Mach Number and Temperature Effects on Jets

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Abstract

MEASUREMENTS were carried out in a round jet over a range of exit Mach numbers from 0.3 to 1.7 and exit-to-ambient temperature ratios of 0.8 to 2.3 using a laser velocimeter. Mean velocities and turbulence intensities were measured and their distributions in the radial and axial directions were obtained. A systematic study was made of the changes in the distributions as the jet Mach number and temperature ratio were varied progressively. Attempts to reduce the many radial and centerline distributions of given quantities, obtained at various jet exit conditions, to universal curves proved to be successful and empirical formulae were derived to describe these curves.

Contents

In the past four decades, turbulence research has benefited greatly from the development of hot-wire anemometers, primarily because they have special capabilities. However, hot-wires suffer from two major drawbacks. First, the hot wire has to be inserted into the flow before a measurement can be made. This introduces disturbances into the flow, but more importantly, there is constant danger of breakage especially in the more severe flow environments. The second drawback is that hot wires actually measure mass-flow rate, and when compressibility or temperature variations are present there is a problem of proper manipulation of the data so that velocity information may become available. In the present effort where the intent is to observe the jet field over a wide range of exit conditions, the laser velocimeter is the most appropriate instrument for the purpose since it has practically all the capabilities of hot wires without the same drawbacks.

Independent studies were carried out by Barnett and Giel[1] and Lau et al.[2] to assess the capabilities of the laser velocimeter by comparing the LV and hot-wire measurements in unheated jets at low Mach numbers. They found that the magnitudes of the mean velocity compared favorably. Radial distributions of the turbulence intensity also exhibited identical trends, although the magnitudes of the LV data tended to be uniformly greater by about 2% in turbulence intensity. (The reasons for the discrepancy are dealt with in another paper.[7]) Moreover, Lau et al.[2] found the spectra of the fluctuating velocities to be of comparable shape. In particular, the narrow band peak, which has featured prominently in spectra of hot-wire signals in the potential core of the jet,[3,4] is also faithfully reproduced in the LV spectra and occur at the same Strouhal number.

Radial distributions of the axial mean velocity have long been known to be similar, and Lau et al.[2] have found that distributions as far downstream as two potential core lengths from the nozzle exit plane may be reduced to one curve if U is normalized by the jet exit velocity (U_J) and the radial position is defined by $\eta^* = (r - r_{0.5})/x$ (where $r_{0.5}$ is the position where the velocity is 0.5 U_J). They also found that the spreading rate of the mixing region, defined by $\delta_\eta = U_J/(\partial U/\partial \eta^*)_{max}$, decreased with increasing Mach number for isothermal jets ($T_J/T_0 = 1.0$). Figure 1 shows the variation of δ_η for this case (solid triangles). The variation for the cases where $T_J/T_0 = 1.5$ and 2.32 are also shown (by the solid squares and diamonds, respectively). They suggest that there is very little difference between the $T_J/T_0 = 1.0$ and 1.5 cases. The spreading rate falls with M_J until about $M_J = 1.4$, where a trough is reached. Subsequent increases in Mach number cause the spreading rate to rise. It should be noted that the convergent-divergent nozzles used for the supersonic cases have been designed to produce essentially shock-free flow. Therefore, the rise observed from about $M_J = 1.4$ would seem to signify the presence of a meaningful trend. A cursory review of the conditions indicates that the troughs are located at jet conditions when the eddy convection velocity, which is about 0.7 U_J, is supersonic relative to the ambient speed of sound (a_0). At $T_J/T_0 = 2.32$, δ_η does not change as markedly, but nevertheless a slight trough may be seen about $M_J = 1.0$ and this would also correspond with the eddy convection velocity being supersonic.

Results of other investigations collected by Birch and Eggers[5] are also shown. Except for Cary's,[6] the results were obtained with a pitot tube and they tend to lie higher than the present results. On the other hand, Cary's, which were obtained with an interferometer, lie close to the present results. Selected pitot-tube measurements were carried out in the present study (shown by the flagged solid symbols) and they are located above the present LV data but close to the previous pitot data.

