RAYLEIGH-TAYLOR-INDUCED TURBULENT MIXING LAYERS

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Abstract We study mixing layers generated by Rayleigh-Taylor instability. It develops in various physical situations, such as supernovae explosions and inertial confinement fusion, which aims at obtaining thermonuclear ignition by compressing a pellet filled with deuterium-tritium. The numerical simulations we have carried out start from rest and several physical models are involved: Boussinesq, anelastic, and compressible. This allows for a wide exploration of parameters. Results from DNS spectral simulations with around 900 millions collocation points are presented. Anisotropy, compressibility effects, characteristics of turbulence and mixing, are explored.

PHYSICAL MODELS AND NUMERICAL TOOL

Rayleigh-Taylor instability develops when a heavy fluid layer is located above a lighter one, with the presence of an acceleration field. Each fluid layer is stably stratified. The magnitude of the stratification is measured with the dimensionless parameter $Sr = \frac{gL}{RT_r}$, where L is the horizontal size of the calculation domain, and T_r is the homogeneous initial temperature. The density jump at the interface is measured with the Atwood number, varying between two limiting excluded cases: from $A_t = 0$ (homogeneous density, no instability) to $A_t = 1$ (finite density heavy fluid over vacuum). The simulations start from rest. When initialized with a single-Fourier-mode perturbation of the interface, the instability produces a single mushroom, while a multi-mode perturbation generates a mixing layer.

The word "compressible" often refers to two different phenomena: static compressibility and dynamical compressibility. The former is associated with stratification undergone by both fluid layers under gravity. The latter corresponds to acoustics, Mach number and equation of state. We focus on two elliptic-type models, established through asymptotic analysis [1]: anelastic and Boussinesq models. Anelastic model offers a way to study slightly stratified Rayleigh-Taylor-mixing layers where acoustic waves are filtered out. This physical model is valid for small and moderate Atwood number. Adiabatic indexes γ may take any value: small (gases) or high (liquids). Static compressibility is handled while dynamical compressibility is only partially supported. Boussinesq model is only valid for liquids, vanishing Atwood number, and no stratification. This model does not handle any form of compressibility. Anelastic and Boussinesq simulations are less costly than compressible ones, thanks to the absence of acoustic waves which allows for a higher time step.

Our simulation tool, Amenophis, is based on a pseudo-spectral Chebyshev-Fourier-Fourier numerical method. In the vertical Chebyshev direction, the grid is splitted into subdomains whose physical size and location are automatically adapted during the calculation. Simulations begin with a small number of collocation points, which is increased through interpolations as turbulence develops. Anelastic and Boussinesq models are solved with the Uzawa method[2]. Concentration and temperature equations lead to Helmholtz equations. Both direct and iterative solvers have been developed, the latter producing more accurate and more stable results.

NUMERICAL SIMULATIONS

We present several simulations, carried out with up to a billion collocation points. The grid is described as "(Number of domains × Number of Chebyshev points) × Number of Fourier points". Anelastic simulations were run with gases, $\gamma = 5/3$.

- First anelastic simulation: $(20 \times 48) \times 816^2 = 0.639\,10^9$ collocation points, $Sr = 2$, $At = 0.25$. This simulation displays turbulence ($R_{\lambda z} = 131$) and surprisingly strong compressibility effects.
- Second anelastic simulation: $(30 \times 48) \times 816^2 = 0.959\,10^9$ collocation points, $Sr = 0.4$, $At = 0.10$. Parameters are close to a Boussinesq simulation, except that we deal with gases. Calculation is in progress, current state displayed on the right of figure 1.
- One Boussinesq simulation: $(24 \times 40) \times 940^2 = 0.848\,10^9$ collocation points, $Sr = 0$, $At = 0.10$. This simulation presents a very large turbulent mixing layer, and $R_{\lambda z} = 142$. Final state is displayed on the left of figure 1.
- Two anelastic 300-million-point simulations have also been carried out, for a higher Atwood number $At = 0.5$, $Sr = 0.4$ (first one) or $Sr = 2$ (second one), and stopped before turbulence is fully developed.

