# Experiments on the Expansion Wave Driven Rayleigh-Taylor Instability

**R.V. Morgan, O.A. Likhachev, and J.W. Jacobs**

## 1 Introduction

The Rayleigh-Taylor (RT) [1, 2] instability occurs when a perturbed interface between two fluids of different densities is accelerated such that the pressure gradient is directed from the heavier fluid to the lighter one. The instability causes small perturbations to grow with time, rolling up into a multi-valued interface, and finally transitioning to turbulence. In contrast to previous studies, an expansion wave is used in this study to produce the pressure gradient generating the instability. This instability is of interest in astrophysics in the study of supernovae [3] as well as in inertial confinement fusion, where it impedes the initiation of thermonuclear burn [4].

For early times the RT instability grows exponentially, and later transitions into turbulent mixing that takes the self-similar form

$$h - h_0 = \alpha A g (t - t_0)^2 \tag{1}$$

where $g$ is the acceleration of the system, $t$ is time, $\alpha$ is a constant of proportionality, $(t_0, h_0)$ is the virtual origin of the self-similar growth, and $A$ is the Atwood number defined as $A \equiv (\rho_2 - \rho_1)/(\rho_2 + \rho_1)$ where $\rho_1$ and $\rho_2$ are the densities of the light and heavy fluids respectively [5].

The present study uses an expansion tube similar to that utilized by Billington [6] to study the refraction of an expansion wave at an interface. The interaction of the expansion wave with the interface results in the large but non-constant acceleration of the interface $\ddot{z}_i$ that is given approximately by

$$\ddot{z}_i \approx -\frac{2}{\gamma+1}\left(\frac{a_L^2}{L_i}\right)\left(\frac{t a_L}{L_i}\right)^{-2\gamma/(\gamma+1)}, \tag{2}$$

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where $z_i$ is the vertical position of the interface, $\gamma$ is the adiabatic index of the light gas, $a_L$ is the speed of sound in the light gas, and $L_i$ is the initial location of the interface relative to the virtual origin of the centered expansion wave transmitted into the light gas. Therefore, the results of these experiments are good candidates for comparison with self-similar variable acceleration RT models [7] which require $g \propto t^n$.

Contrary to previous experimental studies using incompressible fluids, the expansion wave impacts the RT turbulent mixing by stretching material lines due to gas dilatation. Thus, it is anticipated that the rate of growth of the interface consists of two parts: 1) RT turbulent spreading, and 2) gas dilatation. In addition, decompression that occurs across the expansion wave results in a continuous reduction in the Atwood number from its initial value during the process of interface development.

## 2 Experimental Apparatus

Figure 1 shows the layout of the expansion tube. The experiment is initiated by flowing $SF_6$ gas entering at the bottom of the test section, and air entering at the top of the apparatus. The gases exit the test section via small holes that are 0.7m from the bottom of the test section resulting in a diffuse interface centered at the holes yielding an Atwood number of $A = 0.67$. The interface is perturbed using loudspeakers to oscillate the gas column in the vertical direction causing stochastic finite amplitude Faraday waves imposed on the interface. The perturbation generation technique is identical to that utilized by Jacobs et al. [8] in their Richtmyer-Meshkov instability experiments. The vacuum tank is then evacuated using a vacuum pump to approximately 0.1atm before a thin polypropylene membrane separating the vacuum tank from the test section is ruptured with an arrow-shaped blade mounted on a solenoid inside the vacuum tank.

The rupturing of the diaphragm results in an upward traveling expansion wave in the test section and a downward traveling shock wave in the vacuum tank. Figure 2 shows an x-t diagram of a 1D simulation showing these waves along with their interactions. During an experiment, the expansion wave passes two pressure transducers, allowing the precise determination of its arrival time at the interface. The traveling expansion wave then refracts through the interface causing the acceleration of the interface. The transmitted wave then travels upward through a long 2.2m section used to delay the wave reflection from the top of the apparatus and consequently prevent any interference with the developing interface.

