On the Effect of Initial Velocity Field and Phase Shifting of an Initial Binary Perturbation for Rayleigh-Taylor Instability

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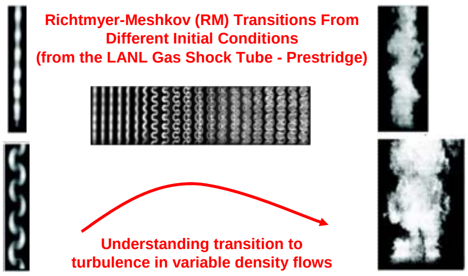
1. Abstract

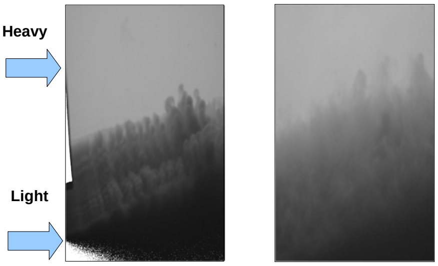
Starting (initial) conditions (ICs) can influence the development of hydrodynamic turbulence and material mixing in buoyancy driven flows. The overall goal of our research is to determine the extent to which starting conditions can be used to predict and design turbulent transport/material mixing. In particular, this work studies the effect of the initial velocity field and phase shifting on a binary initial perturbation. Results of an experimental investigation in which precisely defined initial conditions have been prescribed are presented. These experimental results serve as references that we try to match as closely as possible with numerical simulations. Our simulations show that the initial velocity field drives the growth of the initial perturbation in this experiment. Also, a "leaning" of the growing flow structures observed in the experiment is captured by the simulations, and linked to the phase shift.

2. Motivation



Richtmyer-Meshkov (RM) Transitions From Different Initial Conditions (from the LANL Gas Shock Tube - Prestridge)

Understanding transition to turbulence in variable density flows



Long wavelength initial conditions.

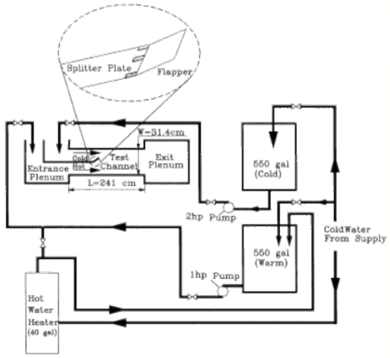
Short wavelength initial conditions.

From the Texas A&M water channel.

3. Central Hypothesis

Carefully prescribed initial conditions could be used to control "late-time" turbulent transport and mixing effectiveness.

4. Experimental investigation



Experimental configuration

The Texas A&M water tunnel experiment is a statistically steady experiment to study Rayleigh-Taylor mixing. In this experiment, two fluids of different densities initially separated by a splitter plate flow in a tunnel. Off the end of the splitter plate, Rayleigh-Taylor mixing occurs if the heavy fluid is located above the light fluid. This experiment has the advantage of long collection times and the ability to characterize initial conditions, but is limited to small density differences between the fluids studied. In the present work, the fluid above the splitter plate is cold water (~20°C), while the fluid below is warm water (~25°C). The temperature difference causes a density difference. A "flapper" on the end of the splitter plate provides an initial disturbance that could be either a single disturbance mode, or a binary perturbation with an amplitude A given by:

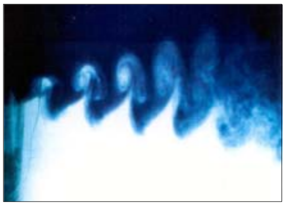
$$A(x)=A_1\sin\left(\frac{2\pi x}{\lambda_1}\right)+A_2\sin\left(\frac{2\pi x}{\lambda_2}+\delta\right)$$

Initial perturbation parameters :

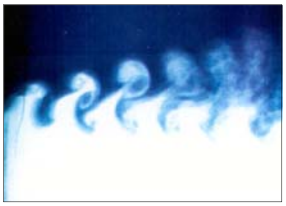
$A_1 = 4mm$	$A_2 = 2mm$
$\lambda_1 = 4cm$	$\lambda_2 = 2cm$
$\rho_1 = 997.7kg/m^3$	$\rho_2 = 996.57kg/m^3$

Mean flow velocity : $U_0 = 5cm/s$

Phase shift : $\delta = 0, \pi/2$



Binary initial perturbation with $\delta \sim 0$

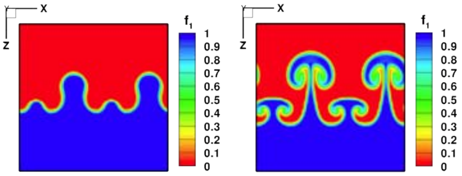


Binary initial perturbation with $\delta \sim \pi/2$

Experimental Photographs

5. Numerical simulations

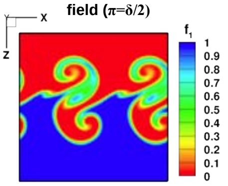
- Simulation started with initial perturbation only ($\delta=\pi/2$)



Volume fraction (non-dimensional density) distribution of the light fluid at time t=2s (left) and t=4s (right)

The experiment suggests that the perturbations develop to full scale after about 2s whereas the simulation, driven only by buoyancy predicts, the same fully developed structures after about 4s. Also there is no "leaning" phenomenon.

- Simulation started with initial perturbation and initial velocity field ($\pi=\delta/2$)



Volume fraction distribution of the light fluid at time t=2s

The simulation result at time t=2s shows remarkable agreement with the experimental photographs.

The flapper motion imposes an initial vertical velocity given by:

$$v=\frac{dA}{dt}=\frac{dx}{dt}\frac{dA}{dx}=U_0\left(A_1k_1\cos(k_1x)+A_2k_2\cos(k_2x+\delta)\right)$$

A suitable potential function for an initial velocity field is then:

$$\phi=-v_0\left(\frac{\cos(k_1x)}{k_1}\exp(-k_1|y|)+\frac{\cos(2k_1x+\delta)}{2k_1}\exp(-2k_1|y|)\right)$$

using: $v_0 = U_0A_1k_1 \quad A_1 = 2A_2 \quad \lambda_1 = 2\lambda_2$

When $\delta=\pi/2$, the angle θ between the x-axis and the trajectory of a particle located at the origin is given by:

$$\tan(\theta)=\frac{v(0,0,\pi/2)}{u(0,0,\pi/2)}=1$$

Hence a "leaning" of the growing perturbation with an angle of $\pi/4$ observed in the experiment and the simulation, and the potential for enhanced mixing.

This analysis suggests that an initial disturbance of the following form:

$$A(x)=A_1\sum_{i=1,n}\frac{\sin\left(ik_1x+(i-1)\pi/2\right)}{i}$$

Might have an initial trajectory angle at the origin given by:

$$\tan(\theta)=\frac{1}{n-1}$$

6. Conclusions

The velocity field drives the growth of the initial perturbation in this experiment. Therefore, the numerical simulations must be initiated with a density initial perturbation and an initial velocity field to reproduce accurately the experimental results. Also, the phase shift between the two modes of the initial binary perturbation causes a "leaning" of the growing structures of the instability. For a given form of the initial disturbance, the "leaning" angle can be predicted.

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