

# CONCENTRATION MEASUREMENTS IN SELF-EXCITED MOMENTUM DOMINATED LOW-DENSITY GAS JETS

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## **ABSTRACT**

Flow structure of self-excited, laminar, axisymmetric, momentum-dominated helium jets discharged vertically into ambient air was investigated using high-speed rainbow schlieren deflectometry technique. Measurements were obtained at temporal resolution of 1 ms and spatial resolution of 0.19 mm for two test cases with Richardson number of 0.034 and 0.018. Power spectra revealed that the oscillation frequency was independent of spatial coordinates, suggesting global oscillations in the flow. Abel inversion algorithm was used to reconstruct the concentration field of helium. Instantaneous concentration contours revealed changes in the flow field and evolution of vortical structures during an oscillation cycle. Temporal evolution plots of helium concentration at different axial locations provided detailed information about the instability in the flow field.

**Keywords:** Color Schlieren, Momentum-dominated jets, Flow Instability.

## **INTRODUCTION**

Flow structure and instability of gas jets has been the subject of several investigations due to their wide ranging applications. When a low density jet is injected into a high density environment, highly periodic oscillations occur in the flow field under some conditions. The important operating parameters in the previous studies included the jet Reynolds number ( $Re=d.U/V$ ), the jet Richardson number ( $Ri=g.d.(p_\infty-p)/(p.U^2)$ ), the momentum thickness ( $\theta$ ) and the density ratio ( $S=p/p_\infty$ ). The instability has been described using flow-oscillation frequency ( $f$ ) or the Strouhal number ( $St=f.d/U$ ). Low-density jets can be classified as either buoyancy dominated ( $Ri>1$ ) or momentum dominated ( $Ri<<1$ ). In the literature, we find several studies conducted in both jet flow regimes.

Subbarao and Cantwell<sup>1</sup> identified the oscillating and non-oscillating regimes for vertical helium jets in the Reynolds number-Richardson number space using a stroboscopic schlieren technique. Measurements revealed large centerline velocity fluctuations, and early and abrupt breakdown of the potential core. They reported the oscillating behavior of the helium jet at moderate values of Richardson numbers ( $0.5 < Ri < 6$ ) and stated that this type of flow was subjected to an unusual type of transition to turbulence consisting of a rapid but highly structured and repeatable breakdown and intermingling of the jet with the free stream fluid. The strong dependence of Strouhal number on Richardson number indicated the dominance of buoyancy effect.

Hamins et al.<sup>2</sup> studied oscillations in both buoyant helium jets and flames. They used shadowgraph technique to observe the oscillation frequencies of helium jets over a range of Froude number ( $\approx 0.001$  to  $\approx 1$ ) which is proportional to  $1/Ri$  and Reynolds number ( $\approx 1$  to  $\approx 100$ ). Strouhal number was correlated as a function of inverse Froude number. Oscillations in the flow were not observed until a minimum flow rate was attained. Measured frequency and the location of the vortical structures were dependent on the helium jet exit velocity.

Several experiments by Cetegen<sup>3</sup> on axisymmetric helium plumes yielded global oscillatory behavior for a range of tube diameters ( $3.6\text{cm} < d < 20\text{cm}$ ). The velocity measurements in a buoyant plume revealed strong buoyant acceleration along the centerline followed by a deceleration in the region of toroidal vortex formation. Cetegen<sup>4-6</sup> found the effects of external forcing on naturally stable axisymmetric buoyant helium-air mixtures. The size of the vortex formed was dependent on the forcing frequency in these buoyancy-dominated jets ( $Ri > 1$ ).

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Most recently Yep et al.<sup>7</sup> used the microgravity environment of 2.2 seconds drop tower at the NASA John H. Glenn Research Center to find that the flow oscillations disappeared in microgravity, demonstrating that buoyancy was the origin of self-excited oscillations in Earth gravity. Yep et al.<sup>8</sup> provided quantitative details of buoyancy-induced changes in the helium concentration field at  $Ri=1.44$  using the Rainbow Schlieren Deflectometry (RSD) technique.

