Numerical Simulations of Rayleigh-Taylor Turbulence with a Complex Acceleration History

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The interface separating two fluids of different densities is unstable if an acceleration is applied from the light fluid to the heavy. The resulting instability is the Rayleigh-Taylor (RT) instability and is a dominant phenomenon in the implosion phase of Inertial Confinement Fusion, where the subsequent turbulent mixing dilutes fuel with pusher material, thus reducing yield. Rayleigh-Taylor-driven turbulence is also an important effect in explaining supernova detonations, and other high-energy density applications. Reliable numerical simulations (NS) of the turbulent phase of RT are thus important to the Validation & Verification (V&V) efforts of Advanced Simulation and Computing (ASC) codes and to the stockpile stewardship program in general.

Hydrodynamic simulations of such high energy density phenomena deal with multiple physics and as a result represent the turbulence using low-order mix models. In this article, we describe NS of RT that will be useful when validating mix models in the demanding setting of a complex acceleration history.

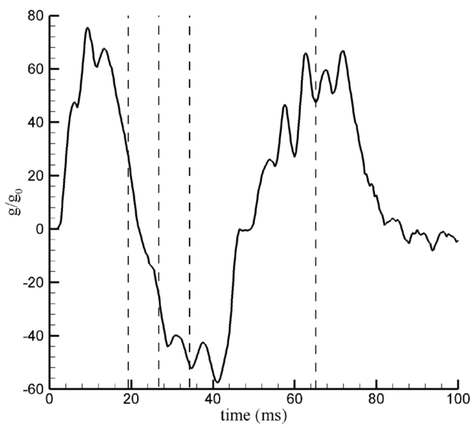

Fig. 1.
Nondimensional acceleration history (g/g_0) used in LEM experiments and NS. g_0 is the earth's gravity.

The simulations employ an incompressible MILES [1] code and reproduce experimental runs on the Linear Electric Motor (LEM) [2,3], which used a three-stage acceleration profile—an initial acceleration stage, followed by a sudden deceleration, and a final re-acceleration stage (Fig. 1). It is expected that not all models will completely describe the separation of phases during deceleration. This is a challenging problem for NS because during deceleration, large bubbles reverse direction and are shredded by smaller bubbles in their way, thus generating small-scales that can only be resolved at large-grid resolutions. Furthermore, the calculations of this incompressible flow would have proved challenging to compressible codes due to their propensity to generate pressure waves during sudden changes in acceleration.

Figure 2 (a–d) shows images of the turbulent density field from experiments and simulations, realized at times indicated by the vertical lines in Fig. 1. A broadband spectrum of density perturbations was used to initialize the simulations, since the experiments are susceptible to ambient vibrations initially, which are expected to have a similar spectral structure. A second set of calculations with energy confined to a narrow band of wavelengths was performed, giving inferior agreement with the experimental results compared with the broadband cases [3]. The subsequent evolution of the bubble penetration depth is shown in Fig. 3 and was found to be sensitive to the initial spectral structure and its r.m.s. amplitude. The calculations accurately describe the initial exponential growth to nonlinearity, the collapse of coherent structures during the deceleration phase, the subsequent recovery during re-acceleration, and the late-time evolution in to self-similarity. It is noteworthy that our high-resolution NS accurately capture the shredding of bubbles into small scales during deceleration, and the associated molecular mixing [3]. We conclude that initial conditions play a critical role in describing RT-driven mixing especially under nonequilibrium conditions.

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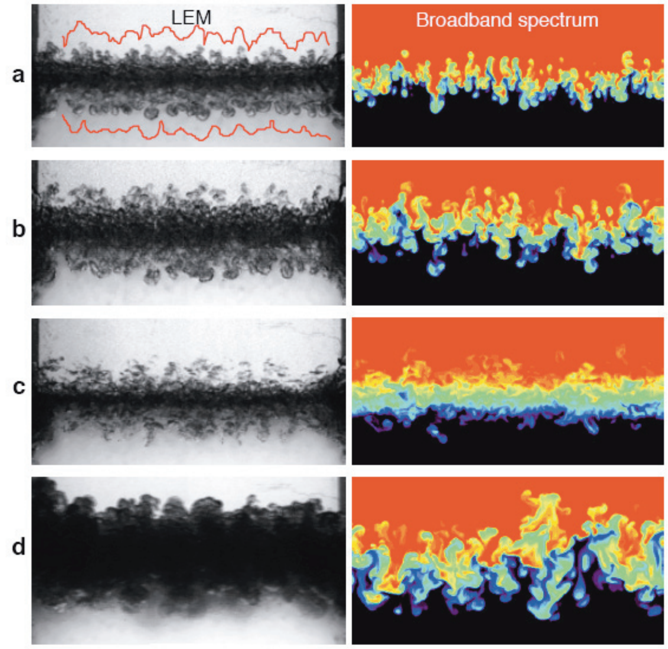

Fig. 2.
Turbulent density field images from experiments (left) and NS (right) at (a) t=19.6 ms, (b) t = 26.8 ms, (c) t = 34.4 ms, and (d) t = 65.2 ms.

[1] Guy Dimonte, et al., *Phys. Fluids* **16**, 1668 (2004).
[2] Guy Dimonte and M. Schneider, *Phys. Fluids* **12** (2), 304 (2000).
[3] Guy Dimonte, et al., "Rayleigh-Taylor Instability with Complex Acceleration History" (submitted to *Phys. Rev. Lett.*).

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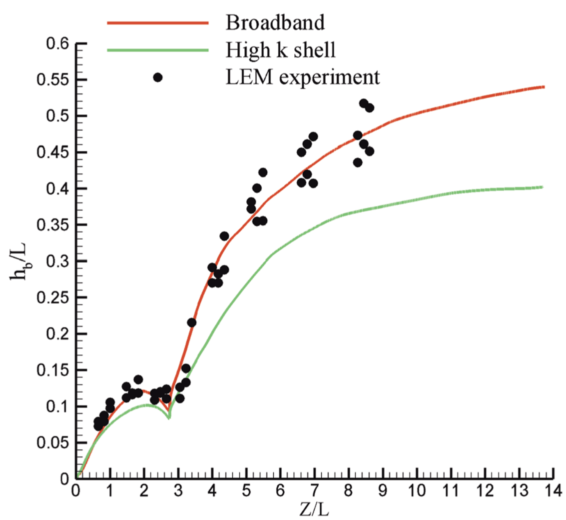

Fig. 3.
Bubble penetration depths h_b-scaled to the cell size L used in LEM runs, from NS and experiments vs Z/L ($Z = \int dt' \int dt'' g(t'')$ cm).