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Interrupted Jet as a Candidate for Mixing Enhancement in Aircraft Ejectors

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The near flowfield of an interrupted turbulent free jet, which consists of four unventilated rectangular jets, has been studied experimentally. The study was done to show the potential of the interrupted jet for passive enhancement of mixing in aircraft thrust-augmenting ejectors. The quantities measured, using hot-wire anemometry, include the three components of the mean velocity vector and the Reynolds normal and primary shearing stresses. The results show that, compared to a single, uninterrupted, rectangular jet of aspect ratio 10, the mixing in an interrupted jet is enhanced. The enhanced mixing is evidenced by a faster decay of the mean streamwise velocity along the centerline of each of the four jets and higher centerline streamwise turbulence intensities. The results also show that the unventilated multiple turbulent rectangular free jets of the present study develop faster into a single jet, implying complete mixing, than their known ventilated counterparts. The measured Reynolds normal and primary shearing stresses are higher than those found at corresponding locations in a round turbulent free jet, and are thus consistent with the faster mixing of the interrupted turbulent free jet.

Nomenclature

D_e = equivalent diameter
U = mean streamwise velocity
$\overline{u'v'}$ = spanwise Reynolds primary shear stress
$\overline{u'w'}$ = lateral Reynolds primary shear stress
$\overline{u'^2}$ = streamwise Reynolds normal stress
$\sqrt{\overline{u'^2}}$ = streamwise turbulence intensity
V = mean spanwise velocity
$\overline{v'w'}$ = Reynolds secondary shear stress
$\overline{v'^2}$ = spanwise Reynolds normal stress
W = mean lateral velocity
$\overline{w'^2}$ = lateral Reynolds normal stress
X = streamwise coordinate
Y = spanwise coordinate
Z = lateral coordinate
Ω_x = mean streamwise vorticity, $[\partial(W/U_{\mathrm{Cl}})/\partial Y - \partial(V/U_{\mathrm{Cl}})/\partial Z]$
Ω_y = mean spanwise vorticity
Ω_z = mean lateral vorticity

Subscripts
Cl = centerline value
max = maximum value

Introduction

THE mixing of a jet of fluid with a surrounding fluid is relevant in several technical applications which may range from aerospace to chemical to mechanical engineering. In thrust-augmenting ejectors for STOL and V/STOL aircraft, e.g., it has been suggested[1–3] that segmenting a slot nozzle at its exit plane, and thus producing multiple jets, will lead to an improvement in thrust augmentation. The thrust-augmentation improvement is a consequence of enhanced mixing between the multiple primary jets and the pumped secondary flow.

Ventilated multiple jets are those which issue from free-standing nozzles. Entrainment of the surrounding fluid between the individual jets, at the common exit plane, takes place in ventilated multiple jets and, consequently, no recirculation regions between the jets are formed upstream of the location where the jets merge. Unventilated multiple jets, such as parallel plane jets issuing from a wall, do not entrain ambient fluid at their common exit plane. As a result, such jets attract each other and this leads to the formation of recirculation regions between the jets upstream of the merging location. The terms "ventilated" and "unventilated" were introduced to the literature on jets by Marsters.[4] An "interrupted" jet is obtained by placing interruptions (or blockage elements) at the exit plane of a large aspect ratio slot (or nozzle). Such an arrangement results in unventilated multiple jets.

Studies of ventilated linear arrays of rectangular free jets issuing from channels (or lobes)[5,6] have been done to illuminate the enhanced mixing which takes place in flows of multiple jets. In the study done by Marsters,[5] the flowfields of three and five jets out of an array of 20 jets, issuing from a linear array of rectangular channels, were examined for two different spacings (18.6 and 37.2 mm) between the channels. Note that only the three or five jets in the array were actually blowing. The channels, which were 99 mm long with cross-sectional dimensions of 38 × 3.96 mm were aligned with their longer sides (of the cross section) adjacent. The individual channels had an aspect ratio of 9.6. The mean streamwise velocity at the exit plane of each channel was 100 m/s, and this resulted in a Reynolds number of 2.29×10^4 based on the smaller dimension of the channel cross section. It was found that the jets develop independent of each other initially, but merge into a single jet flow further downstream, and that the wider the spacing between the individual jets, the farther downstream the merging location is. Krothapalli et al.[6] reported measurements made in the two central planes of symmetry of the central jet in a multiple-jet arrangement of five rectangular jets. The jets issued from a linear array of rectangular channels which were 40 mm long. The channels, which had cross-sectional dimensions of 50 × 3 mm, were aligned, as in the case of the array studied by Marsters,[5] with their longer cross-sectional sides adjacent and were 24 mm apart. The cross-sectional dimensions result in an aspect ratio of 16.7 for each channel. The mean streamwise velocity at the exit plane of the central channel was 60 m/s which resulted in a Reynolds number of 1.2×10^4 based on the smaller cross-sectional dimension of the channel. It was found, by means

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of schlieren photography, that there is no mutual interaction between the jets initially, but that the jets merge into a single jet, as found also by Marsters,[5] further downstream. It was also found that the decay of the mean streamwise velocity along the centerline of one free jet operating in multiple-jet configuration is slower than that of a single free jet, and that mutual interaction—when it does occur between jets—results in a lower turbulence level for each of the jets compared to that of a single free jet. The fact that the measurements were made only in the two central planes of symmetry of one of the jets of a multiple jet arrangement, limited the amount of information that could be obtained from the study of Krothapalli et al.[6] The turbulence measurements made by Marsters[5] were also of limited scope.