Although the instability in low-density jets is caused by buoyancy for  $Ri>0.5$ , in momentum dominated jets, however, the origin of the instability still remains unknown. Generally, buoyancy effect in momentum dominated jets is considered negligible and thus ignored. Monkewitz et al.<sup>8</sup> reported the spectacular spreading of unstable heated air jets below a critical value of density ratio of approximately 0.73, using conventional knife-edge schlieren technique. The spreading of the jet was characterized by the formation of vortex-ring structures and side-jets. The instability was attributed to the vortex-ring formation.

Kyle et al.<sup>9</sup> studied the instability and the subsequent breakdown of axisymmetric jets of helium/air mixtures emerging into ambient air. The oscillating behavior was shown to depend upon density ratio, jet diameter and jet momentum thickness, and it was independent of the jet Reynolds number within the covered range  $1500 < Re < 12500$ . They also noted that the flow structure repeated itself with extreme regularity. The high degree of repeatability of the oscillating mode, with strong vortex interaction, led to large centerline velocity fluctuations. Even though the oscillating mode had high degree of repeatability, it did not exhibit large spatial growth rate. The instability of the jet was enhanced when the density ratio was decreased.

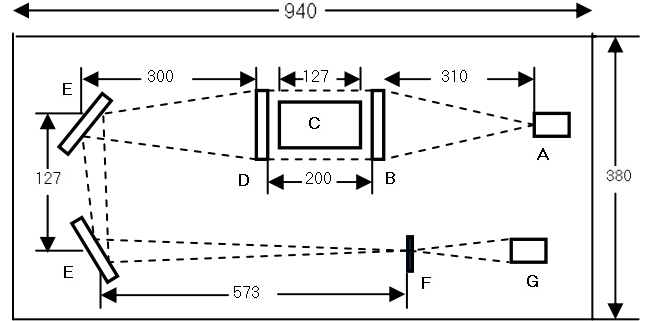
Richards et al.<sup>10</sup> found helium jets in air to display a global or self-excited behavior characterized by intense vortex interaction. Flow visualization was performed using Mie scattering. Concentration measurements at several radial locations obtained by an aspirating probe indicated the presence of side jet behavior with substantially increased level of mixing. Global oscillations were reported for the range of Reynolds numbers between 350 and 1400.

In the present work, we apply the RSD technique to measure concentration in self-excited momentum dominated helium jets and obtain quantitative data on spatial and temporal evolutions of the instability, and length and time scales of the oscillating mode.

## EXPERIMENTAL APPROACH

A compact test rig primarily designed and constructed to conduct experiments in microgravity conditions was used in this study. An external flow system was coupled

with the test rig to eliminate limitations regarding the maximum flow rate. Flow system was comprised of a helium gas cylinder, a pressure regulator, a needle valve, a mass flow meter, plastic flexible hose and a straight jet tube oriented vertically.



**Figure 1. Optical layout of RSD. A) light source aperture, B) collimating lens, C) test section, D) decollimating lens, E) flat surface mirrors, F) rainbow filter, G) high speed camera (All dimensions are in millimeters).**

The optical layout of the rainbow schlieren apparatus is shown in Figure 1. It consists of a light source aperture with 3mm high and 100  $\mu\text{m}$  width connected to a 150-W halogen light source, modified by attaching a focusing optics assembly to the exit route of the light, through fiber optic cable, 80 mm diameter 310 mm focal length collimating achromatic lens, 80 mm diameter 1000 mm focal length decollimating achromatic lens, two aluminum coated flat surface reflecting mirrors, 3 mm wide rainbow filter positioned at the focal length of the decollimating lens, and a high speed digital camera capable of acquiring images at rates up to 2000 frames per second and storing digitally in TIFF format at pixel resolution of 384x512. Exposure time of 299  $\mu\text{sec}$  was used to acquire the images.

