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Shock-Interface Interaction: Current Research on the Richtmyer-Meshkov Problem

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The problem of shock refraction at a material interface has been studied both experimentally and numerically. Recent work (Henderson 1989) has provided insight into the complex problem of anomalous refraction. Emphasis has been placed on the pattern of reflected and refracted waves, including precursors. However, the evolution of the interface itself is of considerable interest in problems ranging from inertial confinement fusion to astrophysics (Klein 1989) and has generated a flurry of activity that encompasses the subject of compressible turbulence.

The basis for the study of the evolution of a shocked interface stems from the question of the Rayleigh-Taylor (RT) instability (Taylor 1950). Starting in the late 18th century, the stability of an interface submitted to gravitational forces was investigated for the case in which the density of one of the materials across the interface was negligible compared to the other. Taylor analyzed the case in which the Atwood number (ratio of the difference of the densities to their sum) is less than 1, and the acceleration of the system is constant. He determined that the interface was unstable to small perturbations only if the direction of the acceleration normal to the interface coincides with that of the density gradient. Richtmyer (1960) extended Taylor's analysis to the case of an impulsive acceleration. His results implied that the interface would be unstable irrespective of the relative orientation of the velocity impulse and the density gradient. His predictions were verified experimentally by Meshkov (1969), and the Richtmyer-Meshkov (RM) instability became a subject of research in its own right. Experimental, numerical, and theoretical works address this problem.

To simplify the following discussion, the case in which the shock is incident from the low-density side on a interface with a denser material will be referred to as RT unstable. An RT stable case corresponds to a shock incident from the high-density side on an interface with a lighter material.

Richtmyer's original prediction was that, for a discontinuous interface, the perturbation would grow linearly with time as

$$a = a_0 (1 + A\, k\, V\, t) \ , \qquad [1]$$

where a_0 = the initial amplitude, after shock compression,
A = the Atwood number, after shock compression,
V = interface velocity, and
$k = 2\pi/\lambda$ = wave number.

1. Experimental work

The RM problem has been studied with both shock-tube and laser experiments. In this paper, only shock-tube work is considered.

1.1 Discontinuous interface with single-wavelength perturbations

Meshkov's pioneering experiments were designed to test Richtmyer's predictions, which strictly applied only to a single wavelength perturbation of an interface. The assumptions were that (1) a_0/λ, the initial amplitude-to-wavelength ratio of the perturbation, was small (<<1) so that the equations could be linearized, (2) the incident shock was normal to the average (unperturbed) interface position, and (3) the flow was nearly incompressible after shock passage. The experiments confirmed that (1) the rate of change of the perturbation's amplitude was constant, as opposed to the exponential growth of the RT instability, and (2) for an RT stable configuration, the perturbation changed phase. However, the measured growth rates were as much as a factor of 3 less than predicted by Richtmyer. Benjamin (1988) performed similar experiments and confirmed Meshkov's results. Actually, to facilitate observations, the experiments were conducted with $0.05 \leq a/\lambda \leq 0.1$ (before shock compression), so that the perturbations became nonlinear within the observation time. In addition, the gases used in the experiments were separated by a thin membrane. Some of the energy transferred from the shock to the perturbed interface could have been lost to the membrane, which was shattered and accelerated with the flow. Finally, particularly when helium was used, diffusion across the membrane could have reduced the Atwood number. Any of these experimental factors could account for the lower growth rate.

The persistence of constant growth beyond the linear phase is reminiscent of results obtained by Youngs (1984) and Read (1984) for the RT instability. They found that, at late times, the amplitude of the perturbation was proportional to the average displacement of the interface. This result can be obtained directly from dimensional analysis, if one assumes that memory of the initial perturbation is lost. In the case of a shock, the interface velocity is constant, and so is the perturbation growth rate. However, the proportionality factor cannot be expected to be identical to that of the small-amplitude growth rate, although it is also constant. Meshkov's and Benjamin's results seem to indicate that, to first order, a similar relationship holds for the transitional regime between small-amplitude growth and the asymptotic growth rate.

