TECHNICAL NOTE

The preferred mode of a tube jet

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The preferred mode of a tube jet, characterized by the Strouhal number, has been deduced from measurements of the frequency spectra of the streamwise turbulent velocity. Three different tubes with length/diameter ratios of 576, 1152, and 2304 were used, and a range of Reynolds numbers from 200 to 20,000 was covered. For a fully developed laminar exit condition, the preferred Strouhal number increases with Reynolds number, while for a fully developed turbulent exit condition, the Strouhal number is virtually independent of Reynolds number and attains a value of about 0.4 at the end of the turbulent core.

Keywords: preferred mode; jet; instability; turbulence

Introduction

The instability characteristics in shear flows and their development in time and space are important for understanding the evolution of coherent structures, the breakdown of laminar flow, and its transition to turbulent flow. In this note, the preferred mode of a jet of air issued from a long tube after a fully developed velocity profile has been attained inside the tube (referred to as a tube jet) has been studied.

In their studies of axisymmetric jets subjected to controlled excitations, Crow and Champagne[1] showed that there existed a "preferred" frequency at which an axisymmetric disturbance received maximum amplification in the entire jet column. The frequency of the preferred mode corresponded to a Strouhal number $\mathrm{St}=fD/U_e$ of about 0.3, where f is the excitation frequency, D is the tube diameter, and U_e is the average jet exit speed. Hussain and Zaman[2] distinguished two types of jet instabilities, namely, the shear-layer mode and the preferred mode. The shear-layer mode arises from the instability of the initial shear layer where the unstable frequency scales with the shear-layer thickness, while the preferred model is a global instability of the entire jet column where the unstable frequency scales with the jet diameter. Extensive studies of instability characteristics have been reported on both axisymmetric and plane jets with thin exit shear layers (see, for example, Hussain and Zaman;[2] Foss and Korschelt[3]), each of which exhibits the shear-layer mode as well as the preferred mode. However, recent studies by Petersen and Samet[4] have shown both experimentally and numerically that the preferred mode is a shear-layer instability and scales with local shear-layer thickness.

Theoretical and numerical studies of instability characteristics of axisymmetric jets with parabolic exit velocity profiles (see, for example, Batchelor and Gill;[5] Kambe[6]) have shown that such a jet is stable against axisymmetric disturbance but unstable against azimuthal disturbance. However, complementary experimental data are lacking. Numerical and experimental studies of tube jets have been mainly concentrated on the development of the velocity profiles with downstream distance and on the transition from laminar to turbulent flow (see, for example, Tucker and Islam[7]). For a tube jet with a fully developed laminar exit condition, the exit velocity profile is parabolic; consequently, the shear layer is thick, and there is only one relevant length scale, namely, the tube diameter. On the other hand, if the exit condition from a tube jet is turbulent, the shear layer is thin; consequently, there are two relevant length scales, namely, the thickness of the exit shear layer and the tube diameter for the jet column. The objective of this study was to determine the preferred mode of a tube jet for fully developed laminar and turbulent exit conditions.

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Experimental conditions

In this study, three tubes with diameter (D) 3.18 mm, 6.35 mm, and 12.7 mm and the corresponding length/diameter ratios of 2304, 1152, and 576 were used. Compressed air was supplied through an air filter, a pressure regulator that adjusted the jet exit speed, and a plenum chamber. The experiments covered both fully developed laminar and turbulent exit conditions with Reynolds numbers ranging from 200 to 20,000. A single 4 μm tungsten hot-wire operated at an overheat ratio of 1.5 with a DISA 55M constant temperature anemometer, and a linearizer was used to obtain the mean streamwise velocity and turbulent intensity. Data acquisition and probe traverses were performed on-line with a Masscomp computer. Power spectra of the streamwise velocity fluctuations were obtained using an FFT signal analyzer (Ono Sokki CF-920).

Results and discussion

Fully developed laminar exit condition

The rms streamwise velocity fluctuation at the jet exit for all test conditions is less than 0.3% of the centerline velocity. The mean velocity profiles at $x/D=0.5$ from the exit for various Reynolds numbers (based on average jet exit speed U_e and the tube diameter) and tubes are shown in Figure 1. The results compare well with a parabolic profile, thus indicating that fully developed laminar exit conditions have been attained at the jet exit.

