MIXING BEHAVIOR OF ABSOLUTELY UNSTABLE AXISYMMETRIC SHEAR LAYERS FORMING SIDE JETS

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1. Introduction

Recently it has been shown that low-density axisymmetric jets can become absolutely unstable and develop highly coherent vortical structures in the near-field shear layer [1],[2],[3]. These jets have several unusual properties when compared to jets which are convectively unstable. The vortical structures grow quickly with downstream distance and rapidly develop three-dimensional structure. Intense pairing of alternate structures is observed. Perhaps the most interesting of all behaviors is the observation of strong ejections of jet fluid, termed "side jets", into the ambient surroundings [1],[4],[5]. Their formation is attributed to the generation of strongly coupled pairs of longitudinal vortices in the developing shear layer [5],[6].

To our knowledge, there has been only one detailed investigation of near-field real-time mixing in jets subject to an absolute instability and forming side jets. Richards et al. [7] have reported aspirated hot-film concentration measurements for downstream distances of two to five diameters for several helium jets. Here we summarize the findings of real-time concentration measurements in the developing shear layer and side jets. The results discussed are part of a broader effort to be described in detail elsewhere [8].

2. Experimental

Axisymmetric jets displaying absolute instability behavior were formed by flowing helium through a contoured 6.35 mm diameter nozzle [9]. Honeycomb, screens, and beads placed upstream of the nozzle exit smoothed the flow. The velocity profile had a uniform "top-hat" contour with fluctuations of less than 0.15%. A mass-flow controller was used to establish the helium flow. The nozzle was mounted on a computer-controlled positioning system which allowed it to be moved relative to the fixed Rayleigh light scattering system described below.

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It has been shown previously [3] that the strength of the absolute instability in round jets depends on both the thickness of the nozzle boundary layer and the jet-to-ambient density ratio. In the current facility, absolute instability behavior was observed for jet velocities (U_o) of 15 m/s to 92 m/s (Reynolds numbers, Re = 800 to 4,900) with the strongest interaction observed for a velocity of 25 m/s and Re = 1,300 [8].

A spark schlieren system was used to visualize the near-field regions of the helium jets. The spark source was a xenon lamp generating an approximately 20 ns light pulse which effectively "froze" the flow. A standard schlieren system consisting of 7 cm diameter collimating and focusing lenses and a knife edge was used to create time-resolved images which were recorded by a cooled CCD camera.

A hot wire was placed near the jet boundary layer, and the signal from the anemometer electronics provided a distinct record of the passage of vortical structures shed by the nozzle. For the absolutely unstable flows, the resulting signal was highly coherent and could be used to trigger the flash lamp at particular phases of the flow development. In this way it was possible to track the growth of the vortical structures as a function of time.

Real-time point measurements of helium concentration in the jets were recorded using Rayleigh light scattering (RLS) [10] induced by a focused 20 W beam from an argon ion laser. Scattered laser light was collected at 90° by an f/2 optical system and focused 1:1 onto a 400 μm pinhole and then onto a photomultiplier tube (PMT). The output of the PMT was frequency filtered, digitized, and stored in a minicomputer. The optical components defined the sample volume to be a cylinder of 75 μm diameter and 400 μm length. Data were recorded at a frequency of 20 kHz. Calibration of the scattering signals for air and helium allowed an arbitrary helium concentration (mole fraction) to be determined using

$$X_{He}(t) = \frac{I(t)-I_{air}}{I_{He}-I_{air}} \quad , \tag{1}$$

where X_{He} is the helium mole fraction, $I(t)$ is the time varying RLS intensity from the observation volume, and I_{He} and I_{air} are the observed scattering intensities from air and helium, respectively.

The nozzle was positioned in the NIST Rayleigh Light Scattering Facility (RLSF) [11] which has a cylindrical working section with diameter and height of 2.4 m. Particles, which scatter light strongly and interfere with RLS measurements, are removed from the working section by air flows passing through high-efficiency particle filters, and the walls are painted black to limit glare. During an experiment the air flow was shut off, and the helium jet entered a quiescent air environment.

In the following discussions downstream distances (z) and radial positions (r) relative to the flow centerline are nondimensionalized by the nozzle radius (r_o = 3.175 mm).

Figure 1. Schlieren photograph of an absolutely unstable helium jet recorded with a 20 ns light pulse showing shear layer structure and side jets. U_o = 24.6 m/s, Re = 1318, and f_o = 1275 Hz.

