VARIABLE DENSITY MIXING UNDER VARIABLE MEAN PRESSURE GRADIENT

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Abstract Turbulent mixing of a heterogeneous mixture of two incompressible, miscible fluids with different densities is investigated by using Direct Numerical Simulations (DNS). The mixing occurs in response to stirring induced by buoyancy-generated motions, in a triply periodic (1024^3) domain subjected to acceleration, g. The acceleration starts as positive and is reversed (g<0) or changed to neutral (g=0) during the flow evolution. These are unit problems that aim to mimic the core of the mixing layer of acceleration driven Rayleigh-Taylor (RT) and shock-driven Richtmyer-Meshkov (RM) instabilities and are also useful for verification and validation of mix models. The flow starts from rest and, for g>0, there is an initial growth of turbulence followed by turbulence decay as the fluids become molecularly mixed. The acceleration is changed at the peak of the Favre averaged turbulent kinetic energy (TKE). When compared to the constant gravity case, acceleration reversal causes a faster decay of total kinetic energy of the system and replaces larger structures with well-mixed small structures. The transition of energy from large to small scales and the dependence of mixing on the acceleration switch are investigated for Atwood numbers ranging from 0.05 to 0.9. In addition, the decay law for the g=0 case, corresponding to anisotropic, variable density turbulence decay and relevant to the RM problem is also examined.

INTRODUCTION

The mixing of two or more miscible fluids with different densities (or molar masses) is of fundamental interest due to occurrence in atmospheric and oceanic flows, supernova formations, combustion and engineering applications [1]. We call these flows variable density (VD) flows [2]. Such flows have been much less studied than those where density fluctuations arise due to acoustic or thermal effects, despite their practical importance. In general, compositional changes lead to significant specific effects on the mixing and turbulence [3]. When the flow occurs in the presence of acceleration, such as the RT instability, the main turbulent kinetic energy production mechanism is through the product between the mean pressure gradient and the mass flux, so that such flows can be regarded more generally as pressure gradient-driven-flows [2]. At the same time, vorticity is produced through the baroclinic mechanism due to misalignment of pressure (p) and density (ρ) gradients, the strength of which vary widely with the Atwood number (the non-dimensional density contrast between the two fluids). Traditionally, VD mixing has been studied under forward mean pressure gradient. Cook and Dimotakis [4] studied miscible fluids mixing initiated by RT instability, with periodic boundary conditions (BC) on the side surfaces and no-slip BC at top and bottom of the domain. In order to focus on the mixing problem without the complications due to the edges of the mixing layer, Livescu and Ristorcelli [2,3] investigated the corresponding triply periodic flow. However, in many practical applications such as blast waves, inertial confinement fusion capsules or astrophysics, the acceleration is not constant. Time varying accelerations have been studied in the context of RT instability in [5,6].

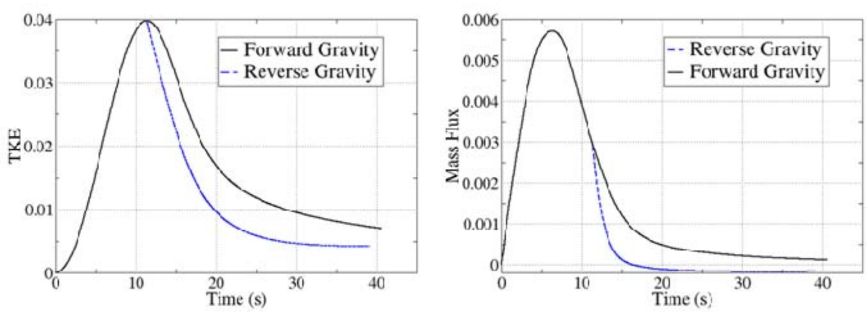

Figure 1. Time evolution of a) TKE and b) Mass flux for forward and reverse acceleration cases at At= 0.05.

In the current work, we will report statistically homogeneous VD mixing under variable pressure gradients due to acceleration changes. In addition to being a problem of fundamental interest, triply periodic, homogeneous VD mixing is crucial in unraveling the evolution of turbulence within the core of the VD mixing layer as occurs in hydrodynamic instabilities. The flow starts from rest, with the two fluids segregated into large-scale random patches. In the forward acceleration case, the turbulent kinetic energy increases at first and then undergoes a buoyancy-mediated decay, as the fluids become molecularly mixed. In order to study variable acceleration effects, we consider two unit problems, when the acceleration is set to zero and fully reversed, at the time TKE peaks. The pure decay case (g = 0) mimics a simplified version of the decay stage in a shock driven RM instability, after the shock has passed through the interface.