RESULTS

We have obtained so far several results. The Boussinesq simulation displays:

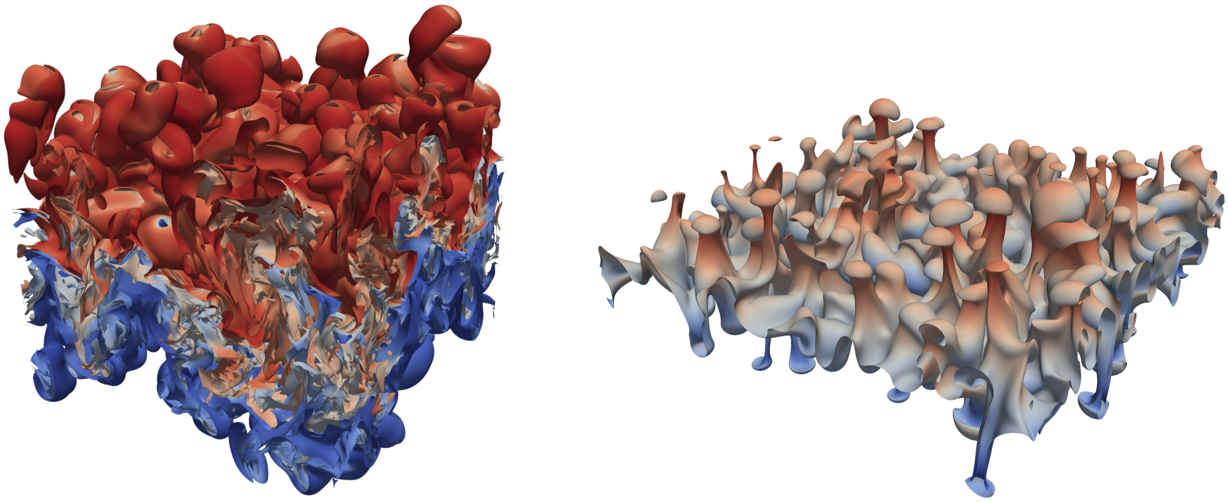

Figure 1. Left: Boussinesq simulation, isosurface of vorticity colored by the concentration in heavy fluid, *final time, t=15.4*. Right: Second anelastic simulation, *in progress, t=13.3*, isosurface of concentration in heavy fluid $c = 0.5$, colored by the divergence $\partial_i u_i$. Both: gravity is top-down. [3]

- a well-verified self-similarity in the mixing layer. Its width h verifies the scaling law $h = \alpha Atgt^2$, and various quantities (such as $\overline{c}$, $\overline{c'^2}^{1/2}$, $h^{-1/2}\overline{\epsilon}$, $h^{-1}\overline{k}$) are well superimposed when plotted versus z/h at different times.
- two main characteristics of anisotropy. While the global spatial average $b_{zz}(t)$ of the vertical component b_{zz} of the anisotropy tensor displays a limit of about 0.3, horizontal-averaged anisotropy $b_{zz}(z,t)$ remains spatially non-homogeneous.
- intermittency, which is revealed by 2D plots of local Taylor-based Reynolds numbers.

Static and dynamical compressibility effects appear in the anelastic simulations:

- asymmetry between the structures on the sides of the mixing layer: bubbles on top and spikes below,
- high Mach numbers (i.e., dynamical compressibility) are located at the edges of the mixing layer,
- stratification (i.e., static compressibility) has an important impact on the growth rate of the instability in the early stages,
- high Atwood number simulations (with gases) display strong dynamical compressibility effects before turbulence is developed. Full compressible model is the only one valid here for calculating large turbulent mixing layers [4].

Moreover, Probability Density Functions and multi-scale concentration variances [5] allow for a deep insight of mixing and turbulence.
This study with the set of simulations allows us to better understand the validity domain of each model, and the characteristics of Rayleigh-Taylor flows.

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