3. Results

Figure 1 shows a schlieren visualization of the near field of a helium jet with an initial jet flow velocity, U_o, of 24.6 m/s. A symmetrical vortical structure has formed near the nozzle. Phase-resolved images reveal that these structures develop very near the nozzle exit and grow rapidly with downstream distance. Alternate vortical structures are observed to pair further downstream .

Two side jets can be seen in Fig. 1 which have been ejected outward from the jet column to the left and right. There is a clear structure apparent in the side jets which suggests that they are formed by repeated pulses of helium from the jet core.

Time records of helium concentration were recorded using RLS at various locations in the near fields of the jets. Figure 2 shows an example of a short time record for z/r_o = 2 and r/r_o = 1.1, which lies within the shear layer close to the nozzle. U_o is 24.6 m/s. Helium concentration is plotted as a function of time nondimensionalized by multiplying by the primary shear-layer oscillation frequency, f_o = 1275 Hz, determined for this flow.

A highly repeatable oscillation of the helium concentration over a mole fraction range of 0.57 to 0.90 is observed. The full data record indicates that these fluctuations are extremely stable. The experimental data can be represented very well by a cosine function as seen in Fig. 2 by comparing a calculated curve having the appropriate amplitude, phase, and frequency with the experimental data.

The concentration time record shown in Fig. 3 was recorded at the same spatial location as Fig. 2, but the jet velocity was increased to U_o = 37.5 m/s. The shear-layer

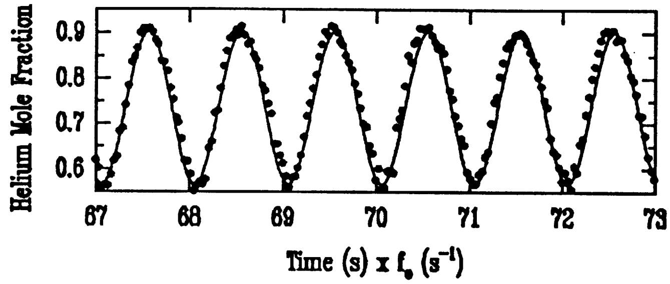

Figure 2. Helium mole fraction as a function of time nondimensionalized by the primary frequency, f_o, of the jet for $z/r_o = 2.0$ and $r/r_o = 1.1$. The solid line is a cosine function with phase and frequency adjusted to fit the data. $U_o = 24.6$ m/s, $Re = 1318$, and $f_o = 1275$ Hz.

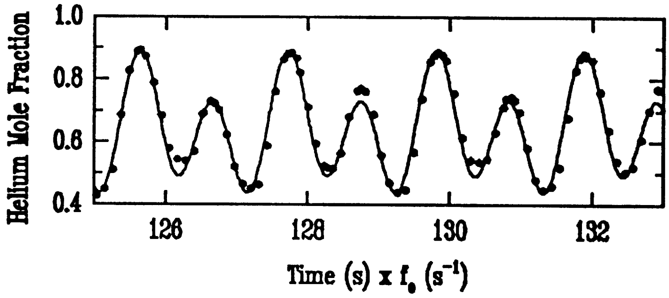

Figure 3. Helium mole fraction as a function of time nondimensionalized by the primary frequency, f_o, of the jet for $z/r_o = 2.0$ and $r/r_o = 1.1$. Solid line is Eq. (2) with $\phi = -18°$ and phase and frequency adjusted to fit the data. $U_o = 37.5$ m/s, $Re = 2010$, and $f_o = 2288$ Hz.

growth rate is known to be more rapid for this flow condition [8]. The observed signal for this case is also very stable, but the concentration time behavior is very different. The primary frequency of $f_o = 2288$ Hz is distinct, but there is clearly a variation at half this frequency as well. The data can be fit to a function having the following form:

$$X_{He}(t) = 0.64+0.17[\cos(f_o t)+0.5\cos\left(\frac{f_o t}{2}+\phi\right)] \quad , \qquad (2)$$

where ϕ is a phase-shift angle which is set to -18° in order to reproduce the observed time dependence of the concentration fluctuations.

