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Near Field of a Coaxial Jet With and Without Axial Excitation

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An experimental study was undertaken to determine the effect of an annular jet on the near-field vortex structure and dynamics of an incompressible axisymmetric jet issuing into a quiescent ambient fluid. The effect of varying the velocity ratio between the two streams was investigated for a single nozzle exit area ratio, a single core flow Reynolds number, and uniform density. A thin laser sheet was used to illuminate the flow for instantaneous photographs of natural and axially excited flow. Natural jet evolution results indicated the initial vortex development in the shear layers occurred independently, but the large-scale structures in the outer layer ultimately controlled the core flow. Axial excitation of the annular flow demonstrated a strong coupling between the large-scale structures in the outer layer and the evolution of the inner layer. Core flow axial excitation produced periodic structures in the inner layer but did not have a significant effect on the evolution of the outer layer.

Nomenclature

D	= jet exit diameter
f	= forcing frequency
Re	= Reynolds number, UD/ν
St_D	= Strouhal number, fD/U
U	= mean nozzle exit velocity
u'	= rms axial velocity
λ	= structure wavelength
ν	= kinematic viscosity

Subscripts

i	= inner or core flow
o	= outer or annular flow

Introduction

It is well known that the near field of circular jets is dominated by vortex rings whose interactions govern the growth, entrainment, and mixing in the jet (e.g., Crow and Champagne[1]). Controlled perturbations from acoustic or other sources can cause major changes in the overall behavior of the jet by governing the vortex patterns and dynamics in the near-field jet shear layer. There have been numerous investigations into the behavior of single jets under controlled excitation with a significant amount of work in the last 25 years. These investigations have included controlled excitation of the axial and/or helical jet mode and have led to widely varying jet characteristics (e.g., controlled vortex mergings,[2] bifurcating jets,[3,4] blooming jets,[4] etc.).

Coaxial jets in which a central round jet is surrounded by an annular jet at a different speed have not received as much attention. Coaxial jets are common in many applications, including, most notably, pulverized coal combustion, jet ejectors, and aircraft propulsion. It is not well known what effect an additional annular stream has on the near-field vortex structure and dynamics of the otherwise axisymmetric jet and what effect controlled excitations can have on the near-field behavior of the coaxial jet.

There are several fundamental differences between a single axisymmetric jet and a coaxial jet exhausting into quiescent surroundings. Figure 1 shows a typical coaxial jet exit velocity profile. The shear layer that develops between the annular flow and the quiescent surroundings, termed the "outer layer," is similar to the single jet in that only one sign of vorticity is present in the shear layer. For the shear layer that develops between the annular flow and the core flow, termed the "inner layer," there are two signs of vorticity merging in the shear layer due to the viscous boundary layers on both sides of the inner nozzle. This velocity profile can be considered as a superposition of a wake profile and a shear layer profile and thus is expected to admit an instability that is related in some way to wake and shear layer instabilities. For instance, if the annular flow and core flow have equal velocities, then the wake instability should prevail, whereas in the limit of U_o/U_i getting very large or very small, the shear layer instability should dominate. The ultimate shear layer structure, therefore, should be a function of the velocity jump across the inner layer.

Early coaxial jet experiments measured the time-averaged characteristics of the flowfield, including mean velocity, static pressure, turbulence intensity, and shear stress.[5–7] These investigations provided necessary flowfield data and found several important characteristics of coaxial jets. In particular, Champagne and Wygnanski[6] found that the annular potential core length was independent from the velocity ratio but the inner core length depended strongly on the velocity ratio as well as the area ratio. However, these earlier investigations did not explain the observed phenomena in terms of the near-field vortex structure and their interactions.

Several investigations have attempted to explain the near-field behavior of coaxial jets and annular jets in terms of the vortex structures in the two mixing layers using velocity and pressure measurements.[8–13] The authors concluded that there are two trains of vortex rings in the outer and inner mixing regions. They found that the outer structures behaved similarly to those found in single jets and were observed over the entire velocity ratio range investigated. The inner structure characteristics depended on the jet ve-