Shadowgraph and laser induced Mie scattering diagnostics are used to study the development of the interface. The shadowgraph system uses light from 3 10w LED lamps reflected through 3 pairs of 200mm f6.0 parabolic mirrors focused onto the sensors of 3 Photron Fastcam APX-RS high-speed CMOS cameras. Images are recorded at 10kHz with exposure times of $1\mu$s.

The laser induced Mie scattering system uses a laser sheet created by a Nd:YLF laser guided through sheet forming optics located at the top of the test section. The

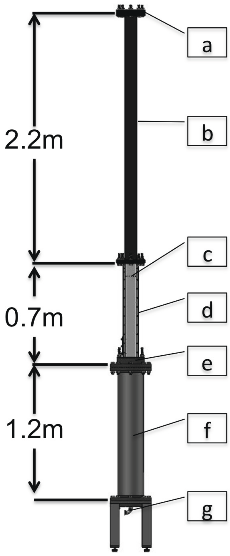


**Fig. 1** A diagram of the experimental setup. (a) Light gas plenum with window for laser sheet, (b) expansion section, (c) interface generation holes, (d) pressure transducers, (e) heavy gas plenum, (f) vacuum tank, (g) vacuum pump attachment.

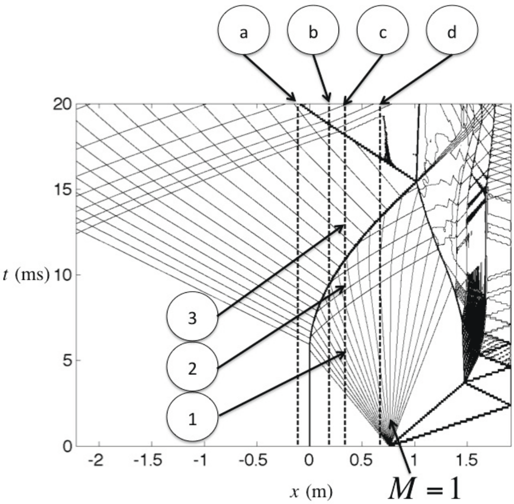


**Fig. 2** An x-t diagram of the wave interactions in the expansion tube. Here (a) is the top of the test section, (b) is the location of the second pressure transducer, (c) is the location of the third pressure transducer, and (d) is the bottom of the test section. For the fixed location of pressure transducer 1 over time (1) is the incident expansion region, (2) is the reflected expansion region, and (3) is the transmitted expansion region.

laser light illuminates smoke seeded in the $SF_6$ gas which scatters light at 90° toward a single CMOS camera. Mie scattering images are recorded at 12kHZ.

## 3 Results

Individual experiments produce very repeatable acceleration profiles as shown in figure 3.

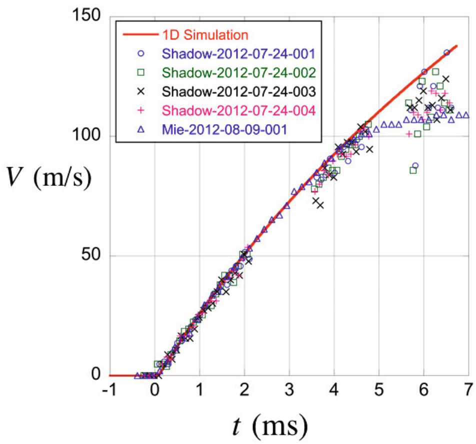


**Fig. 3** Interface velocity during an experiment. The five experiments show good repeatability and compare well with the results of a 1D simulation. At later times, the effect of unchoking can be seen.

The magnitude of the acceleration is estimated using a second order fit to the interface position and is approximately 25.5mm/ms$^2$ or 2600 times that of gravity. This very high acceleration allows for the instability to quickly transition to self-similar RT unstable growth. Figure 4 shows a sequence of images from a Mie scattering experiment wherein small wavelength perturbations are observed to grow quickly. The perturbations can be seen merging into larger scales while small eddies emerge during the transition to turbulence.

