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AN EXPERIMENTAL STUDY OF RICHTMYER-MESHKOV INSTABILITY

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ABSTRACT

Richtmyer-Meshkov (RM) instability occurs when a planar interface separating two fluids of different density is impulsively accelerated in the direction of its normal. It is one of the most fundamental of fluid instabilities and is of importance in fields ranging from astrophysics to materials processing. Because RM instability experiments are normally carried out in shock tubes, where the generation of a sharp well controlled interface between gases is difficult, there is a scarcity of good experimental results. The experiments presented here utilize a novel technique which circumvents many of the experimental difficulties that have previously limited the study of RM instability. In this system, the instability is generated by bouncing a thin rectangular tank containing two liquids off of a fixed spring. Results obtained from these experiments yield particularly well visualized images of the nonlinear development of the instability However, because the run time in these experiments is limited, new experiments capable of achieving longer run times are planned .

INTRODUCTION

Richtmyer-Meshkov (RM) instability is the instability of an impulsively accelerated planar interface separating two fluids of different density. For example, RM instability causes small perturbations on a flat interface, accelerated by a passing shock wave, to grow in amplitude and eventually become a turbulent flow. It is closely related to Rayleigh-Taylor (RT) instability which is the instability of a planar interface undergoing constant acceleration, such as caused by the suspension of a heavy fluid over a lighter one in the earth's gravitational field. Therefore, RM instability is often referred to as impulsive or shock-induced Rayleigh-Taylor instability. Like the well known Kelvin-Helmoltz instability, RM instability is a fundamental hydrodynamic instability which exhibits many of the nonlinear complexities that transform simple initial conditions into a complex turbulent flow. Furthermore, the simplicity of RM instability (in that it requires very few defining parameters), and the fact that it can be generated in a closed container, makes it an excellent testbed to study nonlinear stability theory as well as turbulent transport in a heterogeneous system.

Richtmyer-Meshkov instability is of importance in fields ranging from astrophysics to materials processing. For example, RM instability is believed to occur when the outward propagating shock wave generated by the collapsing core of dying star passes over the helium-hydrogen interface. Observations of the optical output of the recent supernova 1987A seem to indicate that the outer regions of the supernova were much more uniformly mixed than expected, indicating significant RM mixing had occurred (ref. 1). RM instability is of critical importance to inertial confinement fusion. In this case, the shell which encapsulates the deuterium-tritium fuel becomes RM unstable as it is accelerated inward by the ablation of its outer surface by laser or secondary Xray radiation. The degree of compression achievable in laser fusion experiments is ultimately limited by RM and RT instability. Thus, these instabilities represent the single most significant barrier to attaining positive-net-yield fusion reactions in laser fusion facilities (ref. 2). RM instability is also of importance to high speed combustion applications, where, for example, the interaction of a shock wave with a flame front can be unstable, thereby greatly enhancing mixing and significantly altering the burning rate (ref. 3). In addition, RM instability has been identified as one of the phenomena which allows dissimilar metal alloys to be bonded together in explosive welding processes (ref. 4).

The evolution of RT instability from small amplitude perturbations to fully turbulent flow has been well documented by numerous experimental investigations (refs. 5 and 6). However similar experimental verification for RM instability is noticeably lacking. In particular, there is a scarcity of well visualized experimental results. RM instability experiments have traditionally been carried out in shock tubes. Shock tube experiments have had some success in verifying the linear stability theory, and in determining the bulk properties of the final turbulent flow. However, visualizations of the nonlinear transition process in these experiments are virtually nonexistent. The major difficulty in these experiments is in maintaining a well controlled sharp boundary between two gases. One solution to this problem has been to initially separate the two gases with a thin membrane which is then broken by the passing shock wave (refs. 7 and 8). Under the best of circumstances, the membrane is broken into small pieces which produce a minimal effect on the larger scale initial perturbation imposed by the initial shape of the membrane; however, the broken membrane fragments generate uncontrolled small scale perturbations which can seed turbulence production. Under the worst of circumstances, the membrane breaks into larger fragments which disturb even the growth of the initial perturbation. Under all circumstances the presence of membrane fragments impedes Schlieren or shadowgraph visualization, obscuring both the interface and the resulting turbulent mixing region. Other shock-tube experiments have attempted to avoid membrane effects by initially separating the two gases by a solid barrier which is removed immediately prior to firing the shock tube (refs. 9 and 10). Because the diffusion coefficients of gases are large, this technique generates diffuse interfaces (typically l cm thick). In addition, because the interfacial disturbance left behind by removing the barrier is used as the initial perturbation, the resulting instability is nonuniform and difficult to characterize, thus severely limiting the usefulness of the experimental results.