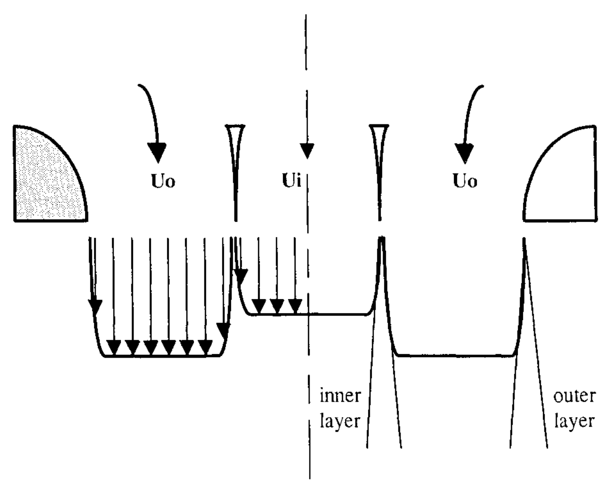

Fig. 1 Typical coaxial velocity profile with quiescent surroundings.

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locity ratio, with limiting cases of an annular jet for large U_o/U_i and a single jet for small U_o/U_i.

Most recently, Dahm et al.[14] investigated the near-field vortex structure and dynamics of a coaxial, naturally developing jet with varying velocity ratios. They referred to the vortex patterns in the inner layer as "wake-like" if the patterns involved vorticity of opposing signs and "shear-layer-like" if the patterns involved only one sign of vorticity. The coaxial jet near-field vortical structures in the inner and outer layers did not develop independently. There was a strong "coupling" between the two layers. The near-field vortex structure and dynamics were found to be functions of the velocity ratio and the absolute velocities of the two streams. Their nozzle exit geometry consisted of two concentrically oriented nozzles with an exit area ratio of 0.94 (diameter ratio of 1.40), and the close proximity of the outer layer might have contributed to the strong coupling between the layers. Furthermore, the question still remains as to the effectiveness of plane wave excitation on the near-field vortex structure and dynamics.

This study examines the near-field structure of a coaxial jet as a function of velocity ratio for a single nozzle exit area ratio where the annular width is equal to the core flow diameter. We also examine the effectiveness of single frequency axial acoustic forcing in controlling the near-field structure. A simple extension of single jet plane wave excitation to the coaxial jet is investigated for the two streams. The extension involves assuming the jet is a single jet when determining outer layer excitation frequencies and applying a linear velocity correction to the inner layer when determining the core flow excitation frequency. The results reported here are instantaneous flow visualizations for both axially forced and unforced flow.

Experimental Facility

Experiments were conducted in the coaxial jet test facility shown in Fig. 2. Compressed air was supplied to the core and an-

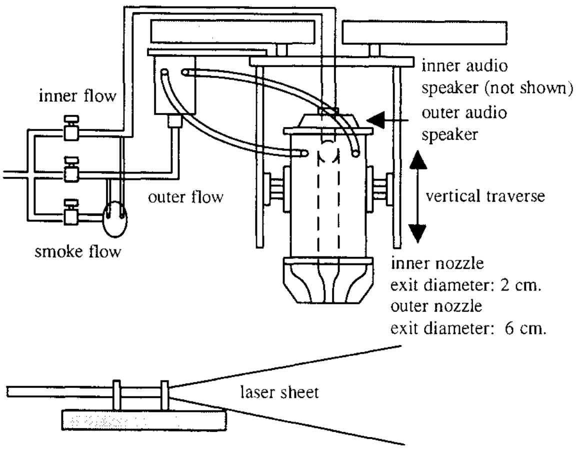

Fig. 2 Coaxial jet test facility.

