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Experimental Studies of Richtmyer–Meshkov Instability*

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Abstract. Two novel experiments are reported which improve upon previous experimental studies of Richtmyer-Meshkov instability in that very well controlled initial interfaces are obtained. The first is an incompressible experiment in which an impulsive acceleration is given to a system of two liquids by bouncing it off of a fixed spring. The second is a shock tube experiment in which a well controlled flat interface is obtained by flowing light and heavy gases from opposite ends of a vertical shock tube. Both of these experiments provide particularly well visualized images of the instability far into the nonlinear regime.

1 Introduction

Richtmyer-Meshkov (RM) instability is a fundamental fluid instability which exhibits many of the nonlinear complexities that transform simple initial conditions into a complex turbulent flow. Yet there is a scarcity of well visualized experimental results. Probably the biggest reason for this deficiency is that RM experiments are typically carried out in shock tubes in which the generation of a sharp well controlled interface between gases is extremely difficult. One approach to this problem has been to use a thin membrane to initially separate the two gases [5] [1]. However, the effects of the broken membrane fragments on the developing instability are significant and difficult to predict, making comparisons with the results of computational investigations problematic. In attempts to avoid the effects of membranes, other researchers have utilized a solid barrier to initially separate the gases which is then removed immediately prior to firing the shock tube [4] [2]. However, because the disturbance produced by pulling the barrier out of the shock tube is normally used as the source of the initial perturbation,

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these experiments have initial conditions which are nonuniform and difficult to characterize, further complicating comparisons with other experimental and computational investigations.

Two new experiments are reported here which improve upon the previous experimental studies in that very well controlled initial interfaces are obtained. As a result, these new experiments provide particularly well visualized images and measurements of RM instability far into the nonlinear regime. The first experiment is similar one reported by Castilla and Redondo [3] in which a box containing two fluids is rapidly decelerated after a short fall, except that in the present experiment an impulsive acceleration is given to a system of two miscible liquids by bouncing it off of a fixed spring. The second experiment is a compressible one in which a well controlled flat interface is obtained by allowing a light and a heavy gas to flow from opposite ends of a vertical shock tube. In both experiments a sinusoidal initial shape is given to the interfaces by gently shaking the experimental apparatus in the lateral direction to produce standing waves.

2 Incompressible Experiments

The experimental apparatus (figure 1) consists of a thin rectangular tank measuring 2.54 cm × 11.75 cm × 25.4 cm which is mounted to a vertical linear rail system oriented so that the tank is free to move in the vertical direction with approximately 1 m of travel. The bottom half of the tank is initially filled with colored salt solution ($Ca(NO_3)_2 + H_2O$) and the top half with clear fresh water, yielding an Atwood number (the difference of the densities divided by their sum) of approximately 0.15. The rails are mounted so that they pivot about a point at their upper end. An initial surface shape is given to the fluid interface by sinusoidally oscillating the rails in the horizontal direction at a prescribed frequency using a stepper motor and a cam to produce standing waves on the interface. The tank is released from an initial height, from which it falls and bounces off of a fixed coil spring mounted to the end of the translator, thus generating an impulsive acceleration. Since the container is in free-fall before and after bouncing, it only experiences a body force during the bouncing event which lasts for approximately 30 ms. The experiment therefore generates an impulsive acceleration without using a shock wave. After bouncing, the system travels upward and downward again before bouncing a second time. During this period the interface is viewed by a shuttered CCD camera mounted to the moving container. The video output from the camera is digitized and stored by a computer system with a frame grabber.

Figure 2 is a sequence of images showing the evolution of the instability as viewed by the video camera. Figure 2(a) was taken immediately before the container contacts the spring. Thus, it represents the initial interface shape. Figures 2(b)–(e) span the period of free fall between the first two bounces, while figure 2(f) was taken during

