The Rayleigh-Taylor Instability at a Water/Magnetorheological Fluid Interface

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The Rayleigh-Taylor instability is studied using a new technique for a liquid/liquid interface without the use of a separation membrane. The interface is created using a magnetic field to maintain an imposed initial condition on a magnetorheological (MR) fluid, and when the magnetic field is released, the instability commences. Experiments are performed on three MR fluid mixtures to show the effect of the interfacial and material properties on the development of the instability. Single mode and multimode initial conditions are studied to evaluated mode growth and competition. Measured growth rates are compared with linear theory incorporating surface tension and viscosity.

Introduction

When a fluid of one density is positioned above a fluid of a different density, the Rayleigh-Taylor (RT)[1,2] instability will occur when an acceleration field is oriented such that the more dense fluid accelerates the less dense fluid. This instability results in an interfacial mixing of the two fluids and can be found in inertial confinement fusion, weather systems, and supernova. There has been a significant amount of research on this instability; however, much of the work has been done without specific concern for strictly specifying the interface shape. Dalziel, Linden and Youngs[3] studied this phenomenon using a layer of water and a layer of salt water initially separated by a rigid barrier, resulting in a flat interface. The removal of the rigid barrier introduced small-scale disturbances at the interface that initiated the RT instability. Dimonte and Schneider[4] used immiscible fluids with the less dense fluid initially resting above the more dense fluid and maintained the initial condition by gravity. An acceleration field was then imposed on the test section such that the more dense fluid accelerated the less dense fluid, thus resulting in the development of Rayleigh-Taylor instability at the interface between the two fluids. Using the same experimental setup, bubbles of the less dense fluid introduced at the bottom (in the more dense fluid) were used to provide the two initial perturbations at the interface.

A more recent experiment done by Andrews and Ramaprabhu[5] used water at different temperatures to create a density difference. The two water streams were set up flowing parallel to each other with the higher density on top. Although the water streams are flowing horizontally while the instabilities developed, good visualization of the RT instabilities was possible in this setup. A fine-mesh screen was used to introduce turbulence to the streams and perturb the interface between the two fluids. This experimental procedure resulted in long data collection times, and showed the mushroom-head shapes characteristic of RT instability development quite well. As with previous experiments, the primary focus was again on the development of the mixing layer, with a primary focus on the self-similar regime at late times.

A majority of the work done with RT instabilities thus far has concentrated primarily on highly turbulent mixing regions that exist on a small scale relative to the fluid interfaces. The goal of this research is utilized in a new experimental technique that resolves the large-scale two-dimensional mixing region with single and multimode sinusoidal interface shapes. These initial conditions are then be used to study the effect of the interface shape on the development of individual bubbles resulting from the RT instability development, as well as the effects of competition between the bubbles.

The most important aspect of this experiment was the development of a method for creating a complex interface shape for the initial condition, without the use of a membrane. To this end, an approach using magnetorheological fluids was chosen. An MR fluid experiences significant increases in viscosity and yield stress with an increase in the strength of an applied magnetic field.[6,7,8] This effect is strong enough to "freeze" the fluid under the normal gravitational acceleration field, but the effect is totally reversible upon removal of the magnetic field. Typically, MR fluids are created using fine iron particles in an oil-based suspension, with surfactants commonly added to prevent particle agglomeration. When the magnetic field is applied, bonds are produced between the iron particles, which arrange themselves into chains, giving the fluid the ability to resist applied stresses. This effect is used to create single mode sinusoidal interface shapes as well as complex multimode shapes without the need to have a membrane separating the two fluids.

Experiment

Three different (MR) fluid mixtures are studied in these experiments. The mixtures contain light grade mineral oil, carbonyl iron powder, and oleic acid, which is based on the mixture used previously in similar experiments by Selig[9]; the only parameter that is varied between the fluid mixtures is the amount of carbonyl iron powder. The volume fractions (ϕ) of the carbonyl iron powder mixtures are 0.15, 0.20 and 0.30, and the density (ρ), MR fluid viscosity (μ), interfacial tension (T), and Atwood number (A) are summarized in Table 1.

