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TITLE: EXPERIMENTAL OBSERVATIONS OF SHOCK STABILITY AND SHOCK-INDUCED TURBULENCE

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EXPERIMENTAL OBSERVATIONS OF SHOCK STABILITY AND SHOCK-INDUCED TURBULENCE

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Abstract

We observe the Richtmyer-Meshkov (RM) instability of a perturbed, shock-accelerated interface between different gases. Instability growth of a singly shocked interface is observed to be consistent with previous experimental data. Late-time growth visually appears nonlinear but the growth rate remains the same as during linear growth Re-shocking the interface produces additional RM growth and substantial profile broadening, which does not show the effect of local vorticity generation.

Introduction

Shock acceleration of an interface between fluids of different density produces a hydrodynamic instability similar to the well-known Rayleigh-Taylor instability of an accelerated interface. Perturbations at the shocked interface grow and eventually produce mixing of the fluids. Re-shocking the interface enhances the rate of mixing, and may be viewed as promoting a transition from instability to turbulence We examine the physics of this transition experimentally by taking shadowgraphs of the flow pattern during the re-shocking of the perturbed interface. We also report measurements of the amplitude growth of a singly-shocked, perturbed interface.

Growth of the shock-induced instability in gases when the initial amplitude of the perturbation is small was first studied theoretically by Richtmyer[1] and experimentally by Meshkov[2] Hence, the shock-induced instability is often called the "Richtmyer-Meshkov" (RM) instability The RM unstable interface is a perturbed contact discontinuity subjected to normal shock acceleration. Using a shock tube and optical diagnostics to study the shocked interface between different gases, Meshkov measured the growth rate for the amplitude of a single-wavelength perturbation to be considerably smaller than predicted by Richtmyer's analytical approximation. Our measurements for amplitude growth rates are slightly higher than Meshkov's results, but significantly less than those given by Richtmyer's formula Measurements of instability growth in gases at much higher Mach number were recently reported[3]

By contrast with these experiments with gases in which the measured values are lower than analytic estimates, experimental results with liquids[4] are higher than the analytic expression derived from Taylor's and Richtmyer's analyses.

Several investigators[5-9] have studied the growth of a *planar* interface evolving into a mixing zone as a consequence of multiple shocks and rarefactions. Although these interfaces are nominally planar, they have uncharacterized perturbations that lead to instability and mixing Recent results[9] suggest that earlier measurements may have been dominated by boundary layer effects that obscured the interfacial region of bulk mixing All of these experiments measured the mixing (or perhaps boundary layer effects) induced by shocking a nominally flat interface between the fluids, but they did not carefully examine the details of the first re-shock to the interface, which is when the growth rate changes most abruptly. Our goal is to investigate this transition experimentally and to develop a database that describes this transition and related phenomena.

Instability growth from a single shock

Richtmyer considered the case of a shock wave moving from a lower-density fluid, having density ρ_L, into a higher-density fluid, ρ_H. He derived the following analytic expression for the growth rate of a small-amplitude, single-mode (i.e., single wavelength) perturbation:

$$d\eta/dt = k\,\eta'_0\,U_I\,[\,(\rho_H - \rho_L) / (\rho_H + \rho_L)\,] \qquad (1)$$

where: η = amplitude of the perturbation (η_0 is the initial amplitude.)

η'_0 = the initial, *shock-compressed* amplitude

k = wavevector of the perturbation = $2\pi / \lambda$

U_I = interface velocity

$(\rho_H - \rho_L) / (\rho_H + \rho_L)$ = Atwood number

Richtmyer also performed a numerical calculation for this light-to-heavy case and found that Eq. (1) is a good approximation to the numerical computation provided one uses shock-compressed values for the Atwood number and initial amplitude. However, Sturtevant[8] pointed out that there is ambiguity about the value of the amplitude compression of the perturbation. Meshkov estimates the compression with an expression involving velocities, whereas Sturtevant suggests alternative expressions using density compressions. For purposes of comparing Meshkov's results and the present work, we use Meshkov's expression.

Experimental details

Both the single-shock and re-shock experiments were performed in a horizontal shock tube having inside square cross section with dimensions 75 x 75 mm. The sinusoidal perturbation of the interface between the test gases was produced by a 0.5 μm thick cellulose nitrate membrane clamped in a sinusoidal shape characterized by wavelength $\lambda = 37.5$ mm and initial amplitude $\eta_0 = 2.4$ mm. These dimensions give an initial (uncompressed) value of $k\eta_0 = 0.40$.

