

Fig. 4 Spanwise traverses of total pressure for five-nozzle array (closely spaced). (Maximum pressure corresponds to nominal nozzle exit velocity of 100 m-s^{-1}, no confining walls.)

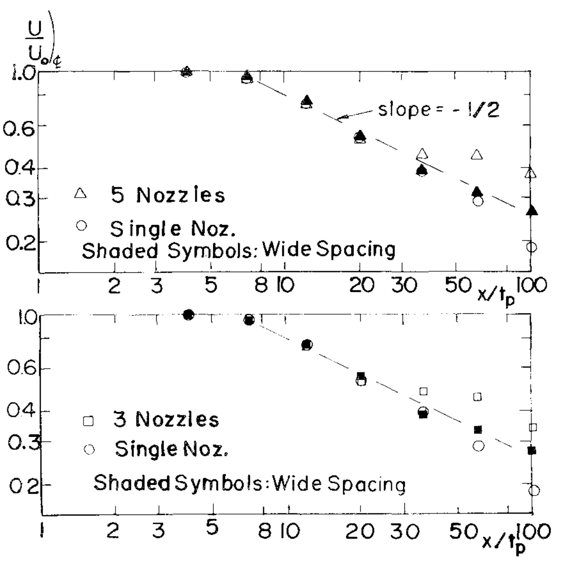

Fig. 5 Decay of maximum mean velocity for four configurations of nozzle array (no confining walls, $Re \approx 22{,}900$, $U_{NEP} \simeq 100$ m-s^{-1}).

used. The nozzle wall thickness was about 1.25 mm. The array consisted of 20 nozzles mounted on a common flange.

In the low Reynolds number runs, extensive sidewall elements (lying in the x-z plane) were used to prevent spanwise spreading of the flows.

Results

High Reynolds Number Flows

The results for the high Reynolds number flows with a small number of nozzles (one, three, or five) will be presented first. Later the results for the entire array, at lower Reynolds numbers and with sidewalls present, will then be presented.

The total pressure field for a high Reynolds number flow using three nozzles at $\times 2$ spacing is shown in Fig. 3a. At this spacing the jet flows develop largely independently and do not interact extensively for at least 20 slot widths downstream. Eventually, however, the jets do merge, as evidenced in the display at 36 slot widths, although each jet remains distinct at this station. In Fig. 3b the pressure field for five closely spaced nozzles is shown, indicating fairly complete merging at $x/t_p = 20$ and is essentially a single jet flow distribution at $x/t_p = 36$, although some nonuniformity is apparent. The corresponding results for a number of spanwise total pressure traverses (at $z=0$) is shown in Fig. 4. In these cases (Figs. 3 and 4) no sidewalls were present. The mean velocity was about 100 m-s^{-1}, and the total temperature of the flow was only slightly different from the ambient temperature.

Both Figs. 3 and 4 are shown primarily for qualitative information. The quantitative results corresponding to Figs. 3 and 4 are given in Fig. 5,† which shows the centerline decay of velocity for one, three, and five nozzles at two different spacings and without sidewalls. Following the terminology of Ref. 10, we identify a characteristic decay region, over the range $10 < x/t_p < 20$ for close spacing and $10 < x/t_p < 60$ for $\times 2$ spacing. The single nozzle exhibits a tendency toward axisymmetric decay at large values of x/t_p. Also, for the closely spaced case, the trend of the data suggest that a return to a characteristic decay behavior occurs following the merging, where a distinct downward trend in the data points appears.

The merging process is clearly indicated in Fig. 5 for the closely spaced nozzle cases. The rate of decay is greatly retarded, relative to the wide spacing. If one characterizes mixing and momentum transfer from the primary jet fluid to the surrounding fluid by the average centerline velocity of the jets, the behavior shown here represents an important reduction in mixing and entrainment. Baines and Keffer[6] interpret this in terms of the reduction of the overall "mixing surface" available, and the fact that the merging "sides" of these jet flows no longer entrain nonturbulent fluid from the surroundings. Thus the jet merging process is one which retards mixing and momentum transfer. Therefore, if one wishes to maximize mixing over large downstream distances, large spacings are in order. For the two spacings studied here, the mixing rates (per nozzle) were essentially the same up to $x/t_p \approx 25$.

