Buoyancy-Driven, Variable Density Turbulence

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Mixing to molecular scale in the presence of turbulence-induced stirring is an important process in many practical applications. In general, the fluids participating in the mixing have different densities and we refer to such flows as variable density (VD) flows. In these flows, the specific volume changes in both time and space depending on the amount of each fluid in the mixture and the resulting velocity field is not divergence-free even for constant density fluids. Variable density mixing is encountered in atmospheric and ocean flows, combustion and many flows of chemical engineering interest, astrophysical flows, etc.

Here we consider a simple form of VD multi-material mixing which involves two miscible fluids with different microscopic densities [1,2], in the presence of a constant acceleration, as occurs in the Rayleigh-Taylor (RT) instability. The current investigation focuses on the nonlinear dynamics and statistics of buoyantly driven turbulence in the statistically homogeneous configuration. As such the new nonlinearities due to large density variations in the advective terms of the Navier-Stokes equations become important. The problem is an extension of the buoyantly generated turbulence in a Boussinesq fluid studied in [3] and in a VD fluid examined in [4]. From the modeling viewpoint, this is a benchmark problem that any turbulence model for VD-RT should handily predict.

In VD turbulence with arbitrary boundary conditions, the two first-order moments, the mean pressure gradient, and the mean specific volume are dynamical variables evolving as the mixing proceeds. For periodic boundary conditions though, the mean pressure gradient can be determined up to a constant gradient, which is a free parameter. This is chosen such that the energy conversion of potential to kinetic energy is maximized (see [2]), ensuring a benchmark flow that is the maximally unstable flow in this configuration.

The flow starts with zero solenoidal velocity in a nonpremixed state and turbulence is generated due to the baroclinic production of vorticity and eventually dies as the two fluids become molecularly mixed. The problem involves both the transition to turbulence and the decay of turbulence as the friction forces overcome buoyancy generation. Results from Direct Numerical Simulations are used to follow the turbulence birth-life-death process and examine the influence of various parameters, Atwood, Reynolds, and Schmidt numbers, and initial length scale of the density field on the mixing. The cases considered cover the Atwood number range At = 0.05–0.75, in order to examine small departures from the Boussinesq approximation as well as large Atwood number effects. Simulations with resolutions up to 1024^3 are performed. The numerical methodology employs a new pressure projection algorithm that treats the pressure step exactly and represents an improvement over the methods presently used for variable density flows [4,5].

The study shows that the rate of conversion of potential energy into kinetic energy as well as between Favre mean and turbulent kinetic energies are mediated by the mass flux so that the mass flux is likely the most important quantity to predict in lower dimensional models [2,6]. Numerical and analytical approaches are also used to examine the morphology of the scalar structures and the influence of various parameters on the mixing progress. In particular, it is shown that the specific volume density covariance is a better measure of the flow evolution than the density variance for variable density flows, as it directly appears in the dynamical equations. Nevertheless, the normalized density variance can be related to the variance of the excess reactant in an infinitely fast hypothetical chemical reaction. Under special circumstances this represents a metric for the progress of the fully mixed fluid. Neither measure though can express the amount of pure fluid in the flow, which is related to the tails of the density probability density functions (PDF) [7,8]. A model for the density PDF transport equation is proposed to predict the evolution of the pure and mixed fluids.

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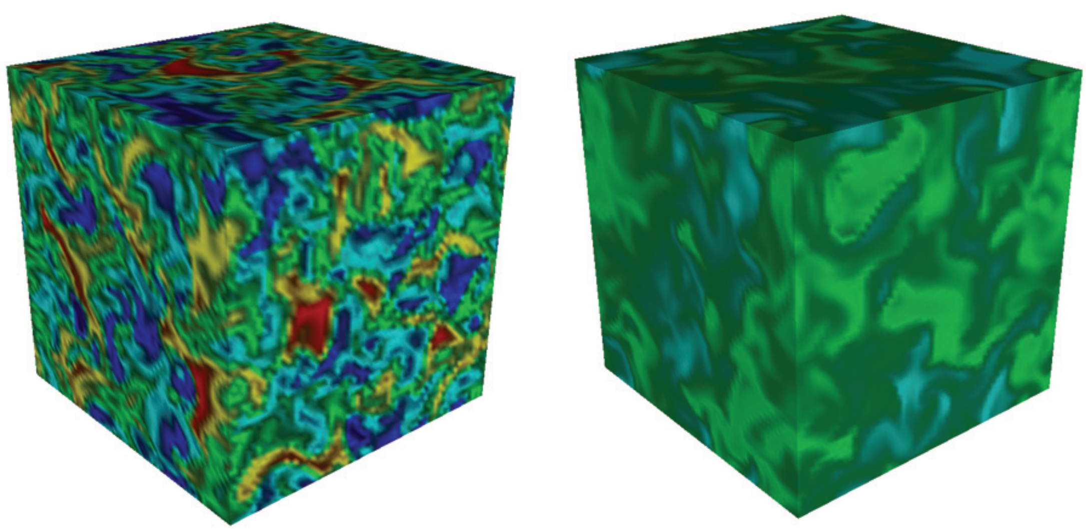

Fig. 1.
Typical density field at maximum density variance (left) and late time (right).