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Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

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University of Wisconsin, 1500 Engineering Dr., Madison WI 53706, USA

Abstract. Shock tube experiments for the study of the Richtmyer-Meshkov instability are presented. The shock tube is vertical with a square inner cross section. Two new techniques are used to prepare the interface and to determine its initial shape, prior to shock-acceleration. The interface is prepared by retracting a sinusoidally shaped plate initially separating CO_2 from air at atmospheric pressure. The gases are arranged with the heavy gas above the plate and, as the plate is retracted, the Rayleigh-Taylor instability commences, causing the initial sinusoidal amplitude to grow. At later times, the interface develops into the mushroom shapes typical of the onset of the Kelvin-Helmoltz instability. The interface is accelerated by a shock while its shape is still sinusoidal but its amplitude/wavelength ratio is large enough to study the post-shock evolution in the non-linear regime. Planar Mie scattering is used to image the pre-shock evolution of the interface (using a CW Ar^+ laser) and to capture one picture of the shocked interface (using a pulsed Nd:YAG laser). The growth rates of the perturbation amplitude are reported and compared with those predicted by some of the most recent non-linear analytical descriptions of the RM instability.

1 Introduction

The Rayleigh-Taylor (RT) [15] and Richtmyer-Meshkov (RM) [13], [10] instabilities are driven by the vorticity that develops at the interface between fluids of different acoustic impedance as a consequence of the misalignment of the density and pressure gradients due to a constant (RT) or impulsive (RM) acceleration. They both play important roles in the physics of inertial-confinement nuclear fusion experiments and astrophysical phenomena like supernova core overturn. Shock tube experiments are an ideal setting for the study of the RM instability, in that they separate the fluid dynamics from the plasma, radiation and phase transition physics that take place in a laser-driven experiment of the kind conducted on the Nova and Omega facilities. Many shock tube experiments have been performed in the past, in both the horizontal and vertical configurations, with a number of different ways to prepare the initial interface, and to record its pre- and post-shock properties. Some of the most common methods of interface preparation include: use of a nitrocellulose or mylar membrane [10], [4], [6]; use of a flat, retractable plate [5], [3]; use of a gas curtain [7]; use of a counterflow of two gases [9] or gravitational stratification of two liquids [8], coupled with a forced oscillation of the experimental facility. The objectives pursued at the time of interface preparation are multifold: minimize the presence of external disturbances (like membranes) that may affect the flow and/or the imaging of the interface; form an initial shape whose geometry and density gradient can be measured and documented in detail; and force the interface into a particular post-shock regime (linear, non-linear, single-mode, multi-mode, etc.). After various attempts to prepare a sinusoidal interface using mylar film and a flat, retracting plate [2], [11], we have developed a new technique that makes use of a sinusoidally shaped plate that is retracted in the same direction as the line of sight from the test section window to the imaging device. The heavy and light gases are placed above and below the retractable plate, respectively. Thus, upon plate retraction, the RT instability develops, causing the initial single-mode sinusoidal perturbation first to grow in amplitude and, later, to distort into the well known mushroom shapes. The experiments are timed so that the incident shock strikes the interface when it is still a near single-mode sinusoid with a large enough amplitude/wavelength ratio to enter "quickly" into the non-linear growth regime. The objective of the experiments is to develop a database to be compared with some of the more recent theoretical [14], [16], [1], [12] descriptions of the RM instability.

2 Apparatus and Instrumentation

The shock tube facility is described in detail in [2]; here we mention briefly its most relevant features. The shock tube is vertical, downward-firing. The driver section is round, with inner diameter of 41 cm and length of 9.2 m. The driven section has an outer round cross section, 46 cm in diameter, and an inner square cross section 25×25 cm. It consists of seven segments that can be arranged in different order so as to achieve the distances between the initial interface location, the test section and the tube's end wall necessary to study an interface of prescribed post-shock age. A high-pressure boost tank is connected to the driver section via a large flow rate, pneumatically-driven, fast-opening valve. In preparing for an experiment, the driver section is pressurized up to 200 kPa below the diaphragm rupture pressure and the boost tank filled up to 13.8 MPa. Once a signal is sent to the fast-opening valve, a shock wave is released within 100 ms. The driver gas is always helium because both stronger shocks can be generated and timing uncertainties minimized. Piezoelectric pressure transducers placed at various locations in the driven section are used to trigger some of the controlling electronics and to measure the shock speed.

The interface is prepared in a special tube segment (interface section) designed to allow a retractable plate to slide along two grooves in opposite, inner tube walls. The plate is shown in Fig. 1: it is made of copper (chosen for its malleability) and it is given a single-mode sinusoidal shape with amplitude 3.2 mm and wavelength 38.1 mm by drawing an initially flat plate through two shaped rollers. The plate is retracted from the interface section by a pneumatic cylinder operated with room temperature, high-pressure helium.

