AIAA JOURNAL
Vol. 31, No. 3, March 1993

Mixing Enhancement Due to Global Oscillations in Jets with Annular Counterflow

P. J. Strykowski* and R. K. Wilcoxon†
University of Minnesota, Minneapolis, Minnesota 55455

A novel control technique is described which leads to the enhancement of mixing in axisymmetric jets. The approach relies on the self-excitability of the jet and does not require elaborate feedback control schemes or actuators. Self-excited global oscillations are established in the jet by applying suction to an annular cavity placed around the jet periphery. These oscillations are responsible for enhanced mixing between the jet and the surrounding fluid, and can be maintained at relatively low levels of counterflow. Furthermore, the global oscillations and increased mixing appear to be insensitive to the jet initial conditions. The present study included jet Reynolds numbers between 3.4×10^4 and 1.1×10^5 for initially laminar and turbulent separated shear layers. The study also examined the influence of nozzle design on jet mixing.

Introduction

THE response of axisymmetric jets to monochromatic external excitation is well documented. Crow and Champagne[1] were the first to systematically examine the influence of discrete-frequency forcing on the development of circular jets. They reported that jet mixing could be enhanced considerably if the forcing could be tuned to the natural instability modes, which scaled on the jet diameter. This so-called "preferred mode" was described as being the most dispersive in the jet, owing to the absence of vortex pairing and a corresponding maximum amplification at this frequency.

In the spirit of Crow and Champagne,[1] Zaman and Hussain[2] reexamined the jet response to monochromatic forcing and reported that a larger total amplification could be achieved if vortex pairing was encouraged at forcing frequencies above the preferred mode. Subsequent work by the same authors[3] revealed that jet mixing could be enhanced or suppressed depending on the forcing frequency. The jet response to forcing is complicated by the multiple length scales in the problem, namely, the jet diameter and the thickness of the separating shear layer. Consequently, the jet must be viewed as an "amplifier" to disturbances scaling on the shear layer thickness as well as those scaling on the jet diameter. Hence, a careful documentation of the jet initial conditions is required for a proper physical understanding of the mechanisms responsible for alterations in jet mixing.

The motivation behind this forcing study was the development of more efficient turbulent control schemes for jets operated under technologically relevant conditions, e.g., at high Reynolds and Mach numbers. For instance, recent experiments by Lepicovsky et al.[4] indicate that high-speed subsonic jets are relatively unaffected by large-amplitude monochromatic acoustic excitation. Some attempts have also been made to control jet development by employing sensor/actuator based feedback networks,[5-7] however, these control schemes appear to be limited to moderate and low Reynolds numbers. Hence, it appears that the energy input required to alter jet mixing using external forcing techniques will simply be too high to be of practical utility in the harsh environments encountered in most applications. Clearly, more robust control schemes need to be exploited if we hope to advance the design of high-speed mixing chambers.

The technique described in this paper is based on the principle that feedback of information is more efficient through the vorticity field itself, in comparison with feedback mechanisms which rely on the relatively weak coupling between acoustic and vorticity waves. The feedback loop is established by creating a counterflowing stream around the jet periphery. In principle, the counterflowing stream is used to set up the conditions of locally absolutely unstable flow in a finite region of the jet near field. If a sufficiently large region of the flow becomes absolutely unstable, we can anticipate the emergence of a self-excited global mode.[8] The aim of the present study was 1) to identify whether a global mode could be established in a jet with counterflow, and 2) to determine the effect of the global self-excitation on jet mixing.

Jet Facility

The nozzle configuration used to establish countercurrent mixing in the shear layers of an axisymmetric jet is shown in Fig. 1. Air is supplied to the inner nozzle from a variable-speed centrifugal blower, after passing through a flow management section including a diffuser, flow straighteners, screens, and an intermediate nozzle contraction. The air exhausts into the laboratory after encountering the 25:1 area contraction ratio inner nozzle producing the nominally uniform stream U_1; the streamwise velocity U_1 is defined as the value on the jet centerline in the nozzle exit plane. The jet diameter D in the nozzle exit plane is 2.54 cm. The jet was operated under both laminar and turbulent initial conditions. A

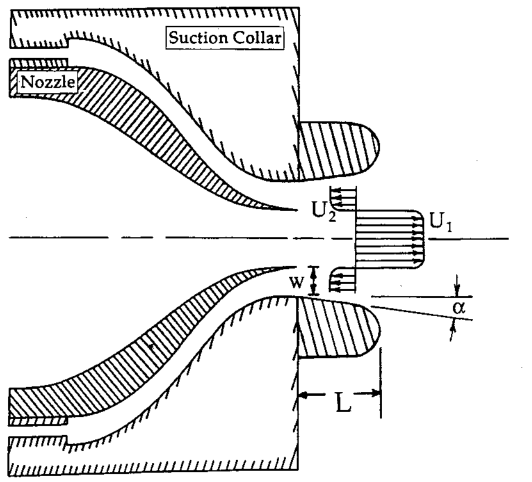

Fig. 1 Nozzle configuration used to establish counterflow in an axisymmetric jet

---

Presented as Paper 92-0538 at the AIAA 30th Aerospace Sciences Meeting, Reno, NV, Jan. 6–9, 1992; received Jan. 10, 1992; revision received July 2, 1992; accepted for publication July 6, 1992.