The present experimental study of multiple unventilated free jets in an interrupted jet arrangement was undertaken with the objective of examining the potential of this multiple-jet configuration as a candidate for passive mixing enhancement in aircraft thrust-augmenting ejectors, and thus to contribute to the knowledge base on mixing in flows of multiple rectangular jets. The four jets of the present multiple-jet configuration are produced by placing equally spaced interruptions at the exit plane of a sharp-edged rectangular slot of aspect ratio 50 as shown in Fig. 1b. Each slot has an aspect ratio of 11.6. It should be noted that the interrupted jet concept is similar to that of the "hypermixing" nozzle.[2,3] The mean streamwise velocity at the center of each of the four jets was 60 m/s, and this resulted in a Reynolds number of 1×10^5 based on the D_e (which is the same as the diameter of a round slot with the same exit area as the rectangular slot) of each slot. The streamwise turbulence intensity at the center of each of the jets was 0.5%. As a first step towards contributing to the understanding of this complex flowfield, the complicating effects of the shroud in a thrust-augmenting ejector have been removed in the present study. Note that because of the presence of multiple shear-layers, the flowfield considered here can indeed be classified—following Bradshaw[7]—as complex.

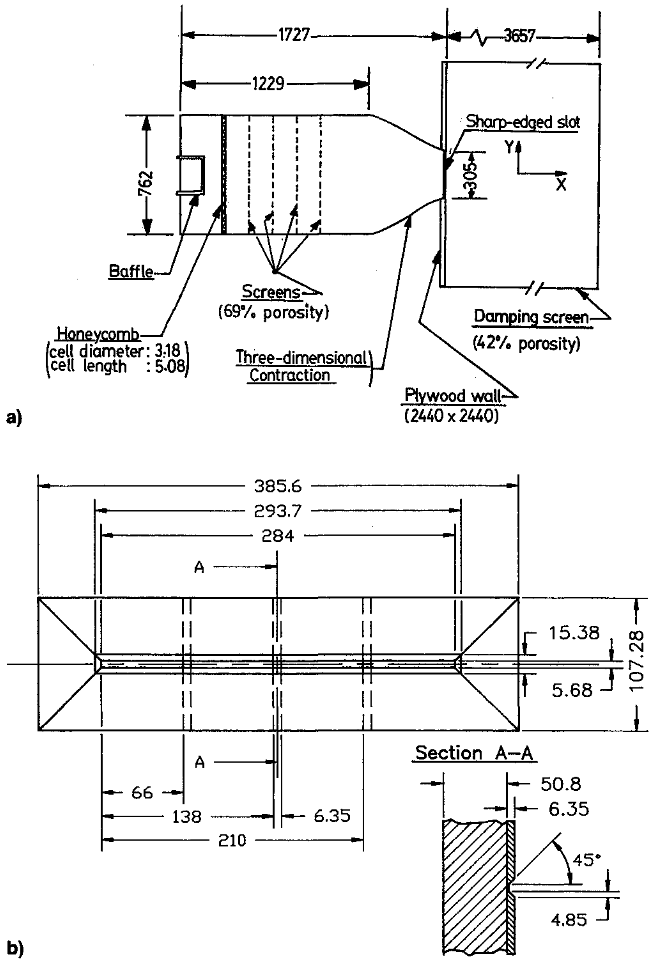

Fig. 1 a) Plan-view section of the jet flow facility and b) slot detail. All dimensions are in millimeters.

Experimental Details

The jet flow facility used in the present study is described in detail elsewhere.[8] A brief description is in order here. The jet flow facility, a plan-view section of which is shown in Fig. 1a, consists of a centrifugal fan, a settling chamber which is fitted with honeycomb and meshwire screens, a three-dimensional contraction, and the sharp-edged rectangular slot. The details of the slot are shown in Fig. 1b. The slot is attached to the downstream end of the contraction. The four rectangular jets discharge into a cage which is covered on the top and sides with steel damping screens. The upstream end of the cage is fitted with a plywood wall which is flush with the downstream end of the three-dimensional contraction.

