SIMULTANEOUS VELOCITY AND DENSITY MEASUREMENTS IN VARIABLE DENSITY MIXING OF FULLY TURBULENT BUOYANT GAS JETS

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Abstract Fully turbulent buoyant jets with high and low density ratios (Atwood numbers) at an initial jet Reynolds number of ~19,000 are studied at several locations downstream of the orifice. Simultaneous planar PIV and acetone PLIF are used to compute density weighted velocity statistics to determine the evolution of the turbulent behavior in the flow. Buoyancy effects preserve or increase the turbulent behavior with distance in large density ratio flow, but not when the density ratio is small. Also, asymmetries in the PDFs appear for buoyant flows that are absent for non-buoyant conditions.

INTRODUCTION

Variable density mixing plays an important role in a wide variety of physical systems, including inertial confinement fusion at very small scales [1, 2], and atmospheric and oceanic flows at large geophysical scales [3, 4]. Variable density effects arise when fluids of differing molecular weights begin to mix, or when compressibility effects modify the density of adjacent fluid parcels. For low density ratios, the density field can often be modeled as a passive scalar or using Boussinesq type approximations, but for higher density differences these approximations no longer hold and the density plays an important role in the transport of fluid and the evolution of the turbulent characteristics in the flow. This becomes obvious when the conservation equations, such as that for momentum, are Reynolds averaged:

$$\frac{\partial}{\partial t}\left(\bar{\rho}\tilde{U}_i\right)+\left[\bar{\rho}\tilde{U}_i\tilde{U}_j\right]_{,j}+R_{ij,j}=-P_{,i}+\bar{\tau}_{ij,j}+\bar{\rho}g_i \tag{1}$$

Mean flow quantities appear in density-weighted (Favre averaged) forms instead of Reynolds averaged (such as mean velocity, $\tilde{U}_i$, and Reynolds stresses, R_{ij}). This can also be seen in transport equations for quantities such as turbulent kinetic energy where correlated density-velocity fluctuations appear in production terms. These effects are critical to several types of flows, particularly those driven by Rayleigh-Taylor and Richtmyer-Meshkov instabilities. While buoyant jets and plumes have been studied for many years [5], research has primarily been concerned with large scale and time-average properties and the theory is less developed than classical work on single-fluid jets. Recent investigations [6] have begun a more detailed theoretical examination of the properties of turbulent mixing in variable density flows that reinforces the important role the density field plays in the turbulence structure.

In addition to the limited resolution, small sample size, or partial velocity or density information available in previous works, most studies have concentrated on late-time, far-field behavior in a search for asymptotic or self-similar regimes. There is a lack of data for buoyant jets near the orifice as the mixing transitions from shear-dominated Kelvin-Helmholtz instabilities to buoyancy dominated Rayleigh-Taylor behavior. To help fill this gap, studies of a single negatively buoyant jet are being performed at the Los Alamos Turbulent Mixing Tunnel. Previously, Gerashchenko et al. performed measurements in this system at two different density ratios using simultaneous particle image velocimetry (PIV) and acetone-based planar laser induced fluorescence (PLIF) to characterize density-correlated (Favre-averaged) statistical quantities in a small number of downstream locations at initial jet Reynolds numbers that were transitional or weakly turbulent [7]. In this work, we are extending this analysis to more fully turbulent jets at higher Reynolds numbers and are measuring a larger number of positions to better characterize the development with distance of these quantities.

METHODS AND RESULTS

Experiments are conducted in the Turbulent Mixing Tunnel facility (Figure 1) with a jet of diameter d_0=11 mm and a tunnel coflow of 0.5 m/s. Simultaneous velocity and density measurements are acquired at several downstream locations including y/d_0=3.3, 14.5, and 30 for two density ratios (Atwood numbers). Initial Reynolds number as defined by the jet exit velocity were matched near Re=19,000. More details of the experimental conditions are given in Table 1.

