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SHOCK AND RESHOCK OF AN UNSTABLE FLUID INTERFACE*

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ABSTRACT

Difficulties with experimental studies of the Richtmyer-Meshkov Instability are examined. We consider optical systems for explosively driven experiments with liquids, and the problems of the interfacial membrane and diffusion in experiments with gases. We show how the membrane induces deviation from impulsive loading of the unstable interface. Also, we summarize recent analyses of our experiments with a perturbed interface between gases, and show how accelerative instabilities can affect an equation-of-state experiment.

INTRODUCTION AND SUMMARY

We examine the effects of the Richtmyer-Meshkov instability (RMI)[1,2] at shocked liquid/liquid[3,4] and gas/gas interfaces.[5] The RMI is the impulsive analog of the Rayleigh-Taylor instability, an interfacial instability between fluids of different densities. These accelerative instabilities are potential problems in inertial confinement f.sion targets, and other applications involving highly accelerated interfaces. An equation-of-state experiment is such an application, as discussed below.

RMI experiments performed with an explosively driven shock tube (X-ST) have advantages over experiments using a compressed-gas shock tube (G-ST) because a liquid/liquid or (liquid/gas) interface in an X-ST can be formed without a membrane. By constrast, the G-ST is limited to either a continuous interface having a diffusive, initial mixing zone width about 1 cm,[6,7] or a discontinuous interface with a membrane initially separating the test gases.[2] However, X-ST experiments are more expensive because much of the apparatus is destroyed each experiment, and they can be fielded only at the few laboratories with explosives capabilities. Also, optical methods are more difficult to use for the X-ST, as we describe below.

We have compared experimental air/He and air/SF_6 results with 2D simulations[5] and found excellent qualitative agreement. The simulation produced a flow pattern quite similar to the experiment shadowgraph[8] of the reshock event in which the air/ SF_6 interface is severely distorted during the reshock in a manner that enhances vorticity production.

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The interfacial membrane used in G-ST experiments is believed to influence interfluid mixing, but its effects have not been previously measured or calculated precisely. In the "Membrane" section we show results of a 1D calculation of membrane inertial effects that shows the incident shock wave to be transmitted as a series of compression waves, which produces non-impulsive loading of the interface. Two-dimensional or 3D simulations can use this membrane-induced pressure loading to calculate more accurately the growth rate of the mixing zone. This deviation from impulsive loading may contribute to the lower growth rates observed experimentally, as compared with linear theory.

Another membrane problem is diffusion. We have problems with helium diffusing into the air chamber during air/He experiments. Using measured shock speeds, we estimate the consequent contamination and its effect on growth rates.

APPLICATION

Interfacial instability is a potential problem in equation-of-state (EOS) experiments where high explosive (HE) is used to launch a driver plate toward impact on an EOS sample,[9] as shown in Fig. 1. The hot,

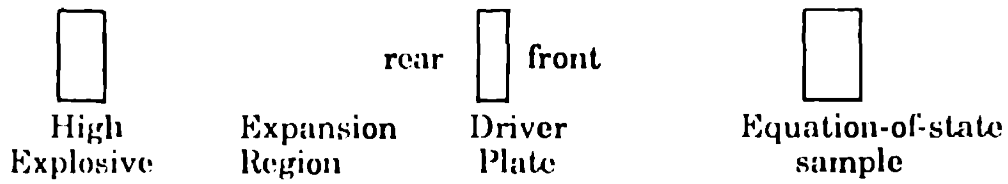

Fig. 1. Schematic layout of an EOS experiment having a flyer plate, where the rear surface may be eroded by accelerative instabilies.

Fig. 2. Time-resolved photograph of the front surface of a flyer plate, showing the penetration of hot gases caused by interfacial instability.

gaseous HE products stagnate against the rear surface of the driver plate, causing acceleration and heating. Because pressure and density gradients are opposed at this interface, accelerative instabilities may erode the surface, to the extent that it is fluid-like. Erosion is enhanced for high- temperature conditions by ablation of the surface. Bubbles of the hot HE gases may penetrate the driver plate, destroying its usefulness as a planar impactor on the EOS sample. An example of this problem is shown in the photograph in Fig. 2. Here the imaged front surface of the driver plate contains patches of light emitted from the hot, penetrating HE gases. Thus, accelerative instabilities limits the minimum thickness of a driver plate.

EXPLOSIVELY-DRIVEN SHOCK TUBE

We consider the possibility of improving the backlighting of our X-ST experiments by using collimated, rather than diffusive illumination. Our conclusion based on the ray-trace calculation discussed below is that collimated lighting would produce caustics[10] and thereby not improve the imaging.

Design of the test chamber is constrained by the interaction between shock wave and windows. We used[3] a large-volume chamber to avoid the interaction of the shock wave with windows. Thus, the lateral dimensions of the test section were larger than the shock front supported by the high explosive. This condition causes a "shock dome," which refracts light. We model the shock dome in optical ray-trace calculations as a spherical lens (viewed perpendicular to its axis) of refractive index, n = 1.51, corresponding to a 50-kbar shock in water. Values for the refractive index of shock-compressed water[11] are given as a function of density ρ (g/cm^3):

$$n = 1 + 0.334\,\rho \qquad (1)$$

The shock dome is immersed in a medium of uncompressed water with n = 1.33. An optical ray-trace calculation was performed for collimated light to determine whether better spatial resolution is attainable, but caustics were found. We conclude that backlighting with a diffusive source is better for measuring the time-resolved profile. Future comparisons of experimental data with 3D simulations having excellent graphics[12] may encourage the use of other imaging and illumination systems, possibly with front lighting.

