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Experimental Observations of Rayleigh-Taylor Instability in a Shock Tube

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Abstract

Rayleigh-Taylor instability in a shock tube has been investigated experimentally. Such instability was produced by accelerating a liquid column down a vertical circular tube employing shock wave impact. The liquid column is a combination of decane and salt solution. Acceleration of about 26 times gravitational acceleration with decane depth of 150 mm and salt solution depth of 100 mm were studied. The resulting instability of the gas/liquid (air and decane) interface and the liquid/liquid (decane and salt water) interface was recorded and later analysed using high-speed video images. Cavity formation was observed in the middle of the gas/liquid interface soon after the shock wave impact; bubbles and spikes then developed across the rest of the interfacial plane. Measurements showed that the growth coefficient of the cavity is about twice of that of the bubbles. The growth coefficient of the bubbles is nearly independent of the Atwood number, while the growth coefficient of spikes is sensitive to the Atwood number.

Introduction

It is well known that a perturbed interface between two different fluids driven by inertial forces pointing from a heavy fluid to a light fluid is unstable. This phenomenon is known as Rayleigh-Taylor (RT) instability[1,2], and may occur wherever the pressure-density gradient product, $\nabla p \cdot \nabla \rho$, is negative. Such instability is important in many applications such as astrophysics, fusion, lasers, turbulence, plasmas, etc [3,4]. Supernova explosions and inertia confinement fusion (ICF) targets are among the applications most often cited.

Much knowledge concerning RT instability has been gained in the past 50 years that today it is considered as a classic physics problem. Experimental studies to date can be divided into two main classes according to the initial interface perturbation. One is periodic constant wavelength perturbation in the form of a forced standing wave, which has served as a basis for theoretical modelling[5,6]. The other is one whereby the interface was not given an initial disturbance, so the instability evolves from some sort of random excitation[3,4]. Both classes have been studied extensively since Taylor's classical treatment in the 1950s[2]. In addition, localized perturbation in the form of a singularity point is another type of initial interface arrangement which can be of interest for its many practical applications. This phenomenon is important when plates or shells containing surface fractures are accelerated by explosives. Although there is a clear need for experiments to understand such a physical phenomenon, experimental studies so far have been quite rare. This deficiency is largely the result of the anticipated experimental difficulties in generating a well-defined localized perturbation at a fluid interface. Volchenko and Meshkov [7] have tried to solve this problem by using jelly as the test fluid, which is suitable for manufacturing complex structures. However, their experiments were correspondingly explosively driven, and thus involved other more formidable complications.

In this paper, we will describe an experimental study of RT instability at the gas/liquid and liquid/liquid interface. A liquid column contained in a circular tube was accelerated by a shock wave from a He/air shock tube. In this way we found that a well-defined initial point perturbation at the center of the gas/liquid interface was generated after the shock wave had passed the interface, as will be shown later. The evolution of such a point perturbation into a cavity was visualized. This method proved to be simple and successful in studying RT instability of localized perturbations. Besides the point perturbation, RT instability development from the rest of the interfacial plane was also observed. Note that most experimental work on RT instability done so far has used rectangular enclosures to contain the test fluids[3,4]. This has the drawback of generating large initial perturbations at the corners due to surface tension effect, which will eventually affect the whole flow field. The use of a circular tube in our experiments is believed to be more advantageous. It is hoped that the present experiment will provide additional data for the understanding of the development of RT instability. It can also serve as a reference for future modelling efforts.

Experimental Method

In the experiments a column of liquid was accelerated down the length of a tube by imposing a pressure differential across it. Figure 1 shows a schematic drawing of the apparatus used for the experiment. A stainless steel tube, A of 34 mm inside diameter was filled with high-pressure Helium gas to serve as a driver section, which extends vertically downwards. Two circular acrylic tubes, B and C, of the same inside diameter as tube A, were bolted to the bottom of tube A to form the driven (test) section. The lower end of tube C opened to the air. Mylar film diaphragms of 16 μm thickness and aluminium foil of 15 μm were inserted respectively into the joints between tubes A and B and C to create three separate chambers. A good seal was achieved by using specially designed flanges with o-rings. The rupture pressure of the driver section A was about 0.25 MPa. Liquid was then poured into tube B on top of a 1-cm thick Teflon disk which rested on the aluminum foil. The disk was used to insure that the lower water surface remained flat.

