Turbulent Plane Jet With and Without Confining End Walls

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Abstract

THE published data on turbulent plane jets show variations in both the mean and turbulence quantities that in most instances have been attributed to differences in experimental conditions. The major influencing factors are the inlet geometry and aspect ratio of the nozzle, the nature of the exit velocity profile and the associated magnitude of the turbulence intensity, the Reynolds number at the nole exit, and the state of the ambient environment.[1,2] However, one fundamental difference among plane jet apparatus that is not well documented concerns the use of confining end walls and/or a wall section at the plane of exit. This paper describes the characteristics of a plane jet issuing from a wall with and without confining end walls. The objectives are to provide a perspective for the comparison of existing data under these conditions and to identify the relative merits of the two configurations for the design of future experiments.

Contents

The plane jet flow facility consists of a centrifugal blower that supplies air via a 1.0-m diffuser section to a 400 mm × 600 mm × 12.5 mm settling chamber, followed by a corner section containing 90-deg turning vanes, a second shorter settling chamber, and finally a 40:1 two-dimensional contraction (based on a cosine curve) that ends as a 600-mm long × 10-mm wide (D) slot. The design of the nozzle insures that the exit turbulence intensity is low $[(\bar{u}^2)^{1/2}/U_0 = 0.008]$ and that the wall boundary layers at the exit will be laminar. The jet issues vertically from a horizontal wall section extending along the length of the slot and 1.1 m to each side and may be confined by removable vertical walls located at each end of the slot and extending 1.1 m to the sides and 1.85 m downstream, and vertical screens of open air ratio 0.8 spanning the ends of the vertical walls. The jet exit velocity U_0 was 11.0 m/s for all of the test runs, and the Reynolds number based on U_0 and the slot width D was 7230.[3]

Mean velocities were measured independently with a pitot tube (connected to an electronic micromanometer) and also simultaneously with a pitot tube and a normal hot-wire (HWA) separated by 5 mm in the spanwise (z) direction.

In addition to near-field pitot tube measurements that confirmed the symmetry of the exit profile, detailed lateral velocity profiles were obtained in the far-field regions of the free and the confined jets to identify any structural differences and to determine the extent of two-dimensionality. The far-field profiles for the free jet show considerably more twisting and variability along the length of the slot than those of the confined jet. The walls of the confined jet achieved the expected effect of extending the region of two-dimensionality. For the streamwise region between $x/D = 50$ and 100, the standard deviation of the growth rates of the confined jet, based on nine profiles measured between $z/D = -20$ and 20, was 3% of the mean, whereas the equivalent deviation of the free jet was 16%. In the case of the free jet, the average growth rate of 0.106 compares well with the average of published data[4]; however, depending on the z/D location, the value varied from 0.081 to 0.133 suggesting that, in general, data based on free jet configurations may be susceptible to significant error bounds. The average growth rate of 0.083 for the confined jet is lower than the free jet value and likely due to the more restrictive entrainment conditions of this configuration.

A comparison of the decay rates of the mean centerline velocity along the slot length reveals less variability in the confined jet than in the free jet data, although not to the degree found in the results on growth rate. The average decay rate of the centerline velocity for the confined jet was 0.222 with a standard deviation of 8%, whereas the free jet had a lower decay rate of 0.182 with a standard deviation of 14%. This observed reduction in the decay rate is significant in comparison to the range of decay rates found in the literature, where the majority lie between 0.16 and 0.24. The variations in reported decay rates may be partially attributed to the effects of confining end walls and aspect ratio. One might assume that the free jet represents the limiting case of the jet with confining end walls and a large aspect ratio. In this case, the relative behavior of the present jet with and without confining ends at a fixed aspect ratio indicates that the decay rate for a confined jet would decrease as the aspect ratio becomes large. Interestingly, this does not agree with other results,[5,6] where the decay rates of the mean centerline velocity tended to increase as aspect ratio was increased between approximately 30 and 140. This conflict suggests that the free jet with its inherent exposure to three-dimensional entrainment effects[7] may not behave similarly to even those confined jets of large aspect ratio.