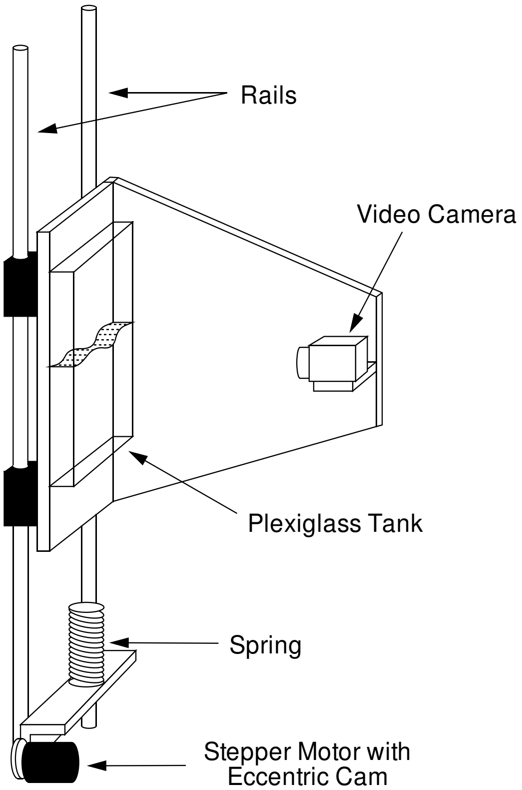


Figure 1: Apparatus used in the incompressible experiments.

