Investigation of the Rayleigh-Taylor and Richtmyer-Meshkov instabilities

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1 Introduction

The present research program is centered on the experimental and numerical study of two instabilities that develop at the interface between two different fluids when the interface experiences an impulsive or a constant acceleration. The instabilities, called the Richtmyer-Meshkov and Rayleigh-Taylor instability, respectively (RMI and RTI), adversely affect target implosion in experiments aimed at the achievement of nuclear fusion by inertial confinement by causing the nuclear fuel contained in a target and the ablated shell material to mix, leading to contamination of the fuel, yield reduction or no ignition at all.

Specifically, our work is articulated in three main directions: study of impulsively accelerated spherical gas inhomogeneities; study of impulsively accelerated 2-D interfaces; study of a liquid interface under the action of gravity. The objectives common to all three activities are to learn some physics directly from our experiments and calculations; and to develop a database at previously untested conditions to be used to calibrate and verify some of the computational tools being developed within the RTI/RMI community at the national laboratories and the ASCI centers.

2 Accomplishments

2.1 Impulsively accelerated spherical inhomogeneities

2.1.1 Laboratory experiments

The experiments are performed in a vertical shock tube of large, square internal cross section, 9 m long, with a 1.8 m driver section. A downward-propagating shock wave is generated by rupturing a steel diaphragm by gas overpressure. The time of shock release is controlled to within ± 100

ms by pre-pressurizing the driver section to about 90% of the diaphragm's rupture pressure and by rupturing the diaphragm by discharging one or two high pressure boost tanks into the driver through fast-opening high-flow-rate valves. The driver and driven gases are usually helium and nitrogen, respectively.

The system to prepare and image a spherical interface is shown in Fig.1.

Figure 1: Schematic of retractable injector.

The spherical interface (essentially a soap bubble) is generated inside the shock tube by placing a known quantity of soap film at the tip of an injector initially protruding from the shock tube wall, blowing the bubble with argon, forcing the bubble to detach from the injector and retracting the injector into the shock tube wall, leading to a free-falling argon bubble in a nitrogen atmosphere and to minimal disruption of the incoming shock wave by the non perfectly flat shock tube wall at the location where the injector is retracted. The Atwood number at the argon/nitrogen interface is $A = (\rho_{Ar} - \rho_{N2})/(\rho_{Ar} + \rho_{N2}) = 0.18$. Experiments have been performed with shock strengths of $M = 1.3$, $M = 2.88$ and $M = 3.38$.

The bubble is imaged during the initial stages of its free fall using continuous, infrared, front lighting and a medium resolution (512×512 pixel) medium framing rate (260 fps) CCD camera. After being accelerated by the shock, the bubble is imaged at three different time delays: once by simultaneous shadowgraphy and Mie scattering planar imaging; and twice more by planar imaging. The shadowgraph illumination is provided by a flashing white source while planar imaging is performed with either a double-pulse Nd:YAG laser at 532 nm or an excimer laser at 248 nm. In planar Mie scattering, the laser light is scattered from the shocked bubble towards a CCD sensor by the soap film which atomizes upon shock acceleration and thereafter acts as a suitable flow-tracer. The

collimated beam used for the shadowgraph image propagates in a direction orthogonal to the laser sheets used for planar imaging. All four post-shock images are recorded on high resolution (1024×1024 pixels) scientific grade CCD cameras: the shadowgraph image on one sensor; the two planar views from the YAG double pulse on a second sensor; and the planar image from the excimer laser on a third sensor. Since the shadowgraph and the first of the two YAG images are recorded at 90° from each other at the same time delay (and thus the same position) the cross section of the laser sheet appears as a bright line in the shadowgraph image and determines the position of the bubble relative to the sheet. This is important when comparing experimental to computational images in that it provides precise knowledge of which bubble cross section is being observed in the laboratory.

At all shock strengths, the following sequence takes place: the bubble is initially distorted because of pure compression; the vorticity baroclinically deposited on the interface then leads to the formation of a vortex ring seen in cross section at the left and right sides of the bubble; in turn, the vortex ring induces very high strain on the top surface of the bubble, causing it to tilt upwards. A typical time series of shocked bubble images is presented in Fig.2 for an Ar bubble accelerated by an $M = 1.33$ shock wave.

The relevant geometrical features (bubble height and width) are measured from the images as schematically described in Fig.3. A secondary mushroom often develops at the top of the bubble (details about its origin are given in Sec.2.1.2 below); in some cases, a jet protrudes above the secondary mushroom. The height always includes the secondary mushroom (when present) but does not include the jet. The width of the bubble measures the outer diameter of the main vortex ring.