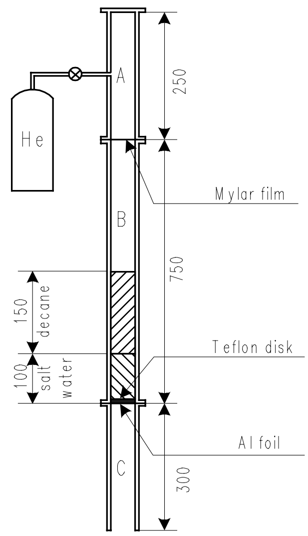

Fig.1 Schematic of the experimental facility.

Once the liquid was introduced and the cameras loaded, the experimental procedure was as follows. Tube A was pressurized until its inside pressure exceeded the rupture pressure of the

Mylar diaphragms. When a Mylar diaphragm ruptured, a shock wave was generated and propagated downwards along the length of tube B, which then impacted on the gas/water interface and in turn ruptured the aluminium foil. The liquid column was then accelerated downward flowing through tubes B and C by the pressure differential across the liquid column.

In the present study, we used decane and salt solution as the working fluids. The decane column was located on the salt water column, since decane has lower density (ρ=0.73 g/mm^3) comparing with salt solution (ρ=1.14 g/mm^3). Clear interface between decane and salt solution was formed because they are immiscible. In this way, instabilities developed from the gas/liquid and liquid/liquid interface can be observed at the same time.

A high-speed video camera (Phantom V4.1, Vision Research Inc., USA) was used to film the development of the RT instability, which was triggered by a pulse signal from a 0.3-mm diameter carbon rod located above the gas/water interface across the diameter of tube B, when it was broken by the impact of the shock wave. The camera speed was 1000 frames per second with a shutter speed of a 1/12000 s. The aperture was set between f1.1 and f2, which produced a reasonable exposure. The lens was focused on the axis of the tube. Lighting was provided by two 500-watt floodlights located behind the test section with a 1.5-mm thick PMMA (polymethyl methacrylate) plate placed in front of the lights as a diffuser, creating a background of uniform light intensity.

Results and Analysis

Acceleration

To determine the acceleration of the liquid column, we first measured the displacement of the Teflon disk as a function of time. Then the square root of the displacement of the disk from its initial position was plotted against time. If the acceleration is constant, this data will fall on a straight line. The slope of this line is then proportional to the square root of the acceleration. Figure 2 is a typical plot of these data along with the line fit to this data, which shows the acceleration is about 260 m/s^2.

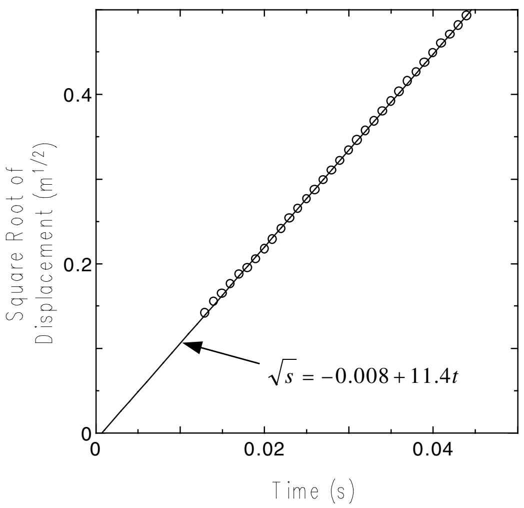

Fig.2 Typical plot of the square root of disk displacement.

Flow Visualization

Figure 3 shows the entire evolution of the instability. Shortly after the water column began to move down, a localized perturbation in the middle of the interfacial plane appeared (see Fig. 3(c)). The detail of this phenomenon can be observed more clearly in the enlarged photograph shown in Fig. 4. This perturbation quickly expanded in transverse and longitudinal directions and soon formed a cavity, which floated down into the liquid. At the initial stage it behaved like a hemisphere, evolving further into an elliptical shape. In Fig. 4(f), liquid drops were found to flow into the cavity. It is believed that a certain secondary instability (such as a Kelvin-Helmholtz type) was involved, which possibly initiated by small-scale heterogeneities. The water drops then collided with the cavity wall, creating an irregular interface (Fig. 4(g)). Later, the cavity with the water changed its shape rapidly and eventually tended to pinch off from the main interface (Fig. 4(j)). It was also observed that the rim of the cavity contracted gradually and finally formed a spike (Fig. 4(d)-(g)), which moved up relative to the interfacial plane.