From Fig. 3 one also observes that the spreading rate in the y direction is significant, while the jets do not grow appreciably in the z direction, at least in the near field. However, at large x/t_p values (>36) the merged jets resemble rectangular jets with the long axis in the y direction, and are expected to show a second characteristic decay region, as mentioned earlier.

Low Reynolds Number Flow

Attention is now turned to the more detailed measurements in the confined flows in which all 20 nozzles were operating. First, some mean flow quantities are presented, which illustrate the gross flow characteristics of the array. Next, detailed maps of the mean velocity field are examined and, finally, maps of the turbulence structure in the near field are presented. The nominal mean velocity at the nozzle exit plane for these low Reynolds number flows was 35-40 m-s^{-1}. The streamwise turbulence intensity at the nozzle exit plane was less than 1%.

Sidewalls were present in all cases under discussion in this section. Although the presence of sidewalls resulted in some minor distortions of the flowfield, Fig. 6 shows a good degree

†U_{NEP} in Fig. 5, and all subsequent figures is the centerline velocity at the nozzle exit plane.

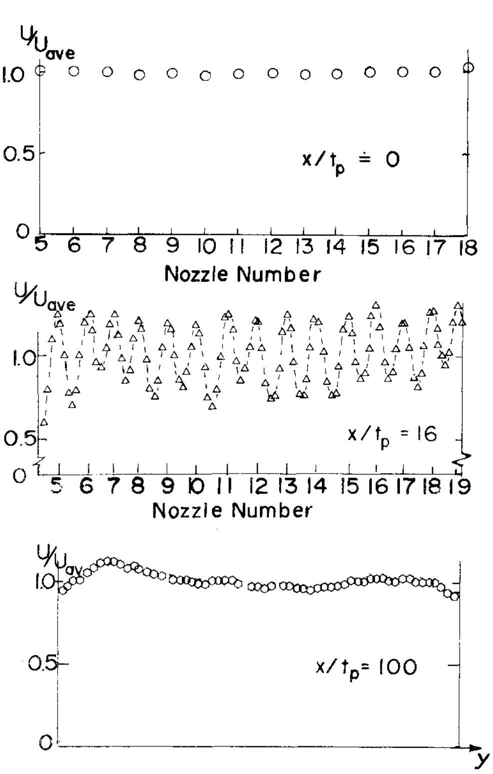

Fig. 6 Spanwise mean velocity distributions for full array (20 nozzles) with sidewalls present at three downstream locations (at $x/t_p = 16$, the average of the peaks is 0.5 U_{NEP} the mean value is 0.4 U_{NEP}; at $x/t_p = 100$, the average value is 0.33 U_{NEP}, $R_e \simeq 10{,}000$).

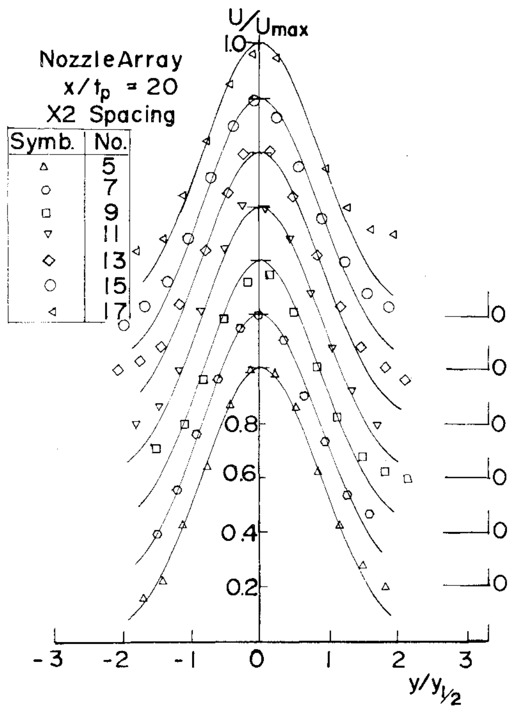

Fig. 7 Mean velocity profiles for seven individual jet flows in full array: $U_{max} = 18.3$ m-s^{-1}, $U_{max}/U_{NEP} \approx 0.46$, $Re \simeq 10{,}000$ (confining walls present).

of uniformity away from the walls. Nozzles 1-4 were inaccessible due to the traversing gear used, while nozzle 20 was essentially a wall jet. The traverse at $x/t_p = 0$ shows the high level of uniformity of spanwise (y direction) distribution. At $x/t_p = 16$ the individual nozzle peaks are distinguishable, but the variations of peak velocity are small, indicating that for