Different approaches have been tried to determine the appropriate normalizing quantities for the bubble macroscopic geometrical features and the post-shock time when images are recorded. The best results are obtained normalizing both the height and the width by the initial bubble diameter D ; and the post-shock time by the time taken by the shock transmitted into the bubble to travel by one full diameter ($\tau = D/W_t$ where W_t is the transmitted shock speed, typically estimated from 1- gasdynamics).

Figures 4 and 5 show a comparison of our experimental data at low Mach number ($M = 1.3$) with analogous experiments by Layes at the Université de Marseilles, France. While our data span a larger time interval than the French data, the agreement in the time ranges common to the two data sets is excellent. More experimental results are discussed in the next section together with the corresponding numerical simulations.

2.1.2 Computational experiments

Extensive computational experiments have been performed using the *Raptor* code made available by Lawrence Livermore National Laboratory. One of our graduate students and one of our scientists have worked very closely from here at UW with Dr. Jeff Greenough of LLNL; and, for the second year in a row, the graduate student spent twelve summer weeks at LLNL for an internship, also performing computational runs simulating the laboratory experiments. In order to make the most effective use of the available computational resources, in this first campaign only one fourth of the bubble was modeled, assuming axial symmetry and no azimuthal variations. We are aware that this is not exact (the Widnall instability being an example of azimuthal asymmetry that onsets after the initial shock acceleration) but several useful results were obtained despite this simplification.

Figure 2: Images of a shock-accelerated argon bubble. $M = 1.33$. (a) 0 ms, (b) 55 ms, (c) 0.76 ms and 1.25 ms, (d) 2.7 ms, (e) 4.15 ms.

The main objectives of the calculations include: to reproduce the laboratory results as closely as possible; to assess the effect of the initial conditions and of the soap film on the post-shock evolution of the interface; and to calculate density and velocity fields and their spectra. The grid resolution typically used in most of the runs is about 0.2 mm.

To avoid the stairstepping effects consequent to the presence of a round object (the bubble) within

Figure 3: Definitions of bubble height and width.

a square grid, a new film-modeling technique was developed: since the grid resolution is much larger than the soap film thickness ($\sim 1\mu\text{m}$), a spherical soap film layer with thickness equal to one cell width is placed in the domain, with a uniformly scaled density to match the actual total film mass used in the laboratory. Sub-cell sampling is then used to determine the amount of soap present within each cell.

Figure 6 shows the calculated argon volume fraction fields (top) in a vertical plane going through the center of the bubble, at several post-shock times, for $M = 2.88$. A qualitative comparison to the corresponding experimental images (also shown in Fig.6) demonstrates that the qualitative agreement between laboratory and computational experiments is very good.

Figures 7 and 8 show laboratory and computational results at three different Mach numbers. The data suggest that: i) the quantitative agreement between the experiments and the calculations is reasonable; ii) a significant change in the bubble evolution occurs in the $1.3 < M < 2.88$ range. We speculate that this change from low to high Mach numbers is due to compressibility effects but more work will be necessary to establish this firmly.

Calculations performed in the previous year of funding had showed that adding a small nonuniformity in the bottom of the bubble film region in the initial conditions (simulating fluid accumulation due to gravity) caused the development of a vertical jet in the middle of the bubble of size comparable to that of the jet observed in the laboratory experiments; formation of a secondary vortical structure at the top of the jet (due to the Kelvin-Helmholtz instability) was also observed in both the computational and laboratory experiments. Further investigation of the origins of the secondary vortex and jet was carried out computationally and the present evidence indicates that, even in the absence of any soap film accumulation at the bottom of the bubble, a secondary jet will

Figure 4: Bubble height for $M = 1.33$.

develop as a consequence of multiple shock refraction effects provided the Atwood number is large enough. An example of that is the reproduction of a calculation by Zabusky and Zheng describing an $M = 2.5$ shock accelerating an R12 filmless bubble in air ($A = 0.613$). As seen in Fig.9, the *Raptor* calculation faithfully reproduces the original results showing a secondary vortex.

The effects of the soap film were also investigated by running calculations with and without soap. The results (a sample being shown in Fig.10), clearly indicate that the film causes the formation of more secondary vortical structures riding on top of the main vortex ring. Naturally, this has very significant implications when it comes to comparing the laboratory to the computational results in that it dictates that soap film be included in the calculations. Indeed, an even better simulation would include some kind of film break-up mechanism but no such feature exists within *Raptor* yet.

