# Rayleigh-Taylor Instability

A heavy fluid (ρ_{heavy}) supported against gravity (g) by a lighter fluid (ρ_{light}) constitutes an unstable situation (Rayleigh-Taylor instability – RT). A glass of water that is held inverted will cause the water to fall out the sides of the container, while a column of air rises along the center in its place. While the atmospheric pressure associated with the air column is sufficient to support the weight of the water, the instability is caused by tiny perturbations at the interface. More generally, the acceleration may be different from the earth's gravity, or even impulsive where the resulting flow is called a Richtmyer-Meshkov instability.

The interfacial perturbations may be of a single wavelength (λ), or comprise of a superposition of many waves (i.e. a spectrum). A single wavelength will grow exponentially in time, before saturating to a constant terminal velocity at late-time. Structures of the light fluid penetrating the heavy are called bubbles, while the corresponding fingers of the heavy fluid are termed spikes. When a spectrum of modes is present, the interactions between modes result in a turbulent flow, characterized by a high level of mixing between the fluids, and self-similarity.
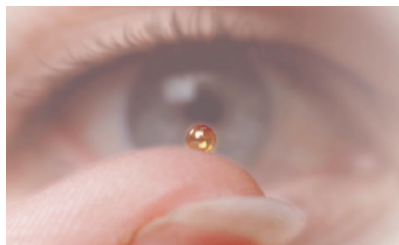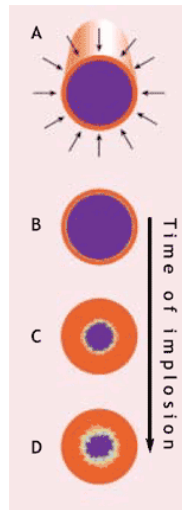
(a)   (b)

Figure 1 *(a) An ICF pellet and (b) a schematic of laser-driven implosion.*

Such instabilities figure prominently during the implosion of fusion targets bombarded by high-energy lasers (Inertial Confinement Fusion). Small irregularities at the pusher-fuel interface are magnified by the unstable hydrodynamics,

ultimately degrading the thermonuclear yield (Figure 1). Such fusion experiments are critical in modeling high-energy density processes that occur during the detonation of nuclear weapons. Consequently, reliable numerical simulations of RT are an essential component to the nation's stockpile stewardship program, and play a key role in the certification of the nation's stockpile.

RT-driven mixing also occurs in diverse applications ranging from supernova explosions to temperature inversions in the atmosphere. A deeper understanding of the mechanism of such flows would shed light on the many processes that underpin fully developed turbulence. Hence, insights developed from studies of RT turbulence may be applied to other canonical flows. We use high-resolution numerical simulations to study the behavior of single bubbles, bubble interactions, and by extension RT turbulence.
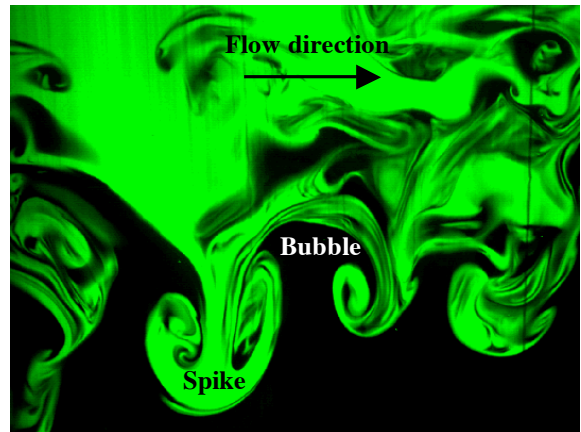

Figure 2 *Laser induced fluorescence image from a Rayleigh-Taylor experiment..*

The difficulty inherent in sustaining an unstable density stratification has challenged experimentalists for over half a century. Several innovative approaches have been developed, and an example is shown in figure 2. Here, the unstable density stratification is set up by co-flowing streams[1] (heavy above light) of different densities that are initially kept separate by a splitter plate. As the two streams leave the edge of the splitter plate at the same velocity, buoyancy-driven mixing occurs. In the figure, the heavy fluid was seeded with a fluorescent dye sensitive to green laser light. Collectively, experiments have provided us with invaluable information on the nature of RT, and

demonstrated that the turbulence is self-similar, with a growth constant $\alpha \sim 0.07$.

With the advent of supercomputers, high-resolution 3D numerical simulations of RT at high Reynolds numbers have become a reality. However, simulations using many different benchmark codes[2] and experiments[1] disagree on the value of the growth constant α associated with the spread of the turbulent mixing zone. Simulations give $\alpha \sim 0.03$, while experimental values are higher by 100%.
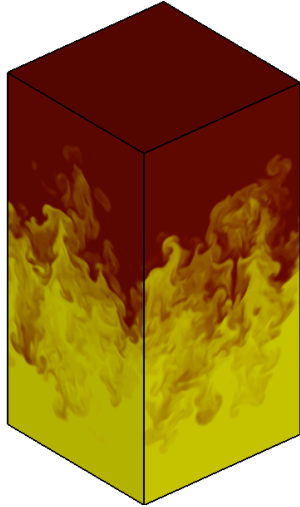
Figure 3 *A snapshot of RT mixing from a high-resolution numerical calculation.*

A recent model postulated[3] that RT flows retain memory of their initial conditions, and that the apparent discrepancy between experiments and simulations is due to differences in their initial spectra. Numerical simulations are initialized with an annular spectrum of modes, while experiments have a broadband distribution of modes often resulting from ambient vibrations in the laboratory. In the former limit (*mode-coupling*), modes within the annulus in wavenumber space interact with each other to produce long-wavelength structures that dominate the flow eventually. This process manifests itself in physical space by the merging or coalescence of two or more bubbles. After a few generations of mergers, the details of the initial spectrum become less important, and α approaches a universal, lower-bound value of ~ 0.02. In the opposite limit (*long-wavelength saturation*), the flow samples modes that are already present in a broadband spectrum. Here, the amplitudes of such modes remain important even at late-time, and will determine the value of α. As a result, if the modal

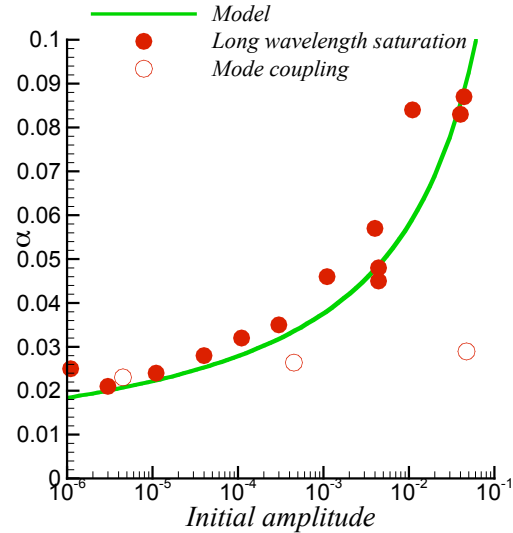amplitudes are large (as they are in experiments), α can be proportionally high.

Fig. 4 *Comparison of α from numerical simulations and a recently proposed theory.*

We put these ideas to test using simulations with initial conditions designed to evolve through both these routes[4]. Figure 4 is a summary of our results and validates the above hypotheses. We believe these ideas may be useful in devising effective control strategies for RT turbulence. Furthermore, such an approach based on coherent structure dynamics may be applied to address the question of universality of other turbulent flows.

References

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