The test section was also specially designed, to perform both line of sight and planar flow visualization. In the present experiments, only one fused silica window is used; the other opening is closed with an aluminum plug. The inside walls of the test section are painted matte black to minimize the reflection of any stray light rays.

The end wall is equipped with an optical port, to allow the laser sheet to enter the tube. Gas inlet/outlet ports are located in the end wall and in the interface section, just below the retractable plate. To set up an experiment, the driven section is evacuated of all gas left from the previous run and filled with room pressure CO_2. The sinusoidal plate is inserted and air is injected from the port in the end wall, while CO_2 exits the tube through the port below the plate. Once the test gas below the plate is sufficiently pure air, it is seeded with cigarette smoke to cause Mie scattering of the laser sheet light.

Planar Mie scattering imaging is performed in two different setups. To study the evolution of the pre-shock interface, whose amplitude grows from the moment of plate retraction due to the RT instability, continuous planar Mie scattering is used. A series of experiments, without shocks, is performed to establish a database from which to infer the initial condition in each shock experiment. In this series, the interface is prepared inside the test section, in order to use its optical port to image the two gases. A 1.5 W, CW Ar^+ laser and a CCD camera with a 256×256 pixels sensor array, operating at about 100 fps, are used to generate the illuminating sheet and to image the interface, respectively. The camera has an 8-bit digital output, connected to a PC-based frame grabber board. To capture an image of a shocked interface, planar Mie scattering is performed using a pulsed Nd:YAG laser (delivering a 10 ns pulse of about 400 mJ at 532 nm) and a CCD camera with a 1024×1024 pixel, thinned, backlit, Peltier cooled sensor array and slow readout for noise minimization. The YAG laser was retrofitted to allow it to hold the capacitor charge without continuous Q-switching until a signal is sent to it to deliver a light pulse.

In a typical shock experiment, with the driven and smoke-seeded test gases on either side of the plate, plate retraction begins at a rate of 0.5 m/s. When the plate traverses the plane where the laser sheet will enter the test section, its retraction speed is increased to 1.8 m/s and a pulse is sent to the fast-opening valve. As it travels down the tube, the shock is sensed by a piezotransducer that triggers the delay box that activates the laser at the time when the interface is

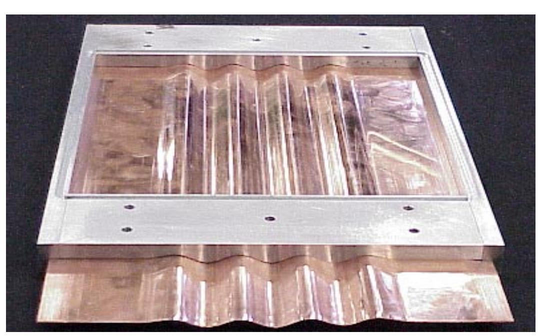


Fig. 1. Sinusoidally shaped plate and its support frame

expected to be within the test section. The whole sequence takes place in the dark, with the CCD camera shutter open for about 5 s.

3 Experiments

Representative images of the RT instability that develops when the plate is retracted are shown in Fig. 2. The time is measured from the instant when the plate traverses the laser sheet. The digital images show that up until $t = 120$ ms the interface is still sinusoidal, while at later times, it begins to exhibit some of the double-valued, mushroom shape features. Over such short times, the diffusion at the interface is minimal (the diffusion layer thickness is estimated to be less than 1 mm), thus the technique produces a sharp, membraneless, single-mode interface whose geometrical properties are precisely measurable, making it an ideal initial condition for a RM experiment. In the sequence shown here, no 3-D effects are visible. In other series, any fluid motions along the direction of plate retraction only appear after the latest possible time of shock arrival at the interface. From the database of RT images, one can infer the initial condition of any RM experiment by measuring the time elapsed between plate traversal of the laser plane and shock arrival at the interface (the interface's RT-age).