Traversing of the x-array hot-wire probe was done by a stepping-motor-driven, three-dimensional traversing system under microcomputer control. The traversing system employs a rack and pinion in the streamwise direction and lead screws in the spanwise and lateral directions. Figure 1a also shows a definition sketch of the coordinate system. The Z coordinate, which is perpendicular to the plane in which X and Y lie and forms a right-hand system with them, is not shown in Fig. 1a.

The x-array hot-wire probes, which were operated by constant temperature anemometers at a resistance ratio of 1.8, were calibrated on-line in the very near flowfield against the output of a pitot-static tube which was connected to a pressure transducer and a Barocel electronic manometer. The effective angle method, described in Ref. 9, was used and the calibration constants were optimized by a linear least-squares goodness-of-fit procedure. The effects of temperature drift and transverse contamination were accounted for in the data reduction software following Bearman[10] and Champagne and Sleicher,[11] respectively. The x-array hot-wire signals were linearized by the laboratory microcomputer and digitized, at about 1 kHz, by a 12-bit successive approximation A/D converter. A two-channel sample-and-hold unit was used for signal processing and signal conditioning was effected by two low-pass filters with on-board amplifiers. The data reduction was done in real time.

Results and Discussion

The mean streamwise velocity decay along the centerline of one of the four jets which constitute the interrupted jet is shown in Fig. 2 with the results for the plane jets studied by Heskestad[12] and Gutmark and Wygnanski,[13] and for a single, "uninterrupted," rectangular jet of aspect ratio 10 included for comparison. The plane jet in the study of Heskestad[12] issued from a sharp-edged slot of aspect ratio 120 at a Reynolds number [based on the smaller exit cross-sectional dimension (12.7 mm) of the slot] of 3.4×10^4. Gutmark and Wygnanski used a nozzle of aspect ratio 38.5 with contoured upstream shaping and the exit plane Reynolds number [based on the smaller dimension (13 mm) of the exit plane cross section] was 3×10^4. The single, uninterrupted, rectangular jet of the present study issued from a sharp-edged slot at a Reynolds number [based on the equivalent diameter (45.3 mm) of the slot] of 20.8×10^4. The mean streamwise velocity and streamwise turbulence intensity at the center of the slot exit plane were 60 m/s and 0.5%, respectively. Note that U_{max} is found in jets issuing from sharp-edged slots, because of the existence of a vena contracta, downstream of the slot exit plane. The mean streamwise velocity along the jet centerline of the interrupted jet is found to decay faster than that of a single, uninterrupted, rectangular jet of comparable aspect

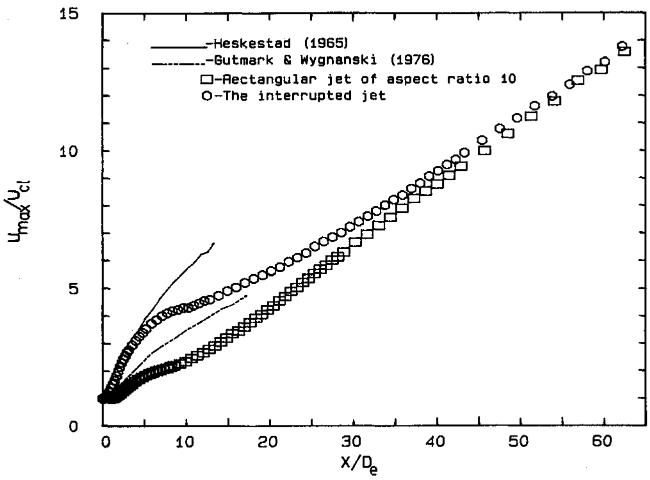

Fig. 2 Mean streamwise velocity decay along the jet centerline.

ratio. If mixing is considered as the engulfing of the surrounding fluid by the jet with the resulting decrease in the mean streamwise velocity and the concomitant increase in mass to ensure that momentum is conserved, then the faster decay of the mean streamwise velocity along the centerline of the interrupted jet indicates enhanced mixing.

The development of the mean streamwise velocity field is shown in Fig. 3. The jets are seen to interact with each other in the very near flowfield (at $X/D_e = 1.0$) and to merge into a single jet, implying complete mixing, at about $X/D_e = 5.0$. The multiple ventilated rectangular jets investigated by Marsters[5] and Krothapalli et al.[6] merged into single jets, without the individual jets interacting with each other in the very near flowfield (i.e., $X/D_e \leq 1.0$), at about $X/D_e = 10.0$ and $X/D_e = 13.0$, respectively. The jets issuing from the closer-spaced channels in the study of Marsters[5] merged at $X/D_e = 5.7$. It should be recalled that the decay of the mean streamwise velocity along the centerline of a ventilated jet is slower than that of a single jet. It is clear that the mixing process in the interrupted jet, which consists of four unventilated jets, is faster than in ventilated jets for which data are available. The estimated uncertainty in the measured mean streamwise velocity is ±1% at 20:1 odds.