For the rest of the interfacial plane, the initial random perturbations grow into bubbles and spikes. As can be seen from Fig. 3 (e)-(l), the bubbles of gas which moved through the water column like fingers were three-dimensional; they were randomly distributed in the transverse dimensions and elongated in the acceleration direction. The width of the larger bubbles was observed to grow with the mixing width (see Fig. 3(e)-(k)), which is usually called self-similarity [3]. Further, the bubbles produced from the randomly perturbed initial fluid interface were of different sizes. The larger of which was found to overtake adjacent smaller ones so as to form larger bubbles (Fig. 3 (e)-(k)). This phenomenon is called bubble merger [4]. Bubbles with large radii advance faster than those with small radii, thus find its motion favoured, while those in a retarded position are slowed down and washed downstream.

As for the liquid/liquid interface, cavity formation phenomenon was not observed. The mixing zone enlarges gradually with a plane mixing front. Because the ratio of the acoustic impedance of the gas and liquid is very small, the reflected shock wave in the liquid column will be totally reflected at the gas/liquid interface as expansion waves. We believed that the point perturbation at the gas/liquid interface was generated due to these expansion waves. However, the reflected expansion waves at the liquid/liquid interface were evaluated to be very weak and not enough to generate such a point perturbation, since the ratio of the acoustic impedance between liquid and liquid are comparatively larger.

Growth Coefficient

Figure 5 shows the schematic and nomenclature used for data analysis. According to Read's[3] analysis, the mixed region will grow in proportion to t^2, when the instability evolves towards turbulent mixing. The motion can be expressed by the formula:

$$h_i = \alpha_i A g' t^2 \qquad (1)$$

where α is the growth coefficient, and $i = b, s$ refers to bubble and spike, respectively. The Atwood number is $A = (\rho_1 - \rho_2)/(\rho_1 + \rho_2)$, where ρ_1 and ρ_2 are densities of the heavy fluid and the light fluid, respectively. In the present experiments, $A \approx 1$ for the gas/liquid interface and $A \approx 0.22$ for the liquid/liquid interface. The growth coefficients α_i were obtained with a linear least squares fit of bubble and spike amplitudes h_i to the displacement of the Teflon disk Z as follows:

$$h_i = h_{i0} + \alpha_i \cdot 2AZ \qquad (2)$$

where h_{i0} is the zero offset. The linear behavior is consistent with eq. (1) since $Ag' t^2 = 2AZ$. The zero offset h_{i0} was used to accommodate the initial instability growth because eq. (2) is only valid when the mixing becomes turbulent.

Figure 6 shows the transverse dimension D and the depth H of the cavity as a function of the displacement of the liquid column Z. The data were then fitted to straight lines, and we have $dD/dZ = 0.43$ and $dH/dZ = 0.24$, i.e., the cavity moved down at a velocity which increases in proportion to the time. The measurements also show that the differentiation of transverse dimension D was approximately in proportion to that of the