Figure 4 shows an example of concentration data recorded further downstream at $z/r_o = 3.0$ and $r/r_o = 1.4$ with $U_o = 37.5$ m/s. A short time record of a portion of the data is shown along with a much longer record in which the data have been averaged (smoothed) over fifty points to remove the high frequency contributions due to the primary frequency. The two time records show that while concentration fluctuations

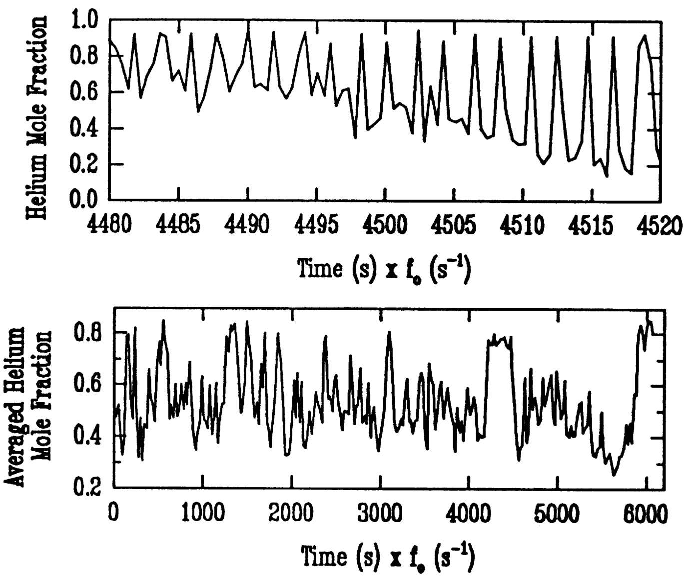

Figure 4. Helium mole fraction as function of time nondimensionalized by the primary frequency, f_o, of the jet for $z/r_o = 3.0$ and $r/r_o = 1.4$. A short real-time record and long-time smoothed (fifty-point average) are shown. $U_o = 37.5$ m/s, $Re = 2010$, and $f_o = 2288$ Hz.

are still present at the primary frequency, the overall mixing is no longer steady and has developed a great deal of both short-term and long-term randomness.

In regions well outside of the shear layer, any helium which is detected is due to the formation of side jets. The concentration time histories in these regions are very complex with a variety of different behaviors. Figure 5 shows an example plotted as a function of nondimensionalized time. A periodic variation is observed roughly every 40 primary vortical periods. There is also evidence for small concentration fluctuations at the primary frequency. Concentration maxima reach values greater than 60% helium.

Figure 6 shows time-averaged contours which have been calculated based on measurements over a range of near-field radial and downstream locations. The rapid spreading of the flow due to the occurrence of side jets is apparent.

4. Discussion

The concentration fluctuations in the boundary layer very close to the nozzle exit are consistent with the expected development of a shear layer subject to an absolute instability. Such layers develop initially highly repeatable azimuthal vortical structures at a single frequency which grow rapidly with downstream distance. The data in Fig. 2 demonstrate the high degree of coherence of these structures near the nozzle. The concentration signal, which closely obeys a cosine function, is the result of the radial

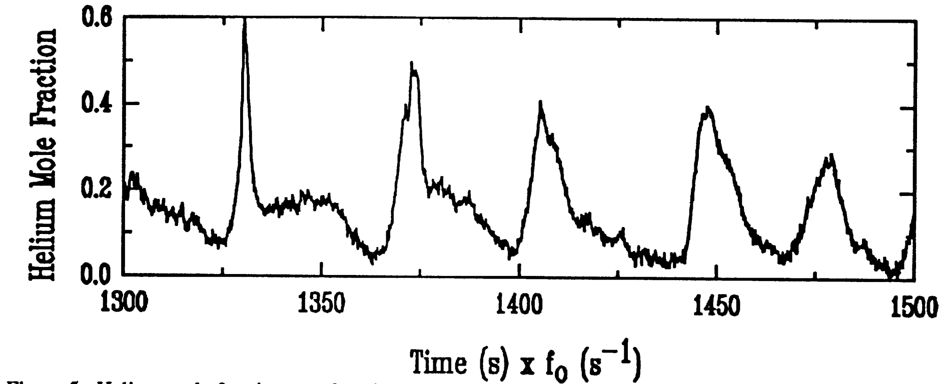

Figure 5. Helium mole fraction as a function of time nondimensionalized by the primary frequency, f_o, of the jet at a location outside the shear layer, $z/r_o = 3.5$ and $r/r_o = 3.0$. $U_o = 19.3$ m/s, $Re = 1034$, and $f_o = 958$ Hz.