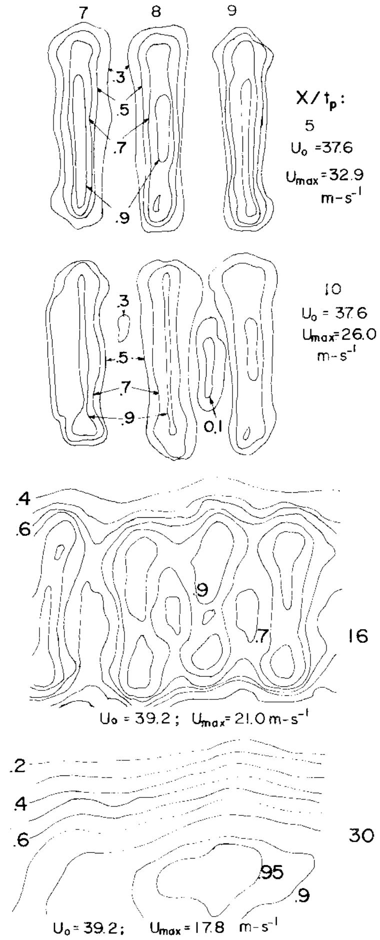

Fig. 8 Selected velocity contours from pitot tube measurements for three nozzles in closely spaced array with confining walls; velocities normalized with respect to peak velocity (U_{max}) for these three nozzles.

close spacing, merging has commenced as early as $x/t_p = 16$. The average peak velocity is $\approx 0.5\ U_{NEP}$, while the mean value of this distribution is approximately 0.4 U_{NEP}. At a large downstream distance (Fig. 6c) the distribution is again quite uniform over most of the flowfield. The average velocity is 0.33 U_{NEP}.

To illustrate the relative independence of the development of each jet for the widely spaced jets, Fig. 7 is included. This shows the mean velocity profiles observed at a downstream distance of 20 slot widths. The error curve, $U/U_{max} = \exp - (\alpha y/y_{1/2})^2$ is superimposed on these data. The degree to which these profiles are fitted by this similarity curve is striking. The jets are seen to develop essentially independently in the characteristic decay region.

Contour maps of constant velocity lines (isotachs) of three selected nozzles are shown in Fig. 8 for four downstream stations and a closely spaced nozzle array. The nozzles selected are interior nozzles in the array, far from the side walls. At $x/t_p = 16$, the degree of merging is extensive, while at $x/t_p = 5$ the degree of independence is very strong. There is evidence of some rather mild saddle back shape (as is often observed for rectangular nozzle flows) in these velocity profiles, but this effect is not as strong here as it is in rectangular jets issuing from sharp-edged orifices. In Fig. 9 similar data from hot-wire traverses are shown, while Fig. 10 shows the distribution of turbulence intensity for these flows. The mean velocity contours in Figs. 8 and 9 show that steep gradients persist at the "ends" of each jet, while the jets merge. This feature has already been noted in the earlier section when it was observed that the jet spreading rates were different in the y and z directions. These data also confirm

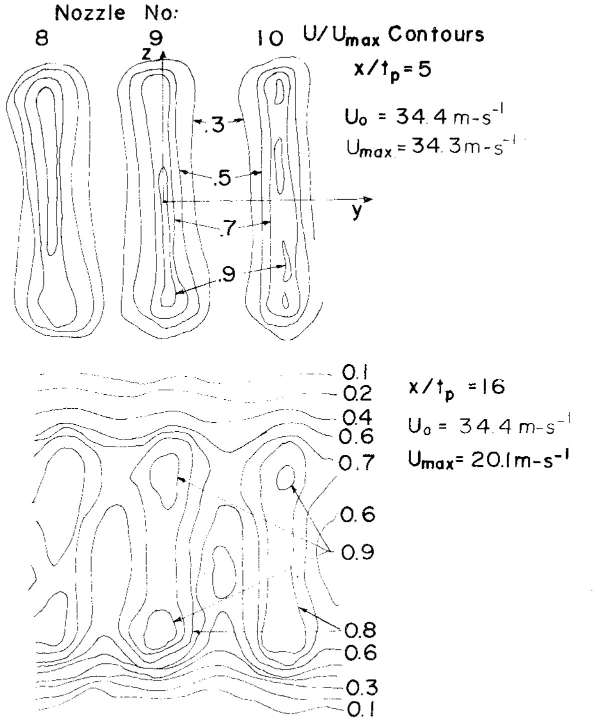

Fig. 9 Selected velocity contours from hot-wire measurement for three nozzles in closely spaced array with confining walls; velocities normalized with respect to peak velocity (U_{max}) for these three nozzles.