In the rainbow schlieren apparatus, the transverse ray displacement at the filter plane is found from measurement of hue in the schlieren image together with a filter calibration curve<sup>11-14</sup>. The transverse ray displacement is related to the angular deflection of a light ray by an axisymmetric refractive index field given by the following relationship.

$$\varepsilon(y) = 2y \int_y^\infty \frac{d\delta}{dr} \frac{dr}{\sqrt{(r^2 - y^2)}} \quad \text{Equation 1}$$

The refractive index difference is found using Abel inversion of Equation 1 given in discrete form as<sup>15</sup>:

$$\delta_i = \delta(r_i) = \sum_{k=i}^{NJ} D_{ik} \cdot \varepsilon_k \quad \text{Equation 2}$$

For a mixture of gases, the refractive index difference is given as<sup>11</sup>

$$\delta = \frac{P}{R \cdot T} \sum_j \kappa_j \cdot X_j \cdot M_j \quad \text{Equation 3}$$

Equation 3 is used to construct a plot between refractive index difference and helium mole fraction, assuming standard air comprising nitrogen to oxygen mole ratio of 3.76.

The uncertainties in the experiments are caused by hue measurement uncertainties and instrumental bias error. The variation of hue values in filter calibration led to uncertainties in calculations of deflection angle, refractive index and helium concentration. Maximum uncertainty in the deflection angle occurred near the jet centerline where the density gradients are small. Calculated uncertainty for deflection angle was  $5 \times 10^{-4}$  degree. The uncertainty in the concentration of helium was found to be 8 %. Uncertainty in the jet exit velocity was  $\pm 0.013$  m/s corresponding to uncertainties in Reynolds number and Richardson number of  $\pm 2$  and  $\pm 10^{-4}$ , respectively.

## RESULTS AND DISCUSSION

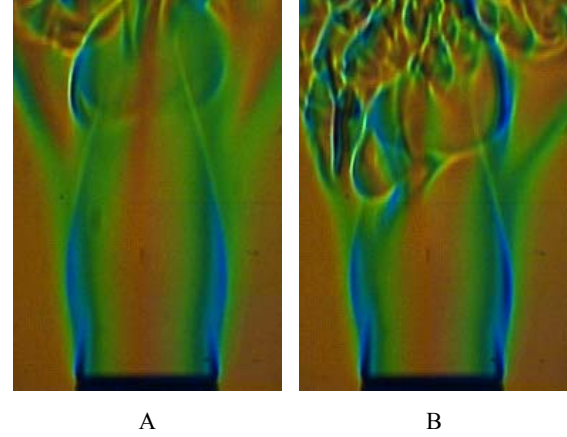
In this study, helium concentration measurements are presented for the following two test cases with  $d=19.05$  mm.

Test case	Re	Ri
1	910	0.034
2	1250	0.018

First, we will discuss oscillation characteristics of self-excited momentum dominated jets. Power spectra taken at various locations in the flow field will be presented in this part. Then, we will examine the instantaneous contours of helium mole fraction during an oscillation cycle, and show the repetitiveness of the flow and the vortical structures. Finally, the temporal evolution plots of helium concentrations will be presented and discussed.

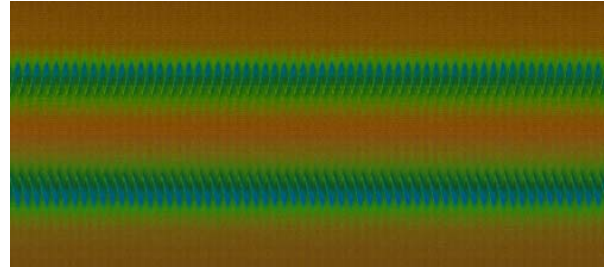
### Oscillating Characteristics and Global Features

Sample images for the two test cases are shown in Figure 2. The hue in the background and jet center is caused by the undeflected light rays where the density gradients are small or absent. Hue other than the background hue is caused by light ray deflection due to density gradients in the medium. Power spectra at various locations in the near flow field were generated using a Fast Fourier transform (FFT) algorithm.