The mean streamwise vorticity has been calculated from the mean spanwise and the mean lateral velocity data and the results are shown as contour maps in Fig. 4. It should be noted that positive and negative Ω_x indicate counterclockwise and clockwise rotation, respectively. Since vorticity cannot be created within the core of a homogeneous fluid,[14] the mean streamwise vorticity must originate upstream of the slot exit plane. Considering the flow through the three-dimensional contraction, which is square in cross section, and applying the transport equation for the mean streamwise vorticity (see, e.g., Bradshaw[15]), it is found that mean streamwise vorticity is produced from the rotation (or skewing) of spanwise and lateral vortex lines in the X-Y and X-Z planes by the spanwise ($\partial U/\partial Y$) and lateral mean shear ($\partial U/\partial Z$), respectively, in the boundary layers and, to a lesser extent, from gradients in the Reynolds spanwise and lateral normal stresses (i.e., the turbulence anisotropy) and the secondary shear stress. The mean streamwise vorticity thus produced is convected downstream in the three-dimensional contraction. As the flow leaves the slot exit plane, the vortices must necessarily exist as counter-rotating pairs, as Fig. 4 shows. It should be noted that the mean streamwise vorticity produced from the rotation of spanwise and lateral vortex lines in the X-Y and X-Z planes by the spanwise and lateral mean shear, respectively (commonly referred to as Prandtl's secondary motion of the first kind) will be more dominant than that, otherwise known as Prandtl's secondary motion of the second kind, produced by gradients of the turbulence anisotropy and the secondary shear stress.[16]

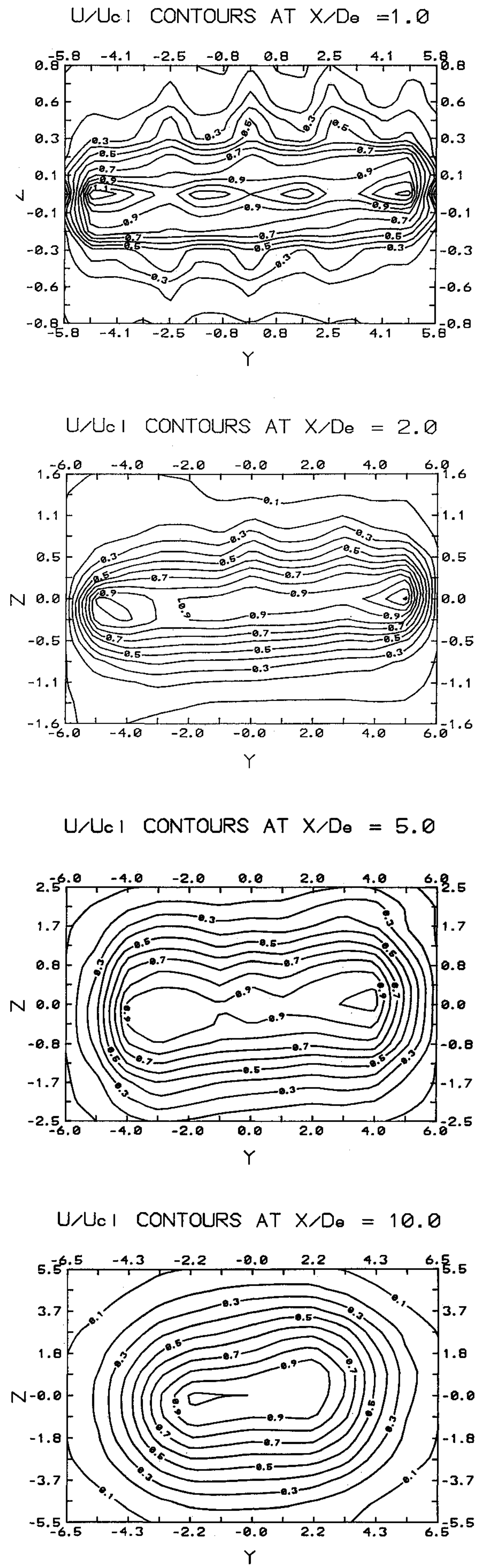

Fig. 3 Mean streamwise velocity contours.

