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Jet Excitation by an Oscillating Vane

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Forced vibration of a small vane located in the jet potential core is used to excite a two-dimensional turbulent jet. The experimental apparatus and the measuring techniques used to determine the mean flow and entrainment characteristics are described. At the streamwise measurement stations and test conditions, jet spreading and entrainment are found to increase significantly with increasing frequency and amplitude of vane oscillation over the steady jet values.

Introduction

EXCITATION of turbulent jets by acoustic, mechanical, and fluidic means has attracted considerable interest in recent years because of the fundamental and practical implications of an improved understanding of the jet turbulence and mixing characteristics. Acoustic excitation studies have been performed by Crow and Champagne,[1] Vlasov and Ginevskiy,[2] Goldschmidt and Kaiser,[3] Morkovin and Paranjape,[4] and Fiedler and Korschelt.[5] Fluidic excitation was pioneered by Viets.[6] Mechanically pulsed jets with time-varying mass flows were studied by Binder and Favre-Marinet,[7] Curtet and Girard,[8] and Bremhorst and Harch.[9] Mechanical jet oscillation was investigated by Simmons et al.[10] A comparison of the entrainment characteristics of both pulsing and oscillating jets was given by Platzer et al.[11]

Although these studies have produced some detailed measurements of the unsteady jet flow characteristics, many questions remain about the underlying flow mechanism, especially concerning the presence of distinct jet instabilities[12,13] and the formation of discrete vortices.[5,8]

The present investigation was stimulated by a remark in Ref. 5 concerning the encouraging effect of a freely vibrating vane on jet excitation. In contrast to the experiment by Fiedler and Korschelt,[5] in this study a vane is forced to undergo small amplitude pitch oscillations. The experimental apparatus, measuring technique, and results are described in the following sections.

Experimental Apparatus and Procedures

Mean velocity measurements were made in a two-dimensional turbulent jet of air excited by two different methods: 1) periodic perturbation of the nozzle exit velocity and 2) oscillation of a vane located in the potential core. The jet issued from a plenum chamber through a rectangular nozzle with length $L=300$ mm and width $h=6$ mm (Fig. 1). The mean nozzle conditions about which the jet was perturbed were: velocity, $u_0=36.6$ m/s; Reynolds number, $u_0h/\nu=1.4\times10^4$; rms turbulence $\simeq 0.002\ u_0$; temperature $\simeq 8°$C above ambient.

The jet exit temperature of 8°C above ambient is due to inadequate cooling. However, it should not affect the mixing at the downstream measurement stations. The exit velocity along the length of the nozzle was two-dimensional within 1%, except over small regions at the extremes. No side plates were used to contain the jet. At about 100 nozzle widths downstream in the unexcited jet, the variation of the jet centerline velocity along the central 100 mm of the jet length was less than 6%.

In excitation method 1, the nozzle exit velocity was varied harmonically at 10 Hz with a zero-peak amplitude of 10% of the mean. This was achieved by venting air from the plenum chamber through an orifice with harmonically varying area.

Excitation method 2 was used in most experiments, two sizes of vanes being tested. Both vanes had a symmetric airfoil section (Fig. 1) with a thickness of 1.3 mm and a span of 360 mm. The chords of the larger and the smaller vanes were 10 and 5 mm, respectively. An electromagnetic vibrator was used to oscillate the vane in pitch about an axis 3 mm aft of its leading edge. The vane was located symmetrically with respect to the nozzle, and it could be oscillated at various frequencies and amplitudes about a mean position set at zero angle of attack.

Mean velocity measurements were made across the width of the jet at its midspan and at distances of 20, 40, and 60 nozzle widths downstream of the nozzle. A constant temperature hot-wire anemometer was used, the wire being a platinum alloy 10 μm in diameter with its 4-mm length aligned parallel to the length of the nozzle. The anemometer was operated at a constant resistance ratio of 1.3, which gives a mean wire temperature of the order of 700 K. Typical jet temperatures on the centerline at 20, 40, and 60 nozzle widths downstream were 4, 3, and 2°C, respectively, above ambient so that the cold resistance of the wire varied by at most 1%. An analysis showed that a temperature change of 8°C gives a change of only 2% in the temperature sensitivity of the wire. Hence, a first-order temperature correction to the anemometer calibration was adequately achieved by operating the wire at a constant resistance ratio with its cold resistance determined by local jet conditions.

Some additional mean velocity measurements were made with a pitot tube aligned parallel to the jet centerline, and by surveying the low-velocity inflow of surrounding air to the jet with a rotating vane anemometer. The axis of the latter device was aligned with the streamlines by use of flow visualization with smoke.