A few full-sphere runs (instead of the quarter-sphere based on axial symmetry) have been completed in preparation for a comprehensive final campaign. Among other results, the formation and evolution of the secondary vortex and of the upward jet and the visualization of azimuthally-travelling disturbances along the main vortex tubes are particularly remarkable. A sample motion picture summarizing the full-sphere computation can be watched on our website: <http://silver.neep.wisc.edu/~shock/rmbubble.html>.

Figure 5: Bubble width for $M = 1.33$.

2.2 Impulsively accelerated 2-D interfaces

A technique analogous to that first used by Jeff Jacobs at the University of Arizona has been developed to prepare a 2-D sinusoidal interface without resorting to a membrane or a retractable plate: two different gases flow into the shock tube from its top and bottom and meet head-on forming a stagnation flow that generates a flat interface; two pistons, in opposite shock tube walls, extending about 3 cm both above and below the plane of the stagnation flow, oscillate synchronously extending out of and retracting into the walls, imposing a standing wave onto the interface whose modal content can be adjusted by varying the amplitude and frequency of the pistons' oscillations. Experiments were performed using shock strengths of $1.3 < M < 1.5$. The gases were N_2 doped with acetone ($\sim 28\%$ volume fraction, corresponding to saturation) coming from the top and SF_6 flowing upward from the bottom of the tube.

The interface is visualized once before and twice after interaction with the shock wave either via Mie scattering (doping one of the gases with fog or smoke) or by planar laser-induced fluorescence (PLIF) (doping one of the gases with acetone). Both techniques present advantages and challenges, Mie scattering being easier to implement but yielding no quantitative concentration data, PLIF requiring fairly sophisticated image normalization algorithms to account for laser attenuation and refraction. A schematic of the system is shown in Fig.11.

Samples of some of the experimental images are shown in Fig.12 together with the corresponding *Raptor* calculations run using the FFT spectrum of the interface shape extracted from the pre-shock

Figure 6: Comparison between computational (top) and laboratory (bottom) experiments. Argon volume fractions for $M = 2.88$.

experimental images as initial conditions. Clearly, *Raptor* correctly predicts the macroscopic dimensions of the main interface features but fails to resolve the fine-scale details (secondary instability) visible inside the mushroom roll-ups.

Figure 13 shows our experimental data together with: data from Jacobs (University of Arizona); a *Raptor* calculation; and three analytical models that have been proposed in the past to predict the evolution of a single-mode interface. Time is normalized with the wavenumber k and the initial post-shock growth rate $\dot{a}_0$; amplitude is normalized with the wavenumber and offset by its initial value a_0 . The large scatter in the data point at a normalized time near 6.8 is known to be due to an instrumentation malfunction. The rest of the experimental scatter is acceptable for data from a large facility like the one used in these experiments. The data indicate that the Sadot model provides a better fit for Jacob’s data while Mikaelian’s and Di Monte’s models adequately describe the present results.

2.3 Rayleigh-Taylor instability

In the first year of funding, a new experiment had been developed for the study of the RT instability, based on the use of a magnetorheological (MR) fluid as one of the two fluids at a perturbed interface. The MR fluid used here is a dispersion of Fe particles (average diameter $4.5 \mu\text{m}$, 15% volume fraction) in mineral oil, with a small addition of a surfactant (oleic acid) to prevent coalescence of

Figure 7: Bubble height from laboratory and computational experiments.

Figure 8: Bubble width from laboratory and computational experiments.

Figure 9: Comparison of *Raptor* results with previous calculation by Zabusky and Zheng: R12 filmless bubble in air, $M = 2.88$.

the Fe particles. The resulting Atwood number when the MR-fluid is paired with water is $A = 0.315$. The MR fluid can be “frozen” into any shape by applying a sufficiently large magnetic field; thus, an arbitrary shape can be imposed on the free surface of an MR fluid, and the “frozen” MR fluid can be coupled with a different fluid (*e.g.* water) to form a pair of fluids of different densities separated by a perturbed interface; when the magnetic field is removed, gravity drives the RT instability. Use of an MR fluid thus allows for the preparation of interfaces of any desired shape (in particular, with any superposition of sinusoidal modes) and ensures that the experiment begins with both fluids at rest. Like in the case of the RMI, the experiments aim at measuring the growth rate of the perturbations and the mixing rates between the different fluids.