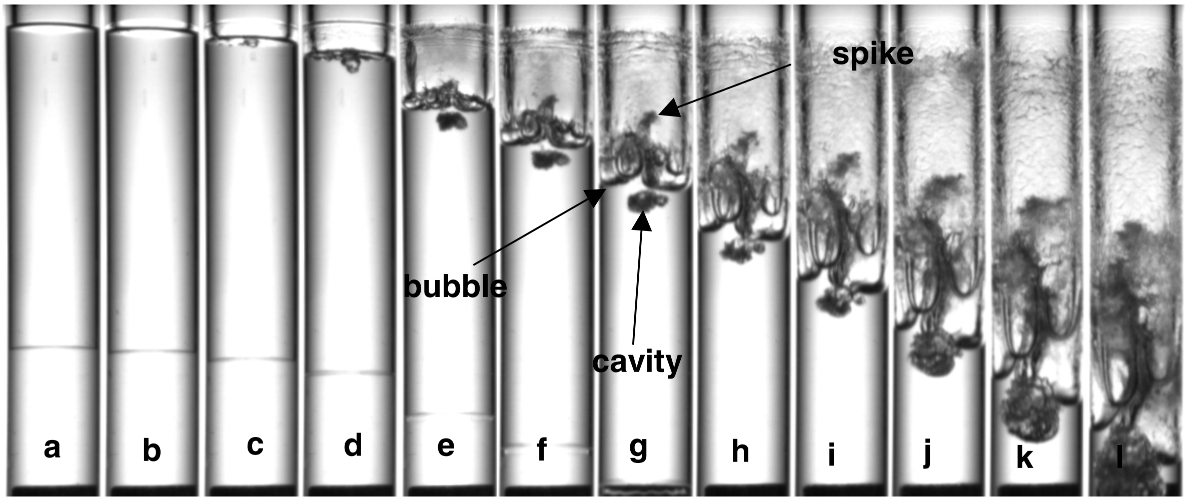

Fig. 3 A sequence of high-speed video images showing the development of RT instability in a shock tube. Time interval between the frames is 3 ms. For scale, the outside diameter of the tube is 45 mm.

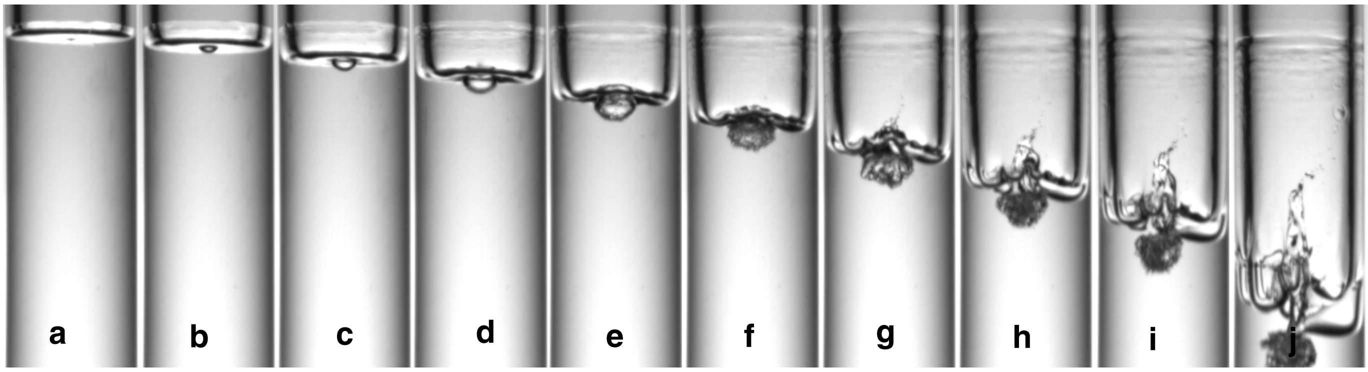

Fig. 4 A sequence of high-speed video images showing the development of RT instability in a shock tube. Time interval between the frames is 4 ms. For scale, the outside diameter of the tube is 45 mm.

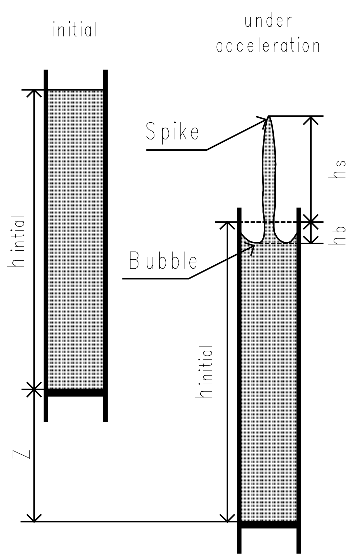

Fig.5 Schematic and nomenclature used for data analysis.

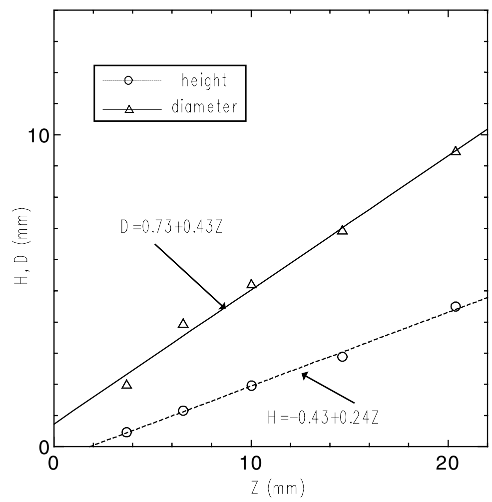

Fig.6 Diameter and height of the cavity as a function of the water column displacement for run 5345.

depth H, i.e., $dD(t)/dH(t)=1.8$. Such behaviour can also be called self-similar. Our measurements are in good agreement with the results calculated by Garanin [8] in an effort to interpret the non-stationary flows in the proximity of angular points based on self-similar analysis. Their calculations showed that dD/dZ and dH/dZ were equal to 0.40 and 0.25, respectively.