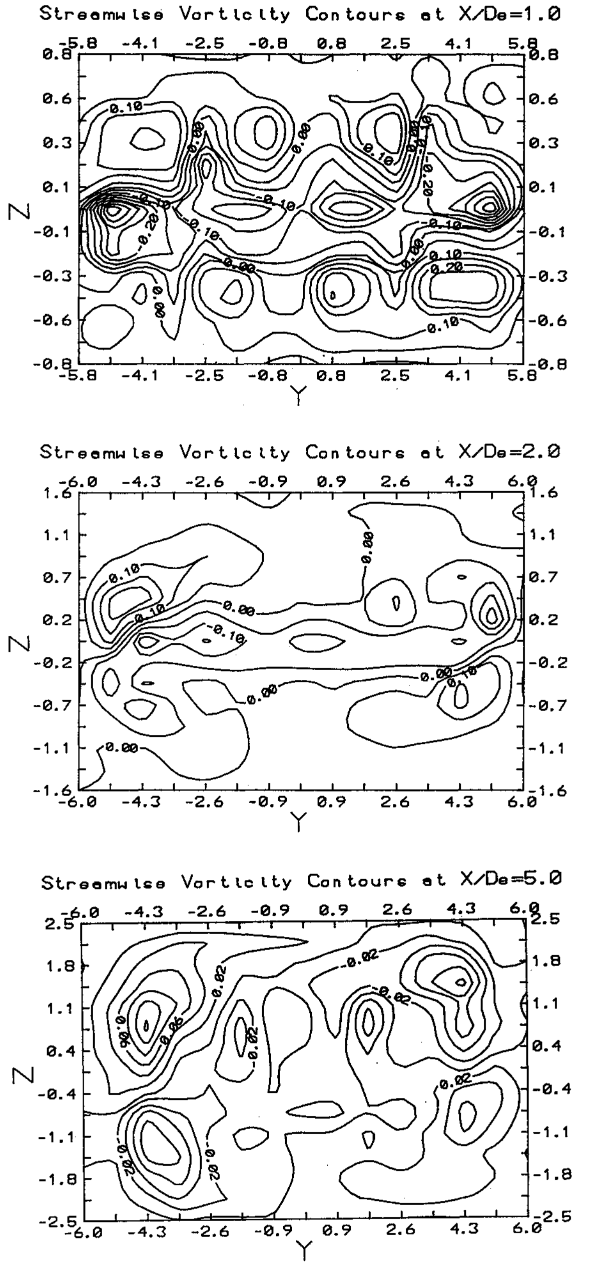

Fig. 4 Mean streamwise vorticity contours.

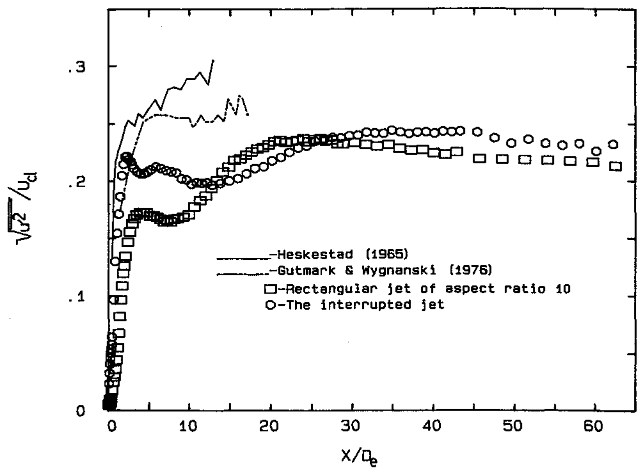

Fig. 5 Streamwise turbulence intensity variation along the jet centerline.

The counter-rotating streamwise vortices will facilitate rapid mixing by acting as vehicles for moving high-momentum fluid to areas where there is low-momentum fluid and vice versa. The estimated uncertainty in the mean streamwise vorticity is ±19.5% at 20:1 odds.

The streamwise turbulence intensities, corresponding to the mean streamwise velocity decay along the jet centerline shown in Fig. 2, are shown in Fig. 5. The centerline streamwise turbulence intensities in the interrupted jet are found to be consistently and significantly higher than those in the single, uninterrupted, rectangular jet up to about $X/D_e = 12$. This provides further evidence of enhanced near-field mixing of the interrupted jet. The streamwise turbulence intensities measured by Heskestad[12] and, to some extent, those measured by Gutmark and Wygnanski,[13] exceed more recent data for jets, see, e.g., Hussain and Husain[16] for hot-wire data, and Ramaprian and Chandrasekhara[18] for laser-Doppler-anemometer data. It is clear that for a turbulent free jet, measurements made with a laser Doppler anemometer, which does not rectify its output voltages like a hot-wire anemometer does in the high-intensity turbulent regions of the flow, will be more reliable than those made with a hot-wire anemometer. The turbulence data of the present study, shown in Fig. 5, and those of Hussain and Husain[17] are closer to the laser-doppler-anemometer data of Ramaprian and Chandrasekhara[18] than they are to the data of Heskestad[12] and Gutmark and Wygnanski.[13] The more recent data were acquired on-line, therefore eliminating operator errors which may have plagued the data of Heskestad[12] and Gutmark and Wygnanski[13] in reading and recording the data correctly.

