Revisiting the Late-Time Growth of Single-Mode Rayleigh–Taylor Instability and the Role of Vorticity

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The Rayleigh–Taylor instability (RTI) appears at a perturbed interface when a light fluid (ρ_l) is accelerated against a heavy fluid (ρ_h). It can significantly degrade a target's performance in inertial confinement fusion. In Ref. 1 Layzer predicted the nonlinear stage development on assuming a potential flow with Atwood number $A \equiv (\rho_h - \rho_l) / (\rho_h + \rho_l) = 1$. Later, in Ref. 2, Goncharov generalized Layzer's theory to arbitrary Atwood numbers. The model predicts a terminal bubble velocity of $U_\mathrm{b} = 2Ag / [(1+A)Ck]$, where $C = 3$ in 2-D and $C = 1$ in 3-D; k is the perturbation wave number.

Recent studies have shown the limitation of potential flow models in both ablative[3,4] and classical RTI.[5–7] In this study, we perform high-resolution, fully compressible simulations with the highest resolution (1024 × 8192 in 2-D and 256 × 256 × 2048 in 3-D). The late-time behavior of bubbles and spikes is studied systemically at both low and high Atwood numbers at different perturbation Reynolds numbers:

$$\mathrm{Re_p} \equiv \lambda \sqrt{\frac{A}{1+A} g\lambda} \Big/ (\mu / \rho_I),$$

where λ is the perturbation wavelength, g is gravity, and ρ_I is the interfacial density. A comparison between 2-D and 3-D RTI is also conducted.

As shown in Fig. 1(a), the analysis of $\mathrm{Re_p}$ suggests that (1) at sufficiently large $\mathrm{Re_p}$, the enhancement in bubble velocity beyond the "terminal" value is sustained and does not decrease at later times, as had been previously observed in lower-resolution simulations,[6] and (2) even at lower $\mathrm{Re_p}$, when the re-acceleration fails or is not achieved altogether, the bubble velocity does not maintain a constant value but decays instead at late times.

Figure 1(b) shows that increasing A makes it more difficult for bubble speed to increase and persist above the "terminal velocity" value of potential flow theory. This is consistent with the findings of Ramaprabhu *et al*.[6] However, Ramaprabhu *et al*.[6] showed an eventual deceleration back to the terminal velocity after a transient re-acceleration stage for all Atwood numbers. In contrast, our results indicate that the bubble speed enhancement above the terminal value can be sustained regardless of A if the $\mathrm{Re_p}$ is sufficiently large. The differing results are most probably caused by the difference in resolution and our code guaranteeing momentum conservation. The results reported here maintain symmetry, which is necessary for momentum conservation, and are at a significantly higher resolution than what was possible several years ago when the study by Ramaprabhu *et al*.[6] was conducted. Compared to the simulations in Ref. 6, our simulations show a clear and sustained bubble-speed enhancement at $A = 0.04$ and 0.25. At $A > 0.25$, the bubble velocity exhibits intermittent oscillations above the terminal value with an intensity that increases with increasing $\mathrm{Re_p}$, suggesting that a clear sustained bubble-speed enhancement is possible if $\mathrm{Re_p}$ is sufficiently large.