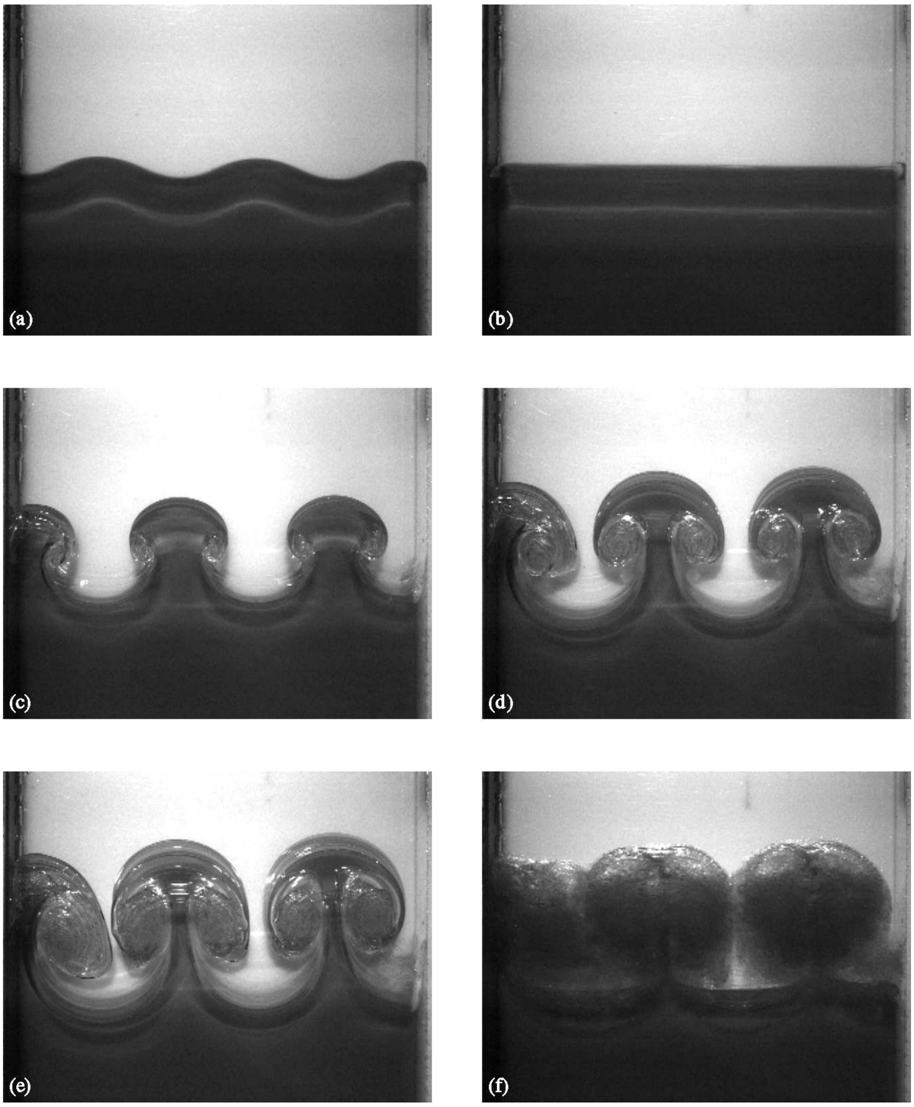


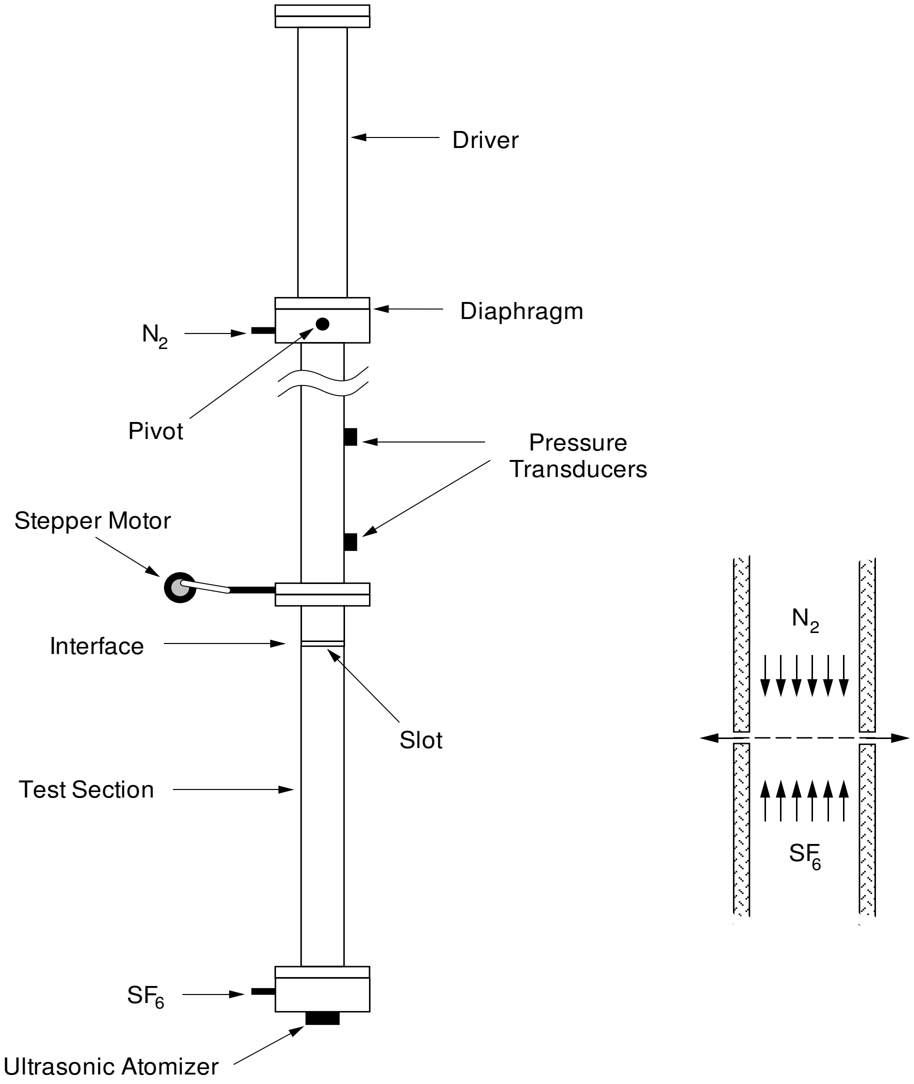
Figure 2: A sequence of video images showing the development of the instability in the incompressible experiments. Times relative to the point of first contact with the spring are: (a) −8 ms, (b) 25 ms, (c) 142 ms, (d) 275 ms, (e) 392 ms, (f) 525 ms. The second spring contact occurs between (e) and (f).

the second bounce. The impulsive acceleration in these experiments is directed from the heavier fluid into the lighter fluid. Thus the sinusoidal initial interface inverts phase before growing (figure 2b). Immediately after inversion, the instability retains a sinusoidal shape. However, with time, vortices begin to form at points midway between the crests and troughs, producing the mushroom pattern typical of the RT and RM instability of fluids with small or moderate density differences (figure 2c). As time advances, these vortices grow in size as they roll the interface around their centers to form a spiral pattern (figure 2d and e). Note that, characteristic of the instability with small density differences, the interface shape retains its top-to-bottom symmetry well into the nonlinear regime. The container bounces a second time, and thus receives a second acceleration beginning at a point between figures 2(e) and 2(f). In figure 2(f), one can see a dramatic change in the interfacial pattern in which the mushroom features rapidly collapse and erupt into turbulence.