**Figure 2. Rainbow schlieren images, A) test case 1, B) test case 2.**

To obtain the power spectra, first the time-space images were generated at desired axial locations using 2048 consecutive rainbow schlieren images. A typical time-space image for test case 1 is shown in Figure 3. The vertical direction in Figure 3 indicates the radial coordinate and the horizontal direction represents the time. For improved visualization, only 0.5 sec time interval is shown. After generating the space-time, the hue values at desired radial coordinates were used as the input for FFT analysis to obtain the power spectra.



**Figure 3. Time-space image at  $z/d=1$  for test case 1.**

Figure 4 shows power spectra at  $r/d=0.45$  for different axial locations ( $z/d=0.05, 0.5$  and  $1.0$ ) for test case 1. Results depict a dominant oscillation frequency of 125 Hz at all axial locations. Figure 4 shows that the oscillation amplitude increased in the flow direction. The increase in the oscillation amplitude is attributed to the growth of the vortical structure affecting the flow field. Figure 5 shows power spectra at  $z/d=1.0$  for different radial locations ( $r/d=0.55, 0.6$  and  $0.65$ ). Again, a dominant oscillation frequency of 125 Hz was obtained at all radial locations signifying the oscillation mode is global and independent of spatial coordinates. The highest oscillation amplitude was obtained at  $r/d=0.6$ .