Power spectra of the streamwise velocity fluctuation u' for the 3.18 mm tube at location ($x/D=15$, $r/D=0.3$) are shown in Figure 2 for various Reynolds numbers. The spectral humps

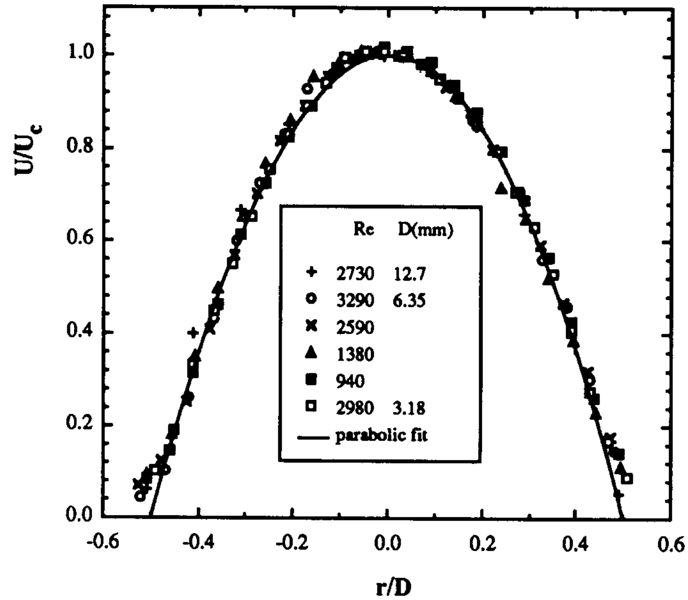

Figure 1 Mean velocity profiles at $x/D=0.5$ from jet exit for laminar exit conditions (U_c is the centerline velocity and r is the radial distance)