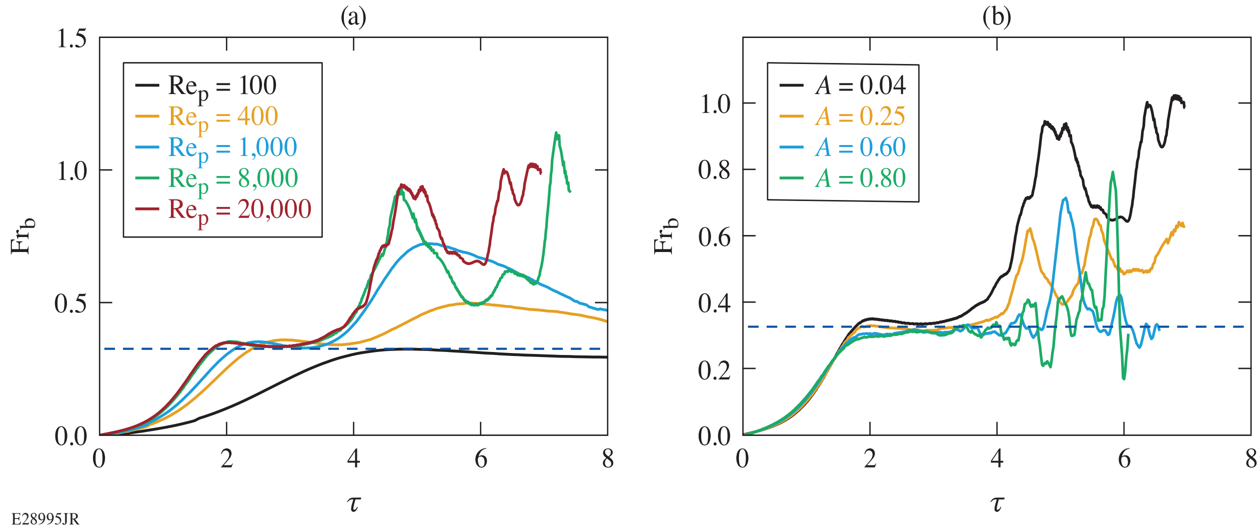

Figure 1
(a) The effects of $\mathrm{Re_p}$ on the bubble velocity in 2-D RTI at A = 0.04; (b) effects of A on the bubble velocity in 2-D RTI at $\mathrm{Re_p}$ = 20,000. The dashed lines in (a) and (b) show the potential model prediction. $\mathrm{Fr_b}$ is the nondimensional bubble velocity; τ is the nondimensional time.

Three-dimensional density visualizations are shown in Fig. 2. The effects of A and $\mathrm{Re_p}$ on RTI are qualitatively similar in 2-D and 3-D; however, 3-D bubbles are easier to re-accelerate, having a lower $\mathrm{Re_p}$ threshold for any A.

The strong correlation between vorticity and bubble velocity suggests that re-acceleration and deceleration of the bubble front is determined by vorticity accumulation inside the bubble, consistent with the previous findings.[3,7] Here, we quantitatively show that the vortices that propel the bubble front are not generated inside the bubble but are instead generated far below the bubble tip. The vortices then propagate toward the bubble tip. Note that the vortices need to move faster than the bubble tip, which implies that the induced vortical velocity should enhance the advection velocity.

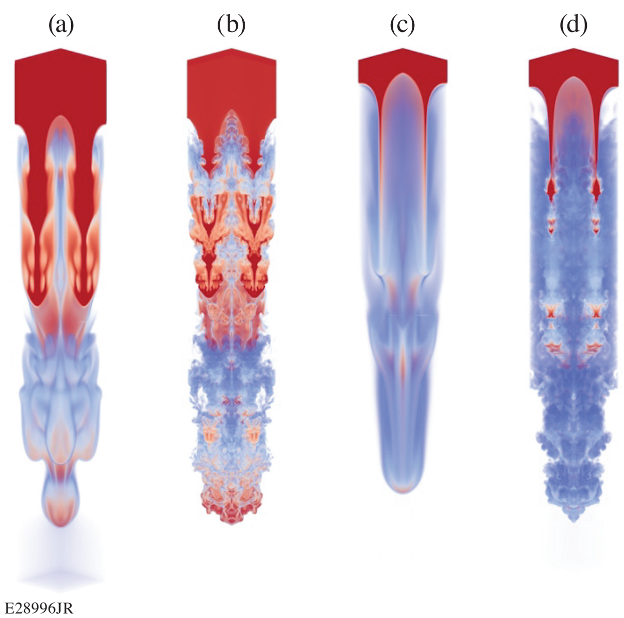

Figure 2
Three-dimensional density visualization at τ = 5. [(a),(b)] Results at A = 0.04 for $\mathrm{Re_p}$ = 1000 and 8000, respectively; [(c),(d)] results at A = 0.8 for $\mathrm{Re_p}$ = 1000 and 8000, respectively.

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