The use of liquids instead of gases eliminates the problems with generating a sharp well defined interface because the very low diffusion coefficients of liquids allow for the easy generation of sharp interfaces. Low speed liquid phase experiments are, however, complicated by the fact that gravity strongly influences the flow development. RM instability involves the flow evolution and turbulent mixing of a system of two fluids of different density. However, the effects of body forces must be kept small except during the impulsive acceleration. In shock tube experiments, the flow induced by the earth's gravitational acceleration is negligible when compared with the high fluid velocities of the induced RM instability. However, in low speed liquid experiments the earth's gravitational influence is much more dominant, and can stabilize (or destabilize) the developing RM instability. Furthermore it can strongly effect the turbulent flow development. Thus, these types of experiments must be carried out in a low gravity environment.

Recently, we have developed a novel experimental technique to study the RM instability of a liquid system (ref. 11). In these experiments a tank containing two stably stratified liquids is impulsively accelerated by bouncing it off of a stationary spring. These experiments represent a significant advancement in the study of RM instability because: (1) a sharp liquid/liquid interface is easy to form and visualize, and (2) the relatively low speed of the flow allows for the use of standard video imaging. The problems with gravity in liquid phase RM instability experiments are solved in these experiments by keeping the fluids essentially in free-fall during the evolution of the instability.

EXPERIMENTAL DESCRIPTION

The experimental apparatus (figure 1) consists of a thin rectangular tank with inside dimensions of 2.54 cm x 11.75 cm x 25.4 cm which is mounted to a linear rail system oriented so that the tank is free to move in the vertical direction with approximately 1.25 m of travel. This system utilizes a set of 4 linear bearings which ride with very little friction on a pair of 1.91 cm diameter rails. At the bottom of the rail system is a vertical fixed spring which is secured at one end. The rails are mounted to a steel plate which is pinned at the top, thus allowing it to pivot in the lateral direction. The bottom half of the tank is initially filled with a colored salt water solution, and the top half with clear fresh water, while the tank is held at a position approximately 0.5 m above the spring using an electromagnet. A nearly saturated salt solution is used, consisting of $Ca(NO_3)_2$ (and water and having specific gravity of approximately 1.35. This combination produces an Atwood number (i.e. the difference of the densities divided by their sum) of approximately 0.15.

An initial surface shape is given to the system by sinusoidally oscillating the rail system in the horizontal direction to produce standing waves on the interface. This is accomplished using an eccentric circular cam mounted to a stepper motor which rides on the side of the steel plate. The sinusoidal motion generated by the rotating cam generates a sinusoidal surface pattern. The wavelength of this surface pattern can be controlled by properly specifying the input signal to the stepper motor. In addition, the amplitude of the initial shape can be controlled by changing the amplitude of oscillation through adjustment of the degree of eccentricity of the cam. Note that initial conditions produced by this technique are ordinarily not motionless. However, in the present experiments the electromagnet release can be synchronized with the container oscillation. Therefore, the experiments can be timed so that the initial velocity is zero.

At the start of each experiment, the tank is released by disconnecting the power to the electromagnet, thus allowing the tank to fall and bounce off of the fixed spring. Because the container is nearly in free-fall before and after bouncing, the only body force that it experiences is 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 the experiment ends on the second bounce. During the entire event, the interface is viewed using a shuttered CCD camera which is mounted to the moving container. The video signal from the camera is fed to a computer system with a frame grabber where it is stored for later viewing. The time between bounces is approximately 0.5 s. The camera is operated in an interlaced mode so that it effectively acquires 60 frames per second, thus yielding 30 pictures of the evolving interface per experiment. The camera also views a vertical scale attached to the stationary rails which allows for measurement of the instantaneous position of the tank. In addition an accelerometer mounted to the tank records the acceleration history of the fluid system.