We diagnose the interfacial instability by side-viewing the interfacial region with either of two shadowgraph systems. One system is used to take a flash shadowgraph that gives one high-resolution frame per event. The frame duration, determined by the light source, is about 2 μs. This shadowgraph gives a detailed view of the flow patterns. The other system uses a multi-frame camera[11] to measure growth rates. The camera produces 12 frames equally spaced in time, but having less spatial resolution. The interframe time set by the camera is 18.5 μs, and a long-pulse (i.e., several ms) light source is used.

Observations for a singly shocked interface

Our measurements of the singly shocked, corrugated interface are qualitatively in agreement with Meshkov's results, but slightly different quantitatively. We examined two systems in which the shock wave moved from:

air into SF_6 (light-to-heavy);

air into helium (heavy-to-light).

In the light-to-heavy experiment, the shock wave moves from the lower-density gas into the higher-density gas, and vice versa for the heavy-to-light. The qualitative agreement with Meshkov's results is seen in Fig. 1. The perturbed interface is observed to be unstable in both the light-to-heavy and the heavy-to-light cases, since large growth of the amplitude occurs when the interface is subjected to a single shock in either direction. The amplitude grows immediately in the light-to-heavy case, whereas in the heavy-to-light case, one observes a phase inversion at early time and growth at later time. During the phase inversion the amplitude appears to be stabilizing, but its later growth shows that the velocity field in the flow is characteristic of the instability. These qualitative features were observed by Meshkov[2] and confirmed by our present results.

Our multi-frame shadowgraphs provide time-resolved data from which we measure the growth rate $d\eta/dt$. We find that the amplitude η grows linearly in time, even at later times when the visual appearance of the interface takes on the spike-and-bubble configuration of nonlinear growth.

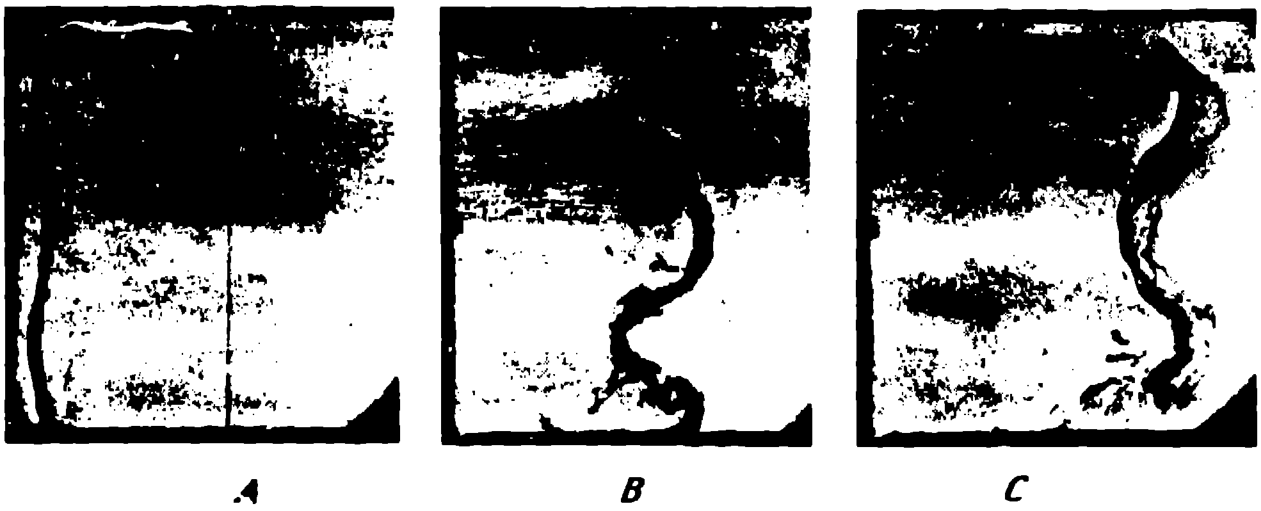

Figure 1 These three flash shadowgraphs show the effects of different density gradients across the interface. In all three cases the interface is accelerated by a shock wave moving from air on the left into the downstream gas on the right side of the sinusoidal membrane. *A*. The downstream gas is air, so the perturbed interface is stable, although the amplitude is shock-compressed. The transmitted shock front (moving left to right) is seen to the right of the perturbed interface.
B, *light-to-heavy case*: The downstream gas is SF_6, which is about five times more dense than air. The perturbation's amplitude is observed to grow without inverting phase.
C, *heavy-to-light case*: The downstream gas is helium, and the amplitude is observed to invert phase and grow. Note that the transmitted shock wave is out of the viewing area in *B* and *C*.

