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Laser-Sheet Imaging of HE-Driven Interfaces

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Abstract

This is the final report of a three-year, Laboratory Directed Research and Development (LDRD) project at Los Alamos National Laboratory (LANL). We made substantial progress in developing the MILSI (Multiple Imaging of Laser-Sheet Illumination) technique for high explosive (HE)-driven fluid interfaces. We observed the instability, but have not yet measured the instability growth rate. We developed suitable sample containers and optical systems for studying the Richtmyer-Meshkov instability of perturbed water/bromoform interfaces and we successfully fielded the new MILSI diagnostic at two firing-site facilities.

Background and Research Objectives

Interfacial instability problems are scientifically challenging and directly relevant to the core mission of the Los Alamos National Laboratory (LANL). Maintaining and enhancing our competency in this field is therefore of great importance. Instability of a shock-accelerated interface between two fluids of different densities, known as the Richtmyer-Meshkov (RM) instability, has been studied at LANL experimentally, theoretically and numerically. Richtmyer's seminal work at Los Alamos during the 1950s was published in 1960. The problem continues to be a challenge of central importance to the inertial confinement fusion (ICF) and weapons physics communities. The performance of ICF capsules is degraded by shock-induced mix resulting from this instability. Design calculations are limited in their capability to correctly compute complex flows driven by interfacial instability, and the presence of validating data often limits the credibility of such design calculations. Consequently these complex experiments have a direct impact on the credibility of design calculations and predictive capabilities.

The acceleration of a thin layer (e.g., a thin shell) is as important to applications as the acceleration of a single interface. Shock-acceleration of a thin fluid layer produces flow phenomena unexpected from experience with a single, shock-accelerated interface.

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Such phenomena have been observed [1-5] and partially understood [1-4] for shock-tube experiments in which the fluids are gases. The phenomena are three distinct flow patterns that evolve from shock-acceleration of a thin layer with perturbations on both upstream and downstream interfaces. Two patterns show strong vortex pairing, observed as "mushroom" profiles, and the third pattern is sinuous with mushrooms developing much later in time. The pattern that actually occurs in a particular experiment appears to depend sensitively on upstream/downstream asymmetry in the initial perturbations. These phenomena strongly influence the interfluid mixing characteristics of the shock-accelerated layer. These three distinct flow patterns are not observed in the shock-acceleration of a single, RM-unstable interface. The present project attempted to examine both single-interface and double-interface mixing phenomena at liquid/liquid interfaces.

The experimental discovery of three patterns resulted from the application of a laser-sheet probe that enables superb visualization of a two-dimensional section of a three-dimensional flow field. The sensitivity of these flow patterns to initial conditions was noticed experimentally, although this problem has been the subject of numerous computational studies during the fifty-year history of the Laboratory. If the effects observed in shock-tube experiments are also found in high explosive (HE)-driven experiments, they may help interpret data previously thought to be inconsistent. Comparison of simulations with the three experimental flow patterns has been used to validate the RAGE code during its infancy and this comparison became a showcase example of science-based stockpile stewardship.

The purpose of this investigation is to develop this optical measurement technique and conceptual experimental design for complex experiments driven by high explosives (HE). Numerical simulation codes have been used to help design the experiment. The experimental effort provides new firing-point diagnostic capabilities that complement existing methods. The laser sheet imaging observes a slice of the flow, whereas radiography and line-of-sight optical methods record an image spatially integrated along the line of sight or of an opaque surface. Consequently, the laser sheet imaging complements radiography and traditional optical photography.

Interfacial instability in HE-driven systems has been observed [6,7] for single-interface systems. These experiments examined the perturbed interface between water and Wood's metal. Nonlinear growth was observed with backlighting and compared with an analytic impulse model incorporating both Richtmyer-Meshkov and Rayleigh-Taylor effects. These observations did not use laser-sheet techniques or thin layers. The present work utilizes the experience of previous experiments, but is far more complex

because of the laser-sheet imaging, the presence of a thin, imbedded layer and two transparent fluids. A long-range goal is to field both laser-sheet imaging and radiography on the same experiments to learn the strengths and limitations of each method in diagnosing unstable interfaces.

Our primary research objective has been development of a new diagnostic, MILSI, for experiments at high-explosive firing sites. MILSI is multiple imaging of laser-sheet illumination, meaning a sheet of laser light illuminates a two-dimensional slice of a complex flow, and then a high speed camera records multiple images of the event. Experimental data produced by MILSI are valuable for the validation of fluid simulations developed under the Accelerated Strategic Computing Initiative (ASCI).

Importance to LANL's Science and Technology Base and National R&D Needs

Essential competencies of the Laboratory are: (1) the ability to understand and accurately predict complex fluid flows, particularly those driven by shock impulses and (2) complex experimentation. A firm understanding of flows at shock-accelerated layers has eluded us for fifty years, but new insights and important progress toward this goal may be within sight by virtue of MILSI. Theory and computation have made similar progress [2]. The collaboration supported by this project has promoted cutting-edge, complex experiments and computation within a single project.