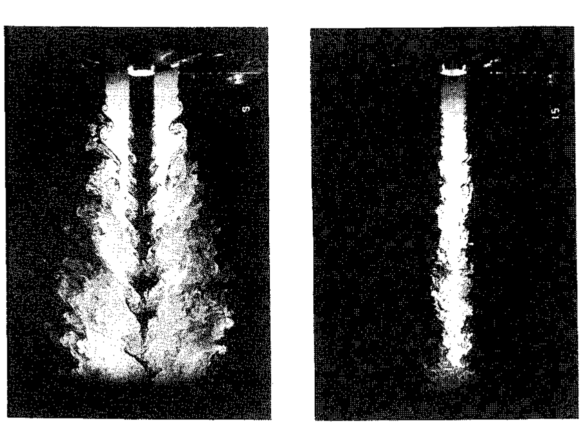

Fig. 3 $U_o/U_i = 0.55$, $U_i = 10$ **m/s, natural.**

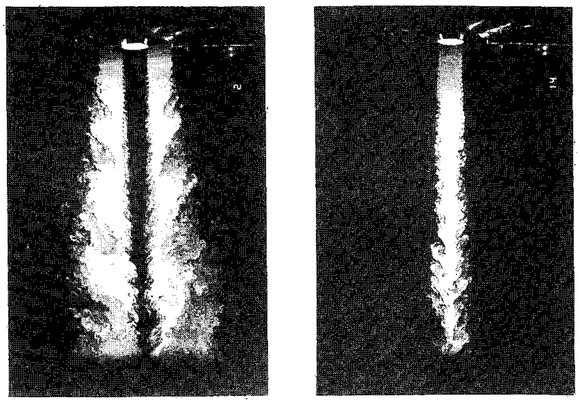

Fig. 4 $U_o/U_i = 0.71$, $U_i = 10$ **m/s, natural.**

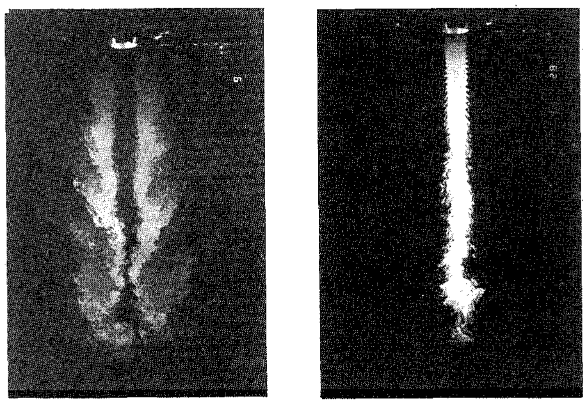

Fig. 5 $U_o/U_i = 1.23$, $U_i = 10$ **m/s, natural.**

nular plena through independently metered air lines. The coaxial jet issued into the quiescent ambient fluid through concentrically oriented axisymmetric round nozzles with contoured walls and coplanar exits. The core flow was supplied from a 5-cm diameter primary plenum chamber exiting through a 6.45:1 area ratio nozzle with a 2-cm exit diameter. The annular plenum chamber had a cross-sectional area of 158 cm^2, and the annular flow discharged through a 6.30:1 area ratio nozzle with a 6-cm exit diameter. The contoured nozzle walls were fifth-order polynomial curve fits with zero slope and curvature specified at the inlet and exit. The core nozzle had a knife-edge exit boundary condition resulting from a 15-deg chamfer of the 1.3-mm exit wall thickness that yielded an annular width of 2 cm. The resulting exit annular to core diameter ratio was 3, and the annular to core area ratio was 8.

A Yamaha YCS500 4.5-in.-diam 4-Ω audio speaker and a Draco 8.0-in. 4-Ω audio speaker were located on top of the core and annular plenum chambers, respectively. The acoustic drivers could be used to supply either flow with periodic axial excitations to control the resulting vortex patterns in the jet shear layers. An IBM XT computer with a National Instruments DT 2801 series board was used to supply either acoustic driver with the periodic waveform. The computer-generated waveforms were low pass filtered and amplified before being sent to the drivers. The turbulence intensities for each frequency and amplification were measured at the exit plane with a TSI-1210 single hot-wire probe and a TSI IFA-100 bridge and are given with the results for each photograph.

A third pressurized air line was used for flow visualization. Cigarette smoke was used in all of the experiments as the flow tracer. Smoke could be seeded into the bulk flow of either jet. Flow illumination was provided by a pulsed 10-W copper vapor laser formed into a 1-mm-thick and 24-cm-long vertical sheet. Instantaneous photographs were acquired by triggering the laser, so a single 30-ns laser pulse occured while the 35-mm camera shutter was open.