We make quantitative measurements of $d\eta/dt$ by time-resolving the shadowgraphs with an electronic framing camera that takes a series of twelve frames per event, having an interframe time = 18.5 μs. For an incident shock wave of Mach 1.24 in air, the measured growth rates of the amplitude are:

Air --> SF_6 (light-to-heavy) $d\eta/dt = 7.9$ m/s ($U_I = 81$ m/s)

Air --> He (heavy-to-light) $d\eta/dt = 19$ m/s ($U_I = 185$ m/s)

Using Meshkov's method to estimate the compression of the initial amplitude, we compare the air/SF_6 growth rate with Eq. 1:

$$(d\eta/dt)_{LANL} / (d\eta/dt)_{Eq.\ 1} = 0.46$$

By contrast, Meshkov's interpolated result for the Atwood Number corresponding to air/SF_6 ($\rho_H/\rho_L = 5.1$) gives a growth rate:

$$(d\eta/dt)_{MESHKOV} / (d\eta/dt)_{Eq.\ 1} = 0.35$$

Thus, the present results are somewhat higher than Meshkov's experiments, but substantially lower than the growth rate given by Eq. 1 using Meshkov's estimate for the initial compression.

Observations for a re-shocked interface

When an air/SF_6 interface is re-shocked after its amplitude has grown into the nonlinear regime, the profile of the interface appears to broaden substantially and the mean profile of the interface undergoes RM growth. The broadened interfacial region, denoted "mixing zone," contains a mixture of air, SF_6 and membrane debris. These features are seen in Fig. 2.