This project extends the Laboratory's core competencies in Complex Experimentation and Measurements, and in Nuclear Weapons Science and Technology. The work also contributes directly to two DOE Core Competencies: Advanced Computing, Modeling, and Simulation; and Integrated Defense Science and Technology.

Scientific Approach and Accomplishments

We successfully fielded MILSI systems at two Laboratory firing sites during FY 1997. We tested several combinations of lasers and cameras, and found the best system to be an array of frequency-doubled YAG lasers for illumination and an eight-frame, intensified CCD camera for recording. Tests with argon lasers and image-converter cameras produced less satisfactory results.

Experimental Configuration

The basic experimental configuration is laser-sheet illumination of a sample containing one or two interfaces between fluids of different densities. The interfaces become unstable when subjected to shock wave loading, meaning that ripples at the interface rapidly grow in amplitude as a consequence of shock-wave acceleration. A detonator provides the high-explosively formed shock wave. The container holding the fluid sample is transparent, enabling illumination of the interfacial region and viewing by

a high-speed optical camera. We describe below each component and development of this experiment and then describe combinations that we tested, including experimental results.

Firing Sites

We fielded experiments at three LANL firing sites: Eenie, R306, TA-9/bldg. 37. The selection of sites for particular phases of the experiment was dictated by availability of camera and illuminators, scheduling of firing sites and firing-site technicians, and shot turn-around time. The flexibility of being able to do these complex experiments at a variety of firing sites contributed significantly to the success of this work.

We acquired the initial data on the transparency of shock-compressed fluids at Eenie Site (TA-36). This site was convenient because the framing camera and suitable illumination sources were stationed there. The site was quite accessible when we needed to do these tests. We acknowledge the technical assistance of Robert Critchfield for the work done at Eenie.

We then fielded the first experiments with HE-driven interfaces at R306 (formerly site of the Ector radiographic facility). R306 is well suited to MILSI experiments because it routinely hosts experiments with optical diagnostics. Optical ports are maintained and laser safety systems are in place. Laser safety precautions including access limitations, laser warning lights and laser beam enclosures provide a hospitable environment for the development of optical diagnostics. For example, much VISAR (Velocity Interferometry with Scattering from Any Reflector) development and experimentation occurs at R306. We performed several series of "liquid curtain" experiments at R306. Clearance procedures and shot complexity limited experimentation to only a few shots per day. We acknowledge the technical assistance of firing site leader, Walter Quintana, for the work done at R306.

Subsequently we moved the experiment to TA-9/bldg. 37 to evaluate the usefulness of an eight-laser array of pulsed YAG lasers. This laser array is not portable so the experiment was forced to move to the laser source. This facility is also equipped with a container (i.e., a "boom box") for firing detonator-driven events that produce little shrapnel. The container is compatible with our water/bromoform samples. Shot turn-around time is excellent, enabling several shots to be fired within one hour. The work at TA-9/bldg. 37 convinced us that the eight-laser array of frequency-doubled, Q-switched YAG lasers is an excellent illumination source for MILSI. We acknowledge the technical assistance of Blaine Asay and Chris Fugard for the work done here.

Samples and Containers

This project requires two liquids that remain transparent at moderate shock-wave loading. The liquids must be distinguishable from each other in the high-speed images and must be different densities in order that the Richtmyer-Meshkov instability is excited at the liquid/liquid interface. Because the instability growth rate depends on the density contrast, we seek liquids having a high-density ratio. Preferably the refractive indices of the two liquids are closely matched so that optical distortion is minimized when imaging the dynamic interface. Our experiments focused on interfaces between water and bromoform. Both are transparent under shock loading. Bromoform has density nearly three times that of water and is not miscible in water.

We explored the use of other candidate liquids to use with water as the "ambient liquid." Mineral oil remains transparent, but its density is nearly the same as water. Paraffin seemed a strong candidate because one observes that candle wax becomes transparent when melted, but we found that shock-induced melting does not produce this transparency. This property may be worth investigating as an interesting study in materials science.

We investigated water/bromoform interfaces in two configurations: double-interface and single interface. The double-interface configuration is a frozen layer of bromoform mounted with water on both sides. The bromoform slab is a square about 50 mm on each side by about 5-mm thick. We developed cooling methods with dry ice (i.e., frozen CO_2) that enabled freezing the bromoform with a structure of fine crystals, having a frosty appearance. Earlier attempts at quicker freezing produced samples of large crystals, which we believe is not appropriate for these experiments. We were unable to fabricate samples of frozen bromoform that are transparent or even translucent.

The single-interface configuration is a layer of liquid bromoform on the bottom and water on top, both within a transparent container. The explosive is attached to the bottom of the container, so a shock wave is transmitted through the bottom of the container and through the bromoform layer before it interacts with the water/bromoform interface. The shock wave is then transmitted into the water. The water/bromoform interface under investigation is a horizontal interface that can be initially perturbed by mechanically rocking the sample container, causing waves to form at the water/bromoform interface. We did the mechanical rocking with an acoustic speaker, enabling control of the amplitude and frequency of the rocking motion. This speaker technique was successful. However, if more precise control of initial perturbations is needed for future experiments, we can modify this method to use a stepping motor instead of a speaker, following the method of J. Jacobs (University of Arizona at

Tucson), who uses this method on his current "Drop Tank" experiment studying Richtmyer-Meshkov instability as well as his previous work on Rayleigh-Taylor instability.