Table 1. Magnetorheological fluid/water interface properties

ϕ	ρ (kg/m^3)	μ (Pa-s)	T (N/m)	A
0.15	1782.2	0.0229	0.051	0.28206
0.20	2050	0.100	0.051	0.34514
0.30	2772.3	0.643	0.051	0.47059

The Non-Newtonian nature of MR fluids results in the fluid having a range of viscosities dependent upon the shear rate, rather than a discreet value as found for ideal Newtonian fluids. The values presented in the tables above correspond to an optimized viscosity from within that range that allow the viscous theory to best correlate with the experimental results.

The experimental setup consists of a test section, two magnet magazines (Fig. 1), a magnet magazine retraction device (Fig. 2), and the imaging equipment. Each magnet magazine consists of six NdFeB magnets; each is rated at a maximum magnetic flux Br =

1.21 T and overall energy density of the magnetic field BH_{max} = 279 kJ/m^3. The magnets are arranged to produce a nearly constant magnetic field in the vicinity of the MR fluid/water interface and this field is strong enough to immobilize the MR fluid at a distance of 7 cm for all fluid mixtures tested.

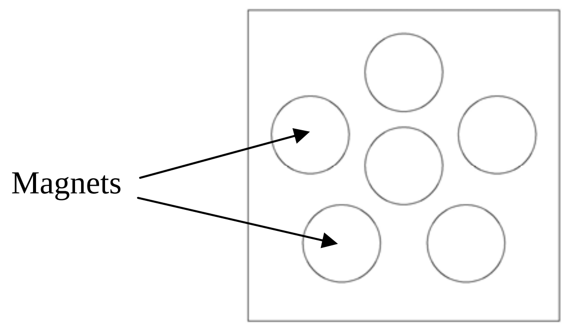


Figure 1. Magnet magazine.

The retraction device where the magazines are mounted is shown in Fig. 2. This device uses two pneumatic pistons to retract the magazines along four rails. The pistons utilize compressed nitrogen to withdraw the magazines and are triggered using an electric valve at the onset of the experiment.

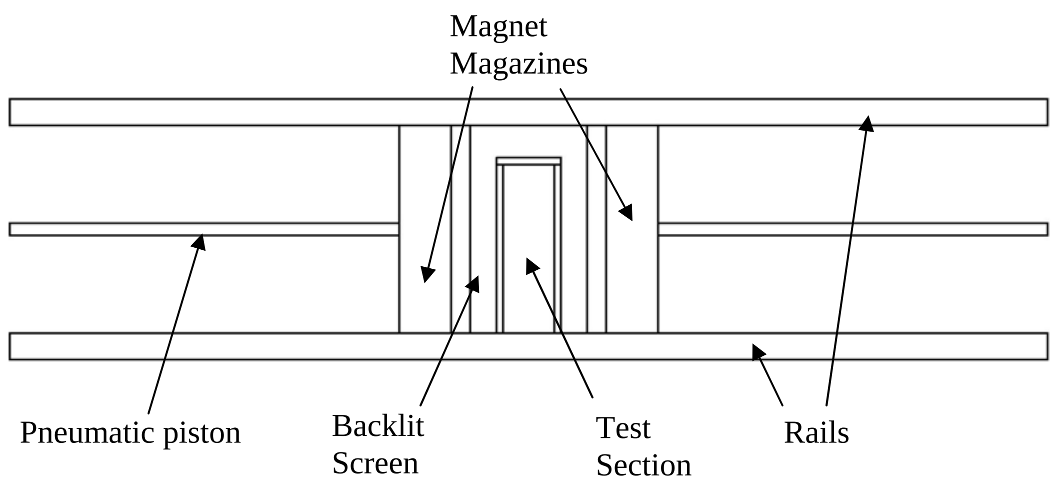


Figure 2. Side-view of the experimental setup.

Two different CCD camera systems (Dalsa Inc.) have been used to record the evolution of the RT instability: 1) 256×256 array, 8 bit resolution, 200 frames per second (fps), and an upgraded model, 2) 532×516 array, 8 bit resolution, 250 fps. Images are stored directly on a personal computer using an EPIX frame-grabber pci card and XCAP imaging software.

Figure 3 shows the test section and the multimode aluminum sheet metal form. The test section consists of a main chamber, a plunger, and two end caps. O-rings are used to seal the end caps to prevent leakage of the fluids during the experiment. The plunger is designed using a compression fit to prevent water from leaking during the freezing process, and also, to facilitate easier removal of the plunger.