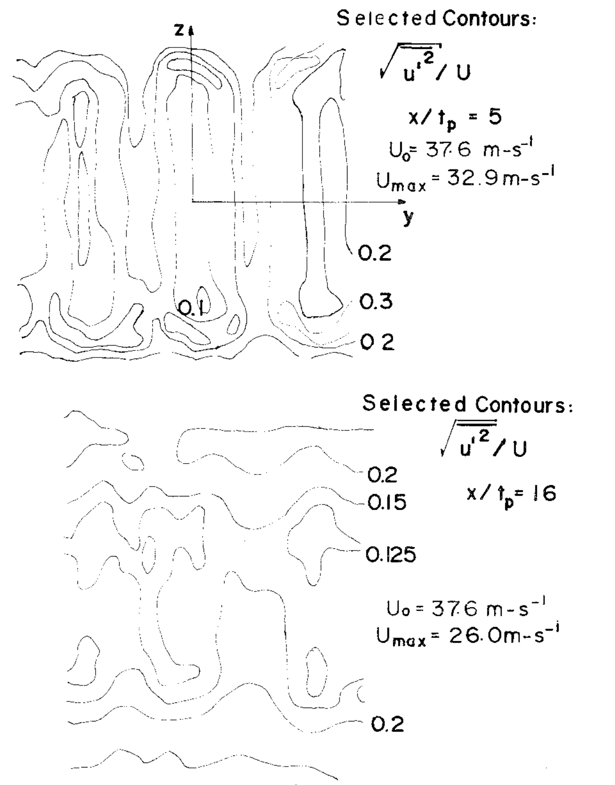

Fig. 10 Selected contours of longitudinal turbulence intensity, relative to *local* mean velocity, nozzle arrangement as in Fig. 9.

what has already been observed in Fig. 6b showing that merging is fairly well established at $x/t_p = 16$ in a closely spaced array.

The turbulence intensity data of Fig. 10 shows high intensities at the "ends" of the jets while the distribution across the array suggests a less vigorous mixing process and the

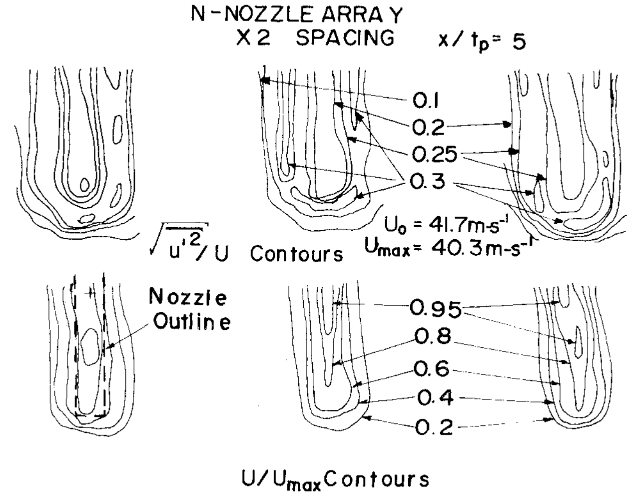

Fig. 11 Mean velocity and streamwise turbulence intensity contours for ×2 spacing; straight hot wire was in *x-z* plane, U_{max} = 40.3 m-s^{-1}.

