ACOUSTIC AUGMENTATION OF THE ENTRAINMENT COEFFICIENT OF AXISYMMETRIC FREE AIR JETS

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Introduction

The entrainment by steady turbulent axisymmetric free gaseous jets may be subdivided into entrainment in the initial zone, up to about 15 diameters axially downstream of the jet orifice; and by entrainment in the fully developed zone, ie., greater than about 15 diameters axially downstream of the jet orifice. The first direct measurements of fully developed entrainment were made by Ricou and Spalding (1) and Hill (2) extended the technique to make direct measurements of the local entrainment rate in the initial zone. These measurements showed that the entrainment coefficient varied non-linearly from 0.11 at one diameter downstream of the jet nozzle orifice, to the fully developed constant value of 0.32 at about 13 diameters.

Jet flow mixing plays a major role in the performance of combustors of the gas turbine type and jet entrainment is responsible for the mixing produced by a jet. The possibility of increased jet entrainment and mixing by acoustically pulsing the jet flows, thereby improving combustor performance, is therefore of important technical interest. Responding to this possibility Vermeulen, et al. (3) made the first direct measurements of fully developed entrainment by acoustically pulsed air jets, and found that the entrainment was increased by up to six times. They adapted the Ricou and Spalding technique for these measurements, and just recently by extending Hill's work Vermeulen, et al. (4) made the first direct measurements of the local entrainment rate in the initial region of pulsed jets.

Consider a normal local slice of thickness ΔX, between the jet orifice exit plane and the fully developed region, with $\Delta \dot{M}_e$ as the corresponding local entrainment mass flow rate. Then the entrainment coefficient C_e can be shown to be approximately expressed by

$$C_e \approx \frac{D}{\dot{M}_j}\left(\frac{\rho_j}{\rho_s}\right)^{\frac{1}{2}}\frac{\Delta \dot{M}_e}{\Delta X}$$

where D is the jet orifice diameter, $\dot{M}_j$ is the jet mass flow rate at the orifice, ρ_j is the jet density at the orifice and ρ_s is the density of the surrounding fluid. C_e varies with X, the axial distance to mid point of slice ΔX from the nozzle orifice exit plane, as was shown for steady jets by Hill (2). This equation is the basis for the direct measurement of the entrainment coefficients of steady and pulsating jet flows. The novel experiments on pulsating jets discussed in this work were designed to investigate the influence on C_e of geometry, Reynolds number Re, acoustic driver power or pulsation strength U_e/U_j (U_j is the steady jet velocity and U_e the jet velocity pulsation amplitude) and Strouhal number St. In essence this paper is a consolidation of ASME references (3) and (4).

Experimental

Figure 1 shows the apparatus was essentially a ΔX thick porous walled entrainment chamber which can move coaxially about the jet flow. A loudspeaker driver of 250 W capacity was used to pulse the jet flow. Air was supplied to the chamber such that the porous walled cylinder pressure was atmospheric with uniform radially inward flow and with no axial pressure gradient. Thus free-jet flow conditions were established and the measured supplied air mass flow rate to the chamber was equal to the local entrainment mass flow rate of the jet. This measurement method was used for jets with or without acoustic drive.

Figures 2 and 3 present typical experimental C_e versus X/D data for two nozzle sizes, for low and medium Reynolds numbers, and Strouhal numbers were almost identical. The system had a strong response at 163 Hz producing the good range of pulsation strength effect exhibited. As shown the entrainment coefficient varied strongly with X/D and pulsation strength. The acoustic drive considerably increased the entrainment coefficient as well as extended the developing zone. The fully developed value for C_e at a particular U_e/U_j magnitude could not be established because of measurement difficulties at the extended X/D values required.

All the available data at X/D = 10, 163 Hz, are summarised in Figure 4, showing C_e versus U_e/U_j with Re and St as parameters. There was no clear effect due to Strouhal number, therefore, an optimum jet response Strouhal number value cannot be deduced.