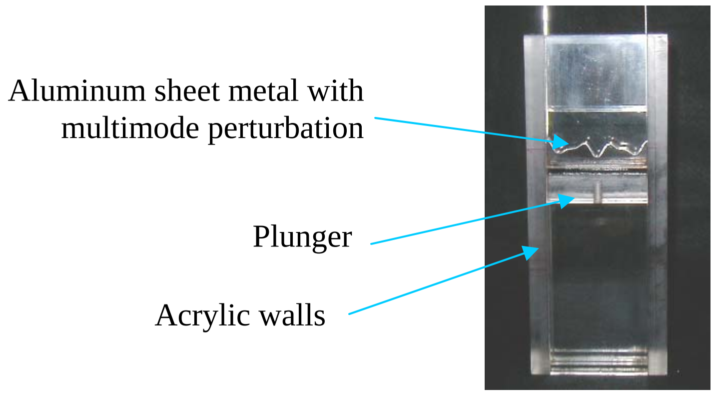
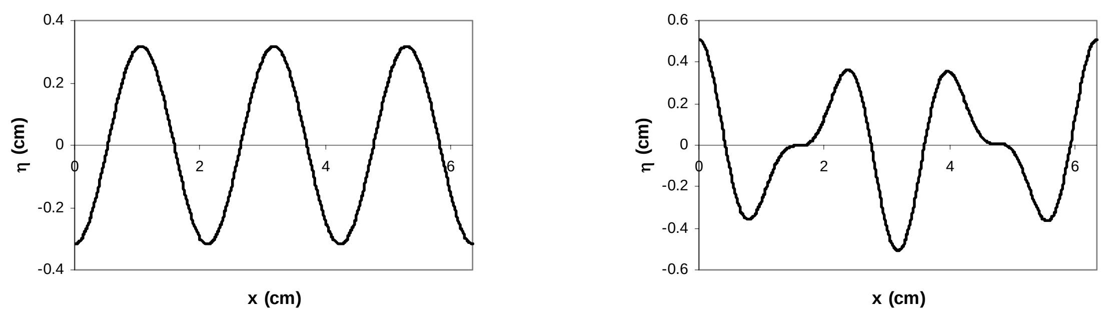


Figure 3. Test section for MR fluid/water interface.

Two different initial interface shapes (Fig. 4) were studied in this set of experiments. The first is a single mode cosine wave with a wavelength of λ=2.12 cm and an amplitude of η=0.318 cm; the second shape is a multimode cosine wave consisting of two modes-three and five. Mode three has the same wavelength and amplitude of the single mode interface shape and superposed on this is mode five, λ=1.27 cm, η=0.191 cm.



(a) Cosine waveform (b) Multimode waveform

Figure 4. Initial conditions for the single mode and multimode experiments.

The initial condition shape was programmed into a numerically controlled mill and a block of aluminum was machined with the top surface of the interface, and a second block with the lower surface, Fig. 5. A thin aluminum strip was pressed between the two machined shaping blocks, thereby, plastically deforming the strip to the desired initial condition geometry, and then the aluminum strip was inserted into the test section as shown in Fig. 3.

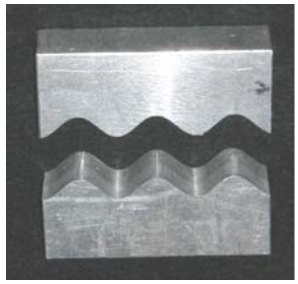


Figure 5. Shaping blocks for initial condition.

To prepare the water/MR fluid interface, the plunger is placed in the test section, the test section is partially filled with water, and then the aluminum strip (Fig. 3) is placed into the water. The test section is then placed into a freezer, and when the water has turned completely to ice, the test section is removed, the aluminum strip is withdrawn, and the remaining volume filled with MR fluid and sealed. The test section is now placed in the magnetic field to immobilize the MR fluid, the plunger is removed, water is poured into the test section (melting and displacing the ice), and the test section is oriented so the heavier MR fluid is above the water.

