Experimental Study of a Strongly Shocked Gas Interface with Visualized Initial Conditions

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Presented at the 8th International Workshop on the Physics of Compressible Turbulent Mixing (8th IWPCTM), California Institute of Technology, Pasadena, California, 9–14 December 2001 (submitted to *Lasers and Particle Beams*).

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I. Introduction

The Richtmyer-Meshkov (RM) instability[4][2] is studied for a strongly shocked gas-gas interface in the nonlinear regime. The impulsive acceleration of the interface by a shock wave imparts a velocity to the interface and baroclinic vorticity ($\nabla\rho\times\nabla p$) causes the amplitude of a single mode perturbation to grow. Experiments are conducted in a large, square cross-section, vertical shock tube[1]. The shock tube has been modified to facilitate imaging of a single-mode, diffuse interface prior to acceleration by a planar shock wave. The gas pair combination CO_2-air is studied in the strongly shocked regime, M=2.90.

II. Experiment

Experiments for the compressible, turbulent mixing of a gas-gas interface are conducted in a shock tube. The shock tube is oriented vertically (9.3 m high), has a large square cross section (25.4 cm), is modular (for studying interfaces of different gases) and has a structural capacity of 20 MPa. The experimental diagnostic setup is show in Fig. 1. The driven and test section gases are initially separated with a thin copper plate. The copper plate has an imposed single-mode sinusoidal perturbation along its length. The interface between the two gases is created via retracting the sine wave plate through the back wall of the shock tube. After the sine wave plate has exited the shock tube, a planar shock wave impulsively accelerates the interface down into the test section where the shocked interface is studied. The sine wave plate has three wavelengths of λ=38.1 mm and an amplitude of η_0=3.175 mm. The wave number, $k=2\pi/\lambda$, is used to define the linear regime for the perturbation. The linear regime is $k\eta_0<<1$, and for this perturbation $k\eta_0$=0.52 which is in the linear to nonlinear transitional regime.

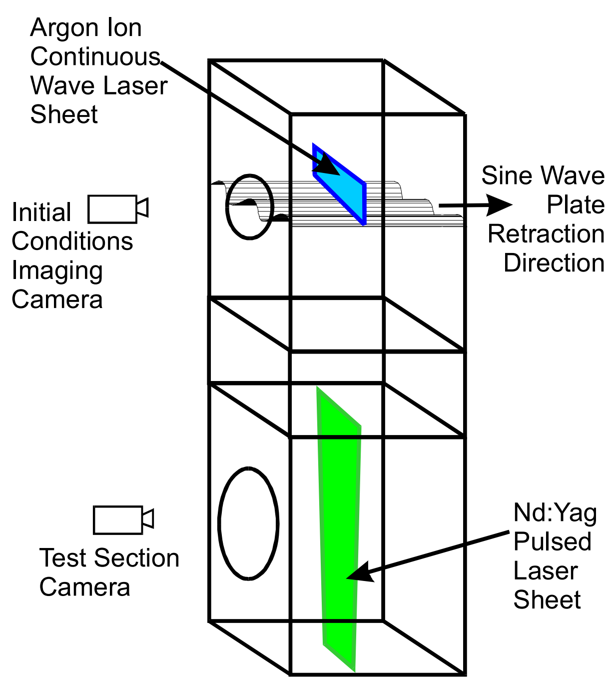

Figure 1. Schematic of initial condition and shocked interface imaging diagnostics.

There are two lasers and cameras used in the experimental setup as shown in Fig. 1. The test gas is seeded with smoke particles (~0.5 μm) so the interface may be imaged by Mie scattering. The development of the initial condition is imaged with an 8-bit CCD camera, 256x256 pixels, framing at 100 fps. An argon-ion laser sheet enters the side of the shock tube just above the sine wave plate. When the plate is retracted past the laser sheet position, the interface is illuminated by the smoke particles in the test gas scattering light. When the shock wave is incident on the interface the interface is accelerated downwards. The test section pulsed laser is triggered with timing circuitry that pulses the laser sheet that enters the shock tube from the bottom flange. A single image of the shocked interface is obtained per experiment with a 1024x1024, 16-bit CCD camera.

The initial condition of the interface with the retractable plate technique is dependent on the Atwood number:

$$A = \frac{\rho_1 - \rho_2}{\rho_1 + \rho_2} \tag{1}$$

where ρ is the density and the subscript 1 is the lower fluid and 2 is the upper fluid. For a positive Atwood number the interface is stable while a negative Atwood number interface is unstable. The Rayleigh-Taylor[3][6] instability is the phenomenon whereby a heavier fluid supported by a lighter fluid, in the presence of gravity, is unstable. The instability manifests itself by the growth in amplitude of the perturbation. The Richtmyer-Meshkov studies of a CO_2-air interface utilize the Rayleigh-Taylor instability to provide the initial condition. A Rayleigh-Taylor stable interface cannot be studied with the current retractable plate technique as the perturbations at the interface dissipate before the interface can be shocked.

