Self-Similarity, Scale Separation, and Universality in Rayleigh-Taylor, Boussinesq Turbulence

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The Rayleigh-Taylor (RT) instability occurs when a heavy fluid is pushed by a light fluid. Two plane-parallel layers of fluid, the heavier on top, are in equilibrium; with the slightest perturbation the heavier fluid moves down under the gravitational field, and the lighter fluid rises. The development of the instability leads to enhanced mixing and growth of the mixing zone. Dimensional arguments, supported by large-scale modeling [1], suggest that the half-width of the mixing zone, h, grows quadratically at late time, $h \propto \alpha A g t^2$, where A is the Atwood number characterizing the initial density contrast and g is the gravitational acceleration; α is a dimensionless coefficient, studies of which have dominated the RT turbulence literature for the last 50 years [2].

We focus here on analysis of the mixing zone internal structure rather than α. Available phenomenology [3] can be summarized in the following statements: (i) the small-scale turbulence in the mixing zone is adiabatically adjusted to the large-scale buoyancy-controlled dynamics; (ii) in three dimensions, velocity fluctuations at smaller scales are asymptotically decoupled from weaker buoyancy effects; and (iii) the spatial scalings of the velocity and density fluctuations are similar to the scalings in homogeneous Kolmogorov turbulence. Also notice a couple of important deficiencies of the phenomenological approach: (A) it treats all z-slices within the mixing zone equally; (B) it does not differentiate between the mixing zone width, h, and the energy-containing scale, R_0, for the turbulent fluctuations.

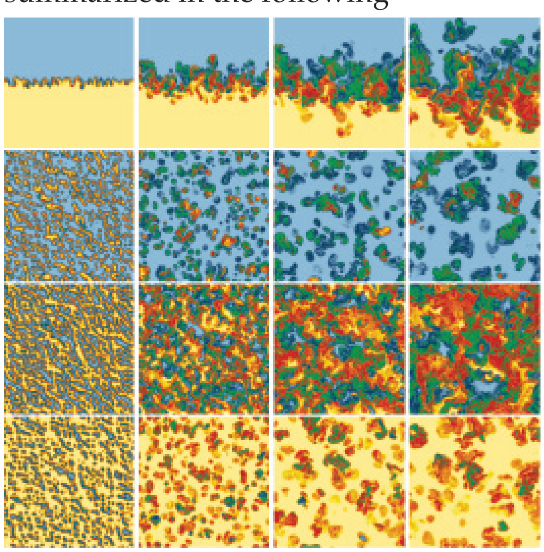

Fig. 1.
Slices of temperature at times t = 32, 64, 96, 128 (left to right). From top to bottom, the images correspond to vertical slices at y = 480 and horizontal slices at z = +0.75h, 0, –0.75h.

Experimentally [4] and numerically [5,6] obtained energy spectra, averaged over a snapshot of the mixing zone, are all consistent with predictions of Ref. [3]. One important consequence of the phenomenology is a decrease of the viscous and dissipative scales, η and r_d respectively, also predicted in [7] and numerically observed in [6,7].

Here we address questions raised by the phenomenology through simulations from the spectral element code developed by Tufo and Fischer [8]. We consider 3-D incompressible RT flow in the Boussinesq regime with finite viscosity and dissipation (Fig. 1). The two fluids are allowed to mix through diffusion.

1) Can the relative dependence of scales be a more reliable indicator of universal behavior than the time-dependence of each individual scale?

We found that R_0, η, and r_d exhibit monotonic evolution with z/h (Fig. 2). This scaling behavior is consistent with predictions of Ref. [3].

2) How does the energy containing scale, R_0, compare with h? We found that at late time, the ratio of R_0 to h taken at the center of the mixing zone is ≈ 1:20 (Fig. 3).

3) Do the turbulent spectra vary as a function of vertical position in the mixing zone? We did not observe any qualitatively new behavior in spectra at any off-centered slices in comparison with the central slice (Fig. 4).

4) How different are the scales and spectra corresponding to qualitatively different initial perturbations? We found that the dependence of R_0, η, and r_d vs z/h on the initial perturbations is weak.

We plan to extend this analysis to account for effects of chemical reactions on the RT turbulence.

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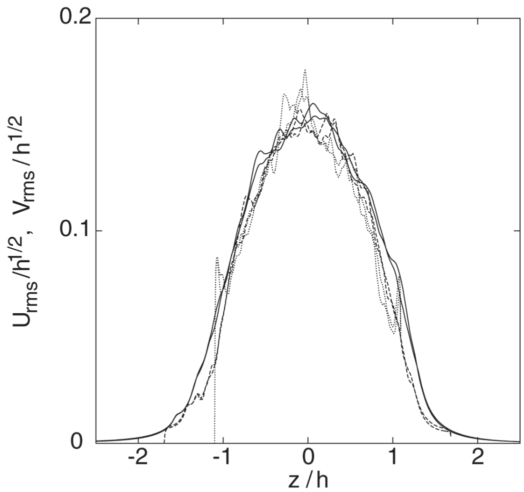

Fig. 2.
Horizontal velocities vs height at times **t** *= 64 (solid line),* **t** *= 96 (dashed line), and* **t** *= 128 (dotted line). Curves taken at different values of* **h** *are almost indistinguishable from each other.*

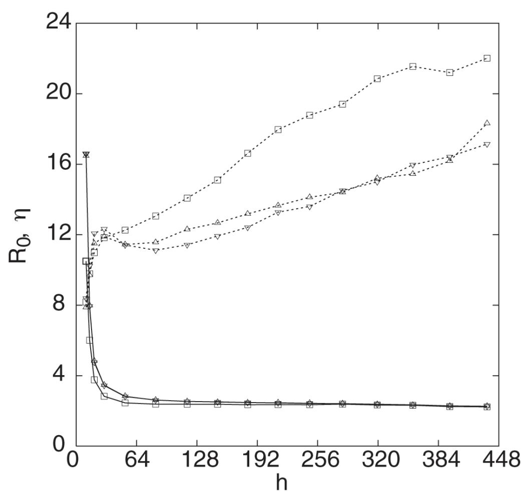

Fig. 3.
The energy-containing scale (dashed lines) and the viscous scale (solid lines) in the middle of mixing layer. Squares correspond to vertical component of velocity, while triangles correspond to horizontal components of velocity.

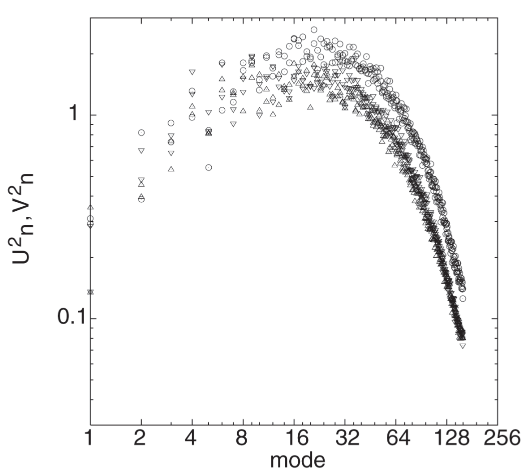

Fig. 4.
Energy spectra at time **t** *= 64 in horizontal planes* **z** *= 0 (circles) and* **z** *± 0.75***h** *(triangles).*

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