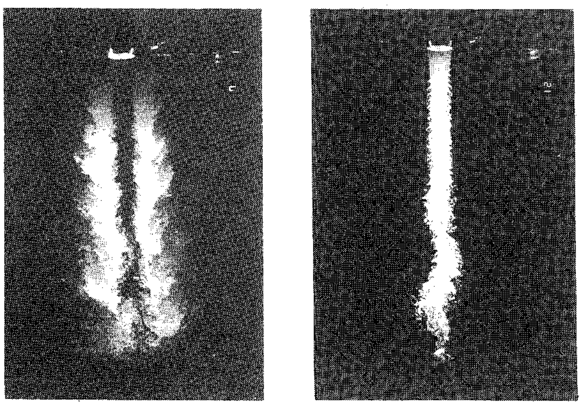

Fig. 6 U_o/U_i **= 1.45,** U_i **= 10 m/s, natural.**

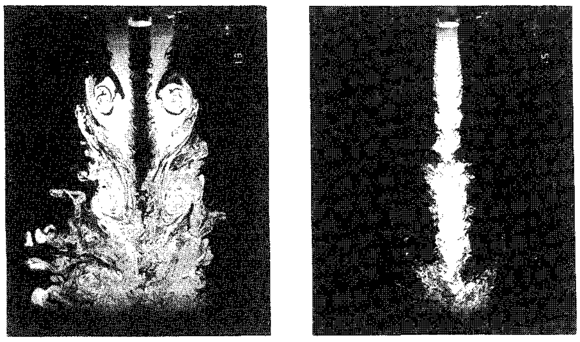

Fig. 7 $U_o/U_i = 0.55$**,** U_i **= 10 m/s,** f_o **= 48 Hz,** $St_{Do} = 0.53$**,** $u'_o/U_o = 0.18$**.**

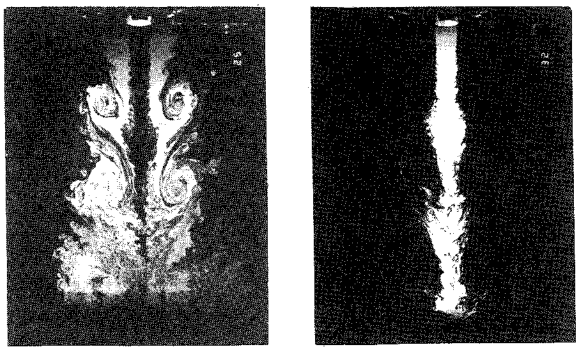

Fig. 8 $U_o/U_i = 0.71$**,** U_i **= 10 m/s,** f_o **= 64 Hz,** $St_{Do} = 0.52$**,** $u'_o/U_o = 0.15$**.**

Results and Discussion

Experiments were conducted for four velocity ratios U_o/U_i equal to 0.55, 0.71, 1.23, and 1.45. The inner jet velocity U_i was held fixed at 10 m/s in all of the experiments giving a core flow Reynolds number Re_i of 13×10^5. For the natural jet flows, the turbulence intensities at the exit plane were $u'_i/U_i = 0.008$ and $u'_o/U_o = 0.013$. The figures for the forced flow contain the corresponding turbulence intensities at the exit plane. All of the flow figures include side-by-side images of the flowfield with annular flow seeding on the left-hand side and core flow seeding on the right-hand side. The 24-cm-long laser sheet gave a four annular jet diameter region of illumination. It is important to note that each image represents the instantaneous flowfield but not necessarily the same phase in the jet development.

Natural Jet Development

Figures 3–6 illustrate the natural jet development for the four velocity ratios. The outer layer in all of the figures appears to develop like a single jet. It admits an axisymmetric instability that rolls up and appears to remain axisymmetric over the four outer jet diameters of illumination. For the velocity ratios investigated, the annular structures appear to have a constant wavelength that leads us to conclude that the outer layer behaves independently of the inner layer. A simple application of single jet control strategies would therefore seem to apply to the outer shear layer. Furthermore, the annular potential core appears to persist for approximately three outer jet diameters by which point the large-scale vortex rings in the outer layer have filled the entire width of the annular flow.

The inner layer, on the other hand, appears to depend on the velocity ratio. For U_o/U_i equal to 0.55 in Fig. 3, the velocity jump across each shear layer has the same sign and approximately the same magnitude. The inner layer admits a high-frequency, short-wavelength instability that persists for approximately three inner jet diameters where successive pairings or collective interactions