The layout of the experimental image is shown in Fig. 2. The initial condition is shown on the left and the shocked image on the right. The smaller interface section window (12 cm ϕ) images the center of the interface and captures three peaks and two troughs of the single-mode perturbation on the interface. The larger test section window (28 cm ϕ) allows imaging of four peaks and three troughs. The raw images are processed to determine the perturbation amplitudes of the initial condition and shocked image, η_{IC} and η_{RM}. A median filter is applied to the raw image to remove noise. The processed image is converted to a 2-bit image (black and white, shown on the left beneath each raw image) and a Sobel operator is applied to the 2-bit image for edge-detection and to reveal the interface. The peak to peak perturbation distance (δ) is determined using the following formula:

$$\delta = (\overline{P}_{pix} - \overline{V}_{pix} - 1) P_{\mathrm{dim}} \tag{2}$$

where $\overline{P}_{pix}$ is the average pixel row number of the perturbation peaks, $\overline{V}_{pix}$ is the average pixel row number of the perturbation valleys and P_{dim} is the pixel dimension. The perturbation amplitude is half of the peak to peak distance, $\eta = 1/2\delta$.

An experimental result is shown in Fig. 3. The initial amplitude of the interface is η_{IC}=4.64 mm and the shocked amplitude is η_{RM}=13.83 mm. The age of the shocked interface at the time of imaging is τ_{RM}=0.70 ms. The shocked interface has inverted phase (typical of a shocked interface where the shock travels from the light fluid to the heavy fluid) and the perturbation amplitude has grown well into the nonlinear regime. The amplitude is approximately the same from wavelength to wavelength and the initial sinusoid geometry has evolved into mushroom-like features.

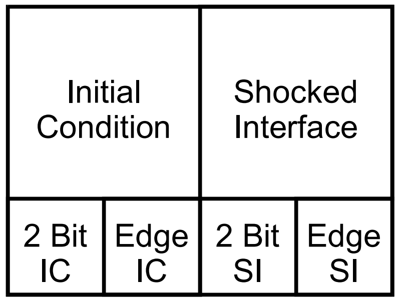

Figure 2. Layout of experimental images. The lower portion of the figure contains the processed initial condition (IC) and shocked image (SI) images.

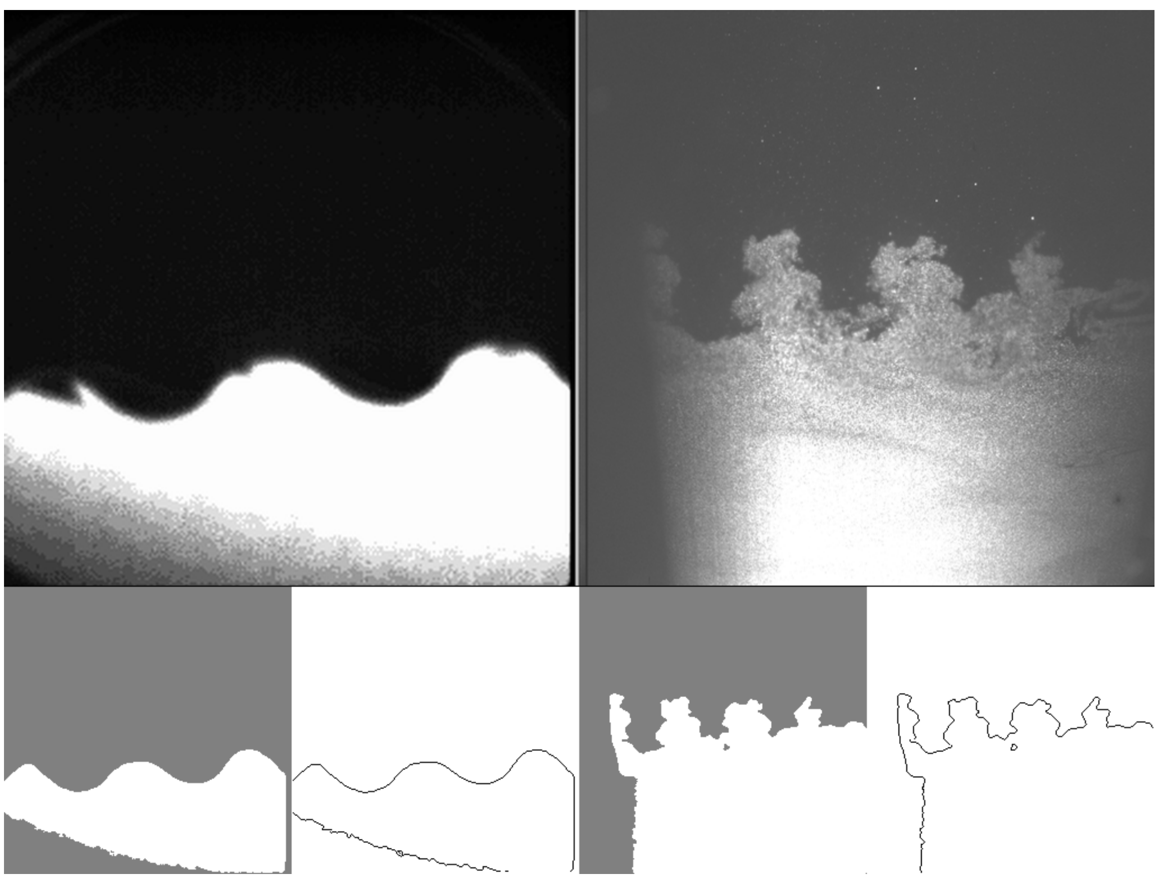

Figure 3. Experiment 322, CO_2-air, M=2.90, η_{IC}=4.64 mm, η_{RM}=13.83 mm and τ_{RM}=0.70 ms.