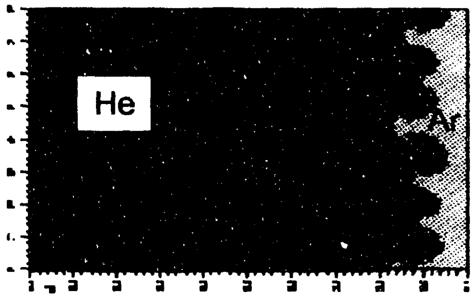
Meshkov's and Benjamin's experiments were conducted for weak shock waves (incident Mach number ≈ 1.3). Aleshin (1988) and Zaitsev (1991) studied the case of a stronger shock (incident Mach number ≈ 3.5) and found better agreement with Richtmyer's prediction. In this case, the compressed value of a/λ was smaller so that a true linear phase was observed. In addition, the thicker membrane used provided a better definition of the Atwood number. However, if the membrane itself had been the origin of the discrepancy observed in Meshkov's and Benjamin's experiments, a similar discrepancy should have been observed in Aleshin's experiments. Indeed, work of Smith (1989) indicates that thick membranes can have a significant effect on the flow. A closer look at the data from these various experiments should shed some light on the role of membranes, which tend to be blamed for much of the disagreement between experiments and numerical results.

Other high-Mach-number experiments with single wavelengths were reported by Vasilenko (1988), who used an electromagnetic shock tube and obtained better agreement with theoretical estimates. In this case, however, a strong deceleration of the flow behind the shock resulted in a significant RT phase, so the results are not a direct test of the RM problem.

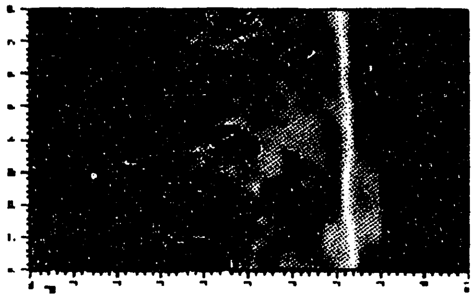
1.2 Discontinuous interface with random-wavelength perturbations

While the study of single-wavelength perturbations provides some insight into the RM phenomenon, usual interfaces are nominally flat but comprise a spectrum of small-amplitude perturbations. The spectrum is often near white, in which case the component of the perturbation with the smaller wavelength grows the fastest, according to Richtmyer's formula. As the value of a_0k reaches ~0.4, its growth rate starts to decrease, and the next component takes over, so that a nonlinear phase is attained quite rapidly. In the process, mode coupling occurs, and the spectral content of the interface is modified. When several dominant wavelengths are present, larger scales develop by means of a bubble-competition mechanism (Zufiria 1988) and vortex pairing. Simultaneously, a breakup of the perturbation occurs, generating much smaller scales, and the flow becomes fully turbulent. In such cases, it is not possible to distinguish the shape of the perturbed interface; rather, a mixing region is obtained, where quantities such as the overall width or average concentration profile can be determined. Figure 1 (Rupert,1991) illustrates a similar evolution for a small number of wavelengths.

Experiments were performed with a nominally flat membrane separating the test gases in a shock tube (Andronov 1976; Zaitsev 1985; Brouillette 1988; Houas 1988; and Cavailler 1991). One of the most noticeable result from these experiments is the small growth rate following the passage of the incident shock through the interface and its significant increase after the incident shock reflects off the end wall. In the latter case, the reflected shock interacts with a pre-existing turbulent region that results from the incident shock, transfers energy to it, and increases the turbulence, thus accounting for the increased growth rate of the mixing layer. Experimental results for similar initial conditions are the center of an unresolved controversy resulting from the difference in growth rates quoted by Andronov (1976) and Brouillette (1988). Andronov's values are about an order of magnitude larger than Brouillette's, whose data were recovered by Cavailler (1991). Two possible causes for the discrepancy have been proposed: the influence of the boundary layer (Brouillette) and the effect of the membrane (Meshkov). Because of shock/boundary-layer interaction, large vortices develop along the walls after reshock and grow at a much faster rate than do the perturbations at the center of the shock tube. Because schlieren is an image of the density gradients integrated over the width of the tube, separation of the signature of the main flow from that at the boundary is sometimes difficult. Brouillette's measurments of wall vortices gave growth rates similar to those quoted by Andronov.