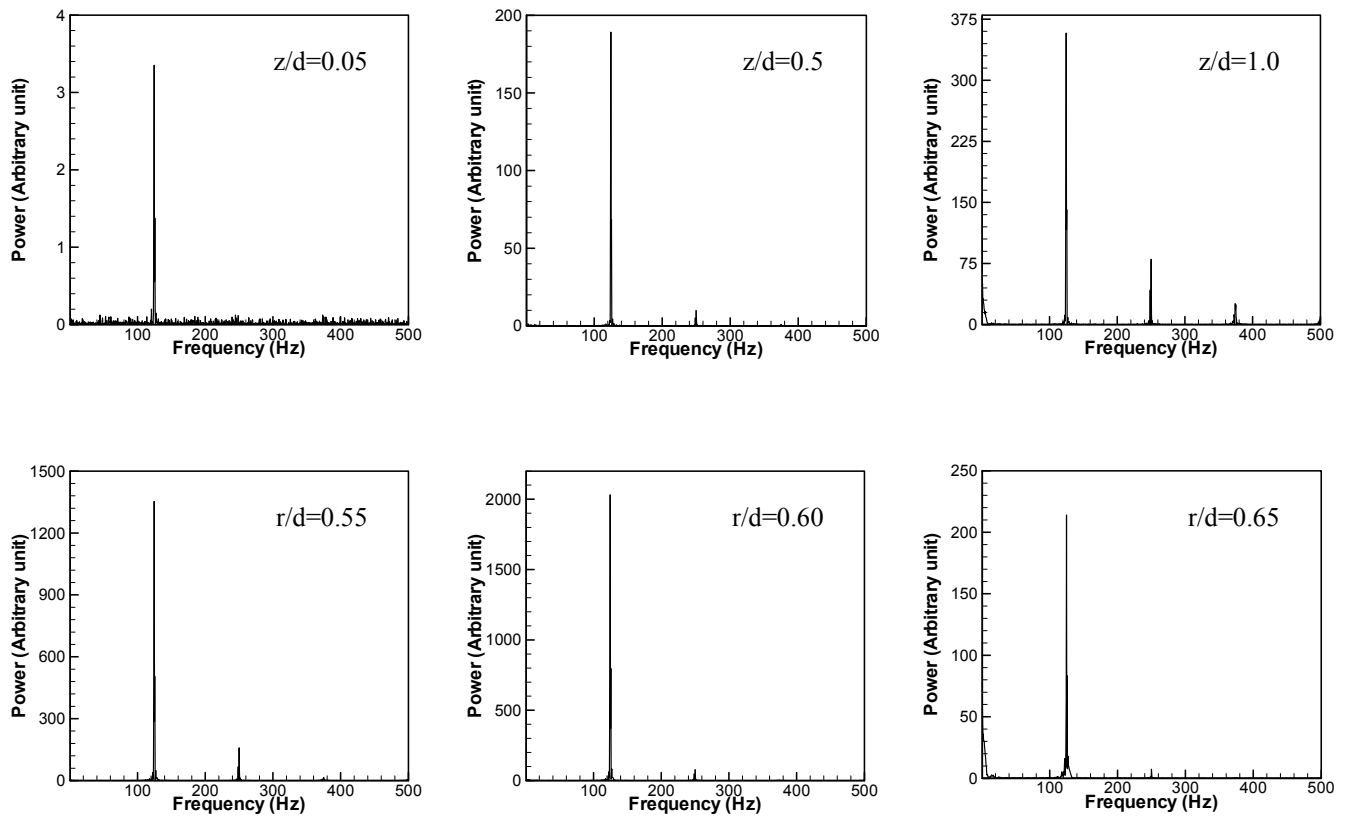


Figure 5. Power spectra at  $z/d=1$  for test case 1.

Figure 6 shows power spectra for test case 2 at  $z/d=1.0$  and  $r/d=0.4$  to demonstrate the oscillatory behavior. A global oscillation frequency of 180 Hz was found for this case.

#### Instantaneous Contours of Helium Mole Fraction

Instantaneous contours of the helium concentration were generated to explore the oscillatory behavior of

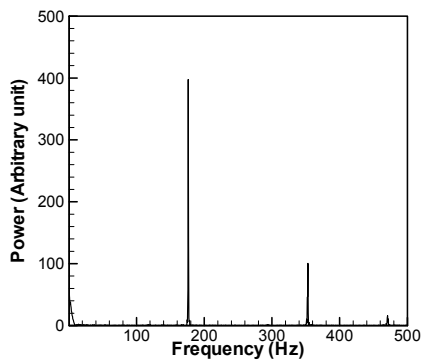


Figure 6. Power spectral at  $z/d=1$  and  $r/d=0.4$  for test case 2.

the flow during a cycle. Results are shown in Figure 7 for test case 1. Owing to the axisymmetric flow, only the one side of the jet is shown. At  $t=0$  ms and  $t=8$  ms (not shown), the contours are identical to each other suggesting the oscillation period of 8 ms or oscillation frequency of 125 Hz. In Figure 7, the concentration field is changing throughout the cycle to depict the instability of the flow. The instability is caused by the vortical structure which evolves and convects downstream during the oscillation cycle. The vortex initiation and its propagation to the downstream can be examined from Figure 7. At  $t=0$  ms, a vortex forms around  $z/d=0.25$  and  $r/d=0.48$  as seen from the indentation on the 70 % concentration level. At  $t=1$  ms, the vortex located at  $z/d=0.40$  has expanded in both axial and radial directions. At  $t=2$  ms, the vortex is located around  $z/d=0.55$ . Subsequently, as the vortex convects downstream it affects a greater portion of the jet. Figure 8 shows the instantaneous contours of helium concentrations for test case 2. Again, the overall trends are similar to those observed at a lower Reynolds number (test case 1).