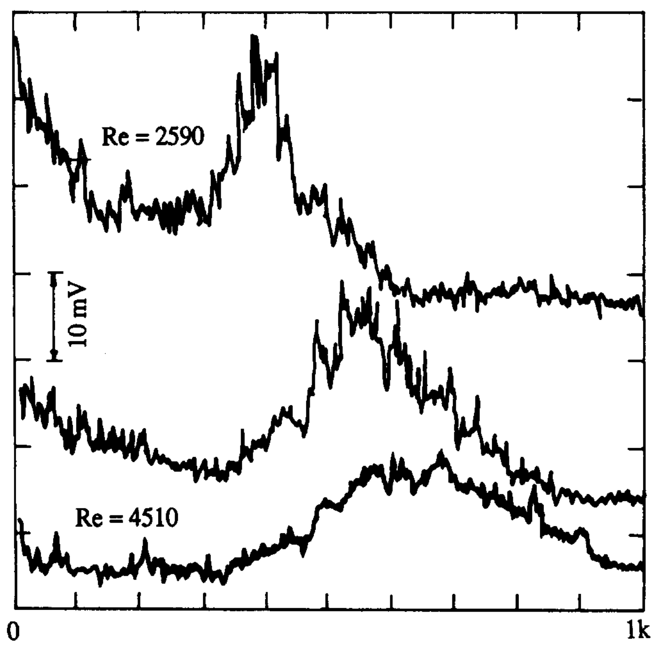

Figure 2 u' spectra at ($x/D=15$, $r/D=0.3$) for a 3.18 mm tube

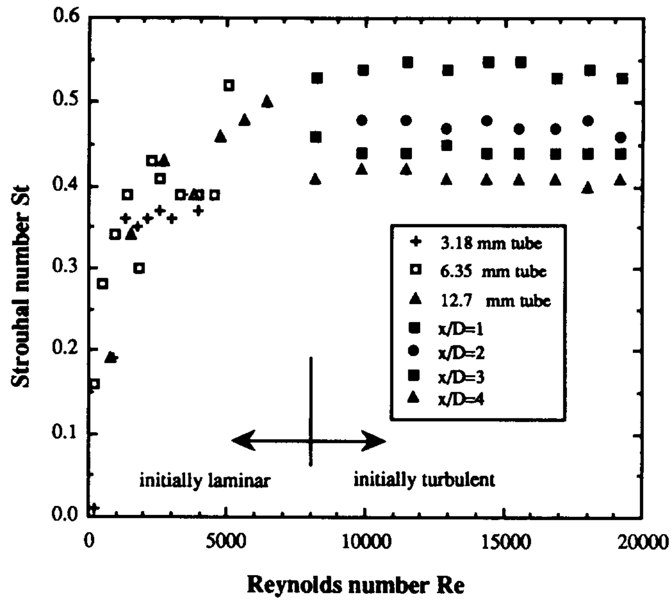

Figure 3 Variation of St with Re

in Figure 2 correspond to energetic instability waves. Though not shown here, it has been found that the mean frequency of the spectral hump is independent of radial locations but decreases with increasing streamwise distance x. Consequently, the preferred mode for a tube jet with fully developed laminar exit condition is determined from the mean frequency of the spectral hump obtained at the end of the laminar core, where the centerline velocity has decreased to 95% of its value at the jet exit.

The preferred mode for a tube jet is expressed as a Strouhal number St (based on U_e and D), which is determined from the preferred frequency for different tube diameters and Reynolds numbers. As shown in Figure 3, St increases with Re and appears to approach an asymptotic value of 0.5.

Fully developed turbulent exit condition

The mean velocity profiles at $0.25D$ from the exit of a 12.7 mm tube are plotted in Figure 4 for various Reynolds numbers, showing reasonable agreement with the 1/7th power-law profile. Figure 5 shows the development of the mean streamwise velocity profiles with downstream distance for this jet for a Reynolds number Re = 14,390, while the corresponding streamwise turbulent intensity profiles are shown in Figure 6.

Typical power spectra of u' at the centerline are shown in Figure 7 for Re = 19,210 and various streamwise distances x/D. By $x/D=5$, the unstable frequency cannot be discerned. Though not shown, the preferred frequency of the spectral hump for a fully developed turbulent exit condition is dependent on the

Notation

D	Tube diameter
f	Frequency (Hz)
Re	Reynolds number, U_eD/ν
r	Radial distance
St	fD/U_e, Strouhal number
U	Mean streamwise velocity
U_c	Jet centerline velocity
U_e	Average jet exit velocity
u'	Root-mean-square streamwise turbulent velocity
x	Streamwise distance measured from the jet exit

