Mixing Asymmetry in Variable Density Turbulence

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Molecular mixing as a consequence of stirring by turbulence is an important process in many practical applications. If the microscopic densities of the fluids participating in the mixing are very different, we refer to such flows as variable density (VD) flows in contrast to the Boussinesq approximation, in which the densities are close. In VD flows, the velocity field is no longer solenoidal, and the specific volume, a function of the amount of each material present, is a new dependent variable. VD mixing is encountered in atmospheric and ocean flows, astrophysical flows, combustion, and many flows of chemical engineering interest [1,2]. Many of these flows are driven by acceleration (e.g., gravity in geophysical and astrophysical flows), which, because the density is not uniform, leads to large differential fluid accelerations. If the acceleration is constant and the fluid configuration is unstable (i.e., density gradient points opposite to the body force), a fluid instability is generated in which small perturbations of the initial interface between the two fluids grow, interact nonlinearly, and lead to turbulence. This instability is known as the Rayleigh-Taylor (RT) instability and is of fundamental importance in a multitude of applications, from fluidized beds, oceans, and atmosphere, to inertial confinement fusion (ICF) and supernova explosions.

The homogenization of a heterogeneous mixture of two pure fluids with different densities by molecular diffusion and stirring induced by buoyancy-generated motions was studied using direct numerical simulations (DNS) in two configurations: a) classical Rayleigh-Taylor instability using a 3072^3 data set [3,4], and b) an idealized triply periodic Rayleigh-Taylor flow named hereafter homogeneous Rayleigh-Taylor (HRT), using up to 1024^3 meshes [2,5].

The datasets used represent the largest simulations to date for each configuration. For the classical RT problem, the simulation achieves a bulk Reynolds number, Re $= \frac{H\dot{H}}{\nu}$ = 32,000, at an Atwood number, A $\equiv \frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$ = 0.5, where $\rho 1$, $\rho 2$ are the pure fluid densities (PDF), and a Schmidt number, Sc = 1. The HRT flows start from rest, with the two fluids in a nonpremixed state corresponding to a double-delta density PDF. The turbulence is generated as the two fluids move in opposite directions due to the body force and eventually dies as the fluids become molecularly mixed. The DNS results are used to follow the turbulence birth-life-death process and examine the influence of various parameters, Atwood, Reynolds, and Schmidt numbers on the mixing rate and the morphology of the active scalar fields. The cases considered cover the Atwood number range A = 0.05 – 0.5, in order to examine small departures from the Boussinesq approximation as well as large Atwood number effects.

As a consequence of the differential accelerations experienced by the fluids, important differences between the mixing in a VD flow, as compared with the Boussinesq approximation, are observed. In short, the pure heavy fluid mixes more slowly than the pure light fluid—in HRT, an initially symmetric double delta density PDF is rapidly skewed, as the pure light fluid vanishes, and only at long times and small density differences does it relax to asymmetric, Gaussian-like PDF. The density PDF skewness generation mechanism, $\langle p(p_{,j})^2 \rangle$, is shown to be determined, through changes in the magnitude of the density gradient, by the eigenvalues of the strain rate tensor and the relative alignment between the density gradient and the eigenvectors of the strain rate tensor, which are different in the pure heavy and light fluid regions. Thus, the local structure of the flow changes in response to the inertia of the fluid particles. Consequently, the inertia of the heavy fluid reduces the rate at which it is broken up by stirring, decreasing the local surface area of the pure heavy fluid blobs, which is related to $\sqrt{(\rho_{,j})^2}$. As a result, the magnitude of the density gradient is lower in the pure, heavy fluid regions, along with the rate of molecular mixing, and the density PDF becomes skewed.

For the RT configuration at large density differences, this suggests that molecular mixing proceeds differently on the two sides of the RT layer. Experiments to date have not investigated this possibility. The results show that one consequence of the mixing asymmetry identified in HRT is that the penetration distance of the pure heavy fluid is larger than that of the pure light fluid. The mixing asymmetry is likely also the cause of the bubble-spike anomaly (higher growth rate on the spike side compared with the bubble side), which was observed experimentally [6].

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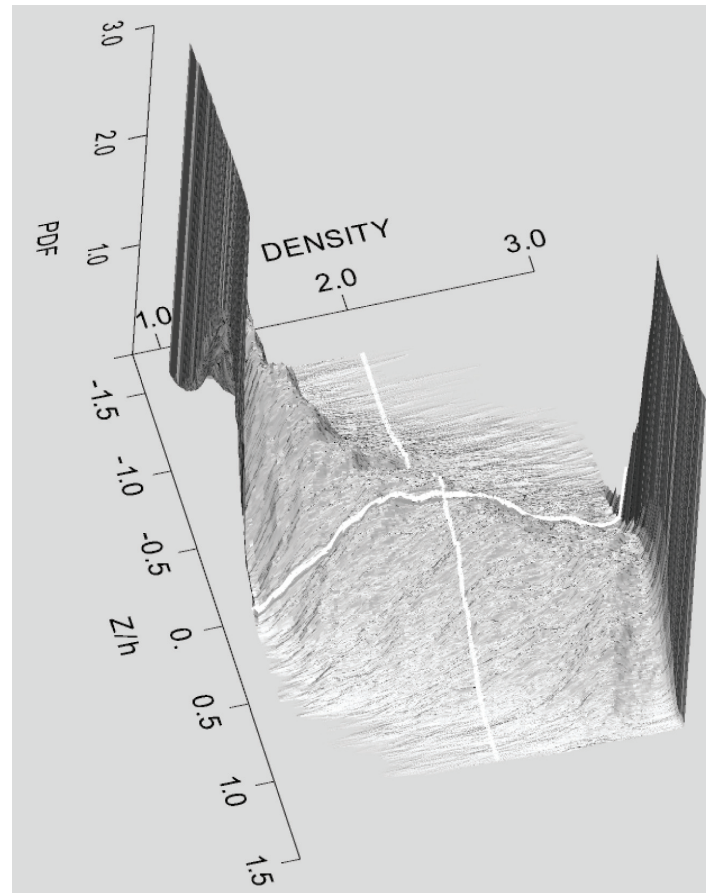
Fig. 1. Surface plot of the density.