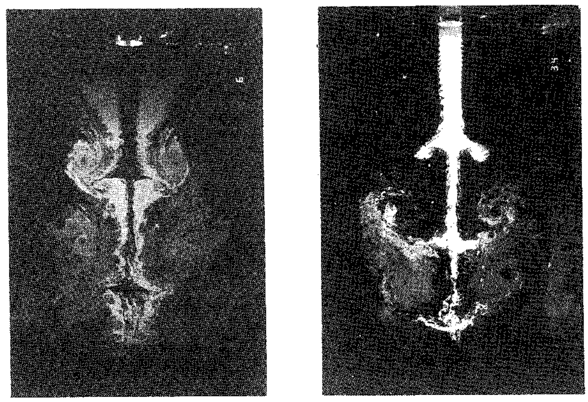

Fig. 9 $U_o/U_i = 1.23$**,** U_i **= 10 m/s,** f_o **= 104 Hz,** $St_{Do} = 0.50$**,** $u'_o/U_o = 0.15$**.**

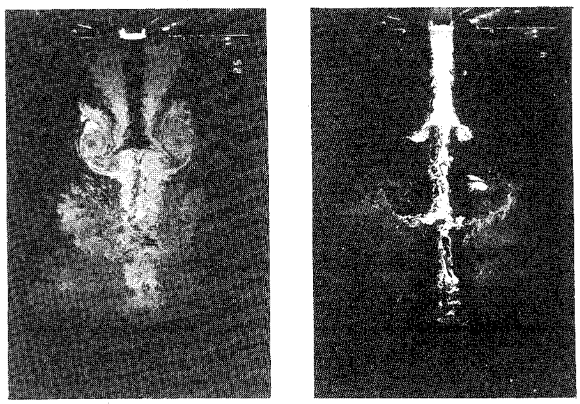

Fig. 10 $U_o/U_i = 1.45$**,** U_i **= 10 m/s,** f_o **= 125 Hz,** $St_{Do} = 0.49$**,** $u'_o/U_o = 0.19$**.**

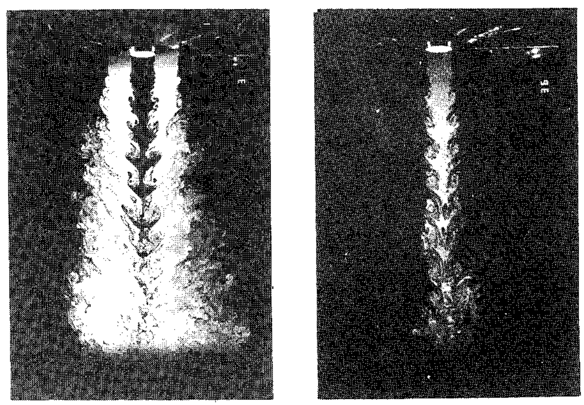

Fig. 11 $U_o/U_i = 0.55$**,** U_i **= 10 m/s,** f_i **= 375 Hz,** $St_{Di} = 0.75$**,** $u'_i/U_i =$ **0.052.**

give rise to a longer wavelength structure. This second structure is similar in size and spacing to the axisymmetric structure found in simple jets. However, the translation speed of the vortex rings, which is approximately the average of the inner and outer jet velocities, is much faster. The second structure seems to survive for another three inner jet diameters where the outer layer large-scale structures disrupt any further development of the inner flow coherent structures.

For U_o/U_i equal to 0.71 (Fig. 4), the velocity jumps across the shear layers still have the same sign but different magnitudes. The high-frequency instability appears again and seems to persist for a greater axial distance before forming the lower-frequency structure. This delay of the larger-scale structures in the inner flow allows the potential core of the inner flow to extend further downstream when compared with U_o/U_i equal to 0.55. Again, the outer layer disrupts any further inner layer development by the end of the illuminated region.

For U_o/U_i equal to 1.23 (Fig. 5) and 1.45 (Fig. 6), the velocity jumps across the shear layers now have opposite signs and different magnitudes. Note that the sign of the inner layer vorticity is reversed and the vortices roll into the core flow. For velocity ratios greater than unity, the high-frequency instability exists, but the annular flow seems to inhibit the formation of lower-frequency structures. The annular flow appears to dominate the inner flow by approximately four inner jet diameters. This domination includes a modulation of the inner layer in response to the large-scale structures in the outer layer. Furthermore, because of the absence of the large-scale structures in the inner layer, the potential core of the inner flow appears to be extended although it loses axisymmetry. Figures 5 and 6 suggest that the inner shear layer has developed a long wavelength helical mode. However, the apparent meandering of the inner jet core may also be caused by a helical mode in the outer jet.