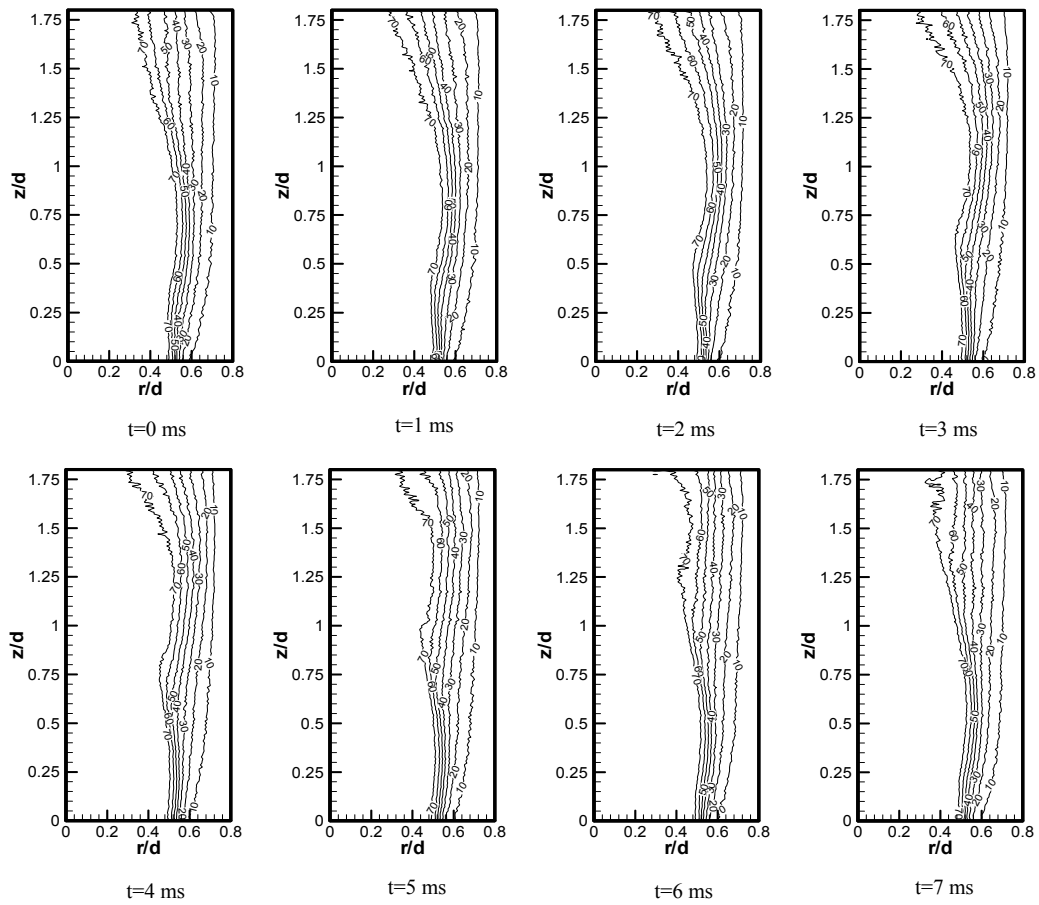


Figure 7. Instantaneous helium mole fraction contours during an oscillation cycle for test case 1.