*Assistant Professor, Department of Mechanical Engineering. Member AIAA.

†Graduate Research Assistant, Department of Mechanical Engineering.

separating laminar shear layer was obtained using the nozzle configuration shown in Fig. 1, and a turbulent shear layer was achieved by introducing a boundary-layer tripping device upstream of the jet exit. The study included laminar flow conditions for forward velocities U_1 between 20 and 60 m/s corresponding to jet Reynolds numbers Re_D from 3.4×10^4 to 1.1×10^5. Turbulent flow was examined at a Reynolds number of 3.4×10^4.

Typical conditions for laminar flow measured in the nozzle exit plane produced turbulence intensities (streamwise velocity component) of less than 0.15% on the jet centerline and a maximum level of 1.5% in the separating shear layer. The streamwise mean velocity uniformity outside the boundary layers was better than 1%. The exiting velocity profile was very "top hat," the momentum thickness of the separated shear layer θ_o being much smaller than the jet diameter. The jet curvature D/θ_o was always greater than 230 under laminar conditions, which was found to be sufficiently large to neglect coupling between instability waves scaling on the shear layer thickness and those scaling on the jet diameter.[9,10]

A turbulent separating shear layer was established by placing a ring trip inside the nozzle. The ring was positioned 0.75D upstream of the nozzle exit and had a diameter of 1 mm, which was approximately equal to the undisturbed boundary-layer thickness at that location. The tripped boundary layer resulted in a slightly elevated centerline exit plane turbulence intensity of 0.2%, however the separating shear layer was highly disturbed with a turbulence intensity of 9.5%; no discrete peaks could be identified in the spectral distribution of the shear layer disturbances. The exiting jet curvature parameter under turbulent conditions was $D/\theta_o \approx 100$.

The counterflowing stream U_2 is created by placing a suction collar concentrically around the inner nozzle as shown in Fig. 1. A regenerative suction pump is connected to the collar and throttled with a bypass valve to control the speed of the reverse flow stream. The forward and reverse velocities U_1 and U_2 are defined in the exit plane of the inner nozzle. This is also the origin of the streamwise coordinate x, which is taken to be positive in the direction of U_1. The reverse stream velocity was obtained by measuring detailed velocity profiles with a hot wire introduced in the annular passageway through the collar wall. The velocity U_2 (which is negative in our coordinate frame) represents the average reverse velocity entering the annulus in the plane of the nozzle exit. The vacuum system accommodated reverse flow streams having a magnitude up to 20 m/s. An important control parameter in the problem is the velocity ratio defined as $-U_2/U_1$, which was varied between $0\leq -U_2U_1 \leq 0.5$. Operationally, the flow dependence on the velocity ratio was obtained by varying the suction velocity U_2 while holding the forward velocity U_1 fixed. (Additional discussion of the counterflowing jet facility can be found in Niccum[11] and Strykowski and Niccum.[12])

The nozzle geometry shown in Fig. 1 introduces a number of length scales which will undoubtedly influence the jet response. In addition to the jet diameter, important length scales include the extension collar length L, the annular slot width w, and the initial shear layer momentum thickness θ_o. The shape of the extension collar also imposes several constraints on the flow which will affect the nature of the reverse stream velocity profile. These include the divergence half-angle α and the outer radius of curvature of the collar. The present study was limited to an examination of the effect of L/D and D/θ_o on jet mixing. Consequently, w/D and α were held invariant throughout the study, having values of 0.5 and 7 deg, respectively. The selection of w/D and α was somewhat arbitrary, the former being chosen as the minimum value which did not appreciably affect the flowfield in the absence of counterflow, and the latter being a representative jet divergence angle from flow visualization.[4] Several extension collars between $0\leq L/D\leq 3$ were carefully machined to maintain the constant divergence half-angle of 7 deg and an outer radius of 1.27 cm at the end of the collar where the reverse flow enters the annulus. The jet curvature D/θ_o was uniquely determined by the fifth-order polynomial nozzle used and varied between 230 and 400 for the laminar flow conditions mentioned earlier. (The phenomena described in this paper depend both on the slot width w/D and collar divergence angle α, but detailed measurements involving these geometrical considerations are quite preliminary and are best postponed to a later time. However, a brief discussion of the effect of w/D is provided in the discussion and conclusion section of this paper.)

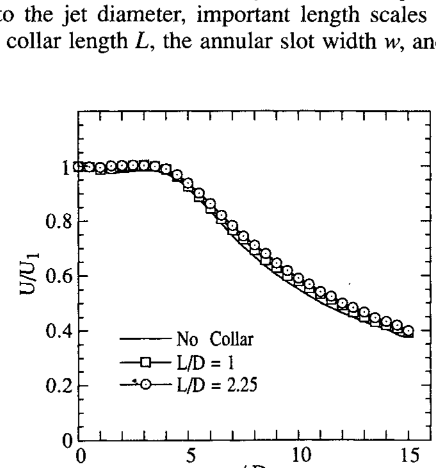

Fig. 2 Axial mean velocity profiles in the absence of suction at a Reynolds number of 3.4×10^4 in a jet with initially laminar shear layers.