Results

Figure 6 shows imaging results from two ϕ=0.15 experiments with the two different initial conditions; the MR fluid is opaque (black) and the water is transparent. The opacity of the MR fluid precludes the observation of the "peaks" of the perturbation growing in time and we are limited to the observation of the valleys, which are, the MR fluid falling into the water. Initial conditions are not as clean as shown in Fig. 4 due to various challenges in preparing the interface, as well as, a small amount of smearing of the MR fluid on the wall surface near the interface.

Asymmetry is a notable feature in the single mode montage of Fig. 6 and the difference in growth rate between the two valleys of MR fluid are due to the difference in initial condition where the peak valley amplitude can vary by as much as 1 millimeter. The sensitivity of the growth rates to the initial position of the interface seems to be quite high, and the peak that shows the faster growth rate is actually slightly lower than the other peak initially. This is result is due to the fact that the lower of the two amplitudes remains in the linear (exponential growth) regime longer than the higher initial amplitude and the increase in velocity (momentum) sustains a slightly higher growth rate.

The side-walls of the test section have a minimal effect on the valley growth in the early stages of the observed instability development (t<120 ms); however, there is a strong effect at later times, especially in the multimode case, where the outer valleys are initially attracted to the wells, then at later times, appear to reflect off the walls and move towards the center. The growth is visibly two-dimensional and the MR fluid does not stick to the test section walls as the neck of the mushroom is visible above the mushroom head at later times.

Three different linear theories are evaluated for comparison with the single mode growth rate data: inviscid theory, inviscid theory with interfacial tension (IFT), and viscous theory with IFT (S. Chandrasekhar)[10]; results for the comparisons are shown in Figs. 7-9. From the work by Cook and Dimotakis[11], the amplitude in these plots is normalized with respect to the width of the test section (L=6.35 cm), and time is normalized by $\tau = \sqrt{L/(Ag)}$, where g is the acceleration of gravity. The linear theories agree well with the experiment at the very early times and agreement is extended to later times when IFT is included. Including viscosity in the evaluation extends agreement to even later times and the shifts in the theory evaluations show that the interfacial tension plays a more dominant role than viscosity. At higher concentrations of carbonyl iron powder, there are increases in both A and m, these competing processes result in an increase in the amplitude growth rate (Fig. 10).