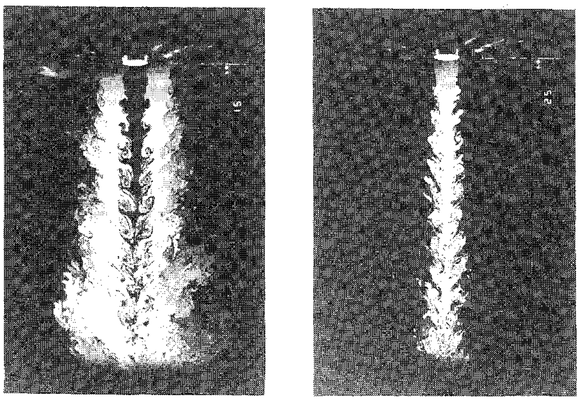

Fig. 12 $U_o/U_i = 0.71$, $U_i = 10$ m/s, $f_i = 437$ Hz, $St_{Di} = 0.84$, $u_i'/U_i = 0.033$.

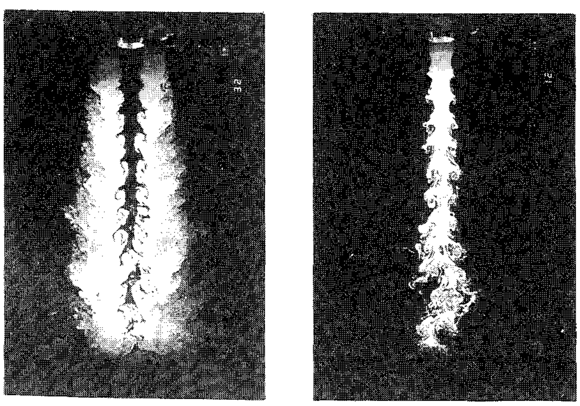

Fig. 13 $U_o/U_i = 1.23$, $U_i = 10$ m/s, $f_i = 562$ Hz, $St_{Di} = 1.11$, $u_i'/U_i = 0.045$.

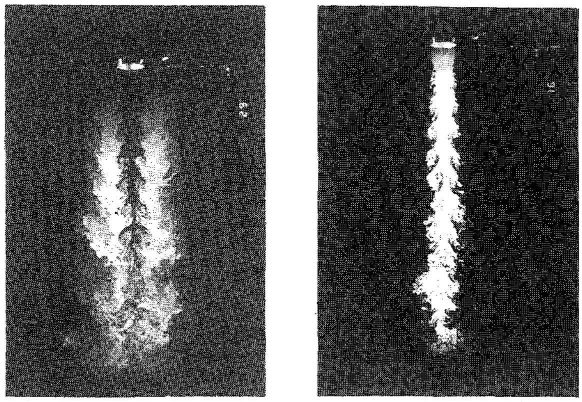

Fig. 14 $U_o/U_i = 1.45$, $U_i = 10$ m/s, $f_i = 625$ Hz, $St_{Di} = 1.18$, $u_i'/U_i = 0.022$.

Axially Excited Flow

The natural jet studies led to the conclusion that the extension of single frequency forcing strategies to the outer layer would be simple, but the effect of outer layer forcing on the inner layer was not known. Figures 7–10 contain axially forced images where the outer layer is excited at a frequency corresponding to a Strouhal number St_{Do} of approximately 0.5. Note that the axial fluctuations are also applied to the inner layer via the boundary layer on the outside of the inner nozzle.

The technique used to select the amplitude of the excitation was to strobe the laser at the forcing frequency and incrementally increase the amplitude until a well-defined vortex core appeared. This method was rather subjective as evidenced by the wide variation of the forcing intensities in the figures. A qualitative comparison of photographs led us to conclude that there was a "threshold" of forcing intensity at the exit plane to obtain our well-defined vortex cores which corresponds to approximately $u_i'/U_i = 0.03$ and $u_o'/U_o = 0.15$.

The annular flow behaves as expected; namely periodic axisymmetric vortex rings are formed at the forcing frequency. In all of the cases, the extent of the annular potential core has been reduced to approximately three annular widths due to the rapid growth of the large-scale vortices in the outer layer. The spreading rate of the jets has also increased. The effect of these large-scale structures on the inner layer is significant.

For U_o/U_i equal to 0.55 (Fig. 7), the inner layer initially develops similarly to the natural case but quickly deforms due to the outer large-scale structures. By five inner jet diameters, the outer layer structures have redistributed the core flow in the regions between the outer layer vortices, terminating any further development of the inner layer structures. Furthermore, this redistribution has reduced the inner flow potential core to approximately five inner jet diameters.