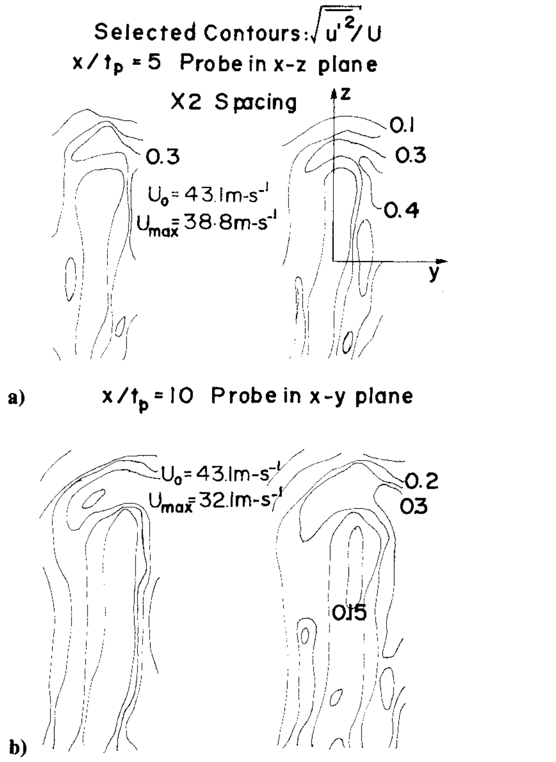

Fig. 12 Selected contours of longitudinal turbulence intensity relative to local mean velocity (measurements with crossed hot-wire probes).

presence of entrained turbulent fluid, just as observed by Baines and Keffer.[6] The rather convoluted nature of these turbulence results indicates the complexity of these flows as the jets merge and mix with each other and the surrounding fluid. Although turbulence intensity measurements are shown, it is clear that the investigation of these very complex flows is at an early stage.

Similar data for mean velocity and streamwise turbulence intensity at two downstream stations is shown in Figs. 11 and 12 for the case where alternate jet flows were blocked. A single normal hot wire was used to obtain the results in Fig. 11. For reference, the nozzle outline is shown on the figure. Because most of the wire measurements were repeated using crossed wires, only a single x/t_p station is shown for comparison with the figures which follow. One should note,

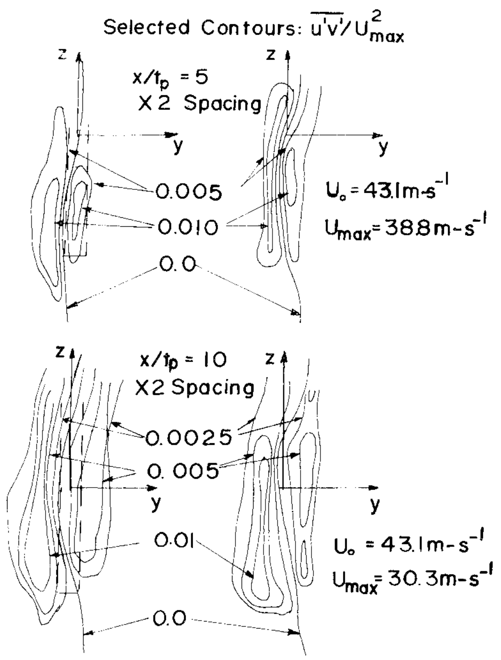

Fig. 13 Selected contours of shear stress $\overline{u'v'}/U^2_{max}$ (dashed line shows nozzle outline).

however, the slight skewing of the mean profiles and the regions of high turbulence intensity at the ends of the jets. The similarity with the information in Fig. 9a and 11a is also worth noting.

Crossed-wire probes were used to obtain maps of mean velocity and turbulence stress quantities. The mean flow data (obtained as a result of "grid" traverses of the type already described) yield mean flow contour plots which are essentially indistinguishable from the results already shown. Similarly, the agreement between the streamwise turbulence intensity, $\sqrt{\overline{u'^2}}/U$, obtained using crossed wires and normal wires was considered to be satisfactory. The features of high turbulence intensity at the ends is, of course, retained. Some typical results for the streamwise intensity are shown in Fig. 12. Attention is called to the definition used for streamwise turbulence intensity: the *local* mean velocity is used to normalize the rms values of the fluctuating component. This is slightly unconventional, and leads to the appearance of very high turbulence levels where the mean velocities are quite low.

Some slight skewing of the flow is seen in these figures and in the mean velocity contours. The origins of this skewing are not known. One possible explanation is a slight tracking error in the vertical traverse gear, which would affect all traverses in the same way.

It is important to note from these figures that transverse traverses along either the y or z planes of symmetry alone could yield misleading results. This is generally true of rectangular (and other three-dimensional) nozzle flows. Thus the task of understanding the mixing process necessarily involves the acquiring and interpretation of large quantities of data.