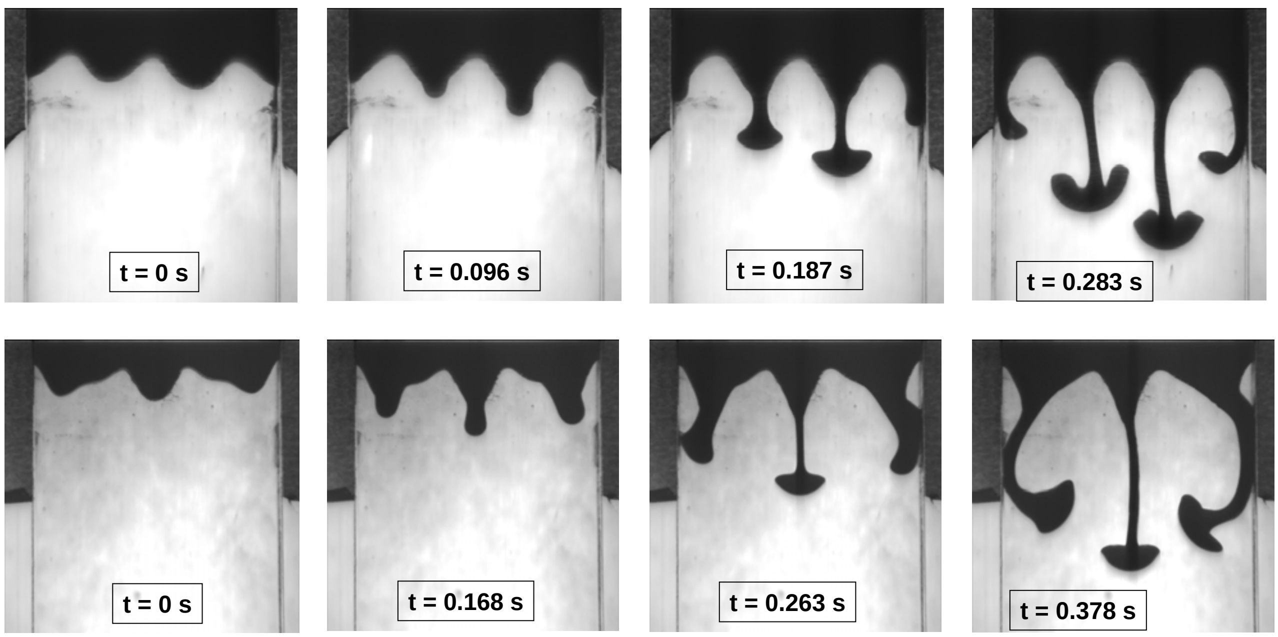


Figure 6. Top row is a montage from a single mode initial condition experiment and the bottom row is from a multimode initial condition.

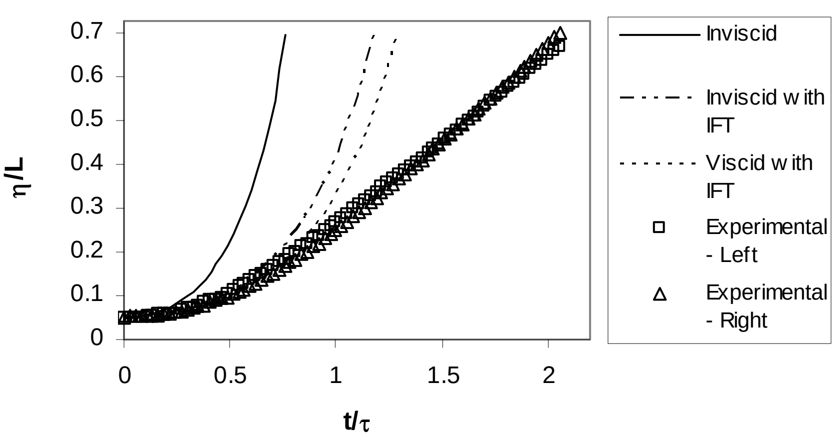


Figure 7. Normalized growth for the ϕ=0.15 mixture.

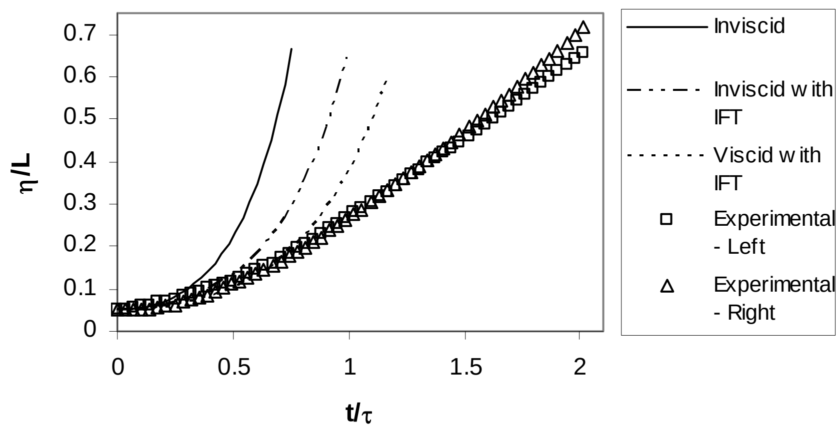


Figure 8. Normalized growth for the ϕ=0.20 mixture.

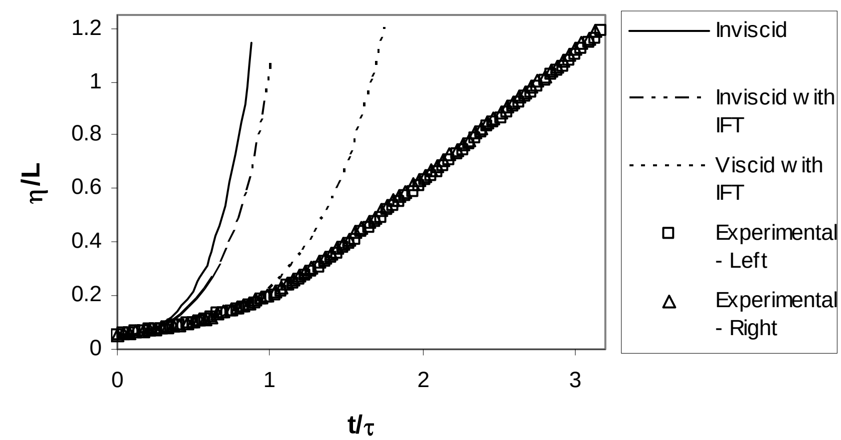


Figure 9. Normalized growth for the ϕ=0.30 mixture.