Sample images of shocked interfaces are shown in Fig. 3. In all cases, the interface RT-age is 110 ms and the incident shock has $M = 3.08$. Since the shock travels from a heavy into a light gas, the interface is expected to undergo a

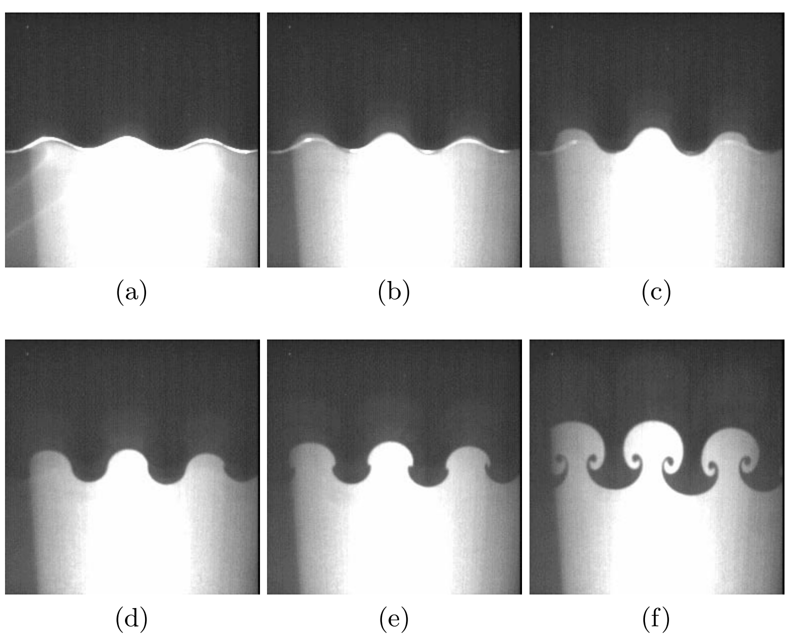
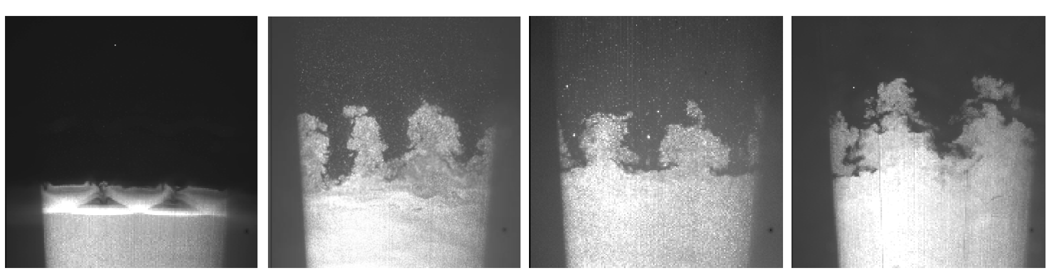


Fig. 2. RT-times from plate traversal of the laser sheet: (a) 0 ms, (b) 50 ms, (c) 80 ms, (d) 110 ms, (e) 150 ms, (f) 250 ms

phase reversal immediately following shock acceleration. All images are digitally processed with a non-linear median filter based on order statistics to remove any outlier, random noise. Next, the image is converted to a two-bit image by application of a threshold filter separating the high pixel values (smoke-seeded air) from the low ones (CO_2). A contour-finding routine extracts the shape of the interface from the black and white image, and the peak-to-peak amplitude is calculated as an average of the minimum and maximum mutual penetrations by the two gases measured from the interface contour. Figure 3(a) shows the phase reversal taking place at the interface and the transmitted shock (seen as the bright, nearly horizontal line just below the top of the interface). Figures 3(b)-(d) show the interface at different post-shock times. In all the images, the interface exhibits very irregular edges, as opposed to the very smooth contours seen in the RT images, and the mixing zone appears turbulent. The reason is that any small amplitude and/or wavelength perturbations superimposed on the main sinusoidal mode, and not resolved by the imaging system used to study the initial conditions, grow extremely rapidly upon shock acceleration because of their large wavenumber and the large velocity jump (≈ 700 m/s) induced on the interface by the incident shock.

The amplitude values extracted from the images are shown in Fig. 4 and compared with theoretical predictions from [1], [13], [14], [16]. The experimental data fall between the models by [14] and [16]. The model in [1] is only meant for the interface's asymptotic behavior and thus it is only plotted for intermediate to late times. A separate comparison, shown in Fig. 5, is performed between the present data and the theory in [12]. In this case, a fitting parameter is adjusted in the expression for the amplitude. It appears that the data are bound by curves generated using values of $p = 1.492$ and $p = 1.923$ (see [12]), for the top and bottom curves, respectively.

The scatter in the data suggests that the interface evolution is extremely sensitive to its initial conditions. This is confirmed by comparison between images of different interfaces, with the same RT- and RM-ages: in some cases, large amplitude perturbations and mushroom-like structures are visible while in others they are much less developed. The explanation is that the initial conditions may be only "nominally" the same in the two cases: indeed, the initial conditions are



(a) (b) (c) (d)

