Rayleigh-Taylor instability: An initial condition study

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INTRODUCTION

- Rayleigh-Taylor (RT) instability occurs when density and pressure gradients are misaligned, \( \nabla \cdot \rho \nabla P < 0 \). The baroclinic torque, \( \nabla \times \vec{v} \) is the source of initial vorticity.
- In the current study, the Water Channel facility, an initial unstable stratification of cold and hot water streams are actuated by gravity.
- A servo controlled flapper mechanism provides precise initial perturbations at the interface of the cold and hot water streams.
- Stages of RT evolution with time: Linear \( \rightarrow \) Non-linear (mode coupling) \( \rightarrow \) Turbulent.

Motivation

- RTI is observed in many natural phenomena such as clouds, salt-water domes, astrophysical events (e.g., nebulae).
- RTI is also witnessed in several applications such as in the ICF (Inertial Confinement Fusion) and spray ignition in engines etc.

EXPERIMENTAL SETUP

Flow parameters
- \( U = 4.5 \text{ cm/s} \)
- \( H = \frac{T_{max}}{T_{max} + 5.0^\circ} \)
- \( \Lambda_0 = 1.2 \times 10^{-3} \)

Diagnostics
- High resolution imaging
- Line of Sight (LOS) imaging
- Thermocouple measurement
- 1Hz temporal resolution
- Density field extracted
- Particle Image Velocimetry (PIV)
- 30Hz temporal resolution

PLIF EXPERIMENTAL PARAMETERS

Initial conditions
- Initial condition
- \( \frac{d_{PLIF}}{2} \leq \frac{x}{H} \)
- \( y_0 \leq \frac{\rho_c}{\rho_0} \times \frac{\Lambda_0}{U} \)

Broadband case
- A waveform similar to Olson & Jacobs (2009) RT experiment was used.
- The wavelengths were rescaled to \( \Lambda_0 \times 2.04-4.0 \text{cm} \), so that they are comparable to case 1.

Analysis details
- Background intensity and laser plane divergence corrected. Linear attenuation of light with \( y \) at low dye concentration
- Ensemble average of 800 images used to calculate mixing width. Equivalent wavelength, \( \lambda_{eq} \) based on initial height

RESULTS & DISCUSSION

- The wake interacts with RT evolution. PIV measurement indicates that the wake is highly symmetric about the splitter plate.
- The peak wavenumbers in \( \omega - \beta \) spectrum (fig. 3(a)) correspond largely to the splitter plate thickness and spacing between the wire meshes.
- The molecular mixing parameter, \( \theta \), obtained from PLIF images indicate that the effect of the wake in diffusion mixing is very small compared to that of baroclinic vorticity.
- \( \chi^2 \) plotted along \( y \sim 0 \) (fig. 3(c)). Here \( t = \frac{y}{\lambda_{eq}} \) using Taylor’s hypothesis

CONCLUSION & FUTURE WORK

- In the mode coupling regime, the growth rates are comparable with each other for different cases (fig. 4(b)). However, saturation has not been attained for many cases.
- The fastest growth rate is of the broadband case while the slowest corresponds to the no-flapper motion case.
- Scalar dissipation rate scales as \( \lambda_{eq}^3 \) and flattens out at late-times, showing independence of fine-scale mixing (fig. 4(d)).
- Simultaneous PLIF + PIV data of these cases will help study of few characteristics such as anisotropy and saturation, and validation of computational RT codes.

ACKNOWLEDGEMENT

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NOMENCLATURE & DEFINITIONS

- \( P \) Pressure
- \( \rho \) Density
- \( \mu \) Fluid viscosity
- \( \lambda \) Mean convective velocity
- \( \alpha \) Temperature
- \( \theta \) Mole fraction of fluid
- \( \beta \) Molecular mixing parameter, \( \beta = 1 - \frac{\rho_c}{\rho_0} \)
- \( \beta_{eq} \) Density fluctuation self-correlation for miscible fluids
- \( \beta_2 \) Density fluctuation self-correlation for distinct fluids
- \( \tau \) Time, \( t = \frac{y}{\lambda_{eq}} \) with time scale, \( \tau = \frac{H}{\lambda_{eq}} \)
- \( T \) Total time of observation
- \( \chi \) Instantaneous scalar dissipation, \( \chi^2 = \frac{\lambda_{eq}^2}{2} \left( \frac{\lambda_{eq}^2}{2} \right) \)
- \( \sigma_c \) Schmidt number
- \( \Lambda_0 \) Total channel height
- \( \Lambda \) Wavelength of initial condition
- \( \Delta \) Displacement of initial condition
- \( \alpha \) Amplitude of initial condition
- \( \omega \) Angular frequency
- \( \beta \) Phase angle of initial condition
- \( \gamma \) Prandtl number
- \( \beta \) Streamwise velocity
- \( \alpha \) Spanwise velocity

RESULTS & DISCUSSION

RT Mixing study

(c) Breakdown with 11 modes (case 16)
(d) Qualitative scalar dissipation rate contours (case 16)

(a) Without flapper motion (case 1)
(b) Qualitative scalar dissipation rate contours (case 18)

Figure 1: Schematic of the Water Channel setup

Figure 2: Flow visualization for select cases

Table 1: List of experiments

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<th>Case</th>
<th>Description</th>
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</tr>
</tbody>
</table>

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