Results and Discussion

General Flow Features

In the first tests, the jet was excited by method 1, that is, by superimposing a 10% harmonic velocity pulsation at 10 Hz upon the steady two-dimensional jet. Although the

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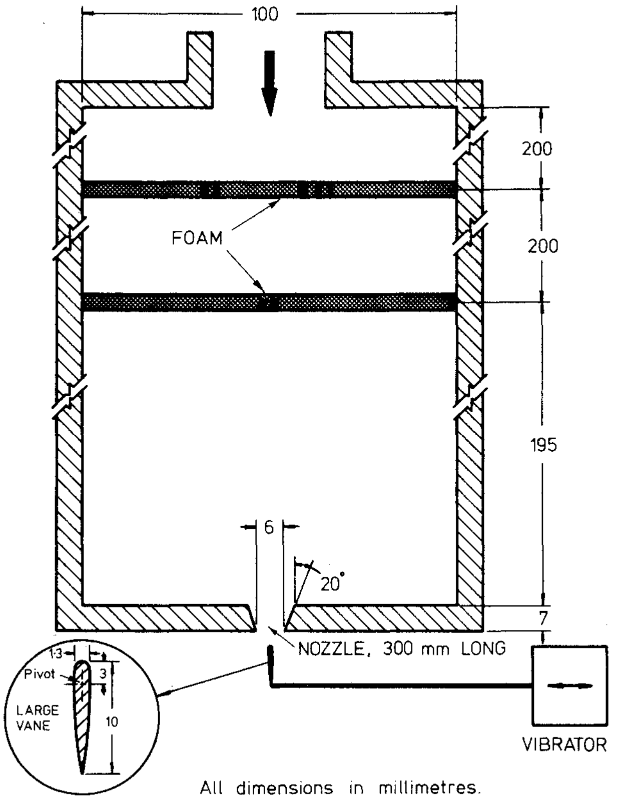

Fig. 1 Configuration of plenum chamber, nozzle, and oscillating vane.

propagation of the resulting small jet velocity perturbation is of intrinsic fluid dynamic interest and thus will be reported elsewhere,[14] it was observed that this type of jet excitation has a negligible effect on flow entrainment. Therefore, no further reference to this experiment will be made here.

In the second tests, the jet was excited by method 2, that is, the small vane in Fig. 1 was oscillated in pitch at various frequencies and amplitudes. It was quickly noticed that this type of excitation produces a widening of the jet which significantly exceeds the spreading angle due to the small amplitude oscillation. Furthermore, velocity measurements close to the nozzle exit showed the vane to have a negligible upstream influence. Thus, jet excitation by an oscillating vane situated in or close to the potential core of the jet appears to be an efficient jet mixing/entrainment device. For this reason, mean velocity profiles were measured at three downstream locations for a more quantitative assessment of the vane's mixing effectiveness.

Velocity Profiles of the Vane-Excited Jet

Hot-wire measurements of the time-averaged velocity magnitudes were taken over the following range of parameters and for the two sizes of vanes:

Vane frequency of oscillation: 0, 5, 10, 20, 30 Hz
Vane amplitude of oscillation: 2.6 and 5.2 deg (zero-peak)
Vane leading edge location: 3.3, 8.5, and 11.5 mm downstream from the nozzle

The development of the jet profiles as a function of downstream distance is shown in Fig. 2 for the steady jet and for four frequencies of oscillation of the larger vane. Measurements of the spreading and decay of the steady jet agree well with available experimental information for two-dimensional turbulent jets, even though the stationary vane is in the potential core. While only a small effect of vane oscillation is visible at a downstream distance of 20 nozzle widths, increasing frequency produces significant jet spreading at locations further downstream. At the same time,