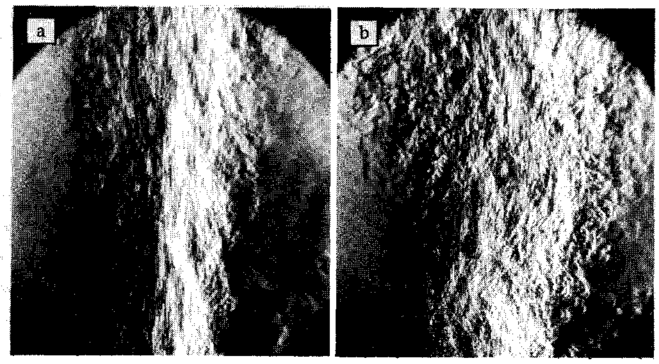

Fig. 3 Schlieren photographs of the jet side view at $Re_D=7.8\times10^4$: a) taken without reverse flow; and b) at a velocity ratio of $-U_2/U_1\approx0.35$. The streamwise extent of the images is from $2.25\leq x/D\leq 9$.

This research was motivated by our earlier findings[12,13] that self-excited oscillations could be observed in the shear layer of a circular jet when the conditions necessary for absolute instability were established in the jet near field. One of the limitations of that earlier work was that the self-excited oscillations scaled on the jet initial shear-layer thickness and, hence, were too high in frequency to directly affect the development of the jet column. In fact, the oscillations were at a frequency which inhibited vortex pairing in the jet shear layers and reduced jet mixing. We believe that the high-frequency oscillations were the consequence of creating only a small region downstream of the nozzle lip over which the flow was absolutely unstable. Consequently, during the course of this study, we set out to examine whether increasing the downstream extent of the absolutely unstable region using extension collars could be used to decrease the self-excited frequency, thereby effectively forcing the jet column and giving rise to enhanced mixing.

Before concluding our discussion on the counterflowing jet facility, a few remarks are warranted regarding the effect of the collar geometry on the mean velocity field in the absence of counterflow. In particular, to rule out the possibility that the Coanda effect was the principal mechanism responsible for the enhanced mixing, axial mean velocity data were obtained in the jet without reverse flow. Figure 2 shows axial jet profiles under laminar flow conditions at $Re_D=3.4\times10^4$ without a collar and for collar extensions of $L/D=1$ and 2.25. The data reveal a very weak dependence of jet mixing on collar length in the absence of counterflow. These variations are indeed small compared to the changes observed in the jet with counterflow, as shown in Figs. 5 and 7 of the next section. The profiles imply that entrainment is somewhat inhibited by the placement of longer extension collars on the nozzle, a result which is opposite to the trend expected if the Coanda effect were

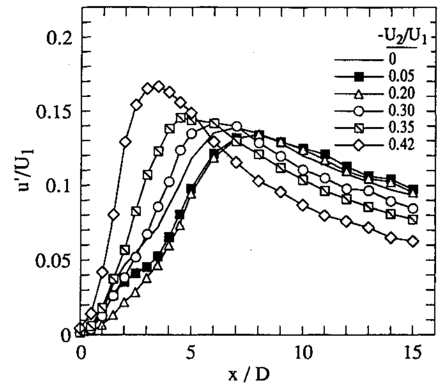

Fig. 4 Axial turbulence intensity profiles at $Re_D=3.4\times10^4$ in an initially laminar jet having $L/D=1$.

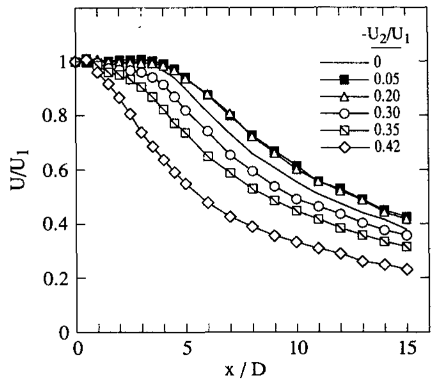

Fig. 5 Axial mean velocity profiles at $Re_D=3.4\times10^4$ in an initially laminar jet having $L/D=1$.

playing an important role in the problem. (Preliminary measurements indicate that the Coanda effect can become quite significant for narrower annular gaps and longer collars.)

Mixing Enhancement Using Counterflow

As an introduction to the effect of counterflow on the mixing of axisymmeric jets, schlieren photographs were taken of the side view of a jet at a Reynolds number of 7.8×10^4; the flowfield was made visible by seeding the jet with sulfur hexafluoride. The photograph in Fig. 3a shows the streamwise development of the jet in the absence of counterflow, which can be compared to a significant increase in the visual spreading of the jet in the photograph of Fig. 3b taken at a velocity ratio of $-U_2U_1 \approx 0.35$; in both photographs the jet was initially laminar with a collar extension of $L/D=2.25$. Although proper interpretation of the flow conditions in Fig. 3b requires the discussion to follow, we can state that the photograph is quite representative of the jet behavior we observe in the presence of sufficient counterflow.

