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Round Incompressible Jets with Asymmetric Initial Velocity Distributions

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Abstract

THE near-field development of turbulent air jets with asymmetric initial velocity distributions is investigated experimentally. The jets emerge from pipes of circular cross section into a still environment. The level of asymmetry of the exit plane mean velocity distribution is controlled by the angle of pipe bend upstream of the exit. Jets with two levels of initial streamwise velocity asymmetry are studied in addition to an axisymmetric jet emerging from a straight pipe. The Reynolds number based on exit bulk velocity and pipe diameter is 13,500. Streamwise velocity measurements, using hot-wire anemometry, indicate that the near-field turbulence structure is significantly modified by the skewed velocity distribution. On the plane of symmetry, higher levels of initial velocity skewness lead to increased disparity of turbulence intensity and unequal rate of growth on the two sides of the jet. Furthermore, higher rates of maximum velocity decay and jet growth are attained with the initially asymmetric jets. The increase in jet spread rate on the symmetry plane is found to distort the initially round cross-sectional shape of the jets beyond 10 pipe diameters from the exit plane.

Contents

A large body of knowledge exists on the structure of planar symmetric and round axisymmetric turbulent jets issuing into a uniform environment.[1-4] Work has also been reported on three-dimensional turbulent jets originating from noncircular, small aspect ratio orifices with rectangular and elliptic shapes. However, no attempt has been made to characterize jets with nonsymmetric (or nonaxisymmetric) initial property distributions. There are applications where a jet emerges from a circular or a rectangular source with an asymmetric velocity distribution, such as in jet ejectors and powered lift generators in advanced aircraft. The structures of these jets are likely to be different than that of their axisymmetric counterparts. In the present paper, the nature of such asymmetric incompressible air jets is investigated. The jets emerge from circular, 25.4 mm diam pipes and thus have round initial cross sections. For the axisymmetric jet, a straight pipe is used with a fully developed exit profile (case I), and the two asymmetric jets are obtained using pipes that are bent 90 (case II) and 160 (case III) deg before the exit. The pipe bends have a fixed pipe radius-to-curvature radius ratio of $a/R = 0.0625$, resulting in a Dean number of 3375. Thus, the secondary motion through the bend and the level of skewness (asymmetry) of the mean streamwise velocity distribution at the pipe exit are determined by the angle of the bend. The flow is fully developed upstream of the bend. Downstream of the bend, each of the two curved pipes has a 5-diameter-long straight section to allow for the recovery of pressure from the perturbation through the bend. Single and x-type sensors are used for the hot-wire measurements in conjunction with a 12-bit A/D converter and a personal computer. The jet coordinate system is as follows: x is the streamwise distance along the jet axis, and y and z are the cross-stream coordinates parallel and normal to the plane of the pipe bend, respectively. Coordinate y is positive on the outer bend side of the pipe.

The two-dimensional contour plots of the mean velocity indicate that the jets in cases II and III are symmetric about the x-y plane and asymmetric about the x-z plane. Figure 1 shows the exit mean streamwise velocity and turbulence intensity profiles on the symmetry (x-y) plane. Here, U_b is the bulk velocity. For cases II and III, the mean velocity exhibits an asymmetric distribution with a maximum occurring away from the centerline and towards the outer edge of the jet. Both the maximum and the minimum of the mean streamwise velocity occur on this symmetry plane. This is accompanied with the maxima and minima of the mean shear, which also occur on the same plane. A stronger jet exit velocity skewness is obtained in case III with higher outer-side and lower inner-side velocity gradients. Larger turbulence intensity peaks occur on the outer side of the jet for both cases II and III. The streamwise distributions of the maximum mean velocity and turbulence, normalized with exit maximum velocity, are presented in Fig. 2 along with results from Lau et al.[4] obtained in an axisymmetric jet with a top-hat initial velocity profile. Comparing the two axisymmetric jets, the initial maximum velocity decay rate for the present jet (case I) is slightly larger. This difference is attributed to the existence of a potential core in the jet of Lau et al., which prevents mixing on the jet axis up to about $x/D = 3$. Nevertheless, the two axisymmetric jets