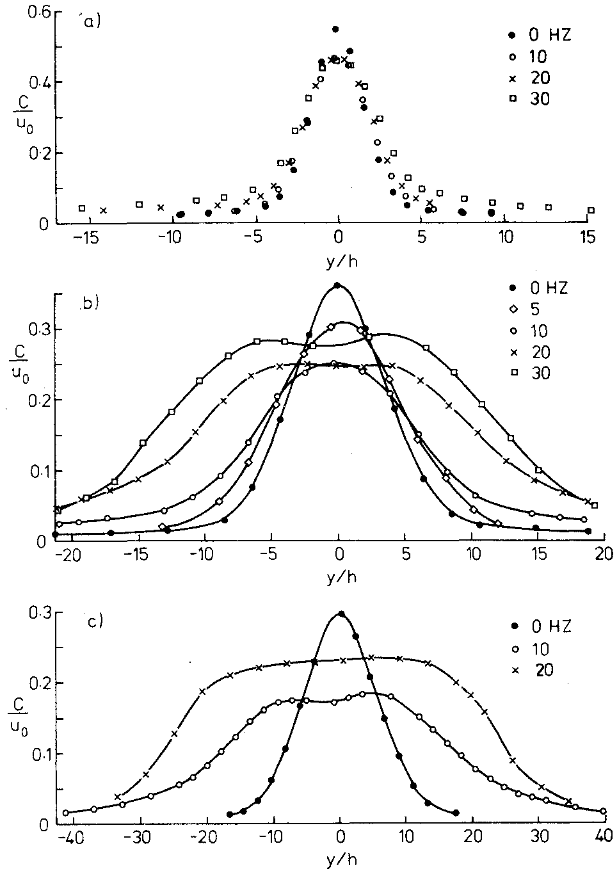

Fig. 2 Profiles of magnitude C of mean jet velocity for large vane at downstream distance of a) 20 h, b) 40 h, c) 60 h where h is nozzle width and u_0 is nozzle velocity. Vane leading edge is 3.3 mm from nozzle and amplitude of oscillation is 2.6 deg zero-peak.

the profiles become flatter, resulting in a faster velocity decay than for the steady jet. Other results not shown here are summarized as follows. Doubling the amplitude of oscillation to 5.2 deg, zero-peak, increases both the jet spreading and the mean velocity magnitude on the centerline. Downstream movement of the leading edge of the vane from 3.3 to 8.5 and 11.5 mm from the nozzle maintains the vane effectiveness. Similar effects, but with smaller magnitudes, were observed with the smaller vane. No tests were made at distances greater than 11.5 mm because the vane started to flutter.

It can be inferred from Fig. 2 that the momentum at any downstream station, if defined as

$$M(x) \equiv \int_{-y_\infty}^{y_\infty} C^2 \mathrm{d}y$$

increases with increasing streamwise distance and frequency. Here, $C = (U^2 + \bar{u}^2 + \bar{v}^2)^{1/2}$ is the signal essentially detected by the hot wire; U and u are the mean and fluctuating velocities in the streamwise direction, respectively; v is the fluctuating velocity in the transverse direction, and y_∞ is a point outside the jet boundaries. In the excited jet, however, the momentum invariant M_I, which should be independent of the streamwise distance, can readily be shown[15] to be of the form

$$\int_{-y_\infty}^{y_\infty} (U^2 + \bar{u}^2 - \bar{v}^2)\mathrm{d}y$$

Hence it is

$$\int_{-y_\infty}^{y_\infty} (C^2 - 2\bar{v}^2)\mathrm{d}y$$

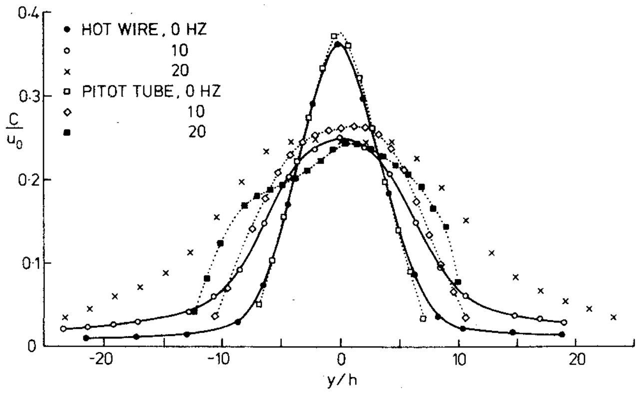

Fig. 3 Comparison of profiles of magnitude C of mean jet velocity measured with hot wire and pitot tube at 40 nozzle widths downstream of nozzle. Large vane is located 3.3 mm from nozzle and amplitude of oscillation is 2.6 deg zero-peak.

which should remain constant. Smoke flow visualization demonstrated a significant transverse velocity component v, which probably results from the flapping of the jet and vortex shedding from the vane and therefore contributes to the apparent momentum increases. The pitot tube measurements compare well with those of the hot wire in Fig. 3 for the steady jet, but not for the excited jet, especially at 20 Hz. This is attributed to the low-frequency response of the pitot tube which essentially measures $U^2+\bar{u}^2$ and hence, as seen from Fig. 3, the apparent momentum increase is less than that from the hot-wire results.

Laser Doppler velocimeter results reported in Ref. 15 show that the momentum integrals

$$\int_{-y_\infty}^{y_\infty} U^2 \mathrm{d}y \quad \text{and} \quad \int_{-y_\infty}^{y_\infty} (U^2+\bar{u}^2)\mathrm{d}y$$

remain fairly constant with downstream distance, except at high frequencies and amplitudes. Hence, there is an indication that momentum is conserved. However, the contribution of the fluctuating flow momentum in both the x and y directions is clearly quite significant. The final assessment of momentum conservation therefore must await the measurement of the v fluctuations. Laser Doppler velocimeter and cross-wire measurements aimed at determining the magnitude of $\bar{v}^2$ are presently in progress. An additional check of the entrainment increases due to increasing vane frequency was performed by measuring the time-averaged jet inflow with a rotating vane anemometer. By positioning this anemometer well outside the turbulent jet boundaries, the inflow velocities were observed to be more than doubled as the vane frequency of oscillation was raised from 0 to 20 Hz.