Recent work has been focused on three-dimensional experiments starting with a hemispherical interface. The test section consists of a small volume ($5 \times 5 \times 20$ cm) filled with MR-fluid resting above a large water tank ($25 \times 25 \times 50$) cm. The hemispherical interface has a radius of 9.5 mm and it is held in place by two sets of permanent magnets (1.5 T each) mounted in two Plexiglas holders. To start the experiment, the magnet holders are retracted away from the test section by two pneumatic cylinders. The interface is illuminated with diffuse, white light and it is imaged using a 512×512 pixel CCD camera, operating at 230 fps. A view of the apparatus is shown in Fig.14.

Images of the interface evolution are shown in Fig.15. The velocity of the interface is measured from the images and compared to the value for a hemisphere simply falling in a viscous medium and to a prediction by Goncharov for the spikes of a 2-D single-mode interface. Goncharov has

Figure 10: Comparison of *Raptor* results without (top) and with (bottom) soap film. Ar bubble in N_2 , $M = 2.88$.

Figure 11: Schematic of 2-D RMI experimental setup.

predicted linear growth for the 3-D case but no constant of proportionality was explicitly given; the data shown in Fig.16 clearly exhibit a linear growth with time.

3 Publications and presentations

Journal article:

Ranjan D., Anderson M., Oakley J., Bonazza R., Experimental investigation of a strongly shocked gas bubble, *Phys. Rev. Lett.* **94**, 184507, 2005

Conference papers:

Ranjan D., Niederhaus J.H.J., Oakley J.G., Anderson M.H., Greenough J.A., Bonazza R., Shock-induced instabilities on a spherical gas bubble, Proceedings of the 25th International Symposium on Shock Waves, Bangalore, India, July 2005

Motl B.J., Niederhaus J.H.J., Anderson M.H., Oakley J.G., Bonazza R. Richtmyer-Meshkov instability of a membraneless, sinusoidal gas interface, Proceedings of the 25th International Symposium on Shock Waves, Bangalore, India, July 2005

Conference abstracts:

Motl B., Niederhaus J., Anderson M., Oakley J., Bonazza R., Richtmyer-Meshkov instability of a membraneless, sinusoidal gas interface, 58th Annual Meeting of APS Division of Fluid Dynamics, Chicago, November 2005

White J., Anderson M., Oakley J., Bonazza R., Study of the Rayleigh-Taylor instability at a

Figure 12: RMI laboratory (top) and computational (bottom) experiments.

hemispherical interface using a magnetorheological fluid, 58th Annual Meeting of APS Division of Fluid Dynamics, Chicago, November 2005

Ranjan D., Niederhaus J., Anderson M., Oakley J., Bonazza R., Interaction of a planar shock wave with a spherical gas inhomogeneity. Part I: Experiments, 58th Annual Meeting of APS Division of Fluid Dynamics, Chicago, November 2005

Niederhaus J., Ranjan D., Anderson M., Oakley J., Bonazza R., Interaction of a planar shock wave with a spherical gas inhomogeneity. Part II: Calculations, 58th Annual Meeting of APS Division of Fluid Dynamics, Chicago, November 2005

Figure 13: Amplitude growth rates.

4 Personnel

Faculty and staff involved in and supported by the program include:

Prof. Riccardo Bonazza, Associate Professor, Dept. Engineering Physics; supported for 2.7 months.

Dr. Mark Anderson, Associate Scientist, Dept. Engineering Physics; supported for 4.0 months.

Dr. Jason Oakley, Assistant Scientist, Dept. Engineering Physics; supported for 10 months.

Mr. Paul Brooks, Instrumentation Specialist, Dept. Engineering Physics; supported for 4.5 months.

Graduate students supported by and fully involved in the program in the past year include:

Mr. Brad Motl (USA; pursuing a Ph.D. degree); supported for 12 months.

Mr. John Niederhaus (USA; pursuing a Ph.D. degree); supported for 9 months.

Mr. Jeremy White (USA; pursuing a Ph.D. degree); supported for 12 months.

Mr. Devesh Ranjan (India; pursuing a Ph.D. degree); supported for 12 months

Three undergraduate students were also involved in and supported by the program at various levels and for different lengths of time.

Figure 14: RTI experimental apparatus.

(a)

(b)

(c)

(d)

(e)

(f)

(g)

(h)

Figure 15: RTI development: (a) $t = 0$; (b) $t = 49$ ms; (c) $t = 141$ ms; (d) $t = 202$ ms; (e) $t = 172$ ms; (f) $t = 210$ ms; (g) $t = 248$ ms; (h) $t = 286$ ms.

Figure 16: Velocity of 3-D interface.