The inner flow for U_o/U_i equal to 0.71 (Fig. 8) responds similarly to the lower velocity ratio case. Again, the outer layer structures redistribute the core flow in the regions between vortex rings by five inner jet diameters, and the inner potential core has been reduced because of this core flow redistribution.

As the velocity ratio exceeds unity, the outer layer structures seem to completely control the motions of the core flow (Figs. 9 and 10). By four inner jet diameters, the core flow has been rearranged into a "treelike" structure where the outward moving flow in the outer layer vortices pulls the core flow outward with the remaining core flow located in the high strain rate regions between outer layer vortex rings. Evidence of this is seen in the right-hand side of Figs. 9 and 10 where the inner flow seed is entrained in the outer layer structures.

Although the natural jet images revealed a significant amount of inner layer structure at a very small wavelength, there was sufficient structure at a wavelength corresponding to a "shear layer" instability (at least for the velocity ratios less than 1) that a simple extension of a single jet forcing strategy was applied. For inner layer axial excitation, a translational velocity correction was used that accounted for the "true" convective velocity of the vortex rings. The forcing frequency was selected to maintain a constant inner layer structure wavelength equal to 2 cm, and assuming the structures translate at the average velocity U_{ave}, of the two streams where

$$f_i = U_{\text{ave}}/\lambda$$

A check of the assumption that the structures translate at the average stream velocity can be made by comparing the actual structure wavelengths in the photographs.

Figures 11-14 contain photographs for plane wave excitations of the core flow at frequencies corresponding to typical shear layer instabilities. When the left-hand sides of Figs. 11–14 are compared with the corresponding natural jet images in Figs. 3–6, inner layer forcing does not appear to have a significant effect on the outer layer development. As was the case with the natural jet, the outer layer appears to admit an axisymmetric instability that develops over the four outer jet diameters of illumination.

The inner layer responds to the axial forcing similarly to a single jet. The inner layer does in fact admit a frequency corresponding to an axisymmetric shear layer instability giving rise to vortices of similar size and shape to a single jet, but the sign of vorticity is a function of the velocity jump across the shear layer. The constant approximate structure wavelength of 2 cm shown in the right-hand sides of Figs. 11–14 shows that the structure translation speed is approximately equal to the average of the stream velocities as assumed. As was the case with the outer layer when forced, the inner potential core is seemingly reduced for all velocity ratios because of the coherent structures in the inner layer.

For velocity ratios less than 1 (Figs. 11 and 12), the high-frequency disturbance gives rise to the lower-frequency disturbance corresponding to the axisymmetric shear layer instability within the first three inner jet diameters where the high-frequency disturbance is no longer visible. Inner layer structures remain coherent for at least five inner jet diameters before breaking down.

For velocity ratios greater than one (Figs. 13 and 14), the high-frequency disturbance again appears before the formation of the lower-frequency structure. Note that the lower-frequency structures do not seem to appear in the natural jet images for velocity ratios greater than 1. In the case of U_o/U_i equal to 1.23, the high-frequency structure no longer appears after the first three jet diameters as was the case for the velocity ratios less than one. However, for U_o/U_i equal to 1.45, the high-frequency disturbances seem to be superimposed on the lower-frequency structures. This is most likely due to the turbulence intensity being below the threshold.

Conclusions

Flow visualization studies of a coaxial jet exhausting into quiescent surroundings show widely varying near-field vortex structure and dynamics depending on the velocity ratio between the two jets and plane wave excitation. Initial vortex development in the shear layers occurs independently, but the large-scale structures in the outer layer ultimately "control" the inner flow. The extent of the inner potential core can be varied by controlling the inner layer structures. Inner layer structure wavelength and size are a function of the velocity ratio between the jets with a large amount of control provided through plane wave excitation. Despite the complex velocity profile of the inner layer, the inner layer admits a frequency corresponding to a simple extension of single jet shear layer instability, at least up to velocity ratios of 1.5. Core flow axial excitation does not have a significant effect on the evolution of the outer layer. Axial excitation of the annular flow produces large-scale outer layer structures similar to a single jet, and these structures provide a strong coupling between the outer and inner layers.

Acknowledgment

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