III. Results

Linear and nonlinear theories are evaluated for comparison with the experimental data. The Richtmyer impulsive model for the perturbation amplitude growth rate is:

$$\dot{\eta} = -kW\eta_0' A' t \tag{3}$$

where W is the interface velocity, η_0' is the post-shocked amplitude, A' is the post-shocked Atwood number and t is time. The post-shocked amplitude is:

$$\eta_0' = \eta_0 \left(1 - \frac{|W|}{Mc}\right), \tag{4}$$

and c is the speed of sound. Zhang and Sohn[7] construct a nonlinear model based on an early linear and compressible model, and a later time nonlinear and incompressible model, which are matched through the use of Padé approximations:

$$\dot{\eta} = \frac{\dot{\eta}_{lin}}{1 + \dot{\eta}_{lin} k^2 \eta_0 t + \max\{0, \eta_0^2 - A' + 1/2\} \dot{\eta}_{lin}^2 k^2 t^2} \tag{5}$$

Sadot *et al*.[5] present a bubble-merger model similar in form to Zhang and Sohn[7]:

$$\dot{\eta} = \dot{\eta}_{lin} \frac{1 + Bt}{1 + Dt + Et^2}, \tag{6}$$

where

$$D_{b/s} = (1 \pm A')\dot{\eta}_{lin} k \quad \text{and} \quad E_{b/s} = [(1 \pm A')/(1 + A')] \times (1/2\pi C)\dot{\eta}_{lin}^2 k^2, \tag{7}$$

with the plus sign for the bubble and minus sign for the spike, and C=1/2π for low Atwood numbers. The theories are compared with experimental data in Fig. 4.

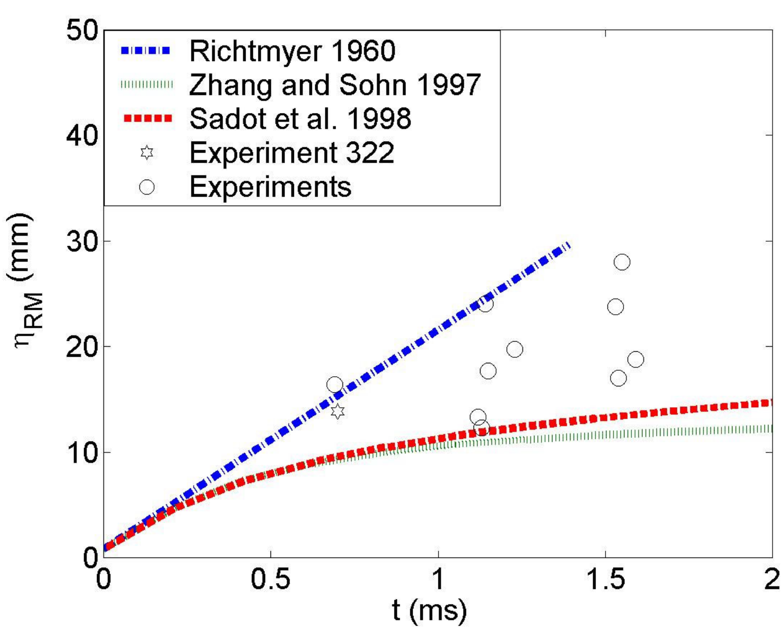

Figure 4. Comparison of experimental data with linear and nonlinear theories for a CO_2-air interface, M=2.90.

The theories are evaluated for experiment 322 where η_0=4.64 mm. The initial condition is in the nonlinear regime, $k\eta_0$=0.76. Additional experimental results are reported in [1], however, the initial amplitude for each experiment varies from 4-10 mm. The linear theory (Richtmyer[4]) compares most favorably with experiment 322 while the nonlinear theories (Sadot[5] and Zhang[7]) underpredict the growth by 40%. As this strongly shocked interface is in the nonlinear regime, it is notable that the linear theory best matches the experimental data. At longer times, the nonlinear theories are predicting a leveling-out of the growth whereas the experimental data suggest the interface is still far from the saturation region.

IV. Conclusion

A new experimental technique has been developed for imaging the initial condition for a strongly shocked interface. The initial condition is a single-mode perturbation of a gas-gas interface in the absence of a membrane. The results show the linear theory best agrees with the experiment while the nonlinear theories underpredict the instability growth.

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