on the plate $(\bar{P}/P_\infty) + \frac{1}{2}(\Delta P/P_\infty) = 4.1$. The strength of these pressure pulsations then decreased as the nozzle pressure ratio R was increased. Figure 2 indicates the fluctuating pressure trace and one of the shadowgraphs at a pressure ratio of 4.33 when large-amplitude shock oscillations occurred. The normal shock wave standing in the jet flow oscillated at a frequency f of about 20 kHz. (Frequencies at the pressure peaks are indicated in Figs. 1 and 3.)

Placement of the plate in the vicinity of the first shock cell of the corresponding freejet (without the plate) produced a spatial zone of shock-wave instability therein and caused the shock wave to oscillate, which resulted in periodic pressure pulsations on the plate. At a lower pressure ratio of about 2.5, the pressure fluctuations ΔP were less because of the interaction of relatively weak diamond shock in the jet. As the nozzle stagnation pressure ratio R was increased, the mean pressure $\bar{P}$ on plate increased (Fig. 1). At higher stagnation pressures, larger pressure losses occurred across the shock waves; i.e., the increase in plate recovery pressure is not directly proportional to the increase in jet stagnation pressure. The local peak and the decrease in mean plate pressure at a nozzle pressure ratio of about 2.6 (Fig. 1) was associated with the weaker diamond shocks in the jet changing to a stronger normal shock cell (Mach disk) as the pressure ratio was increased.

The ratio of the pressure fluctuation ΔP to the mean pressure $\bar{P}$ on the plate, i.e., what the plate experiences, is shown in Fig. 4 with spacing $s/d = 1.5$. The magnitudes of the pressure fluctuations with respect to the mean pressure were relatively large; at the first peak, $\Delta P/\bar{P}$ was about 0.5, and at the second peak, $\Delta P/\bar{P}$ was more than 1.0.

Pressure data obtained with a smaller plate spacing of $s/d = 1.0$ are shown in Figs. 3 and 5. For the first peak, the pressure fluctuations were about the same as for the larger spacing, but for the second peak the pressure fluctuations were less by 0.5 (cf. Figs. 4 and 5). This was due to the smaller amplitude of the standing shock-wave oscillations and less pressure loss across the shock (higher $\bar{P}$) for the smaller spacing.

Conclusions

The experimental investigation revealed local peak pressure fluctuations on the plate at nozzle pressure ratios of approximately 2 and 4.5, with the latter case producing fluctuations of the same order as the mean pressure on the plate. The frequency of the oscillations was as large as 20 kHz. For choked jet flow at ambient pressure higher than atmospheric, the pressure fluctuations would increase accordingly, and, therefore, adjacent solid structures would be subjected to proportionately higher normal stresses. The shock-wave oscillations in the axially varying velocity field of the jet produce stagnation pressure changes across the shock and corresponding pressure pulsations on the plate.

Acknowledgment

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Round Jet in a Cross Flow: Influence of Injection Angle on Vortex Properties

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Introduction

THE study of a turbulent jet of fluid injected at a large angle into a cross flow is motivated by several applications of interest, including the cooling of combustion products and the aerodynamics of V/STOL aircraft. One configuration that has been studied extensively is that of a round subsonic jet of air discharging through a large flat plate into a uniform subsonic cross flow. A dominant and persistent feature of this flow is a pair of diffuse contrarotating vortices that are deflected by the cross flow and swept downstream. A model developed by Fearn and Weston has been utilized to infer the properties of the vortex pair from selected velocity measurements for perpendicular jet injection into the cross flow.[1] These vortices play an important role in determining the pressure distribution on the surface through which the jet exhausts, and it is this pressure distribution that is of primary importance in V/STOL aerodynamics. The purpose of this Note is to present the effects of jet injection angle on the properties of the vortex pair associated with a jet in a cross flow.

Experiment

The experiment was conducted in the V/STOL wind tunnel at NASA Langley Research Center, Hampton, Va. The apparatus utilized in previous tests[1,2] was modified to provide for jet injection angles δ of 45, 60, 75, 90, and 105 deg into the cross flow. A round jet of air 10.16 cm (4.00 in.) in diameter was discharged through a horizontal flat plate into the cross flow of the wind-tunnel test section. Effective jet-to-cross flow velocity ratios of 4 and 8 were studied. As in previous tests, velocities were determined with a rake of seven yaw-pitch probes.