Figure 7 and 8 show the measurements of the gas/liquid and liquid/liquid interface, respectively. The results were summed in Table 1. As can be seen from Table 1, the growth coefficients of the bubbles for the gas/liquid interface and the liquid/liquid interface are almost the same. This implies that the growth of the bubbles isn't sensitive to the Atwood number. For the spikes, they differed a lot. The growth of the spike for the gas/liquid interface is as large as 0.32. This is understandable since the spike penetrates into the gas with smaller friction, comparing with when the spike penetrates into the liquid.

Another interesting finding is that the lines h_b intersect the minus Z axis. This is expected since for bubbles the growth coefficients of the linear and non-linear stages were greater than that of the turbulent mixing stage, the curved meniscus near the tube wall may also trigger the early occurrence of the turbulent mixing stage.

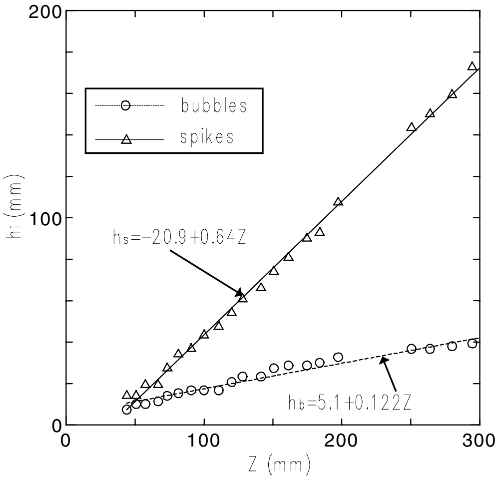

Fig.7 Bubble and spike amplitudes versus the characteristic lengths in Z for the gas/liquid interface. Lines are least squares fits for growth coefficients â.$_{b}$ and â.$_{s}$.

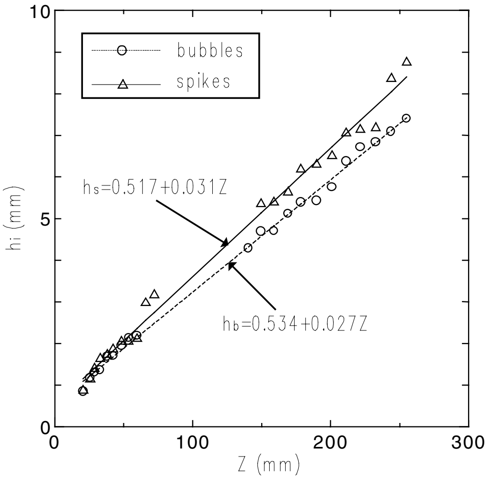

Fig.8 Bubble and spike amplitudes versus the characteristic lengths in Z for the liquid/liquid interface. Lines are least squares fits for growth coefficients â.$_{b}$ and â.$_{s}$.

	α_b	α_s
Cavity	0.12	
Gas/Liquid	0.0610	0.32
Liquid/Liquid	0.0614	0.0702

Table 1 Sum of growth coefficients.

Conclusions

We have experimentally investigated the RT instability of a gas-liquid system in a shock tube. We first observed the formation of a cavity from a point perturbation in the middle of the interface. It is believed that the point perturbation was excited by the interaction between the interface and the complex wave motion in the water column. We found that the growth of such localized perturbations differed from that of periodic perturbations. The former has a higher growth rate of 0.12. Bubbles and spikes that developed from the rest of the interfacial plane were also observed. Measurements showed that the growth coefficient of the cavity is about twice of that of the bubbles. The growth coefficient of the bubbles is nearly independent of the Atwood number, while that of the spikes is sensitive to the Atwood number.

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