Table 1: List of flow conditions for the high and low density ratio test cases

Case	Flow rate, (LPM)	Re_{jet}	Density, (kg/m^3)	*At*	*Ri*	*Sc*
SF_6	37.8	18,600	4.17	0.63	2×10^{-3}	0.15
Air	157	19,300	1.24	0.14	4×10^{-5}	0.68

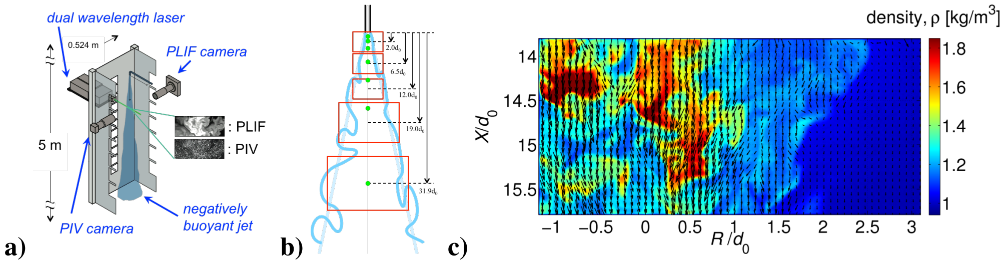

Figure 1: a) Schematic of tunnel test section. b) Diagram of approximate locations and fields of view for PIV and PLIF measurements. C) Example snapshot of simultaneous density and velocity measurements.

For each test condition, up to 10,000 snapshots of the flow were acquired and the final resolution of the processed and registered fields was ~280 μm. Results were studied in terms of Reynolds and Favre-averaged variables. Preliminary analysis has shown similar trends for these high Reynolds number cases as in previous lower flow rate tests [7]. For large density ratios, turbulent kinetic energy and Reynolds stresses are preserved or increased with downstream distance, as shown for Reynolds averaged variables in Figure 2. Additionally, evidence of the initial shear layers at R=±1 persists as far downstream as y=14.5d_0, suggesting that more distance is still required to reach an asymptotic state, if it ever does. The large Atwood number case also demonstrates the development of asymmetries in the density fluctuation and streamwise gradient PDFs that were not present with a low initial density ratio. Measurements of scalar dissipation rate suggest that dissipation is spatially localized and tracks the boundaries of large parcels of denser fluid (Figure 3).

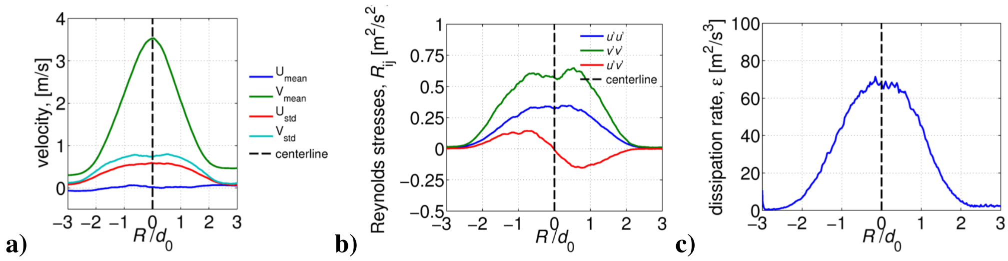

Figure 2: Radial profiles of velocity and turbulent quantities at y=14.5d_0 for the At=0.6 case.

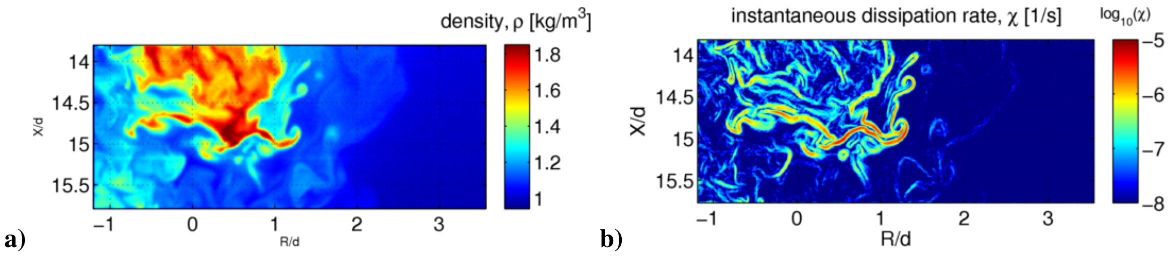

Figure 3: Instantaneous snapshot of the a) density field, and b) scalar dissipation rate

CONCLUSIONS

Simultaneous velocity and density measurements of variable density buoyant jets have been made for fully turbulent jet flow. Analysis of the turbulent statistical quantities shows similar behavior to previous measurements in lower speed jets in similar conditions, and that buoyancy effects play an important role in the final turbulent states achieved.

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