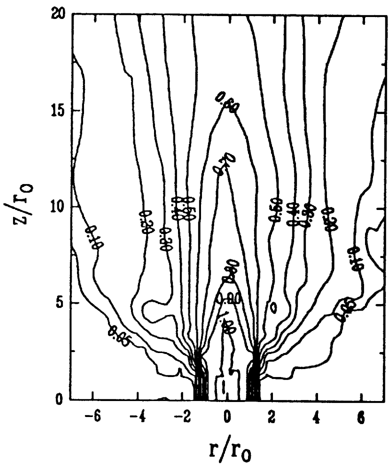

Figure 6. Time-averaged helium mole fraction contours measured as a function of radial and downstream position for a helium jet generating side jets. $U_o = 37.5$ m/s, $Re = 2010$, and $f_o = 2278$ Hz.

expansion and contraction of the concentration diffusion layer at the jet outer edge over the measurement point during the passage of the developing vortical structures. The absence of long-term variations shows that the structures are axisymmetric at this downstream distance. The large concentration fluctuations indicate that the structures have developed rapidly over the one jet diameter flow distance. Note that the smooth nature of the signals indicates that the growing structures have not yet "rolled up".

The data shown in Fig. 3 are for the same downstream distance as in Fig. 2, but the higher initial velocity of the flow results in faster development of the fluctuating shear layer. As a result, two adjacent structures have begun to interact, and a pairing process has been initiated. Observed concentration histories are consistent with a relative rotation of the vortices about a point located between them, with one structure moving toward the center, while the second rotates outward. This motion explains the alternating concentration pattern in the data. The diffusion layer adjacent to the structure which has moved closer to the center also moves in, and the concentration at the measurement point is reduced. The phase angle shift of $\phi = -18°$ necessary in Eq. 2 in order to fit the experimental data shows that the distance between the two interacting structures is decreasing as a result of the interaction. The smooth variations of the concentration indicate that pairing of the structures begins before significant roll up has occurred, while the absence of long-term variations demonstrates that the structures are still nearly axisymmetric about the centerline.

The concentration fluctuations in Fig. 4 show that rapid development of the shear layer continues as the flow moves further downstream. While the primary frequency is still present, the signals have become considerably more random. Concentration variations evident during the passage of individual structures show that vortex roll up has taken place with entrainment of large amounts of air. Large variations in concentration occur over periods long compared to the inverse of the primary frequency. These are attributed to development of azimuthal structure due to the Widnall instability [12], i.e, the structures are no longer axisymmetric. As these structures rotate about the jet center they result in the observed fluctuations.

These observations concerning shear-layer development are consistent with literature discussions of the growth of axisymmetic shear layers subject to an absolute instability [1]-[3],[6]. The availability of quantitative concentration measurements provides details concerning these processes which have been difficult to obtain previously.

Figure 5 is an example of the concentration fluctuations observed for positions near the jet exit, but well outside of the shear-layer flow. Note that only one of a wide variety of different behaviors which have been observed is shown. However, the data does serve to demonstrate several conclusions concerning side jet behavior.

Previous investigators [1],[4],[5] have shown that several side jets are formed simultaneously, which are highly localized in space and have a nonaxisymmetric structure which rotates about the centerline. The structure evident in Fig. 5 is consistent with such a rotation. The high concentration peaks are presumably due to direct side-jet impingement on the observation point, with lower concentrations observed between the side jets.

An unanswered question has been whether side jets are ejected continuously during multiple passages of primary vortices or intermittently during distinct phases of vortex passages. The continuous nature of the high concentrations observed during periods long compared to the inverse of the primary frequency strongly suggests that the ejections are continuous. Additionally, the high concentrations suggest the ejections occur from deep within the jet instead of in the shear layer, where lower helium concentrations are to be expected.

Close inspection of the time profile indicates that there are small variations in side-jet concentration at the frequency of the boundary-layer fluctuations observed in the primary jet. These fluctuations are thought to be associated with a pulsing of the side jet velocity which is responsible for the side-jet structure evident in Fig. 1.

Time-averaged concentration measurements such as shown in Fig. 6 demonstrate that the presence of an absolute instability and side jet formation leads to greatly enhanced spreading and mixing rates in the near fields of these jets.

6. Final Comments

The concentration measurements summarized here have provided new insights into the enhanced mixing as the result of the presence of an absolute instability in the near field of an axisymmetric jet shear layer as well as details concerning the effect of the absolute instability on shear-layer growth. Simultaneous velocity and concentration measurements in these flows have been used to characterize the dependence of side-jet strength on the intensity of the shear-layer oscillations due to the presence of the absolute instability. These measurements are discussed elsewhere [8].

7. References

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