EXPERIMENTAL RESULTS

Figure 2 is a sequence of photographs 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 surface shape. Figure 2(b) was taken during the time the container was in contact with the spring, and figures 2(c)-(j) span the period of free fall between the first two bounces. Figures 2(k) and (l) were taken during and after the time of the second bounce. The impulsive acceleration in these experiments is directed from the heavier fluid into the lighter fluid. Thus the sinusoidal initial surface shape inverts phase before growing (figure 2b). The instability initially retains its sinusoidal shape. However, with time, vortices begin to form at points midway between the crests and troughs (figure 2d), yielding the symmetric mushroom pattern typical of RT and RM instability of fluids with small density differences. These vortices eventually roll the interface around their cores to form a spiral pattern. This large amplitude interfacial pattern is reminiscent of that observed in Kelvin-Helmholtz experiments. However, in Kelvin-Helmholtz instability the vortices all have the same sign, while in this case the vortices alternate in sign. Note that, characteristic of the instability with small density differences, the surface 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 figure 2(j) and 2(k). In 2(k), one can see a dramatic change in the interfacial pattern in which the mushroom features rapidly collapse and erupt into turbulence. In 2(l) mushrooms are no longer detectable in what appears to be a fully turbulent flow.

CONCLUSIONS

The experiment described above represents a significant advancement in the study of RM instability in that extremely well visualized results are obtained. However, the run times achievable in the present experimental apparatus are obviously limited. Previous shock tube experiments and computational studies have shown that turbulent flows can be obtained with a single impulsive acceleration. But because of the limited run time of the current apparatus, it appears that a turbulent flow will not be attainable in this set up. The low gravity environment of space allows a unique opportunity to develop an experiment of this type which could be carried out in earth orbit. If achievable this would provide effectively unlimited run times, and as a result yield valuable information about this fundamental and important fluid instability.

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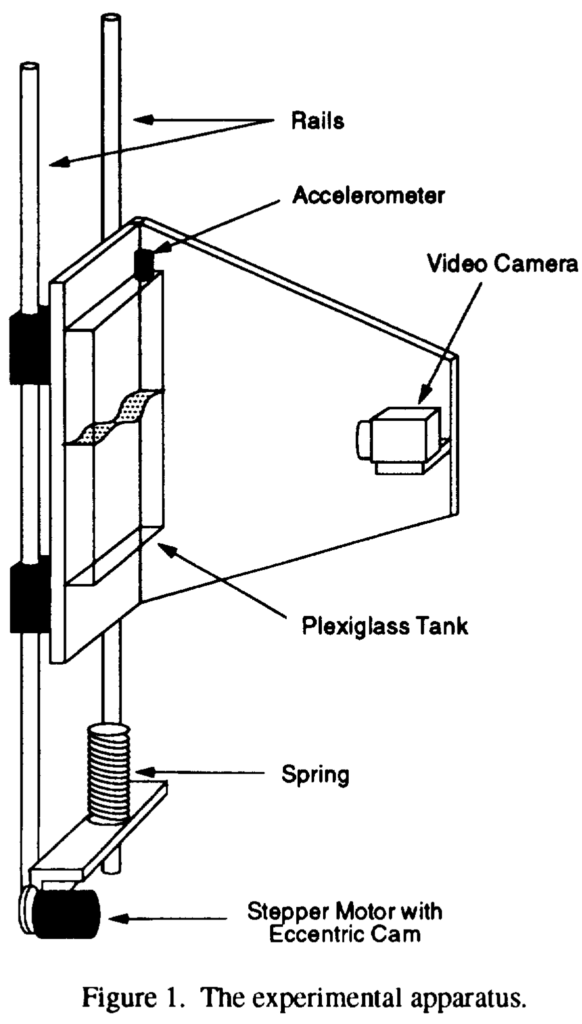

Figure 1. The experimental apparatus.