In the present data for the free jet, the average kinematic momentum flux (M), calculated from the pitot tube profiles at nine locations spanwise across the slot, is nearly conserved at each of three far-field stations. The ratio M/M_0, where M_0 is the exit kinematic momentum flux, was 0.96, 0.96, and 0.95 at the respective distances of $x/D = 50$, 75, and 100. However, taken spanwise across the jet, the standard deviation of this ratio was about 16%, with values ranging between 0.80 and 1.21. Thus, the free jet configuration presents a measurement difficulty in that results extracted from profiles measured in a single x-y plane may be subject to significant errors relative to results integrated across the full two-dimensional span of the jet. The equivalent measurements made in the confined jet show that the average momentum decreased significantly with downstream distance ($M/M_0 = 0.83$, 0.78, and 0.68 ±8%) and had not reached a constant value by $x/D = 100$. The walls in the present confined jet apparatus extended well beyond the furthest measuring location of $x/D = 100$, and their influence on the behavior of the jet obviously continues to this distance, hence, the steadily decreasing momentum was observed and true self-preservation apparently was not attained. This result suggests that self-preservation of the mean flow cannot be established by simply demonstrating constant growth and decay rates.

Figure 1 presents the ratios of the local centerline ($z/D = 0$) to the exit kinematic momentum flux plotted as a function of x/D for the free and the confined jets, each as measured simultaneously by the pitot tube and the normal hot wire. For

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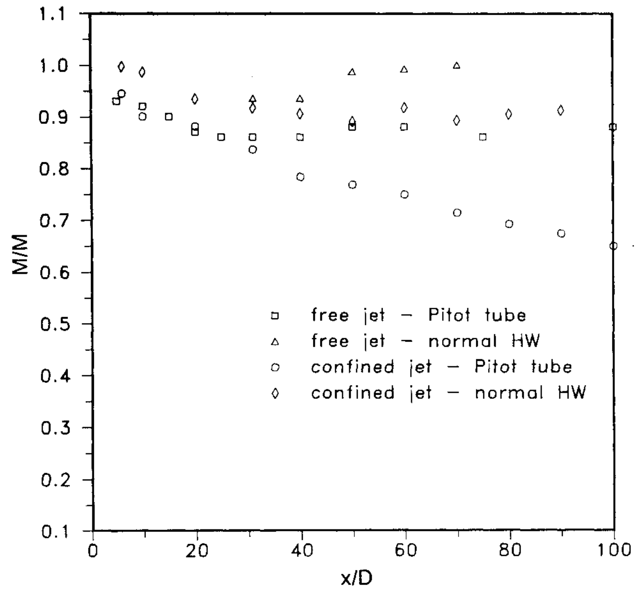

Fig. 1 Kinematic momentum flux ratios plotted as a function of x/D for the free and confined jets.

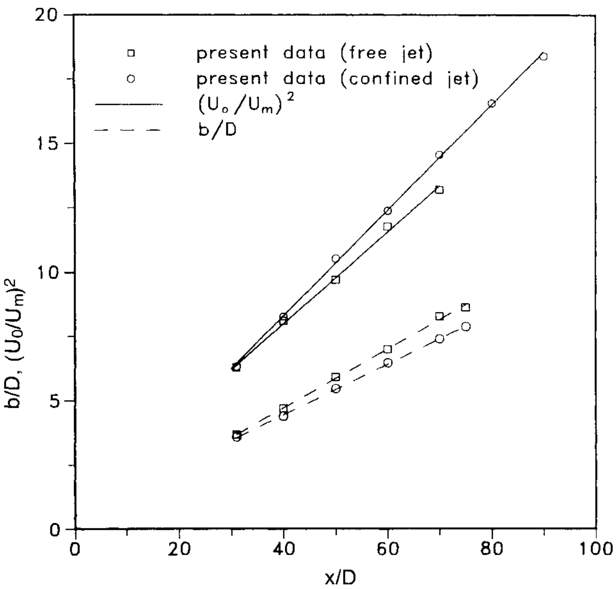

Fig. 2 Growth and decay rates for the present free and confined jets.