The reversal of the acceleration (and mean pressure gradient) is relevant to the interior of the RT layer under complex acceleration histories.

RESULTS

The effects of variable mean pressure gradient on mixing and turbulence are investigated in homogeneous buoyancy driven turbulence using high resolution DNS on a 1024^3 periodic grid, for Atwood numbers, A, ranging from 0.05 (close to the traditional Boussinesq case) to 0.9 (19 to 1 density ratio, as e.g. hydrogen mixing in air), using forward, reverse and zero mean pressure gradient unit cases. The results for the forward acceleration case with A=0.05 are available through the Johns Hopkins Turbulence Databases [7]. In this case, the flow reaches a maximum Taylor-scale Reynolds Number value of 345 and it decays to the value of 184 at the time the acceleration is changed.
As seen in figure 1-a), the acceleration is changed at the peak of the Favre turbulent TKE evolution. The acceleration reversal also changes the direction of the pressure gradient and causes faster turbulence decay. At short times after the reversal, the turbulence decay has similarities to the RT problem under deceleration. However, in this triply periodic flow, unlike the RT instability, the flow does not return to a stable configuration without turbulence and with the two segregated fluids slowly diffusing; instead the turbulence continuously decays until the final state corresponding to fully mixed fluids. As can be seen in figure 1-b) the flow loses memory of the directionality, again unlike the classical RT configuration and begins moving in the opposite direction as indicated by the negative mass flux values.

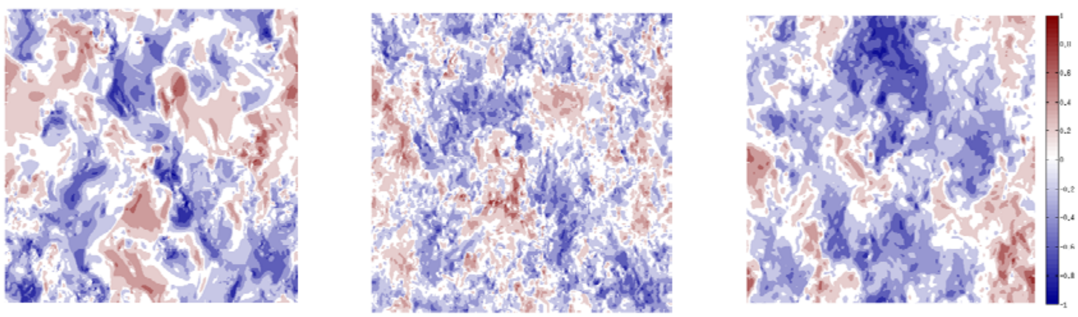

Figure 2. Vertical (-*XZ*) counter plots of the normalized mass flux at a) t=11.4s (reversal time), b) t=16.5s (zero mass flux) and c) t=40.0s (late time).

Figure 2 compares 2-D snapshots of the normalized mass flux for the reverse acceleration case with A=0.05 at three different times that correspond to (a) acceleration reversal (*t* =11.4s); (b) zero mean mass flux (*t* =16.5s); and (c) the end of simulation run time (*t* = 40s). The mass flux values are normalized by the maximum absolute value at the corresponding time. Livescu and Wei [6] reported that acceleration reversal increases small scales activity at short times after reversal in the RT layer. A similar behavior is observed in the current configuration, as it can be seen in figure 2 b). Immediately after reversal, the large scales fragment into smaller structures, but, eventually, the flow recovers, with the small scales merging together to form larger structures and starts behaving similar to the forward gravity case moving in the opposite direction. The sign change in the mass flux is notoriously difficult to be captured by turbulence closures in the RT configuration [5,6] and we hope that these targeted results will lead to improve turbulence models for such flows. The simulations also address the variable density effects on the mixing process, by covering the range of Atwood numbers from 0.05 to 0.9. The differences between the three cases (g>0, g=0 and g>0) addressed here will be examined in terms of various mix metrics, density PDFs, and transport equations budgets for the second order moments (Reynolds stresses, mass flux and density specific volume correlation). Finally, the decay laws for the g=0 case (anisotropic variable density turbulence decay) will be discussed in connection to the RM instability problem.

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