Conclusions

The acoustic drive considerably increased the entrainment coefficient C_e by up to 4.5 times greater than the "no-drive" case at X/D = 10.0, and by up to 5.2 times at X/D = 17.5, for a driver power of 246 W at 163 Hz. The extent of the initial development zone of the jet was significantly increased, however, measurement difficulties prevented fully developed values of C_e being obtained. There was only a tendency for C_e to increase with the Strouhal number, and therefore, an optimum value for jet response could not be discovered.

References

1. Ricou, F.P. and Spalding, D.B., "Measurements of Entrainment by Axisymmetrical Turbulent Jets", Journal of Fluid Mechanics, Vol. 11, 1961, pp. 21-32.

2. Hill, B.J., "Measurement of Local Entrainment Rate in the Initial Region of Axisymmetric Turbulent Air Jets", Journal of Fluid Mechanics, Vol. 15, Part 4, 1972, pp. 773-779.
3. Vermeulen, P.J., Ramesh, V., and Yu, Wai Keung, "Measurements of Entrainment by Acoustically Pulsed Axisymmetric Air Jets", ASME Journal of Engineering for Gas Turbines and Power, Vol. 108, No. 3, July 1986, pp. 479-484.
4. Vermeulen, P.J., Rainville, P. Ramesh, V., "Measurements of the Entrainment Coefficient of Acoustically Pulsed Axisymmetric Free Air Jets", 36th ASME Gas Turbine and Aeroengine Congress and Exposition, Paper No. 91-GT-235, 3-6 June 1991, Orlando, Florida, pp. 1-8.

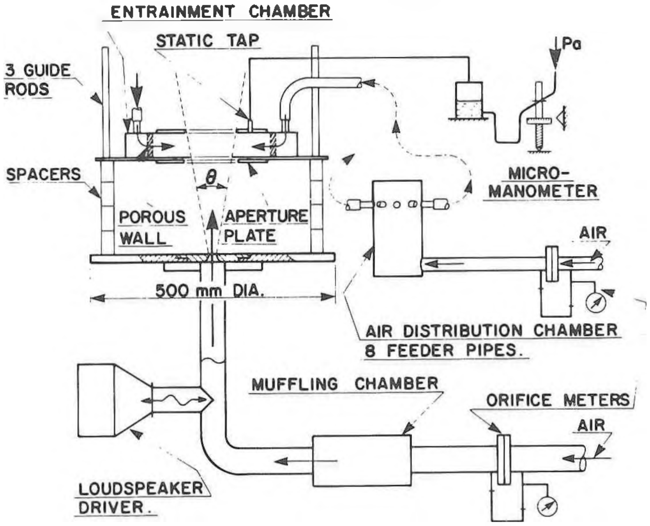

FIGURE 1 - SCHEMA OF APPARATUS FOR MEASUREMENT OF LOCAL ENTRAINMENT MASS FLOW RATE.

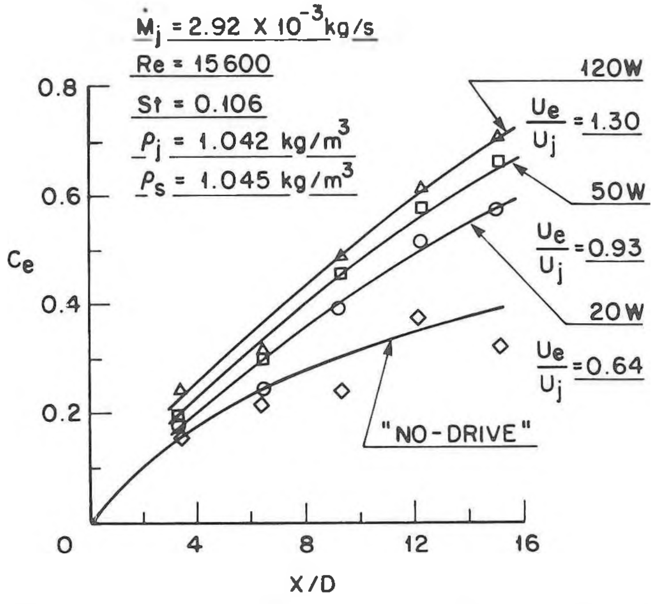

FIGURE 3 - VARIATION OF ENTRAINMENT COEFFICIENT WITH AXIAL DISTANCE AND PULSATION STRENGTH, D = 12.70 mm DIA., U_j = 19.6 m/s, f = 163 Hz.