Integrated Velocity Profiles

To obtain a measure of the flow entrainment as a function of vane oscillation, the velocity profiles were integrated across the jet. As already pointed out by previous investigators of jet entrainment, e.g., Crow and Champagne,[1] the termination of the integration at the jet boundaries requires some care. In this paper, the sides of the profiles were faired to zero in the manner advocated by Crow and Champagne.[1] Also, as previously mentioned, the integrated velocity values based on hot-wire measurements are likely to overestimate the entrainment. Furthermore, it should be noted that the momentum $M(x)$ at any location downstream of the vane should be higher than the steady jet exit momentum M_E due to the momentum transferred to the jet through the vane oscillation. Nevertheless, the integrated velocity values are modified by a factor $(M_E/M(x))^{1/2}$ to correct for the apparent momentum increase so that the modified $M(x)$ will be independent of the streamwise distance. This modification

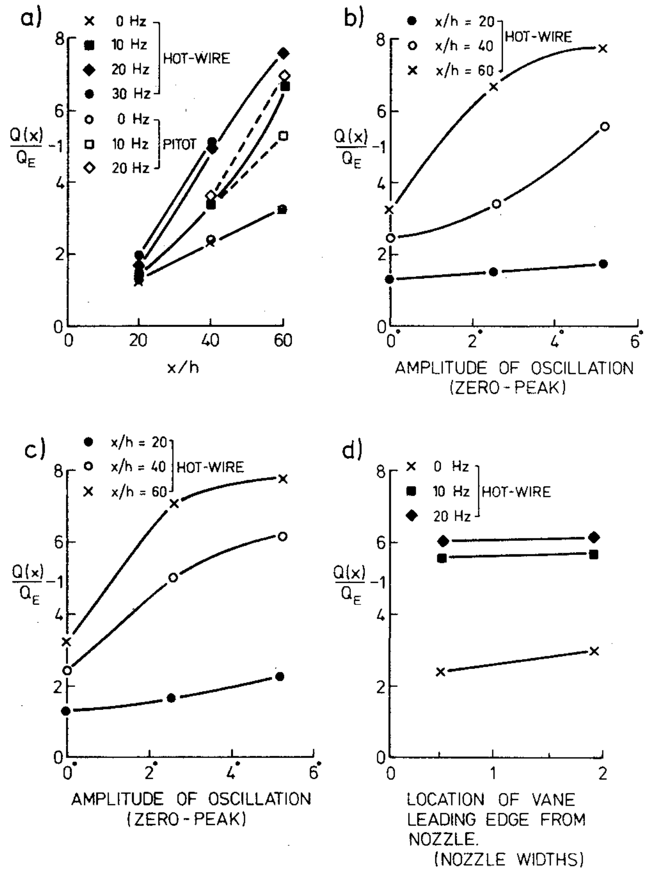

Fig. 4 Modified mean "entrainment" measurements with large vane for a) 2.6 deg zero-peak amplitude of oscillation with vane located at 3.3 mm; b) 10 Hz with vane located at 3.3 mm; c) 20 Hz with vane located at 3.3 mm; and d) 5.2 deg amplitude of oscillation with measurements at $x/h=40$.

provides a conservative estimate of the volume flow in the streamwise direction at distance x downstream of the nozzle. Hence, in Fig. 4, the modified jet "entrainment" (defined as $(Q(x)-Q_E)/Q_E$ where Q_E is the nozzle volume flow per unit nozzle length) is plotted as a function of downstream distance, frequency, and amplitude of vane oscillation and vane location in order to display the major trends. Frequency and amplitude are seen to produce significant entrainment increases and enhanced mixing while the vane effectiveness is maintained and even slightly improved by moving the vane downstream by almost a chord length. However, two-component velocity measurements are needed especially at the higher frequencies to determine the true entrainment and the detailed flow structure.

Conclusions and Recommendation

Forced vibration of a small vane located in the jet potential core was used to excite the jet. Mean velocity measurements show significant increases in jet spreading and secondary flow entrainment over the steady jet values without impairing the nozzle efficiency. More detailed measurements are required to determine the precise flow structure and mixing mechanism initiated by the vortex shedding from the vane. Also, further studies appear to be warranted to explore the effectiveness of oscillating vane excitation at higher nozzle pressure ratios and to investigate the vane's applicability to practical thrust augmenting ejectors.

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