The distribution of the Reynold's stresses, $\overline{u'v'}/U^2{}_{max}$ is shown in Fig. 13 for two downstream stations corresponding to the data in Figs. 11 and 12. Some of the gross features of the flowfield, such as the skewing of the field, are evident. The contours are shown primarily for their qualitative interest, since, if the probe was not precisely aligned with the local flow direction, the values observed would be misleading. (Determination of the local flow direction in strong shear flows using crossed hot wires is virtually impossible.) Moreover, because the turbulence levels are very high (as shown in Fig. 12) and because these results have not been corrected for high turbulence intensities, the contours are left unlabeled. Despite any reservations about probe alignment, etc., the gross features of the flow are correctly shown. This contention is supported by the good agreement between mean flow and longitudinal turbulence intensities derived from single normal hot wires, crossed wires, and total head tube probes. Again, one notes that the mapping approach used is essential, since single traverses in either the y or z directions would yield information which is very dependent upon the points at which the traverses were done. Further, it is clear that detailed studies of spectra and correlations will need to be done with great care to ensure that the regions of high turbulence intensity are correctly located and studied. In this regard, the present work must be interpreted as a preliminary study which provides the basis from which to start detailed exploration of the turbulence quantities.

Discussion

The preceding sections have presented the results of an extensive study of the mean and turbulence properties of the flowfield from an array of rectangular jets. Although the quantity of data which has been obtained is large, these results do not represent a detailed study of the flowfield. Indeed, only two configurations of nozzles were used, and these represented only a minor variation in geometry. It is important to realize that a great deal of work remains to be done to achieve a sufficiently sound understanding of the flowfield so that optimum arrangements of nozzles can be deduced.

It has been common practice to discuss nozzle flows in terms of such mean properties as centerline decay, spreading rate, etc. Indeed, for the purpose of predicting mixing (momentum transfer) rates, the centerline decay is a useful measure of the momentum transfer rate. However, for multiple jets or other three-dimensional configurations, one must insure that the centerline velocity is representative of the jet momentum field. This may not be the case. The centerline decay for multiple nozzles is shown in Fig. 5, where the decay of the peak velocity is plotted vs downstream distance. The decay rate for plane two-dimensional jets is superimposed on these figures (dashed line). In the normal spacing ($P_n = 4.7$) a shift on the decay curve is observed at the point when the jets merge. Thus, for example, at $x/t_p = 60$, the jet momentum for closely spaced jets (per nozzle) is greater than that for the $\times 2$ spacing case. This suggests that the momentum transfer to the surrounding fluid is less effective for closely spaced jets. The retardation of the mixing and momentum transfer is attributed to the reduction in the surface area over which mixing may occur. Upon merging, the jets mix with each other as well as continuing to entrain air from the surroundings. This mutual entrainment reduces the rate of mixing with the surroundings.

The data show that (for example, Fig. 8) the jets spread fairly rapidly in the direction of the minor axis, but there is almost no spreading along the major axis, at least up to the merging region. Steep velocity gradients exist along the "ends" of the combining jets, while velocity gradients in the y direction are reduced, eventually vanishing at large values of x/t_p.

The turbulence features are consistent with the features of the mean flow. The "ends" of the individual jets exhibit regions of high turbulence intensity; and the intensity is diminished in the interjet regions as merging proceeds. In the near field, the turbulence and mean flow properties of the jet are consistent with the features observed for a single jet. The turbulence shear stresses, although not mapped in detail, exhibit feature characteristics of individual rectangular free jets. The results shown indicate that relatively steep gradients of $\overline{u'v'}/U^2_{max}$ appear along the sides of the jet.

Although the data obtained in this work have revealed a great deal regarding the development of multiple jet flows, there remains a great deal to be done. The requirements for continued work in this area are clear.

Conclusions

The experiments reported here enable one to draw some interesting conclusions regarding the flow configuration studied. First, the jet merging process retards mixing and momentum transfer. Second, for the two spacings studied the mixing rates (per nozzle) were essentially the same up to $x/t_p \approx 25$. Third, the velocity profiles across individual jets (parallel to the minor axis) showed a remarkable degree of self-preservation prior to merging; this suggests that the jets decay essentially independently upstream of merging. Finally, in complex three-dimensional flows of the type studied here, extensive probing of the field is required. Traverses along planes of symmetry could yield misleading results. The observed turbulence structure is consistent with these mean flow features, but because the flows are nonsimilar, theoretical development using traditional similarity arguments is not possible. The flows are fully three-dimensional, and the turbulence structure exhibits great complexity.

Acknowledgments

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