# DIRECT NUMERICAL SIMULATIONS OF TILTED RAYLEIGH-TAYLOR INSTABILITY

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*Abstract* The tilted Rayleigh-Taylor instability, where the initial interface is not perpendicular to the driving acceleration, is investigated, for the first time, using Direct Numerical Simulations, on mesh sizes up to $1536^2 \times 7200$. In this configuration, the inclination of the initial interface results in a large-scale overturning motion, in addition to the buoyancy driven instability. Thus, this flow represents a unique turbulence unit problem, with two-dimensional mean flow and both shear and buoyancy production of turbulence. Two sets of simulations are presented: a) using a thin-tank domain in order to compare the results with the rocket-rig experiments of Smeeton and Youngs [7], and b) using a square cross-section domain. The results are used to examine the interaction between shear and buoyancy, including the parameters influencing the overturning and mixing, the role of initial conditions, and the differences in the turbulence characteristics, at large and small scales, between the thin-tank and square cross-section domain cases.

## INTRODUCTION

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 such flows, due to the tight coupling between the density and velocity fields, in addition to the quadratic non-linearities of the incompressible Navier-Stokes equations, new cubic nonlinearities arise. In addition, 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, etc. 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 instability (RTI) and is of fundamental importance in a multitude of applications, from fluidized beds, oceans and atmosphere, to ICF and supernovae explosions [2].

Although this instability has been subjected to intense research over the last 50 years, until recently, numerical studies have been restricted to coarse mesh calculations. On the other hand, it is notoriously difficult, in laboratory experiments, to accurately characterize the initial conditions and provide the detailed measurements needed for understanding the physics of the flow and help turbulence model development and validation. Nevertheless, today's petascale computers allow fully resolved simulations of RTI at parameter ranges comparable to those attained in laboratory experiments, but providing, in carefully controlled initial and boundary conditions studies, much more information than the physical experiments. These extremely high resolution simulations are enabling a look at the physics of turbulence and turbulent mixing in unprecedented detail.

We have have recently generated an extensive database of large classical Rayleigh-Taylor simulations (including the largest instability simulation to date) covering a wide range of parameters (density ratio, Re and Sc numbers, and initial conditions). Our preliminary analysis of the data has shed new light on the long standing open question regarding the discrepancy between the numerically and experimentally computed mixing layer growth rates [2, 5, 6] and has shown, for the first time, that the mixing layer consists in a fully turbulent inner region and a turbulent/non-turbulent interface near the edges. The former is similar for all cases considered, while the latter retains the memory of the initial conditions and can grow at different rates for various classes of initial conditions. In addition, our previous results showed that mixing is fundamentally different at high and low density ratios, with the pure heavy and light fluids mixing at different rates [3, 5]. We have also shown that, in the presence of buoyancy production, there is a persistent, relatively large anisotropy at the dissipation scales, while the intermediate scales become close to isotropic, consistent with the emergence of an inertial range [3, 4, 5].

However, having an initial interface perpendicular to the direction of gravity, as is considered by the classical RTI, is very difficult to obtain in practical applications. Indeed, most RTI experiments have some amount of tilting of the initial interface. Therefore, in order to be able to compare numerical and experimental results, one also needs to understand the effects of this initial tilting. When the degree of tilting is non-negligible, the resulting mean flow is no longer one-dimensional as is the case with the classical RTI, and the two main turbulence production mechanisms, buoyancy and shear, are both present. Therefore, the tilted RTI represents a unique unit problem for studying the competition between shear and buoyancy production of turbulence and the respective effects on the mixing and turbulence properties.

# RESULTS

The “tilted-rig” test problem originates from a series of experiments (e.g [7]) performed at AWE in the late 1980’s, which were followed by several other experiments elsewhere (see [1] for a review). The experiment comprises a tank filled with light fluid above heavy and then tilted on one side of the apparatus, thus causing an “angled interface” with respect to the acceleration (which is time variable) due to rockets. The inclination of the initial interface results in a large-scale overturning motion, in addition to the buoyancy driven growth of the mixing layer. Also, a single bubble and spike form on the lateral walls, which help drive the overturning motion. Nevertheless, the existent experimental measurements are limited to the width of the mixing layer and heights of the bubble and spike near the wall, and very little information is known about the initial perturbation.

In order to study this unique turbulence unit problem, we have performed very high resolution Direct Numerical Simulations with various parameters. The first set of simulations have the domain size matching the experimental conditions, which correspond to a thin tank. The evolution of the mixing layer was found to be strongly influenced, for the duration of the experiments, by the initial perturbation spectrum shape and variance. A set of initial conditions matching the available experimental measurements at 3 density ratios: 2 to 1, 3 to 1, and 19 to 1, has been obtained. Our previous single mode RTI simulations [8] have shown that, at sufficiently large Reynolds numbers, the layer growth becomes quadratic, contrary to the long-held view, that this growth should be linear. Given the importance of the side bubble and spike to the overturning motion, having a sufficiently high Reynolds number (which implies a sufficiently large mesh size) is very important.

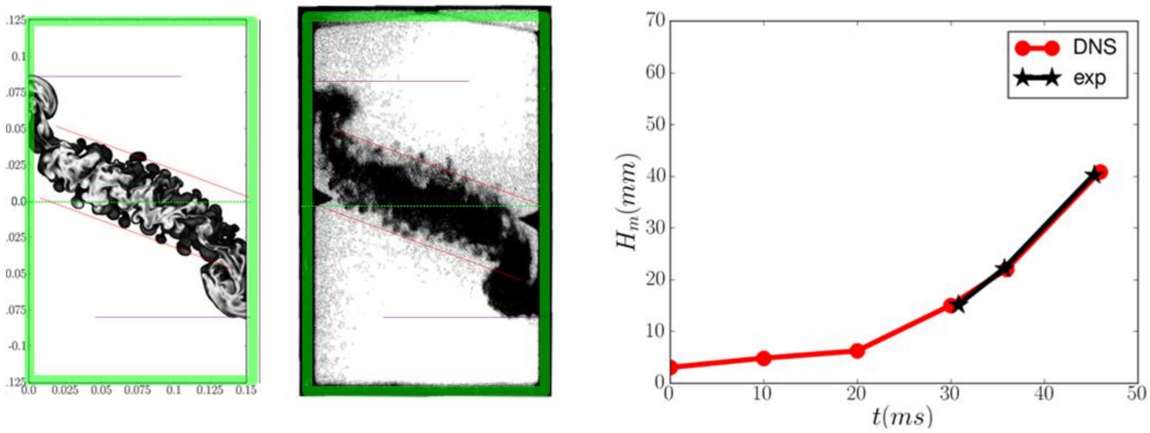

**Figure 1.** Tilted RTI comparison between the DNS and experimental results from Ref. [7]. a) Experimental mixing layer, b) DNS mixing layer, c) Layer width.

We have also performed simulations in square cross-section domains, with meshes up to $1536^2 \times 7200$, and the same conditions as the thin-tank runs. In general, mixing is different for the two cases, due to the inhibition of the vortex stretching mechanism in the thin-tank. In addition, the scales larger than the depth of the thin-tank exhibit a two-dimensionalization, which further affects the structure of the flow. Results will also be presented on the interaction between buoyancy and shear, including the parameters influencing the overturning and mixing, anisotropy, and spectral properties of the flow.

## References

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