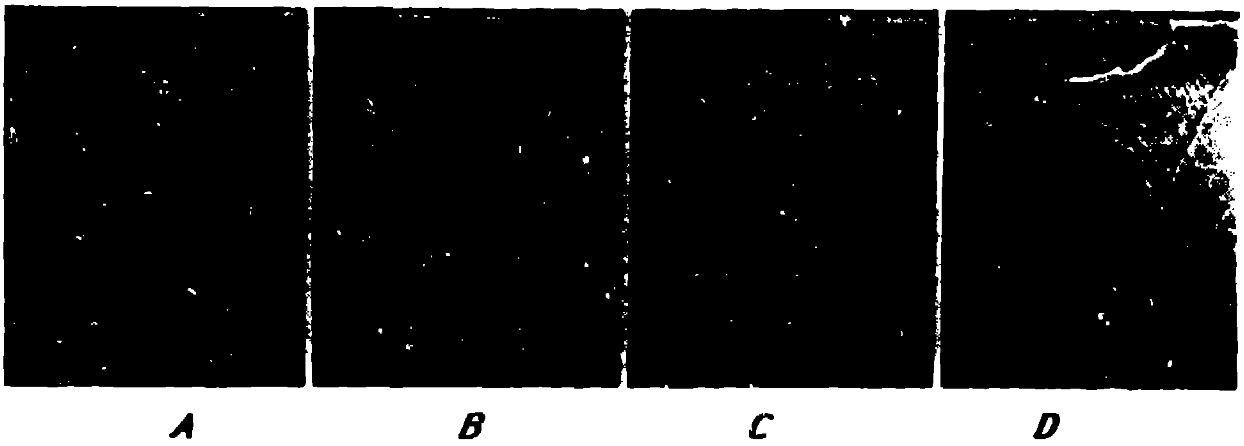

Figure 2. These four flash shadowgraphs, recorded on different events, show the evolution of a re-shocked interface. The interface was initially accelerated by a shock wave moving from air on the left toward SF_6 on the right side of the corrugated interface. ***A***: The shock wave reflected from the endwall is beginning to compress the interfacial region, which had grown into nonlinear (i.e., spike-and-bubble) appearance. The reflected shock is moving right to left. The reflected rarefaction wave (moving back into the SF_6) has begun at the two regions of contact between the shock front and the interface. ***B***: Later, part of the reflected shock wave is transmitted into the air where it accelerates, but the portion of the shock (at the center) that is still in the SF_6 is undergoing a complex interaction with the shock wave refracted into the SF_6 and the rarefaction. ***C***: Later, the interface appears to have stabilized, but it is really inverting. At this moment the amplitude is quite small. ***D***: Still later, the mean profile of the interface inverts phase and grows in amplitude, as expected by the Richtmyer-Meshkov instability. The profile appears much broader because of mixing of gases and wall effects (i.e., the interaction between the boundary layer and the reflected shock). The shock wave transmitted into the air is out of view on the left.

The shock wave reflected from the endwall is moving from the higher-density SF_6 into the lower-density air, which is the "heavy-to-light" case of RM, so the interface's amplitude inverts phase before growing. Thus, the re-shocked interface momentarily appears to be stabilizing as it passes through the inversion phase, but later growth of its profile is clearly observed.

We observe in Figs. 2b and 2c that there appears to be no enhancement of the width of the mixing zone in the two regions where the vorticity production is greatest. These regions are where the pressure gradient of the shock and the density gradient of the interface have the greatest included angle. The growth of the mixing zone appears to be independent of the local angle between the shock front and the interface.

The wave reflected back into the SF_6 appears to be a rarefaction fan, and the wave transmitted into the air appears to be a sharp discontinuity characteristic of a shock wave. The rarefaction has a mottled appearance.

The visual appearance of the interface profile shows many well-resolved features, as seen in Fig. 2, but we observe blurring of a substantial amount of this region. The blurring is distinct from the broadening of the mixing zone; i.e., part of the broadening is well-resolved and part is blurred. The blurring suggests that the refractive index gradients are so steep that ray-crossing occurs before the shadowgraphic system's probe beam reaches the film, which is only a few mm from the window.

Interpretations

The results of the singly shocked interface are consistent with Meshkov's previous experiment. The measured growth rates stated above are within experimental uncertainties of each other. However, both sets of data are significantly less than the growth rate predicted from Eq. 1. The source of this difference between experiment and theory is unknown, although strength effects of the membrane are suspected.

We interpret the qualitative features of the re-shock experiments in terms of two superposed velocity fields, the mean-flow and the fluctuations. If we assume that the mean position of the interface is determined by the mean-flow field, then this field appears to undergo the "heavy-to-light" RM instability, as expected. The fluctuating field is manifest as broadening the interfacial region. The broadening is observed to increase following the re-shock, as seen clearly in Figs. 2C and 2D. However, in those regions where we expect the vorticity generation to be greatest, i.e., where the angle between density gradient and pressure gradient is greatest, we fail to observe substantially greater broadening. Since the broadening appears to be independent of the local angle between shock front and interface, the vorticity generated by the re-shock does not seem to be manifest locally as increased broadening. It appears that such vorticity is either associated primarily with the mean-flow field or it diffuses rapidly in the broadened profile.

The observed mixing zone consists of: (1) the bulk mixing of gases, (2) the boundary layer (i.e., "wall effect"), and (3) membrane fragments.

Related experiments[9] suggest that the boundary layer's signature may dominate, so interpretation of mixing-zone growth cannot be made until further experiments distinguish between bulk and wall effects. If further experiments determine that these observations are indeed of the mixing zone, then the re-shock data, such as growth of the mixing width, can be interpreted as a measure of the effects of shock-wave interaction with pre-existing turbulence and/or with membrane fragments.

The presence of the rarefaction wave reflected back into the SF_6 demonstrates that the shock impedance of the membrane is not influencing the mean-flow field. However, membrane fragments may be influencing the mixing. The mottling of the rarefaction may be a signature of the length scales present in the mix region.

Conclusions

Our observations of singly shocked interfaces between dissimilar gases are consistent with the previous work of Meshkov, but the difference between experimental data and Eq. 1 persists. Also, the persistence of the linear growth rate into the regime of visual nonlinearity is unexplained. The phenomena of a re-shocked interface show simultaneous RM growth and broadening. Strength effects of the membrane on the mean-flow velocity field are negligible, although inertial effects on the broadening may persist. Structure in the mixing region and on the reflected rarefaction may be useful in characterizing the onset of turbulent mixing if further experiments determine that the observed broadening is not a wall effect.

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