3 Shock Tube Experiments

These experiments utilize a vertical shock tube to study the Richtmyer-Meshkov instability of a diffuse interface. The shock tube (figure 3a) is 4.3 m long and has a 1 m long, 10.2 cm diameter driver, and a 3.3 m long driven section with a 8.9 cm square cross-section. The test section has transparent walls to facilitate flow visualization. A flat, well controlled interface is formed in the test section using a novel technique whereby a heavy gas (SF_6) flows upward in the shock tube and collides with a light gas (N_2) flowing downward. The light gas enters through a plenum at the top of the driven section immediately below the diaphragm, and the heavy gas enters through a similar plenum at the bottom of the test section. Both gases exit the shock tube through slots in the test section wall, leaving a well controlled flat interface (figure 3b). The shock tube is mounted by pins at its upper end so that it can be pivoted in the horizontal direction. A sinusoidal initial shape is then given to the interface in a similar manner to that used in the incompressible experiments, by oscillating the shock tube in the horizontal direction, in this case using a stepper motor and crank mechanism. A weak shock wave ($M_s = 1.1$) is generated by puncturing a Mylar diaphragm which travels down the tube where it impacts the interface to produce the instability. The interface is made visible by seeding the heavy gas with a water droplet fog produced by an ultrasonic atomizer. Views of the evolving instability are captured utilizing strobe illumination and a 35 mm camera. The light from the strobe is passed through a 2.54 cm wide slot before entering the test section so that only the center portion of the interface is illuminated.

Figure 4 is a sequence of photographs showing the evolution of the instability in these experiments. Note that only one picture can be acquired per run; therefore, this sequence was assembled from three separate experiments. Figure 4(a) is a view of the initial interface which exhibits a nearly sinusoidal shape. Figures 4(b)–(d), taken 2,



(a)

(b)

Figure 3: Experimental apparatus used in the the shock tube experiments. (a) The shock tube. (b) The interface-forming flow configuration.

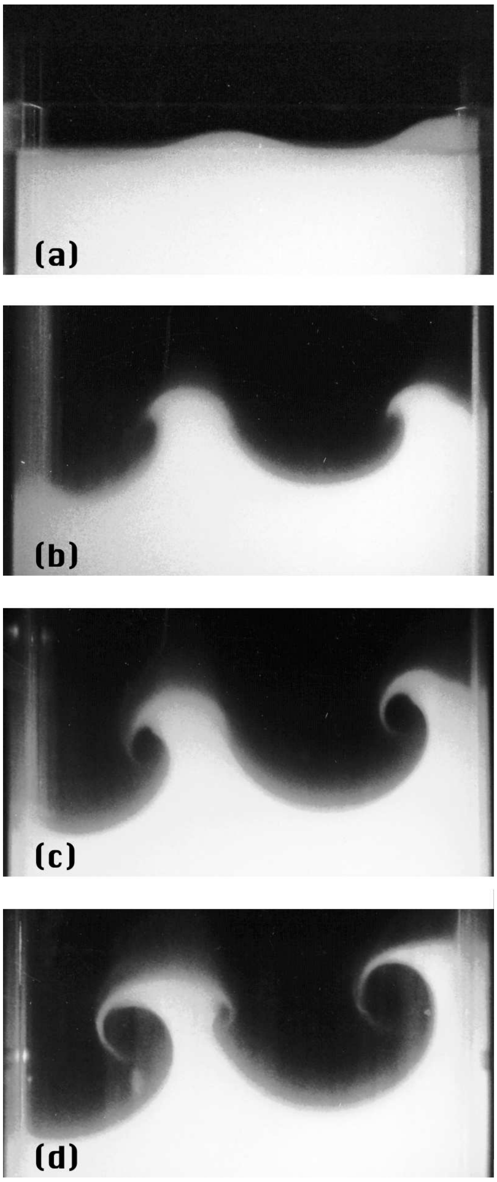


Figure 4: A sequence of strobe illuminated photographs depicting the evolution of the instability in the shock tube experiments. The heavy (lower) gas has been seeded with a water droplet fog, and the strobe light was passed through a 2.54 cm slit, so that only the center portion of the shock tube is illuminated. Times relative to that of the shock passage are: (b) 2 ms, (c) 4 ms, (d) 6 ms, and (a) is a view of the initial condition.

4 and 6 ms after shock passage show the evolution of the instability. As the instability evolves, the interface becomes increasingly non-sinusoidal with the appearances of mushroom structures similar to those observed in the incompressible experiments described above. However, unlike the structures observed in the incompressible experiments, this higher Atwood number instability ($At = 0.67$) shows considerably more top-to-bottom asymmetry. In addition, much less of the heavy gas is entrained into the vortices.

4 Conclusions

The two experiments reported here are unique in that well controlled initial interfaces are obtained. Thus, these experiments yield extremely well visualized and repeatable results. Furthermore, the initial conditions in these experiments can be easily characterized, thereby greatly increasing the possibility of making useful comparisons with future computational studies.

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