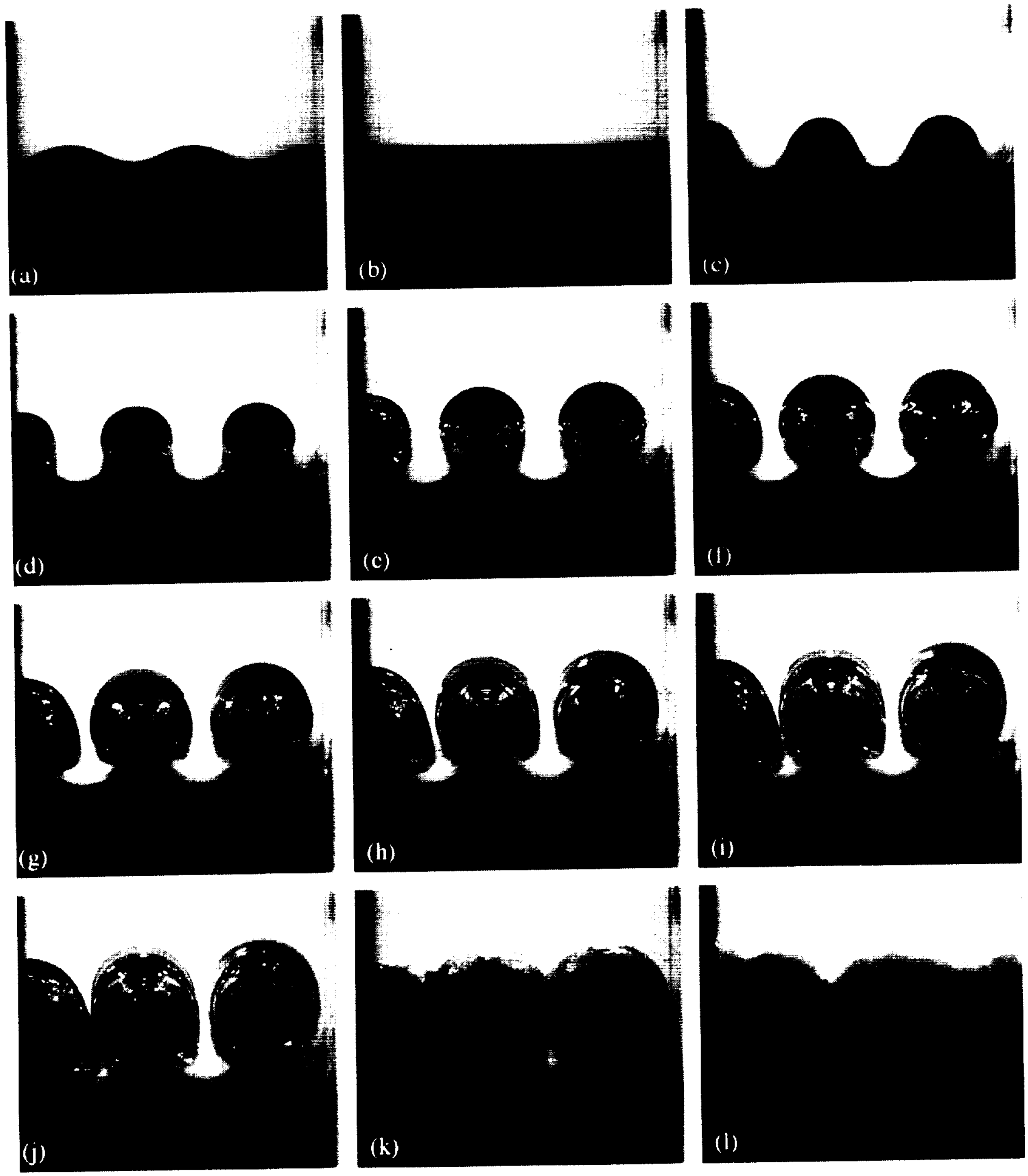

Figure 2. A sequence of images showing the development of the instability in a typical experiment. Times relative to the point of first contact with the spring are: (a) -15 ms, (b) 18 ms, (c) 68 ms, (d) 118 ms, (e) 185 ms, (f) 235 ms, (g) 285 ms, (h) 352 ms, (i) 402 ms, (j) 452 ms, (k) 519 ms, (l) 569 ms. The second spring contact occurs between (j) and (k).