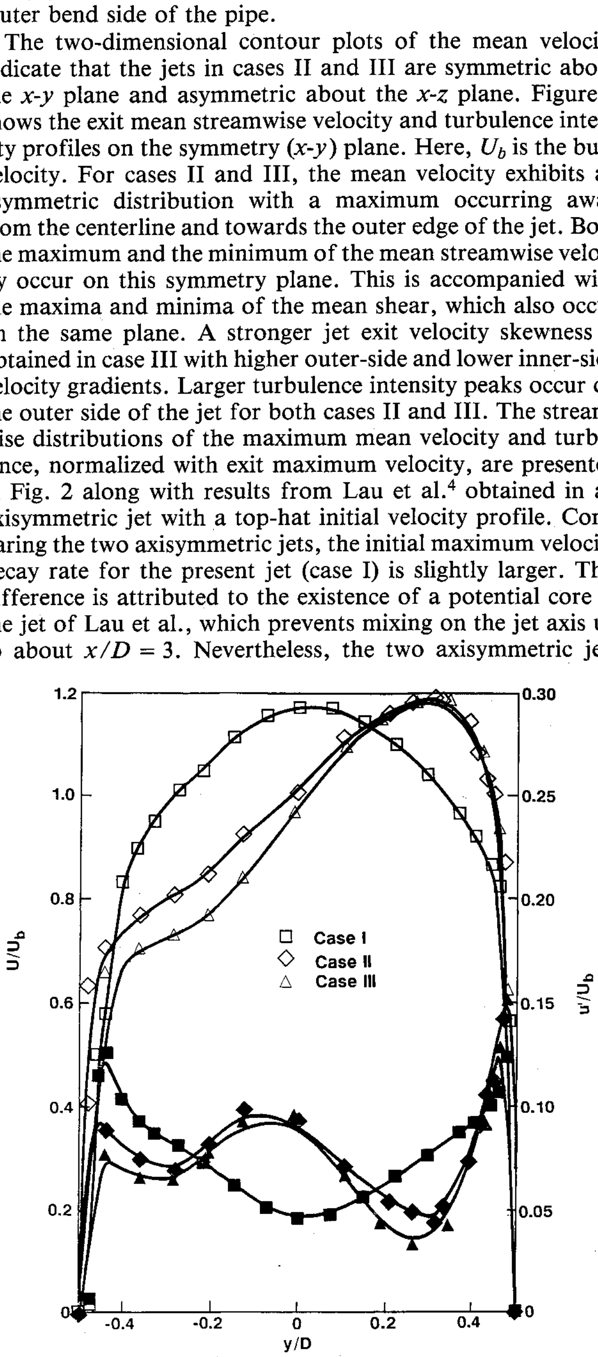

Fig. 1 Mean and turbulent velocity on symmetry plane at jet exit (solid symbols represent turbulence intensity).

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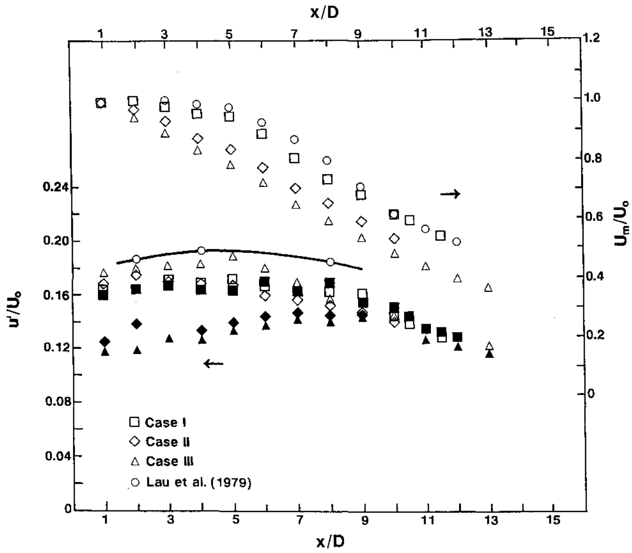

Fig. 2 Streamwise distribution of maximum mean velocity and turbulence intensity.