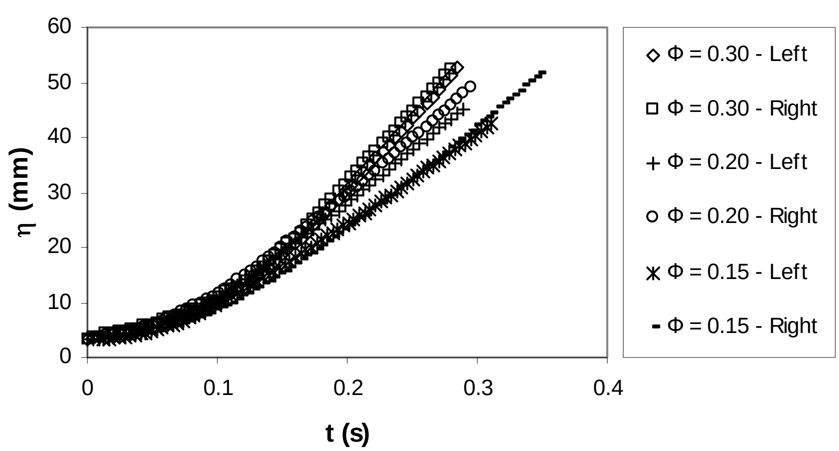


Figure 10. Measured growth rates for all three mixtures.

The multimode initial condition is investigated using Fourier analysis to study the modal growth in the initial stages before the onset of the mushroom-head development where the interface takes on double valued ordinates for a given abscissa. Figure 11 shows the normalized results for the first 10 modes found in the modal decomposition the experiment for a test using the ϕ=0.15 MR fluid mixture. The initial condition modes 3 and 5 experience the expected exponential growth; however, mode 3 unexpectedly grows at faster rate than mode 5 given that both have the same initial η/λ=0.15. Modes 1, 2, 4, and all higher modes, remain basically flat with little increase or decrease in the amplitude.

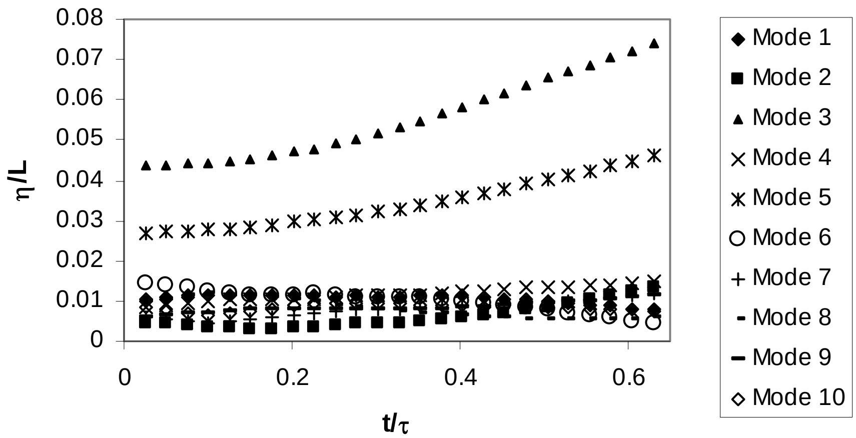


Figure 11. Modal growth for the ϕ=0.15 mixture.

Conclusions

A new method has been developed for the studying the RT instability in a liquid-liquid configuration using a MR fluid. Linear theories compare well with the instability growth at the early times with best agreement when inertial, surface tension, and viscous forces are all considered. The experimental method allows for the creation of two-dimensional interface consisting of one more or any arbitrary number of modes. The ability to carry out the experiment at different concentrations of carbonyl iron powder allows the variation of the Atwood number and is also found to have an effect on the viscosity of the MR fluid mixture. A longer test section is needed to study the instability growth at later times where the mushroom-head structures are more fully developed and they begin to influence one another.

References

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