The evolution of the streamwise Reynolds normal stress field in the near flowfield is shown in Fig. 6. These results are consistent with those of the mean streamwise velocity field shown in Fig. 3. Indeed, one finds that large or small gradients in the streamwise Reynolds normal stress field occur where the local shear in the mean streamwise velocity is correspondingly large or small. The lateral Reynolds normal stress contours are shown in Fig. 7. They are similar in shape to the streamwise Reynolds normal stress contours shown in Fig. 6 at the corresponding streamwise locations. However, the lateral Reynolds normal stresses are generally smaller than the streamwise Reynolds normal stresses from which they derive their energy via the pressure fluctuations. The spanwise Reynolds normal stress contours are shown in Fig. 8; these spanwise Reynolds normal stress contours are also similar in shape to their streamwise counterparts. The spanwise Reynolds normal stresses, while equal to the lateral Reynolds normal stresses at $X/D_e = 5.0$ and beyond, are less than the lateral Reynolds normal stresses at $X/D_e = 1.0$ and at $X/D_e = 2.0$ (i.e., in the very near flowfield). This indicates that, in spite of the interruptions, the individual jets exhibit plane-jet behavior in the very near flowfield. The maximum values of the Reynolds normal stresses are considerably higher than those found at the same locations in a round free jet[19]; this suggests enhanced mixing in the interrupted jet. For example, at $X/D_e = 10.0$, $(\overline{u'^2}/U_{Cl}^2 \times 100) = 3.4$, $(\overline{v'^2}/U_{Cl}^2 \times 100) = (\overline{w'^2}/U_{Cl}^2 \times 100) = 2.6$, whereas the corresponding values in a round jet[18] at the same location are 0.567, 0.146, and 0.125, respectively. The estimated uncertainty in the measurement of the Reynolds normal stresses is ±6% at 20:1 odds.

The lateral Reynolds primary shear stress contours are shown in Fig. 9. Like the Reynolds normal stresses, the lateral Reynolds primary shear stresses are also consistent with the mean streamwise velocity field shown in Fig. 3. Large or small gradients in the lateral Reynolds primary shear stress do indeed correspond to large or small values of the local shear in the mean streamwise velocity. The spanwise Reynolds primary shear stress (which is not shown here), is much smaller than its lateral counterpart at all the streamwise measurement stations. This supports the previously mentioned plane-jet behavior of the individual jets which form the interrupted jet.

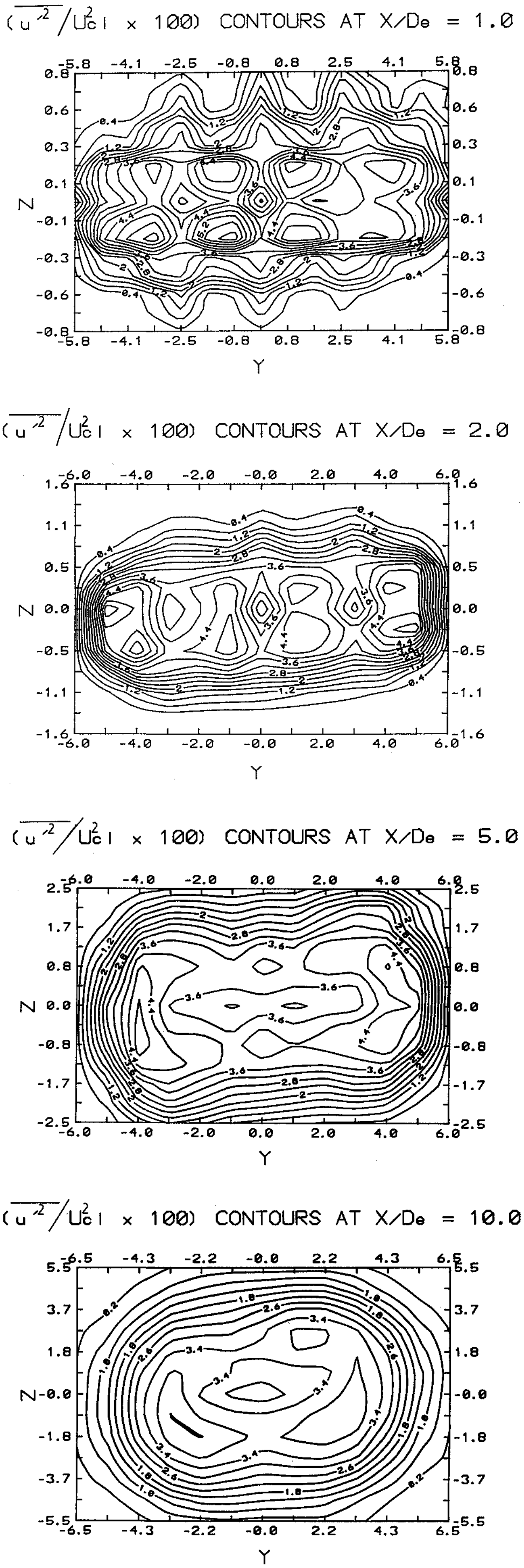

Fig. 6 Streamwise Reynolds normal stress contours.