Fig. 3. RM-times: (a) 5 μs, (b) 646 μs, (c) 1.08 ms, (d) 1.8 ms

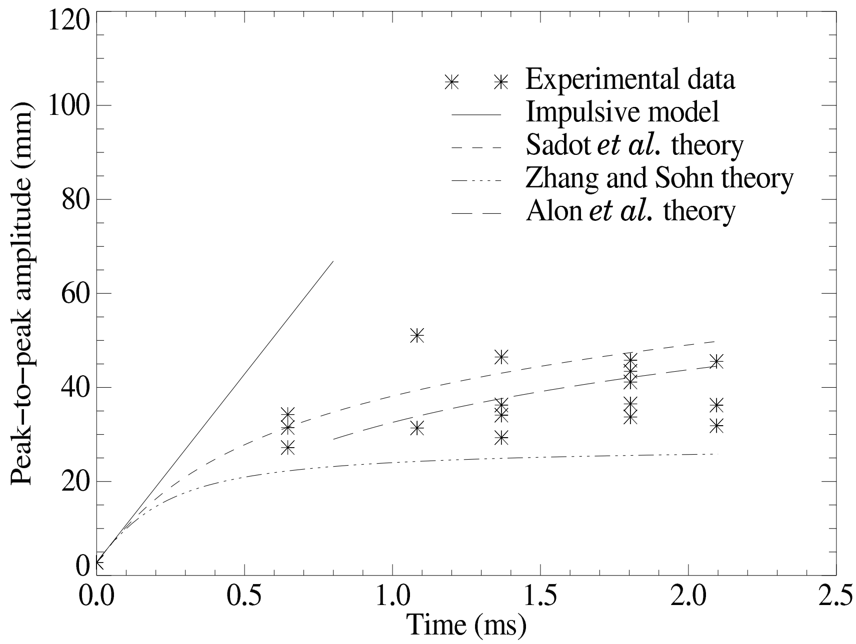


Fig. 4. Comparison of experimental data and analytical predictions

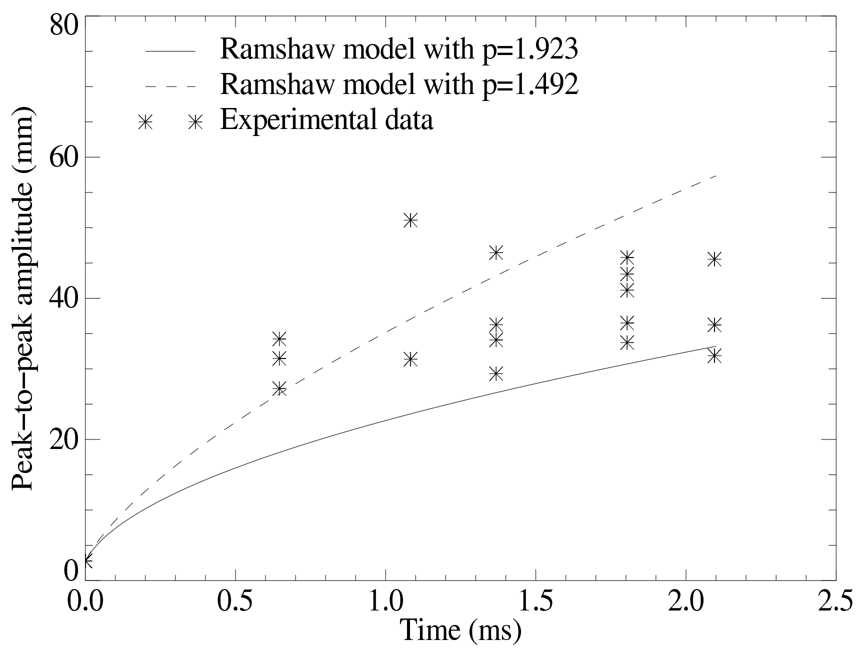


Fig. 5. Comparison of experimental data with predictions from [12]

only *inferred* from the RT data base, by measuring the interface RT-age. Furthermore, the spatial and temporal resolutions of the imaging system used to measure the initial conditions are not high enough to detect any random, turbulent motions initially present at the interface which may contribute significantly to its later evolution, especially the behavior of the smaller scale features. This suggests two improvements that could be brought to the experiment: dynamic imaging of the initial conditions, to be performed "during" each experiment, up until shock arrival at the interface; and increased imaging capabilities to detect small scale motions at the interface, prior to its impulsive acceleration.

4 Conclusions

A new technique to prepare an interface suitable for RM experiments has been successfully developed and demonstrated. Retraction of a sinusoidally-shaped plate generates a sharp, membraneless interface with a well defined single-mode perturbation. Growth rates have been measured for the CO_2/air interface accelerated by a $M = 3.08$ shock and compared to some of the most recent non-linear theories. The interface behavior seems to be highly dependent on the initial conditions, with some of the unresolved initial properties (small scale distortions and motions) possibly playing a critical role in the way the interface evolves. Improvements to the current methodology are being implemented to address the experimental scatter.

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