Developing a container for the single-interface configuration proved to be difficult. We initially used a glass container, which is impervious to bromoform. However, we observed in the high-speed photographs that cracking induced by the shock wave in the glass walls propagated more rapidly than the shock wave in the bromoform. By the time that the shock wave reached the water/bromoform interface, the glass container walls were already cracked so we could not clearly observe the instability growth. Several shots showed qualitative instability growth, but it became clear that we could not measure the growth rate accurately because of the distortion introduced by the cracked glass. Consequently we abandoned glass containers in favor of polycarbonate containers. Then we were faced with the problem that bromoform chemically attacks polycarbonate. The chemical interaction occurs on a time scale of minutes, and the result is that the polycarbonate becomes clouded and leaky. A solution to this problem is a teflon coating to the inside of the polycarbonate container. Teflon is applied in a solution that does not attack the polycarbonate. The coating is applied by swishing the teflon solution inside the container for several minutes and then allowing the solvent to evaporate. The process can be done at room temperature, although elevated temperatures accelerate the drying. The thin teflon layer on the inner polycarbonate surface is transparent and it adequately protects the polycarbonate from chemical attack by the bromoform. The thickness of the teflon coating is microscopic and is therefore believed to be fluid mechanically insignificant with respect to the shock-wave passage between the container and bromoform. The effect of the teflon layer is not included in any numerical simulations.

Illuminators and Cameras

MILSI systems were fielded on two fluid instability experiments: (1) a "liquid curtain" experiment consisting of an initially frozen layer of a high-density fluid embedded in water and (2) single-interface instability between bromoform and water. In both experiments, fluorescent dye is added to the higher density fluid (e.g. bromoform) so the images show optical emission from this fluid. We observed the emitted fluorescent signal and the onset of the instability, but experimental difficulties prevented a measurement of the instability growth rate. Among the difficulties is shock-wave propagation through the container, which causes cracking and consequent obscuration of the instability region. This occurs with glass containers, but changing to polycarbonate

containers solved this problem. Experimental results show how to use MILSI to measure instability growth.

Fluorescent imaging

Because the laser scattering from transparent liquids is weak, we add a fluorescent tracer to one of the fluids. Early tests done with gelatin as a surrogate for the thin bromoform layer used fluorescein as the tracer within the gelatin. That is, fluorescein was added to the gelatin but not the surrounding water. Laser illumination produced a fluorescent image of the gelatin layer while the ambient water produced no scattering. The fluorescent image persisted after shock-wave passage through the gelatin layer.

When we began tests with bromoform, we found that we could not dissolve enough fluorescein in the bromoform sample to produce a good signal. We changed to rhodamine as the fluorescent dopant. Rhodamine is quite soluble in bromoform and produces strong fluorescent images when excited with the green light from a frequency-doubled YAG laser.

Simulations

Simulations of these HE-driven experiments have been done with a numerical model of the shock-tube experiment that was created in FY 1995. The model consisted of a HE-driven shock tube that launched a planar shock wave into a layer of bromoform embedded in water. The simulation examined instability growth and observed amplitude growth that should be measurable in experiments. Subsequently, the model was modified in FY 1997 studies to examine the growth of a single water/bromoform interface. A resolution study determined numerical convergence, so the simulation was used with various values of the initial perturbation amplitude. The simulation is with an Eulerian code, and simulations have also been attempted with a code having adaptive mesh refinement (AMR). Although no definitive results are in hand, it has been determined that exercising these large hydrodynamics codes with the problem of water/bromoform interfaces is useful for developing understanding of the code capabilities and for training users in the hydrodynamic algorithms included in the codes.

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Experimental apparatus

Figure 1. Schematic of HE experiment involving two water/bromoform interfaces. The shock wave moves from left to right and accelerates the curtain to the right. The "liquid curtain" is bromoform doped with rhodamine dye. The camera views from below to capture the fluorescent image induced by the laser sheet.

Figure 2. Sample data for an experiment with a single water/bromoform interface, showing fracturing of glass vessel. The detonator is placed below the sample container so the shock wave moves upward through the bromoform and then through the water/bromoform interface. Before the shock wave reaches the interface, the glass sample container is cracked in the viewing area. The glass fracturing is especially evident in frames 5 and 6. Dark regions show the fluoresced and scattered laser-light signal.

Figure 3. Another sample of data from single-interface experiment shows the shock wave in frames 2 and 3 as it approaches the water/bromoform interface from below. Frames 7 and 8 show glass fracturing before the interface instability has grown substantially.

Figure 4. Sample data with polycarbonate vessel. The polycarbonate container resists cracking. Frames 5-7 show instability of the water/bromoform interface, but these images are a combination of a wall jet and the actual instability growth.