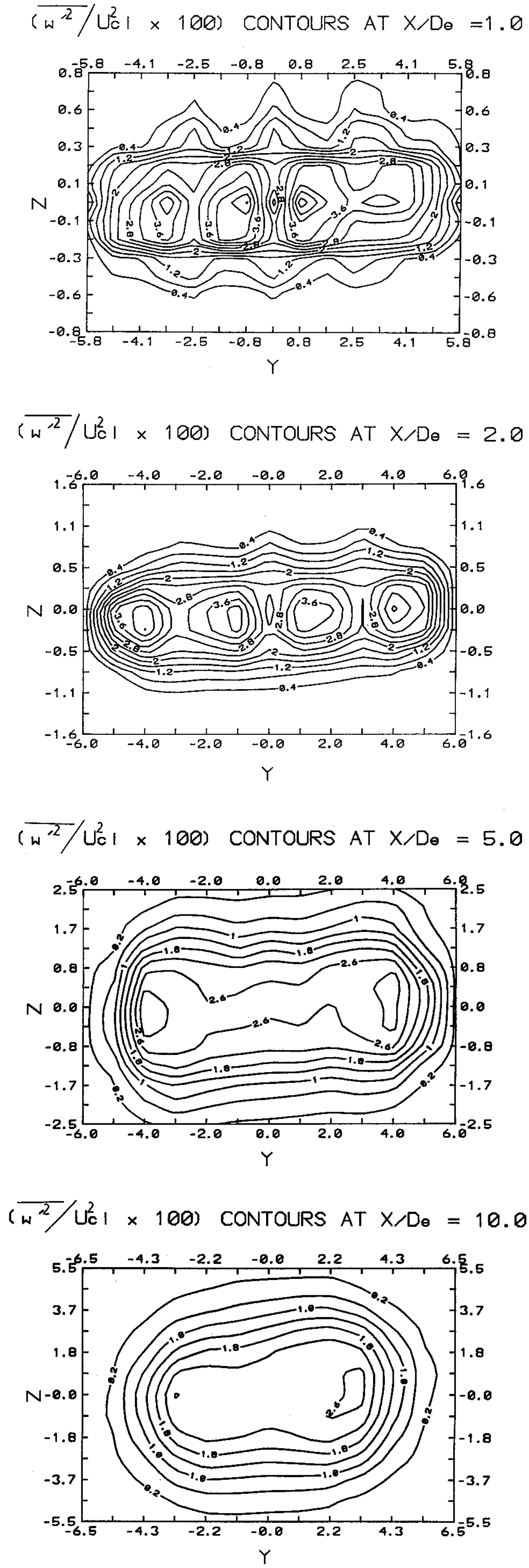

Fig. 7 Lateral Reynolds normal stress contours.