both jet configurations, the momentum based on the pitot tube results are lower than those based on the HWA results. It is known that the HWA results will overpredict the actual jet velocities when the turbulence intensities are high and generally expected that the pitot tube will underpredict the actual velocities in this flow. Thus, the observed trends are consistent with the limitations of the instrumentation. In the free jet case, although HWA data are not available in the near field, it appears that the two measuring techniques show a decrease in momentum out to $x/D = 30$, beyond which the pitot tube results indicate a relatively constant momentum flux, whereas the HWA results increase toward the exit level. One would expect a constant momentum flux in the free jet as indicated by these pitot tube measurements, and therefore the increase shown by the HWA measurements is likely due to the inherent inaccuracies. In the confined jet case, both measuring techniques show a decrease in momentum out to $x/D = 50$, beyond which the pitot tube results continue to decrease, whereas the HWA results maintain a constant level. Again, the pitot tube results are physically more acceptable, since the confining end walls continue to impose a biasing boundary condition on the developing jet.

Figure 2 presents comparisons of growth and decay rates for the present free and confined jets based on measurements made in the x-y plane at $z = 0$. The growth rate of the free jet is greater than that of the confined jet, which is consistent with the notion that the free jet interacts more with the ambient surroundings. For similar reasons, one might expect the decay rate of the centerline velocity in the free jet to be greater than in the confined jet, but the opposite was observed. The greater decay rate in the confined jet is supported by consistently higher axial turbulence intensities relative to the free jet. Evidently, the influences of the walls on the near-field entrainment processes in the present study are transmitted as far as the central plane of the jet, such that differences in jet behavior were observed. Thus, the results of Fig. 2 suggest that even at a moderately large aspect ratio of 60 (with respect to typical values used in previous studies), the effects of confining end walls cannot be ignored in reporting plane jet behavior.

A comparison of published data on free and confined jets confirms the trends found in the present study, and they include 1) less variation in the growth rates of confined jets, 2) the growth rate of the confined jet is on average less than that of the free jet, 3) the decay rate of the mean centerline velocity is greatest in free jets but generally varies more among confined jets, and 4) the self-preserving axial turbulent intensities are generally higher in confined jets. In summary, the present results indicate that nonconservation of momentum persists in the confined jet, with no asymptotic value of the kinematic momentum flux being reached at the furthest measuring distance of $x/D = 100$. In the free jet, after an initial decrease out to $x/D = 30$, an asymptotic value is reached and maintained out to $x/D = 100$. Much better agreement exists among the published decay rates of mean centerline velocity for free jets than for confined jets, which is opposite to the results on growth rates. These results confirm that although the free jet is more sensitive to its surroundings and has a less extensive region of two-dimensionality for a given aspect ratio, the use of confining end walls appears to produce widely varying decay rates, a nonasymptotic momentum flux and, generally, a questionable state of self-preservation.

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References

[1]Krothapalli, A., Baganoff, D., and Karamcheti, K., "On the Mixing of a Rectangular Jet," *Journal of Fluid Mechanics*, Vol. 107, June 1981, pp. 201-220.

[2]Kotsovinos N. E., "A Note on the Conservation of the Volume Flux in Free Turbulence," *Journal of Fluid Mechanics*, Vol. 86, Pt. 1, May 1978, pp. 201-203.

[3]Ray, G. D., "Characteristics of a Vertical Isothermal Plane Jet," M.A.Sc. Thesis, Univ. of Waterloo, Waterloo, Ontario, Canada, 1986.

[4]Rodi, W. "A Review of Experimental Data of Uniform Density Free Turbulent Boundary Layers," *Studies in Convection*, Vol. 1, edited by B. E. Launder, Academic, London, 1975.

[5]Everitt, K. W. and Robins, A. G., "The Development and Structure of Turbulent Plane Jets," *Journal of Fluid Mechanics*, Vol. 88, Pt. 3, Oct. 1978, pp. 563-583.

[6]Bashir, J. and Uberoi, M. S., "Experiments on Turbulent Structure and Heat Transfer in a Two-Dimensional Jet," *Physics of Fluids*, Vol. 18, No. 4, April 1975, pp. 405-410.

[7]Trentacoste, N. and Sforza, P., "Further Experimental Results for Three-Dimensional Free Jets," *AIAA Journal*, Vol. 5, May 1967, pp. 885-891.