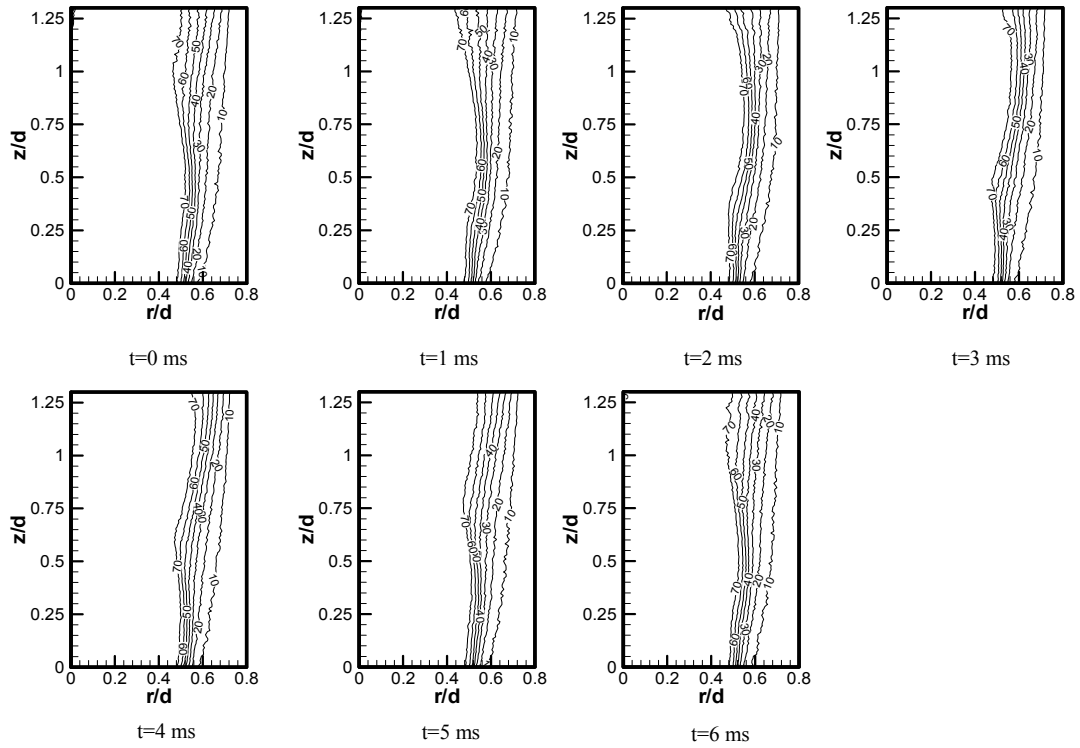
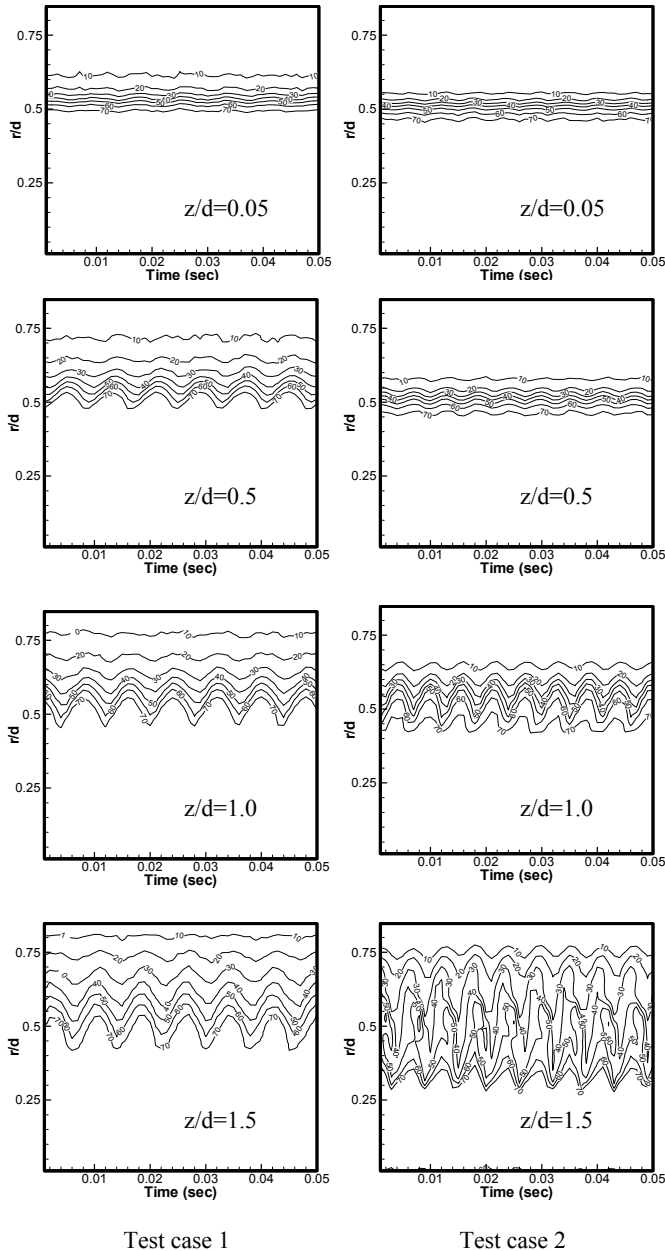