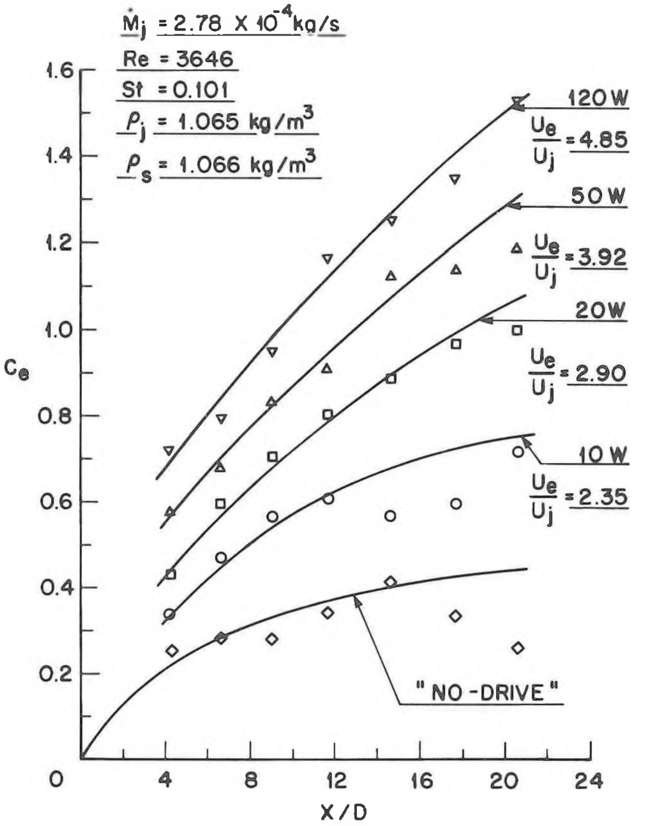

FIGURE 2 - VARIATION OF ENTRAINMENT COEFFICIENT WITH AXIAL DISTANCE AND PULSATION STRENGTH, D = 6.35 mm DIA., U_j = 10.3 m/s, f = 163 Hz.

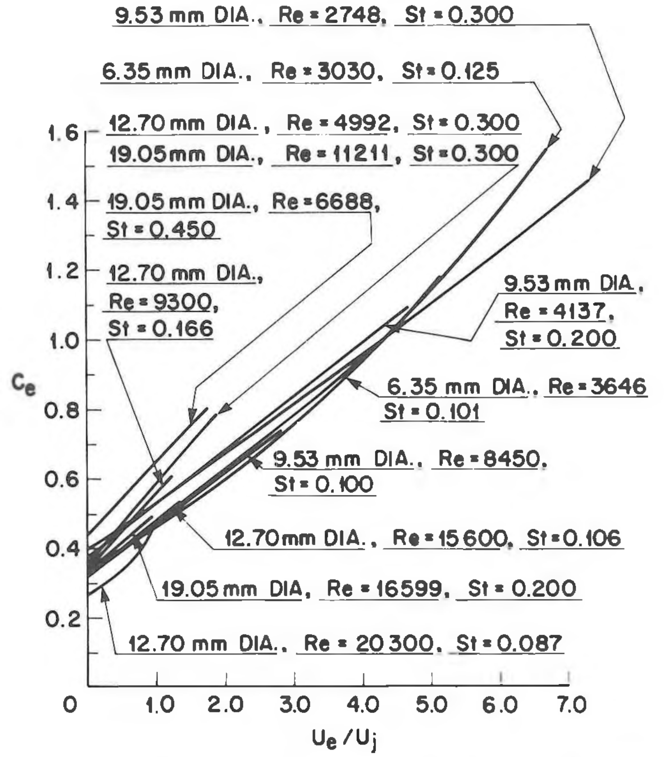

FIGURE 4 - VARIATION OF ENTRAINMENT COEFFICIENT WITH PULSATION STRENGTH FOR THE VARIOUS NOZZLES, f = 163 Hz, X/D = 10, ρ_s = 1.04 kg/m^3.