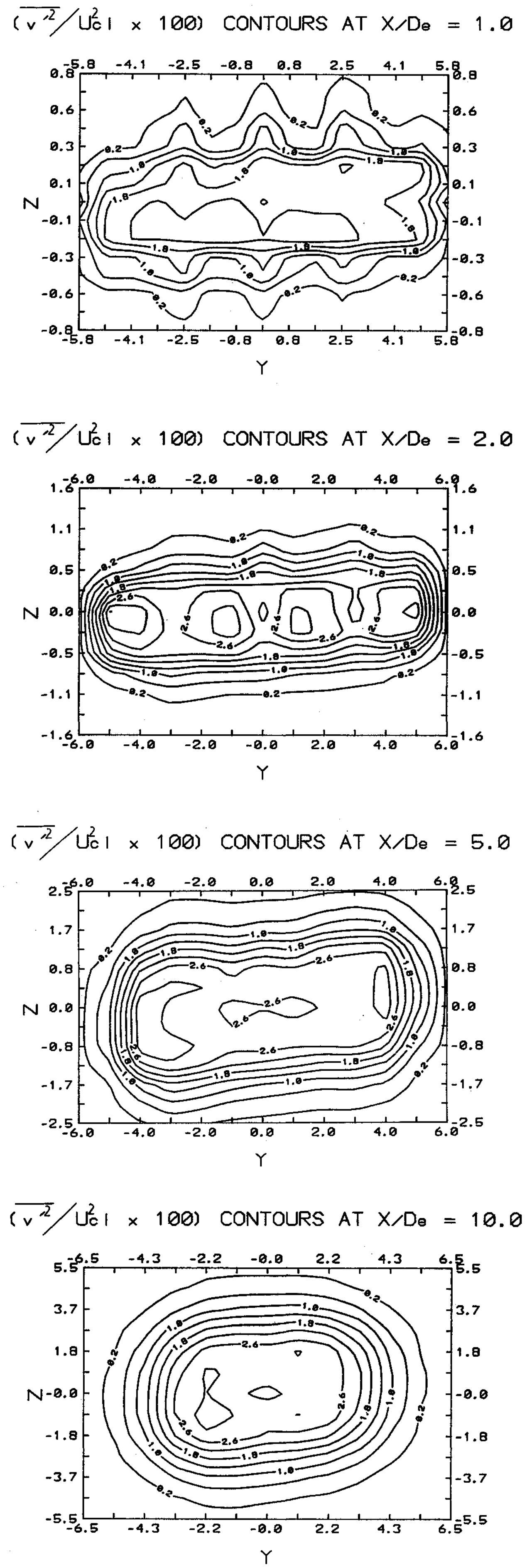

Fig. 8 Spanwise Reynolds normal stress contours.

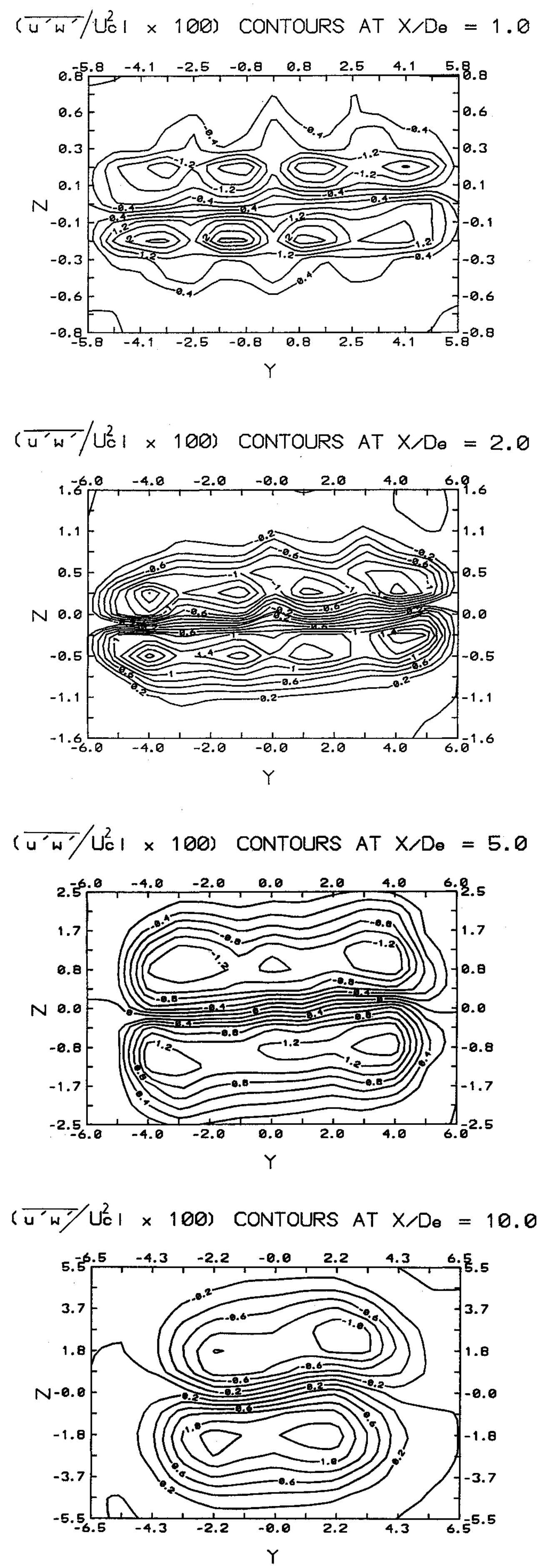

Fig. 9 Lateral Reynolds primary shear stress contours.

The estimated uncertainty in the measurement of the Reynolds primary shear stresses is ±8% at 20:1 odds.

Conclusions

The present experimental study of the near flowfield of an interrupted turbulent free jet, which consists of four unventilated rectangular jets, has provided detailed time-averaged data for the mean streamwise velocity, the mean streamwise vorticity, the Reynolds normal stresses, and the Reynolds primary shear stresses. The mean flow and turbulence data were acquired with hot-wire anemometry, and the mean streamwise vorticity data were calculated from the mean spanwise and the mean lateral velocity data.

The results show that, compared to a single, uninterrupted, rectangular jet of aspect ratio 10, the mixing in an interrupted jet is enhanced. The enhanced mixing is evidenced by a faster decay of the mean streamwise velocity along the jet centerline and higher centerline streamwise turbulence intensities. The results also show that the unventilated multiple turbulent rectangular free jets of the present study develop faster into a single jet, implying complete mixing, than their known ventilated counterparts. The measured Reynolds normal and primary shearing stresses are higher than those found at corresponding locations in a round turbulent free jet and are thus consistent with the faster mixing of the interrupted turbulent free jet.

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