To establish the basic relationship between jet mixing and the velocity ratio $-U_2/U_1$, axial turbulence intensity and mean velocity profiles were taken in the jet at several Reynolds numbers; both laminar and turbulent initial conditions were considered. In this section, we will limit our discussion to the effect of the jet initial conditions (i.e., D/θ_o and tripped vs untripped) on mixing. Consequently, the collar length was held fixed at $L/D=1$. Axial turbulence intensity profiles are shown in Fig. 4 for an initially laminar jet at a Reynolds number of 3.4×10^4 over a range of velocity ratios between 0 and 42%. (The turbulence intensity u' represents the rms intensity of the streamwise velocity component on the jet centerline.) The effect of counterflow can be most clearly seen by comparing the profiles to the case without suction, namely when $-U_2/U_1=0$. At low velocity ratios, the centerline disturbance levels are suppressed in the jet near field, but the trend is abruptly reversed near $-U_2/U_1=0.2$, leading to significant elevations in the jet fluctuation level at higher velocity ratios. Another important trend in the data is the upstream movement of the maximum turbulence intensity in the jet as the velocity ratio is increased above $-U_2/U_1=0.2$.

We anticipate that the elevated disturbance levels measured on the jet centerline at high velocity ratios reflect the passage of larger vortical disturbances than those present in the jet without counterflow. These large structures will undoubtedly be effective at entraining the surrounding fluid and result in a more rapid decay of the mean velocity on the jet axis. (Also see the discussion accompanying Fig. 12 regarding structure size.) The axial profiles in Fig. 5 support this description and illustrate the significant extent to which mixing can be enhanced using counterflow. (The mean velocity U represents the time average of the streamwise velocity component on the jet centerline.) To place these results in perspective with earlier forcing experiments, we compared the data in Fig. 5 with the measurements of Crow and Champagne.[1] Under optimal forcing conditions, they reported axial mean velocity data which approximately correspond to the present results at $-U_2/U_1=0.35$. Their measurements were made at a Reynolds number close to 10^5 and for an initially turbulent jet, but, as we will show in the discussion to follow, the mixing enhancement using counterflow is relatively insensitive to these details.

Before we continue, a few comments should be made regarding the observation at low velocity ratios that mixing can also be inhibited with counterflow. The mean velocity data in Fig. 5 are consistent with the suppressed turbulence levels shown in Fig. 4 at velocity ratios of 0.05 and 0.2, indicating smaller vortical structures in the jet shear layer and consequently less entrainment of the surrounding fluid. Earlier work[11-13] revealed that self-excitation of the jet shear layers very close to the nozzle lip was responsible for the turbulence suppression and reduced mixing in the jet. Although this phenomenon is interesting, it appears to be limited to relatively clean jets. We have not observed the suppression effects at significantly higher Reynolds numbers, or under initially turbulent conditions. The interested reader is referred to the preceding references and the work of Zaman and Hussain[3] for additional discussion of this effect.

The axial turbulence intensity profiles in Fig. 6 measured under tripped boundary-layer conditions display the same trends observed earlier in Fig. 4. In fact, a comparison of Figs. 4 and 6 reveals that equivalent peak turbulence levels occur at approximately the same velocity ratio. The turbulence suppression effect reported in the initially laminar jet was not evident in the presence of the trip ring because the shear-layer instability mechanisms were disrupted. The turbulence data of Fig. 6 together with the corresponding mean velocity data in Fig. 7 indicate that the jet response to counterflow is quite robust and relatively insensitive to the jet initial conditions. To test this observation further, we introduced a coarse screen in the jet exit plane which effectively disturbed the jet in the shear layer and core regions. The screen had a 49% open area ratio and a mesh length equivalent to $\approx D/20$. The

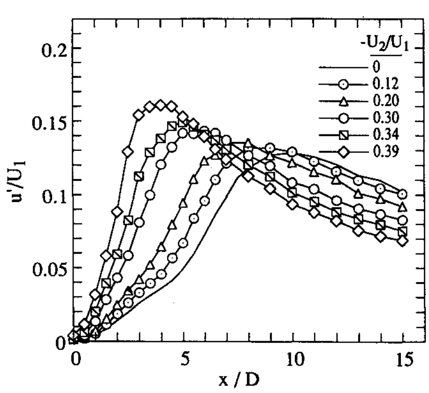

Fig. 6 Axial turbulence intensity profiles at $Re_D=3.4\times10^4$ in an initially turbulent jet having $L/D=1$.

centerline turbulence intensity measured without suction at $x/D=1$ was elevated from 0.15 to 1.5% by placement of the screen. Under the influence of the screen, we measured turbulence intensity and mean velocity profiles virtually identical to those presented in Figs. 6 and 7.

A summary of the jet response to initial conditions is provided in Fig. 8. The extent of mixing in the jet is represented by a single-point measurement of the centerline mean velocity at $x/D=5$. For velocity ratios below 15 to 20%, the jet displays some dependence on initial conditions, but these differences vanish at higher levels of reverse flow. Although detailed studies were not undertaken at all intermediate Reynolds numbers, the data in Fig. 8 provide convincing evidence that mixing enhancement is possible under a wide range of conditions using counterflow. Furthermore, these data suggest that the phenomena just reported are insensitive to jet curvature D/θ_o and independent of jet Reynolds number for velocity ratios above a critical value.

Jet Frequency Response

Power spectra of the streamwise velocity fluctuations were examined on the jet axis to obtain a more complete understanding of the time-averaged jet behavior described in the preceding section. The spectra presented below were acquired at a sampling rate of 4 kHz and averaged over 256 data records of 1024 points, providing a spectral resolution of ≈2 Hz. The streamwise evolution of the power spectral density was obtained at $Re_D=3.4\times10^4$ for an initially laminar jet. We again restrict our discussion to the collar extension having $L/D=1$.