GAS SHOCK TUBE RESULTS

Our observation of a reshocked air/SF_6 interface showed the difficulty of measuring the amplitude growth rate of reshocked interfaces using shadowgraphy. As shown in Fig. 3, shadowgraphic images are greatly obscured by the boundary layer flow. Strong refraction and small-angle scattering cause severe broadening of the interfacial profile. This broadening of the instability profile blocks clear observation of the mean flow, and measurement of the amplitude growth rate within the mean flow. Thus, these data show the need for better diagnostics of the mean or core flow.

As we reported at the 1989 Pleasanton Workshop, our feasibility study using imaged light scattering with illumination by a planar sheet of laser light overcomes this problem. We seeded the SF_6 gas with aerosol particles small enough to trace the SF_6 flow. The particles produced strong Mie scattering that we photographed. We observed a well-defined interfacial profile without the severe broadening seen in Fig. 3. Unfortunately we have not yet exploited this method to perform a systematic study of reshocked interfaces.

Fig. 3. This shadowgraph of a discontinuous, single- wavelength air/SF_6 interface that has been reshocked shows the broadening of the interfacial profile that obscures measurement of the amplitude growth rate. Air is above the interface and SF_6 below. The initial wavelength was 37.5 mm, and incident shock Mach 1.24.

MEMBRANE EFFECTS

The inertial effect of the membrane is estimated with a 1D code that calculates the fluid dynamical response of the membrane. In addition to this effect, the membrane also possesses strength, which initially inhibits interfluid mixing. Also, membrane fragments may agitate interfacial mixing at later times. Neither strength nor fragmentation effects are modeled here. We find that the inertial effect causes the incident shock wave transmitted through the membrane to become a series of compression waves, which eventually coalesce into a shock front. Thus, the interface acceleration is not actually impulsive. Also, the shock impedance mismatch between air and membrane causes a slight attenuation of the incident shock strength. We find that the compression waves persist for a distance of about 1,000 times the membrane thickness (corresponding to the ratio of densities between membrane material and gas), which is about 20% of the zero-to-peak amplitude in our experiments. In earlier experiments deploying thicker membranes, the non-impulsive acceleration likely persisted for a larger fraction of initial amplitude. This deviation from impulsive acceleration may be a cause of the differences between experimental measurements of amplitude growth rate and linear theory.

The 1D code used for this analysis is MACRAME, developed by Joseph Fritz at LANL for the design and analysis of EOS experiments.[13] Macrame is like a characteristics code, except that increments of pressure and velocity (rather than values of Reimann invariants) are transmitted along the characteristic trajectories. The membrane is modeled as a fluid having the EOS of polymethylmethacrylate (PMMA) and the air on both sides of the membrane is modeled as an ideal gas of $\gamma = 1.40$. Figures 3, 4, and 5 show the calculational results for Mach 1.20 incident shock wave, including the clear evidence for non-impulsive acceleration. These pressure histories provide guidance for improved simulations that can include the fluid dynamical effect of the membrane.

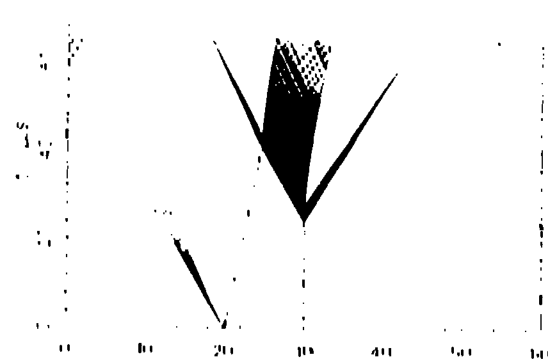

Fig. 3. In this x-t diagram, the incident shock wave in air impacts the membrane at t = 23.9 μs, causing a series of compression waves to be transmitted into the downstream air.

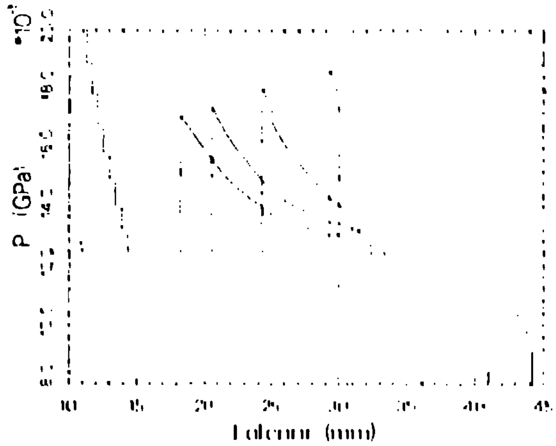

Fig. 4. These pressure profiles for times t = 26, 42, 56, and 65 μs show clearly the transmitted compression waves. A shock wave is formed at about X = 39.5 mm, a distance of 9.5 mm from the 10-μm-thick membrane.