To evaluate the interface growth rate in the presence of nonconstant acceleration, we use the method proposed by Read and Youngs [5] where they take $h = 2\alpha AS$, with $S = [\int \sqrt{g}dt]^2$, and the method of Zaytsev et al. [9] who take $h - h_0 = 2\alpha A(x - x_0)$, where $x$ is the distance travelled by the interface. We find $\alpha = 0.11$ and $\alpha = 0.10$ for the Read and Youngs and the Zaytsev et al. methods respectively. These values of the constant of proportionality are slightly larger than usually reported in the literature. The difference can be attributed to the presence of gas dilatation that influences the turbulent mixing generated by the Rayleigh-Taylor instability. Using the measured mix width and mix width growth rate, we find the Reynold's number reaches a maximum of $\mathrm{Re} = \mathrm{h}\dot{\mathrm{h}}/\nu \approx 30,000$.

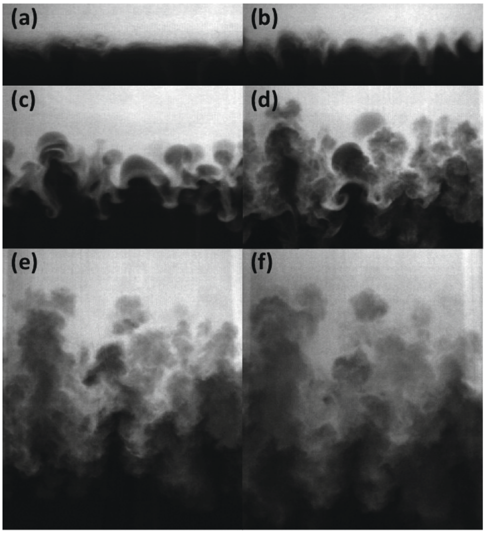


**Fig. 4** Development of an interface during a typical Mie scattering experiment. The images are taken at (a) $t = -0.03$ ms, (b) $t = 1.0$ ms, (c) $t = 2.0$ ms, (d) $t = 3.0$ ms, (e) $t = 4.0$ ms, and (f) $t = 5.0$ ms after the start of acceleration. The perturbation scales can be seen growing, while turbulent eddies form and strong mixing occurs.

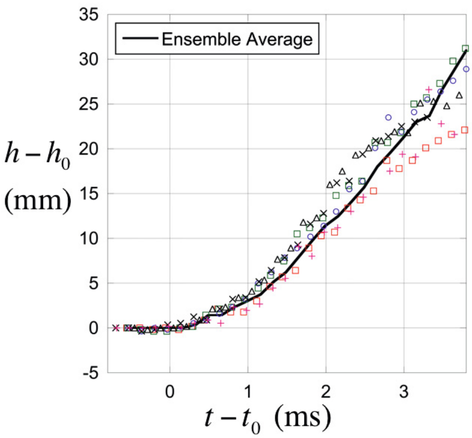


**Fig. 5** Dimensional development of interfaces during Mie scattering experiments. The solid line represents an ensemble average of 5 experiments while the symbols denote individual experiments.

## 4 Conclusions

In the present study of Rayleigh-Taylor turbulent mixing, an expansion wave is used to generate a nonconstant acceleration of the interface between two gases. It has been shown that a very large acceleration of the interface can be achieved using this technique. An air/$SF_6$ gas combination is used that gives the initial Atwood number of $A = 0.67$. Measurements of the time history of the acceleration are found to be well predicted by 1D theory and simulations. The large acceleration of the interface leads to the rapid growth of the finite amplitude stochastic perturbations imposed on the interface that in turn results in the rapid development of RT turbulent mixing. The mixing layer growth rate is evaluated using the methods of Read and Youngs [5] and Zaytsev et al. [9], and an average growth constant $\alpha \approx 0.1$ is obtained. This value falls outside of the range usually reported in previous studies. However, additional effects that would affect the mixing rate such as dilatation of the mixing region and decrease in the Atwood number due to the expansion wave must be taken into consideration. Finally, it should also be noted that the use of an expansion tube allows one to easily study compressible fluid combinations with very large Atwood numbers, for example He/$SF_6$ would yield $A = 0.95$.

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