Figure 9 shows typical spectra in the jet without counterflow. The spectra in Fig. 9 were obtained over the streamwise distance of $0.5\leq x/D\leq5$ which is essentially everywhere within the core of the jet (see, e.g., Fig. 2) and therefore reflect the potential flow oscillations imposed on the core by the vortical activity within the jet shear layers. Between the axial locations of $x/D=0.5$ and 3, a reduction in the dominant frequency by a factor of two can be observed, due to vortex pairing in the shear layer. Downstream of $x/D=3$, the dominant frequency continues to decrease due to the convective nature of the instability and the downstream evolution of the time-averaged flowfield. When the velocity ratio is elevated above a critical level, to be defined shortly, the streamwise spectral evolution in the jet is fundamentally altered. Figure 10 shows this development at $Re_D=3.4\times10^4$ for the velocity ratio of $-U_2/U_1=0.33$. The striking feature of Fig. 10 is the spatial invariance of the spectral distribution in the jet. The entire near field of the jet is excited by an unstable global mode acting at a "single" frequency. The amplitude of this unstable global mode increases with velocity ratio and effectively forces the jet, giving rise to the enhanced mixing observed earlier.

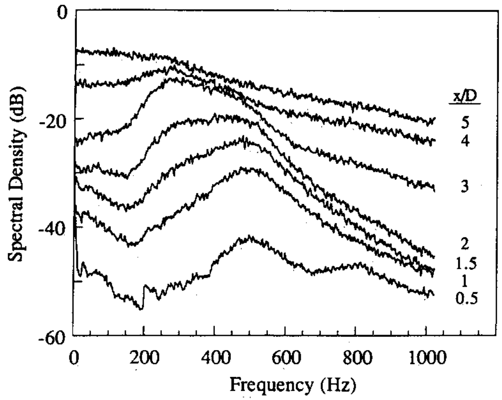

Fig. 9 Power spectral density in an initially laminar jet at $Re_D=3.4\times10^4$ without reverse flow. The collar length is $L/D=1$.

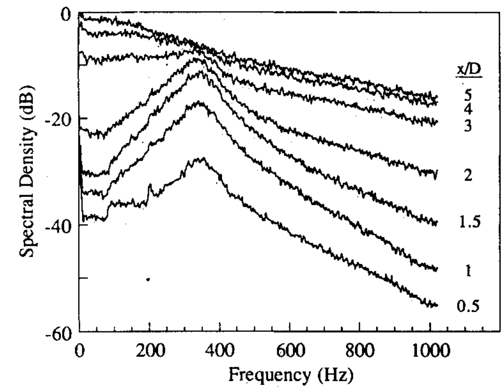

Fig. 10 Power spectral density in an initially laminar jet at $Re_D=3.4\times10^4$ at a velocity ratio of $-U_2/U_1=0.33$. The collar length is $L/D=1$.

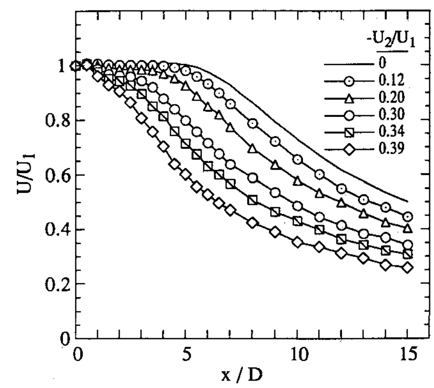

Fig. 7 Axial mean velocity profiles at $Re_D=3.4\times10^4$ in an initially turbulent jet having $L/D=1$.

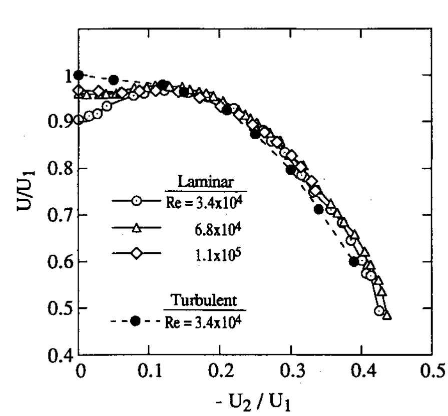

Fig. 8 Mean velocity measured on the jet centerline at $x/D=5$ for a collar extension $L/D=1$.

To identify the nature of the frequency scaling of the global mode in the jet, streamwise spectral records were also obtained at other Reynolds numbers between 3.4×10^4 and 1.1×10^5, and for laminar and turbulent initial conditions. We selected the dominant frequency f on the jet centerline at $x/D=1$ as being representative of the global instability. When the streamwise spectral distributions display spatial invariance, the global mode frequency can be measured with reasonable certainty anywhere within the jet near field. However, the strength of the oscillations are relatively weak in the nozzle exit plane ($x/D=0$) and become broadband soon after $x/D\approx2$. Consequently, we gathered the frequency data at $x/D=1$ where the global mode amplitude was significantly above the background disturbance level for all flow conditions reported here. At the lower velocity ratios where the spectral behavior varies spatially, the measurement at $x/D=1$ is representative of the local disturbances only.