Radial distributions of the axial mean velocity for varying jet exit conditions are reducible to one universal curve which may be expressed approximately by the Görtler error function profile:

$$U/U_J = 0.5[1 - \mathrm{erf}(\sigma\eta^*)] \quad \text{where } \sigma = \sqrt{\pi}/\delta_\eta$$

Centerline distributions of the axial mean velocity are similarly reducible to a universal curve as shown in Fig. 2. (The data in this case do not collapse as well as for the radial distributions.) The curve may be represented approximately

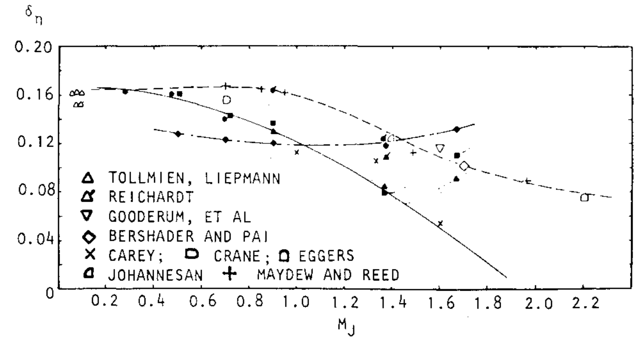

Fig. 1 δ_η vs M_J. Present results: T_J/T_0 = ● cold, ▲ 1.0, ■ 1.5, ◆ 2.32. (Pitot-tube measurements are flagged.)

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

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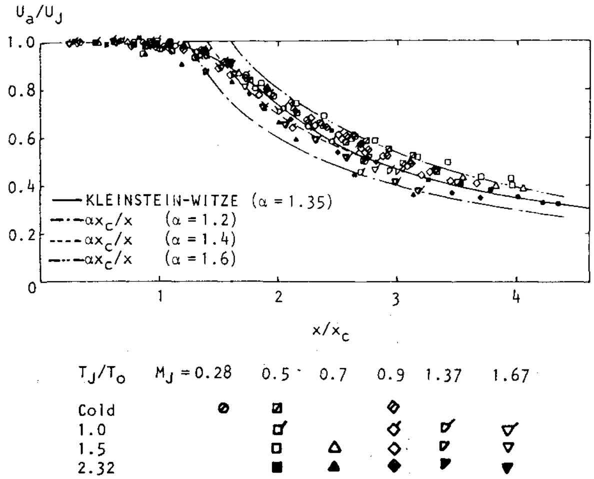

Fig. 2 U_a/U_J vs x/x_c.

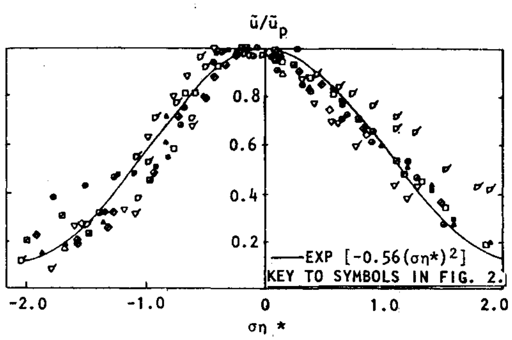

Fig. 3 $\tilde{u}/\tilde{u}_p$ vs $\sigma\eta^*$.

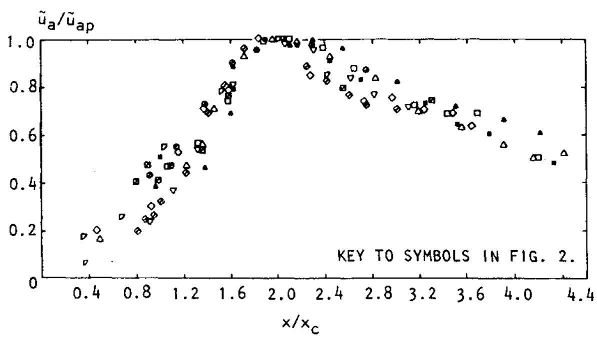

Fig. 4 $\tilde{u}_a/\tilde{u}_{ap}$ vs x/x_c.

by a Kleinstein-Witze type formula: $U_a/U_J = 1 - \exp\{\alpha(1 - x/x_c)\}$ where x_c is the potential core length and $\alpha = 1.35$. For very large values of x, the equation reduces to $U_a/U_J = \alpha x_c/x$. Curves are also shown for this asymptotic case where $\alpha = 1.2$, 1.4, and 1.6.

The potential core length x_c varies as: $x_c/D = 4.2 + 1.1\ M_J^2$ for $T_J/T_0 = 1.0$. When T_J/T_0 is raised to 1.5, an almost parallel variation results and is given by $x_c/D = 3.2 + 1.1\ M_J^2$. Further increase in T_J/T_0 to 2.32 does not cause further changes in the variation of x_c/D with M_J.

Radial distributions of the turbulence intensity for varying jet exit conditions also tend to collect in a fairly narrow band when plotted in terms of $\sigma\eta^*$ and $\tilde{u}/\tilde{u}_p$ (Fig. 3), where $\tilde{u}_p$ is the peak value of the respective distribution.

Centerline distributions of the turbulence level for the various jet conditions studied also tend to collapse in a narrow band when plotted in terms of $\tilde{u}_a/\tilde{u}_{ap}$ and x/x_c, $\tilde{u}_{ap}$ being the respective peak value (Fig. 4).

Acknowledgments

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