Results

A description of the diffuse vortex model and the procedure for inferring the properties of the contrarotating vortex pair associated with a jet in a cross flow from velocity measurements are provided in Ref. 1. The physical properties of the vortex pair for the cases studied in this experiment are presented in Figs. 1-3. Each point on a graph represents a value of a parameter inferred from velocity measurements in a given cross section of the jet plume. In each of these graphs, a vortex property is plotted vs arc length S along the vortex curve (the curve defined by projecting the vortex trajectories onto the plane of flow symmetry). All lengths are nondimensionalized by the jet diameter D, and the effective vortex strength is nondimensionalized by the factor $2DU_\infty$,

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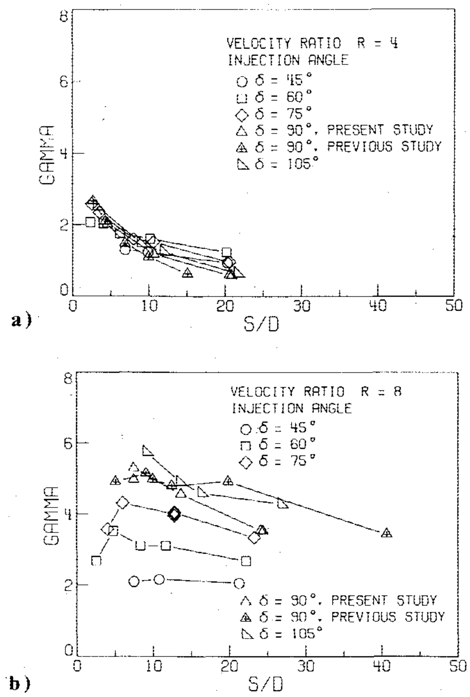

Fig. 1 Vortex strength.

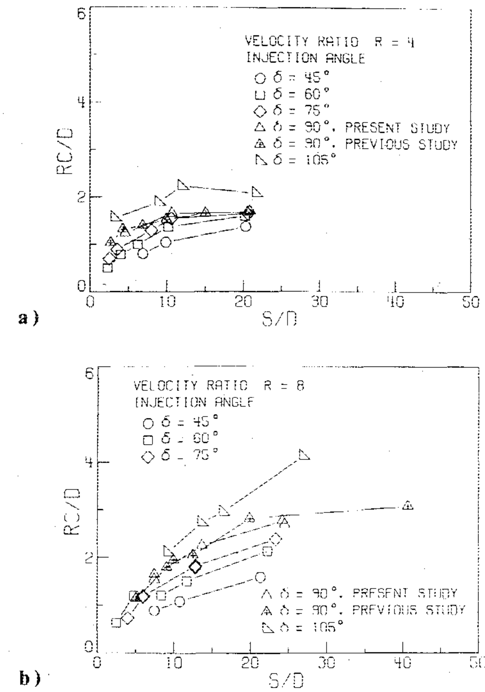

Fig. 3 Vortex core size.

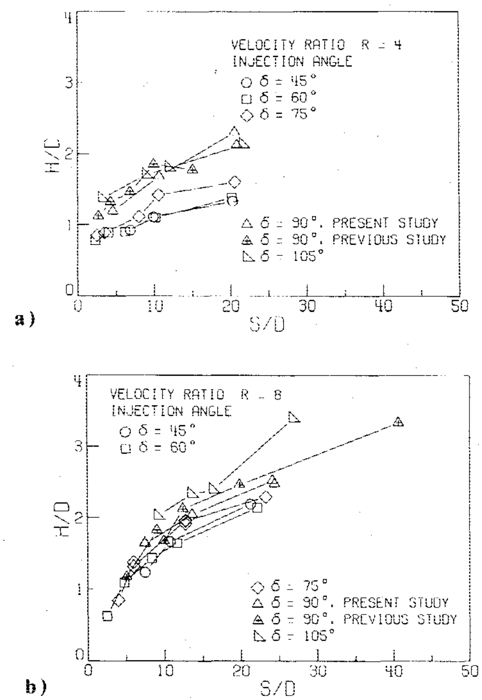

Fig. 2 Vortex spacing.

where U_∞ is the cross flow speed. Comparisons with the results of the previous study[1] for a jet injection angle of 90 deg are included.

This study represents the first quantitive description of the properties of the vortex pair associated with a jet in a cross flow as a function of jet injection angle. This description should be useful in constructing models to calculate the pressure distribution on the surface through which the jet exhausts. It also provides additional information about the properties of the vortex pair which may be useful in understanding the basic fluid mechanics of this complicated flow. Some specific observations from these figures are as follows:

1) The effective vortex strength for both velocity ratios reaches a maximum relatively near the jet orifice and then decreases as the vortices are swept downstream and weakened by diffusion of vorticity across the symmetry plane (see Fig. 1). The effect of jet injection angle on the effective vortex strength is markedly different for effective velocity ratios of 4 and 8. For $R=8$, there is a regular and significant increase in vortex strength γ with increasing jet injection angle. For example, the maximum vortex strength for $\delta=90$ deg is approximately 2½ times as great as that for $\delta=45$ deg. For $R=4$, however, there is no comparable change in vortex strength with jet injection angle.

2) The effective vortex spacing (H) increases as the vortices are swept downstream (Fig. 2). For both velocity ratios, there is a noticeable increase in spacing with increasing jet injection angle. Also, the rate of increase of the vortex spacing with S/D is noticeably greater for $R=8$ than for $R=4$.

3) The core radius (RC) of the vortex also grows with increasing S/D (Fig. 3) and exhibits a behavior similar to the effective vortex spacing.

Acknowledgment

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