The dominant frequency at $x/D=1$ was nondimensionalized with the jet diameter and the forward velocity in the jet exit plane forming the traditional Strouhal number fD/U_1. The frequency data is summarized in Fig. 11 for an extension collar of $L/D=1$. At low

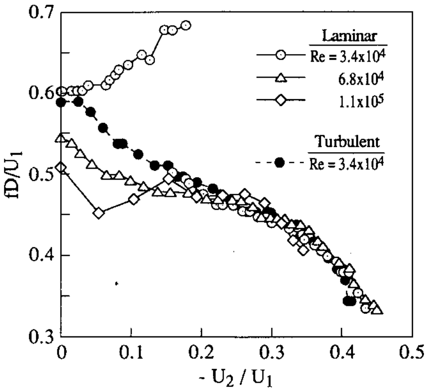

Fig. 11 Strouhal number measured at $x/D=1$ on the jet centerline for a collar extension of $L/D=1$.

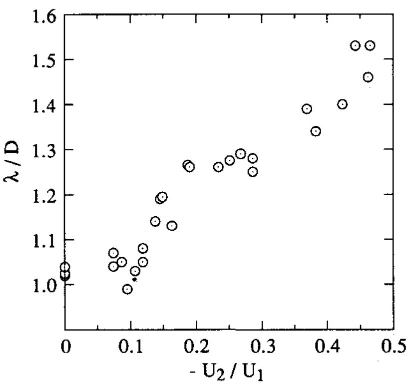

Fig. 12 Disturbance wavelength measured in the jet core at $Re_D=3.4\times10^4$ for a collar extension of $L/D=1$.

velocity ratios, the initially laminar jets are dominated by the shear layer vortex dynamics and scale with the initial shear layer momentum thickness θ_o and not the jet diameter. Consequently, our fixed observation point at $x/D=1$ will capture the shear layer activity at different stages of development. [A proper scaling of the shear layer region requires a normalization in the streamwise coordinate Rx/λ, where $R=(U_1-U_2)/(U_1+U_2)$ and λ is the disturbance wavelength; see Strykowski and Niccum[12] for more details.] Also note that the Strouhal number measured in the initially turbulent jet without suction does not correspond to the typical value reported in the literature of ≈0.35 because it is measured at $x/D=1$ and not at the end of the potential core where this information is usually obtained.

Streamwise spectral distributions were obtained for all laminar and turbulent flow conditions in a similar fashion to those represented in Fig. 10. Independent of initial conditions, these spectra were observed to be spatially invariant when the velocity ratio was increased above $\approx$20%. The data in Fig. 11 confirm that the global mode frequency at velocity ratios above $\approx$20% is independent of the jet curvature D/θ_o and the initial turbulence level of the jet shear layers. Hence, the frequency data in Fig. 11 can be used to define a critical velocity ratio $(-U_2/U_1)_{cr}\approx0.2$ separating those jets displaying spatial variations in spectral evolution (purely convectively unstable) and those characterized by a single dominant mode (globally unstable).

Although the data in Fig. 11 indicate that the global mode frequency is independent of D/θ_o at velocity ratios above 20%, the present study was not sufficiently exhaustive to determine the appropriate combination of length scales governing the instability. In fact, the data presented in the next section will show that the collar length L is at least as important as D in determining the nature of the instability. At this point the satisfactory collapse of the frequency data in Fig. 11 is simply a reflection of the fact that L, D, w, and the extension collar shape were held constant. The selection of U_1 to normalize the frequency was chosen over the average velocity $(U_1+U_2)/2$ or the difference velocity (U_1-U_2) to eliminate the influence of U_2 in both the abscissa and ordinate of the plot. At velocity ratios above 20%, the data will collapse using either alternative velocity scale; however, the scatter is slightly larger in either case due to the higher uncertainty in our estimates of U_2.

A closer examination of Fig. 11 reveals that the global mode frequency f decreases as the velocity ratio is increased. We would like to know whether the frequency reduction is due to larger vortical disturbances in the jet as hypothesized earlier. We expect that the phase velocity of disturbances in the jet near field would decrease with increasing velocity ratio as the disturbance convection speed should be roughly proportional to the average velocity of the countercurrent streams $(U_1+U_2)/2$. Hence, it is difficult to predict from the frequency data alone whether the wavelength λ of the global mode oscillations will increase or decrease with velocity ratio.

To obtain a more complete physical understanding of the mechanisms responsible for mixing enhancement at the higher velocity ratios, the disturbance wavelength was measured directly using standard space-time correlation techniques. Two diametrically opposed hot wires were positioned within the potential core region of the jet at a Reynolds number of 3.4×10^4 under laminar flow initial conditions and using the extension collar having $L/D=1$. One hot wire was fixed at $x/D=1$ and the other was traversed in the streamwise direction to determine the disturbance wavelength as shown in Fig. 12. The data suggest that the disturbance wavelength increases monotonically with velocity ratio. Hence, the vortical disturbances in the jet increase their scale as the velocity ratio is increased indicating why the global mode oscillations are such effective devices for augmenting mixing between the jet and the surrounding fluid.