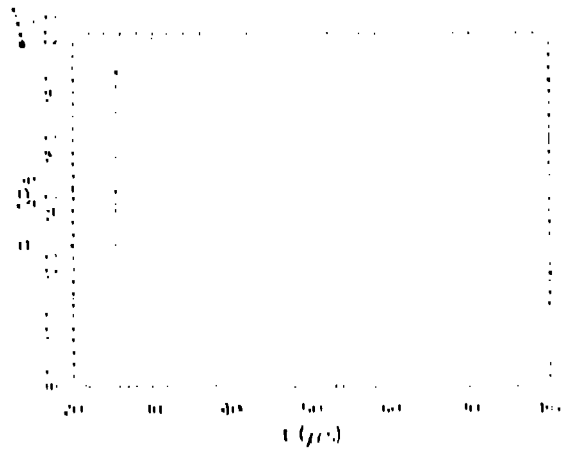

Fig. 5. These pressure histories at four locations show that the interface is not impulsively accelerated.

DIFFUSION

Air/He experiments with extremely thin membranes, ≤ 0.5-μm thick, have a problem with helium diffusion through the interfacial membrane. This problem is manifested by an increase in the incident shock wave speed U_s, which we use to estimate the contamination of helium, c = relative molar concentration of helium in the air chamber. For experiments with incident Mach 1.22 shock, we find that c is typically ~10%, corresponding to a decrease in pure-air mass density of 8.6%, and a decrease in the pre-shocked Atwood number of only 2.6%. The speed U_s is not measured within a few mm of the interface, so it is possible that the helium contamination in the vicinity of the interface is even greater than our estimate, which would additionally reduce the Atwood number.

We estimate the contamination by applying the ideal-gas shock-tube equation[14] as a guide, adjusted for attenuation of the shock wave traversing the shock tube.[15] Our calculations show that the helium contamination in the air chamber does not signficantly change the incident Mach number, $M_s = 1.22$, but it does increase the sound speed A_1, and thereby increase $U_s = M_s A_1$. For example, the 10% helium contamination decreases M_s by only 0.5%, but increases U_s by 5%, which we observe. The increase in A_1 is caused both by an increase in the ideal-gas γ and decrease in density.

Our estimate based on U_s measurements made several cm from the interface suggests that the magnitude of the contamination effect on the amplitude growth rate is small, much smaller than the difference between experimental results and linear theory.

CONCLUSION

Our analyses of difficulties in RMI experiments, including inertia and diffusion of the membrane, show effects that may explain some of the observed differences between experiments and calculations.

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REFERENCES

1 Robert D. Richtmyer, *Commun. Pure Appl. Math.* **13**, 297 (1960).

2 E. E. Meshkov, *Izv. Acad. Sci. USSR Fluid Dynamics* **4**, 151 (1969).

3 R. F. Benjamin and J. N. Fritz, *Phys. Fluids* **30**, 331 (1987).

4 R. F. Benjamin, H. E. Trease and J. W. Shaner, *Phys. Fluids* **27**, 2390 (1984).

5 R. F. Benjamin, D. C. Besnard, and J.-F. Haas, "Shock and reshock of an unstable interface," manuscript in progress, to be submitted to *Phys. Fluids*.

6 M. Brouillette and B. Sturtevant, *Proceedings of the 17th Inter- national Symposium on Shock Waves & Shock Tubes*, Y. W. Kim, ed. (AIP Conference Proceedings #208, New York, 1990), p. 284.

7 C. Cavailler, P. Mercier, G. Rodriguez, and J. F. Haas, *Proceedings of the 2nd International Workshop in the Physics of Turbulent Compressible Mixing* (Pleasanton, 1989), unpublished.

8 R. F. Benjamin, *Proceedings of the First International Workshop on the Physics of Turbulent, Compressible Mixing* (Princeton, 1988, to be published by Springer-Verlag, 1991).

9 R. G. McQueen, S. P. Marsh, J. W. Taylor, J. N. Fritz, and W. J. Carter, "The equation of state of solids from shock wave studies," chap. 7 in *High-Velocity Impact Phenomena*, Ray Kinslow, ed. (Academic Press, New York, 1970).

10 Wolfgang Merzkirch, *Flow Visualization* (Academic Press, New York, 1974).

11 Ya. B. Zel'dovich and Yu. P. Raizer, *Physics of Shock Waves and High-Temperature Hydrodynamic Phenomena*, vol. 2 (Academic Press, New York, 1967).

12 Private communication with Jeff Saltzman (Los Alamos).

13 Joseph N. Fritz (Los Alamos), manuscript in preparation.

14 H. W. Liepmann and A. Roshko, *Elements of Gasdynamics* (John Wiley & Sons, New York, 1957), Chapter 2.

15 Calculation of this estimate by Robert Fuehrer involved solving the shock-tube performance equation implicitly using the Newton-Raphson iteration procedure; to be published as a Los Alamos Report.