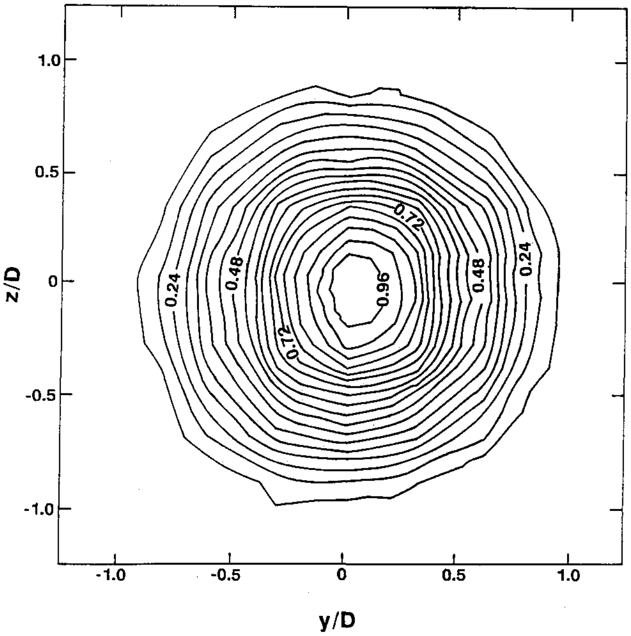

Fig. 3 Constant velocity contours at $x/D = 6$ for case III.

clearly show the same rate of maximum velocity decay beyond $x/D = 9$. The two initially asymmetric jets exhibit increased decay rates of U_m/U_o with the larger initial velocity skewness leading to the highest decay rate. This trend prevails in the region $0 < x/D < 7$. In Fig. 2, the maximum turbulence on the inner and outer sides of the jets are represented by solid and open symbols, respectively. There is a significant disparity in the turbulence level on the two sides of the jet in case II and case III. This disparity is more pronounced in case III, where maximum turbulence intensities are comparable to those obtained by Lau et al. Clearly, the symmetry plane turbulent structure of the jet near field is influenced by the skewness of

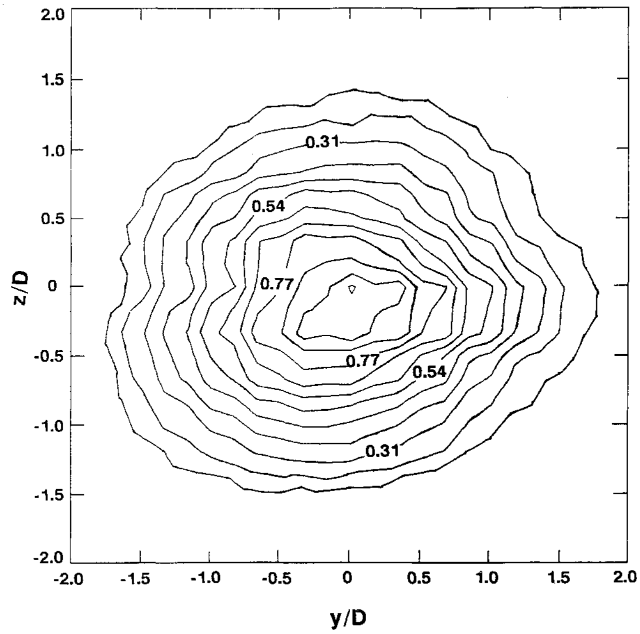

Fig. 4 Constant velocity contours at $x/D = 12$ for case III.

the exit velocity distribution. The turbulence intensity is enhanced on the other side of the jet where a steeper mean axial velocity gradient occurs, whereas on the inner side, turbulence activity is suppressed due to the milder mean shear distributions. The average turbulence intensity across the jet is about the same in cases II and III. Beyond $x/D = 10$, the maximum turbulence intensity disparity vanishes and all three jets possess the same maximum turbulence intensity level at each axial position.

The jet cross-sections at $x/D = 6$ and 12 for case III are shown in Figs. 3 and 4 as contour plots of constant U/U_m, where U_m is the local maximum of mean velocity. At $x/D = 6$, the jet maintains a fully round shape with nearly circular velocity contours and the growth rates along y and z directions are comparable. However, at $x/D = 12$, the constant velocity contours lose their circular shape and the jet is elongated along y direction. This elongation is caused by the increased overall growth rate on the symmetry plane of the jet. The initial skewness of the mean axial velocity distribution first leads to unequal turbulence levels on the two sides of the jet along y, which in turn promotes turbulent mixing on the symmetry plane in the zone $0 < x/D < 10$. As a consequence of this, the round shape of the momentum jet is stretched out along the y direction. The results presented here indicate that the near-field structure of a freejet can be modified by the initial mean velocity distribution.

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