Greek symbols

ν	Kinematic viscosity

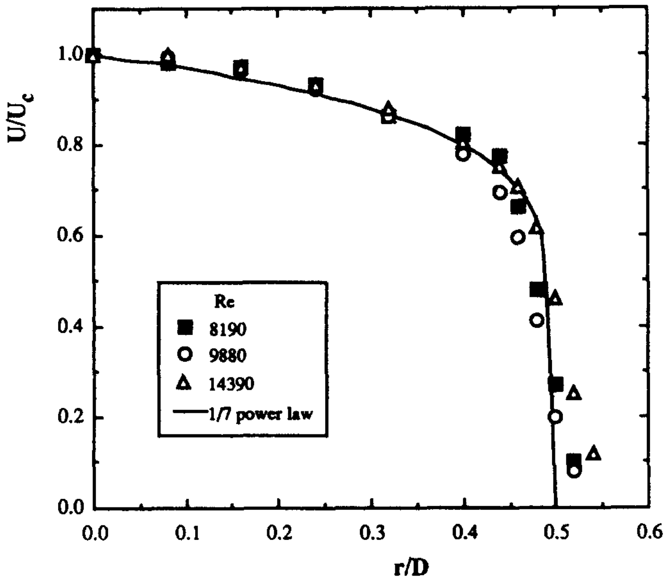

Figure 4 Mean velocity profiles at $x/D = 0.25$ from jet exit

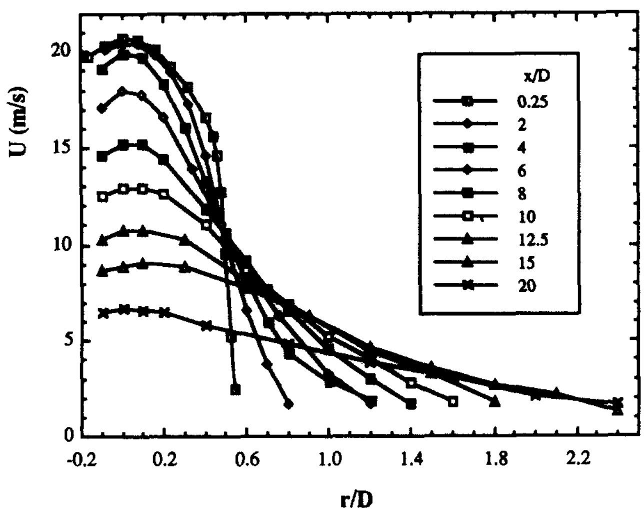

Figure 5 Development of mean streamwise velocity profiles for various streamwise distances for Re = 14,390

radial location. The preferred frequencies, expressed as St, for various Re and x/D have been determined from the mean frequencies of the spectral humps at the centerline of the jet and are plotted in Figure 3 for comparisons with laminar exit conditions. It can be seen from Figure 3 that at a given x/D, St is virtually independent of Re. If the preferred mode is determined at the end of the turbulent core where the centerline velocity is 95% of the exit velocity (and in this case, at $x/D = 4$), St attains a value of about 0.4, which is consistent with results reported in the literature (for example, Hussain and Zaman[2]).

Conclusions

The preferred mode of a tube jet has been determined in terms of Strouhal number St (based on average jet exit velocity and tube diameter). For fully developed laminar exit conditions, St increases with Reynolds number Re and appears to approach an asymptotic value of 0.5, while for fully developed turbulent exit conditions, St is independent of Re and attains a value of about 0.4.

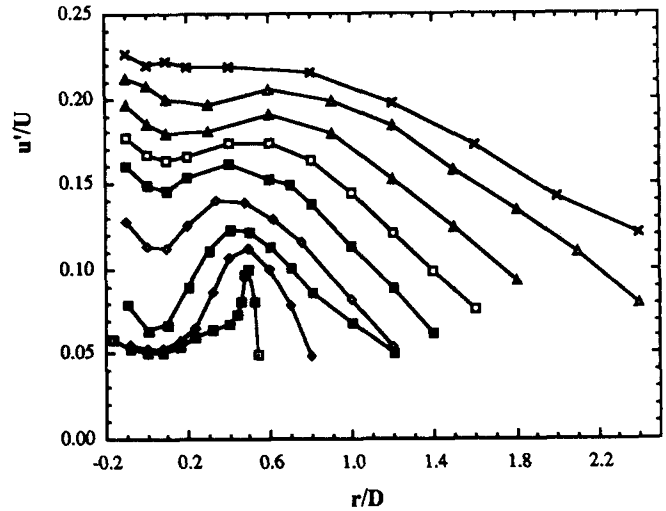

Figure 6 Development of mean streamwise turbulence intensity profiles for various streamwise distances for Re = 14,390 (symbols are the same as in Figure 5)

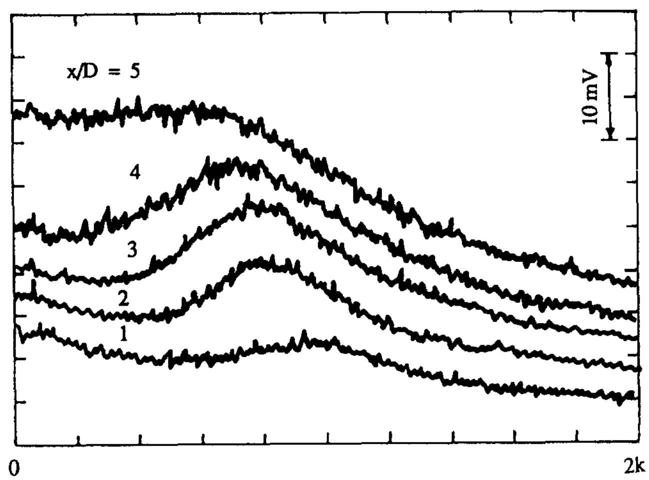

Figure 7 u' spectra at centerline of jet for Re = 19,210

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