Figure 8. Instantaneous helium mole fraction contours during an oscillation cycle for test case 2.

### Temporal Evolution of Helium Mole Fraction

In the previous section, the oscillatory behavior of the flow was discussed using instantaneous helium concentration contours for one oscillation cycle. Temporal evolution plots of helium concentration provide detailed information about the flow structure by containing multiple cycles. Figure 9 shows the temporal evolution plots of helium concentration for the test case 1.



**Figure 9. Temporal evolution of helium mole fraction at different axial locations for test case 1 (left side) and for test case 2 (right side).**

Time traces were shown for 0.05 sec interval for one side of the jet centerline. Changes in the helium concentrations at different axial and radial locations can be monitored from plots in Figure 9. Results show highly repetitive helium concentration at all locations indicating a global oscillation mode. The oscillation frequency based on time interval between consecutive peaks was 125 Hz, which agrees with the value obtained using FFT analysis. The oscillation amplitude increases in the flow direction confirming the results obtained from power spectra plots. Small amplitude oscillations were observed near the tube exit at  $z/d=0.05$ . At  $z/d=0.5$ , the oscillations are dominant as seen from increased concentration amplitudes and helium has diffused up to  $r/d=0.71$ . At  $z/d=1$ , the concentration amplitude has increased about 54 % compared to that at  $z/d=0.5$ . At  $z/d=1.5$ , the amplitude of oscillation is very high. The oscillations penetrate deeper into jet core. Helium has diffused further into air as seen by 10 % concentration level located at  $r/d=0.81$ . In Figure 9, the temporal evolution of helium concentrations are shown for the test case 2. Results are similar to those obtained for test case 1.

### CONCLUSIONS

Flow structure of self-excited, laminar, axisymmetric, momentum-dominated helium jets discharged vertically into ambient air was investigated for two test cases using high-speed rainbow schlieren deflectometry technique. Power spectra plots revealed intense oscillations marked by a dominant frequency independent of the radial and axial coordinates. The increase in peak power with flow direction was also observed from these plots. Instantaneous contours of helium mole percentage showed initiation of the vortex and its interaction with the flow field during an oscillation cycle. Temporal evolution plots of helium concentrations provided information on variations in the jet structure with flow direction.

### ACKNOWLEDGEMENTS

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### NOMENCLATURE

d	Tube Inside diameter
f	Frequency(Hz)
g	Gravitational Acceleration
r	Radial Distance from Centerline
y	Projected Location
D	Geometric Coefficients
M	Species Molecular Weight
P	Atmospheric Pressure (N/m <sup>2</sup> )

R	Universal Gas Constant
Re	Reynolds Number
Ri	Richardson Number
S	Density Ratio
T	Temperature
U	Mean Jet Exit Velocity (m/s)
X	Species Mole Fraction

#### Greek Symbols

$\varepsilon$	Deflection Angle(radian)
$\kappa$	Dale-Gladstone Constant
$\delta$	Refractive Index Difference
$\eta$	Refractive Index Normalized by that of Surroundings
$\rho$	Density(kg/ m <sup>3</sup> )
$\theta$	Momentum Thickness
$\nu$	Kinematic Viscosity (m <sup>2</sup> /s)

#### Subscripts

$\infty$	Ambient Air
i	Projected Radial Location
j	Species

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