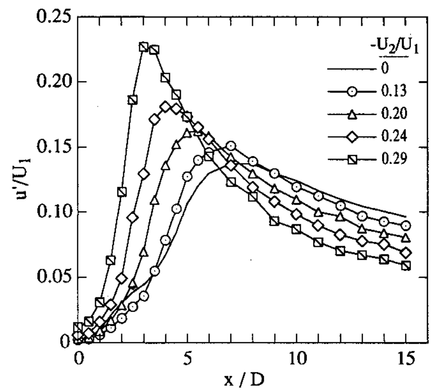

Fig. 13 Axial turbulence intensity profiles at $Re_D=3.4\times10^4$ in an initially laminar jet having $L/D=2.25$.

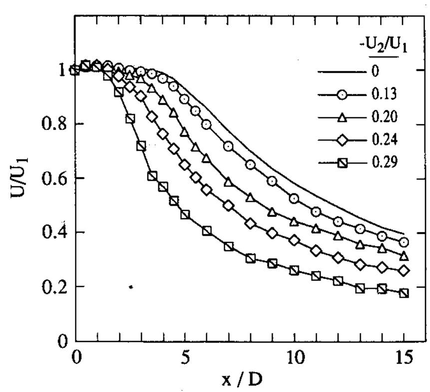

Fig. 14 Axial mean velocity profiles at $Re_D=3.4\times10^4$ in an initially laminar jet having $L/D=2.25$.

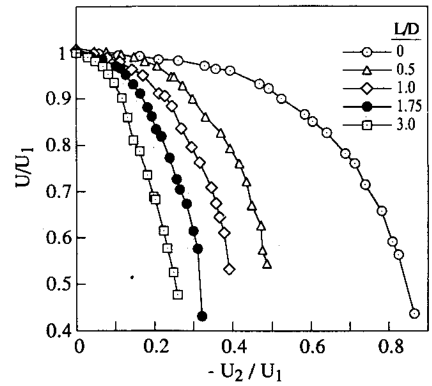

Fig. 15 Mean velocity measured on the jet centerline at $x/D=5$ for an initially laminar jet at $Re_D=3.4\times10^4$.

Effect of Collar Length

The results presented thus far have examined the effect of counterflow on the enhancement of mixing in circular jets for a range of initial conditions, but were limited to a fixed nozzle geometry having a collar extension $L/D=1$. To determine the dependence of jet mixing on L/D, a series of collar extensions were made for L/D between 0 and 3; all collars were machined with a divergence half-angle of 7 deg and an outer radius of curvature of 1.27 cm. The study was limited to an initially laminar jet at a Reynolds number of 3.4×10^4 and an annular suction slot width of $w/D=0.5$.

Axial turbulence intensity and mean velocity data are presented in Figs. 13 and 14 for one of the longer collar extensions having $L/D=2.25$, and should be compared to the data in Figs. 4 and 5 obtained under the same flow conditions but with the collar extension of $L/D=1$. The general trends of the data are in qualitative agreement, but a closer examination reveals that similar levels of mixing can be achieved with significantly less suction when employing the longer extension collar. For example, for an extension collar of $L/D=1$, a peak turbulence level of 17% was attained at 42% reverse flow; however, with the longer collar ($L/D=2.25$) a similar peak turbulence intensity was achieved at almost half of the reverse velocity of 24%.

A comparison of the performance of many extension collars is given in Fig. 15. Again, we use the mean velocity obtained on the jet centerline at $x/D=5$ as representative of the extent of mixing in the jet. The effect of reverse flow on the jet development can be seen to be quite small at low velocity ratios for all collars. As the velocity ratio is increased, it becomes apparent that significantly less suction can be used to enhance mixing with longer collar extensions. It is also clear that the critical velocity ratio must be a strong function of L/D. These results are quite encouraging and indicate that appropriate collar design can significantly reduce the volume of air which must be drawn through the collar system. We are currently examining a number of collar designs to determine the optimal combination of collar length, width, and divergence angle.

Discussion and Conclusions

In this paper we have outlined a new control technique which produces global oscillations in an axisymmetric jet leading to significant increases in jet mixing. The physical mechanism responsible for the phenomenon was described as the consequence of jet self-excitation due to the countercurrent mixing in the jet shear layer. Pending a more complete examination of the flowfield development under stationary as well as transient conditions, our present findings represent strong indirect evidence of self-excitation in the jet with counterflow. This evidence consists of the following observations: 1) Above a critical velocity ratio, oscillations emerge in the jet at essentially a single characteristic frequency. This spatially invariant spectral behavior is characteristic of a global mode in the jet, i.e., an instability which involves the participation of the jet as a whole, in sharp contrast to flows whose spectral character evolves spatially. 2) An important characteristic of a self-excited instability is the insensitivity to external forcing.[14] Although an exhaustive study of the effect of external forcing was not undertaken, we did subject the jet to a range of initial conditions including the random background forcing imposed by tripping the boundary layer and the placement of a screen in the jet exit plane. The tripping devices were responsible for an order of magnitude increase in the disturbance level at the jet exit, but had essentially no effect on the jet development for velocity ratios above the critical value.

From a practical standpoint, it is essential to develop control techniques which do not rely on external feedback loops or fragile sensors and actuators. The feedback of information must be through the vorticity field, thereby establishing a passive and robust means of excitation. In the circular jet, this is possible by applying suction around the jet periphery above a threshold velocity ratio. Measurements made in both clean and disturbed jets over a range of Reynolds numbers indicate that global oscillations emerge in the presence of counterflow and are responsible for enhanced mixing. Preliminary measurements made in high-speed heated jets for both subsonic and supersonic Mach numbers[15] reveal that counterflow is indeed a robust approach to flow control in axisymmetric jets.

One important consideration in the design of counterflowing nozzles for high-speed mixing chambers will be to minimize the volume of fluid drawn through the reverse flow collar for a given level of mixing. Large reverse volumetric flow rates are disadvantageous both because of the necessary power requirements and because the reverse flow is removed from the mixing chamber itself. (In engine applications, large reverse velocities should be avoided because of the associated negative thrust which they develop.) Our measurements indicate that the reverse velocity can be significantly reduced by changes in the nozzle geometry, in particular the length of the extension collar L/D. More work needs to be done here to optimize the nozzle design including collar divergence and width. For instance, preliminary measurements indicate that the width of the annular slot w/D has a strong effect on the jet mixing. When w/D was reduced from 0.5 to 0.25, the velocity ratio necessary to achieve similar axial peak turbulence levels was also reduced by approximately a factor of two. Once the interrelationship between the geometrical parameters of L/D, w/D, and collar shape are more completely understood, radial as well as axial velocity measurements need to be obtained to provide a complete picture of the jet entrainment field.

Although the Coanda effect was ruled out as playing a dominant role in the jet dynamics when $w/D=0.5$, this effect was observed to be much more significant when w/D was reduced to 0.25. Recent work by Reynolds[16] has examined several unique nozzle designs which exploit the Coanda effect to dramatically alter mixing in coannular flowing jets. Perhaps by combining the attributes of self-excitation and the Coanda effect, jet mixing can be effectively altered under more realistic operating conditions than we have examined here.

Acknowledgments

Principal support for this research was provided by the Graduate School of the University of Minnesota. The work was also partially supported by the National Science Foundation under Grant CTS-9116532.

References

[1]Crow, S. C., and Champagne, F. H., "Orderly Structure in Jet Turbulence," *Journal of Fluid Mechanics*, Vol. 48, Part 3, 1971, pp. 547–591.

[2]Zaman, K. B. M. Q., and Hussain, A. K. M. F., "Vortex Pairing in a Circular Jet under Controlled Excitation. Part I. General Jet Response," *Journal of Fluid Mechanics*, Vol. 101, Part 3, 1980, pp. 449–491.

[3]Zaman, K. B. M. Q., and Hussain, A. K. M. F., "Turbulence Suppression in Free Shear Flows by Controlled Excitation," *Journal of Fluid Mechanics*, Vol. 103, 1981, pp. 133–159.

[4]Lepicovsky, J., Ahuja, K. K., Brown, W. H., Salikuddin, M., and Morris, P. J., "Acoustically Excited Heated Jets," NASA CR 4129, Pt. I–III, 1988.

[5]Reisenthel, P., "Hybrid Instability in an Axisymmetric Jet with Enhanced Feedback," Ph.D. Thesis, Illinois Inst. of Technology, Chicago, IL, May 1988.

[6]Reisenthel, P., Xiong, Y., and Nagib, H. M., "The Preferred Mode in an Axisymmetric Jet With and Without Enhanced Feedback," AIAA Paper 91-0315, Jan. 1991.

[7]Kyle, D.,"The Instability and Breakdown of a Round Variable Density Jet," Ph.D. Thesis, Yale Univ., New Haven, CT, May 1991.

[8]Chomaz, J. M., Huerre, P., and Redekopp, L. G., "Bifurcations to Local and Global Modes in Spatially-Developing Flows," *Physical Review Letters,* Vol. 60, No. 1, 1988, pp. 25–28.

[9]Drubka, R. E., and Nagib, H. M., "Instabilities in Near Field of Turbulent Jets and their Dependence on Initial Conditions and Reynolds Number," Air Force Office of Scientific Research, TR AFOSR-TR-82, Illinois Institute of Technology, Chicago, IL, Dec. 1981.

[10]Kibens, V., "Jet Flows and Turbulence Control," McDonnell Douglas Research Lab. Rept. MDRL 89-06, St. Louis, MO, April 1989.

[11]Niccum, D. L, "The Influence of Velocity Ratio on a Counterflowing Circular Jet," M.S. Thesis, Univ. of Minnesota, Minneapolis, MN, Dec. 1990.

[12]Strykowski, P. J., and Niccum, D. L., "The Stability of Countercurrent Mixing Layers in Circular Jets," *Journal of Fluid Mechanics,* Vol. 227, 1991, pp. 309–343.

[13]Strykowski, P. J., and Niccum, D. L., "The Influence of Velocity and Density Ratio on the Dynamics of Spatially Developing Mixing Layers," *Physics of Fluids A,* Vol. 4, No. 4, 1992, pp. 770–781.

[14]Huerre, P., and Monkewitz, P. A., "Local and Global Instabilities in Spatially Developing Flows," *Annual Review of Fluid Mechanics,* Vol. 22, 1990, pp. 473–537.

[15]Strykowski, P. J., Krothapalli, A., and Wishart, D., "The Enhancement of Mixing in High-Speed Heated Jets using a Counterflowing Nozzle," AIAA Paper 92-3262, July 1992.

[16]Reynolds, W. C., "Control of Turbulent Jets," *Bulletin of the American Physical Society,* Vol. 36, No. 10, 1991, p. 2707.