(a) Log density, 0.05 ms



(b) Density, 0.35 ms

Figure 1. The RM unstable interface traverses several stages, following an initial linear growth. These simulations were performed for a Mach 3.45 shock in Ar incident on an Ar/He interface. A multiwavelength perturbation was imposed on the interface. (a) The incident shock has crossed the interface; vortices are developing at the tip of the Ar spikes. (b) After multiple shock transit, larger scales resulting from vortex pairing as well as small-scale turbulence have developed.

Moreover, transverse waves from wall vortices interact with the center flow and influence its evolution. By such a mechanism, differences in wall smoothness could result in different growth rates of the perturbed interface.

1.3 Diffuse interfaces

In a shock-tube environment, the materials impinging on the interface are gases, and it is difficult to obtain a discontinuous interface without some solid membrane whose effect is as yet unresolved. However, because a characteristic of RT or RM instability is the Atwood number, a diffuse interface should result in lower growth rates. This was indeed predicted by Lelevier (1955) for the RT case and reviewed by Mikaelian (1985) for the RM case, in which an incompressible flow behind the shock was assumed. Two facilities have been built to test these predictions experimentally. Both are vertical shock tubes in which the test gases initially are separated by a retractable plate. Just prior to shock passage, the plate is withdrawn, and the gases interdiffuse. In the Caltech tube (Brouillette 1988), the shock is incident from the top, so that RT unstable cases are instigated; in the Vaujours tube (Cavailler 1989), the shock is incident from the bottom. In accordance with predictions, the experimental growth rate after passage of the incident shock is indeed quite small (too small, in fact, to be measured reliably), but again the growth rate increases markedly after passage of the reflected shock. These observations are true for either nominally planar or quasi–single-wavelength interface shapes. For the latter, Brouillette proposed a modification of Richtmyer's formula, in which a growth-reduction factor depends on the Atwood number and the initial thickness of the diffusion zone. His calculations imply growth rates as small as 1/20th of the growth for a discontinuous interface between the same gases. Fair agreement was obtained between his experiments and the formula he proposed, even when the perturbation became slightly nonlinear.

1.4 Discontinuous interface with large-scale perturbations

While the preceding experiments examined the evolution of an interface with small initial perturbations, a few experiments have investigated the large-perturbation case. Two types of experiments were conducted along these lines.

Large-scale sawtooth perturbations can be simulated by studying the interaction of a planar shock with a tilted interface. The same information on the initial interface deformation was obtained in studies of irregular shock refraction through tilted interfaces (Puckett 1989). Haas and Sturtevant (1985) examined the late-stage development of such an interface, including the case of two equally tilted interfaces containing different layers of gas. The large-scale perturbation defined by the tilt evolved as expected (with an inversion of the tilt angle for the RT stable case), and large-scale vortices developed at the tips. Along the interface, in the nominally planar region, small-scale perturbations evolved as a result of both RM and Kelvin Helmholtz instabilities, and a wide mixed region appeared. Yang and Zabuski (1989) performed numerical simulation of these experiments and emphasized the role of dipolar vortex binding in breaking through a thin layer.

Large-scale perturbations of a different kind were also investigated, in spheres or cylinders traversed by a planar shock. Haas (1983) studied this configuration in the context of shock refraction, using schlieren imaging and soap bubbles or thin plastic membranes to separate the gases. Recently, more detailed data on cylindrical perturbations were obtained with buoyant cylindrical jets by Jacobs (1991), who used laser induced fluorescence of a biacetyl dopant, and by Budzinski (1991), who used Rayleigh scattering. These latter experiments bypassed the difficulty of accounting for the effect of the membrane and, with the use of a laser sheet, provided data on a thin slice of the cylinder, yielding more precise information on the two-dimensional evolution of the interface. These experiments show simultaneously the evolution of RT-stable and -unstable interfaces, subjected to varying vorticity, and clearly show the deformation of the cylinders and formation of ring vortices.

1.5 Diagnostics

An important aspect of the work on RM instability is the development of a predictive capability, so that its influence on the structure of the interstellar medium or the efficiency of an inertial confinement fusion implosion can be assessed. To do so requires experimental data that can be compared directly with theories or numerical computations. In most experiments described thus far, schlieren imaging was used to provide the time-dependent width of mix layers. Observation through boundary layers could influence the data, and concentration gradients of the individual components could not be obtained. Other diagnostic techniques are being developed to provide complementary or new information. These include laser scattering techniques (Meshkov 1989; Benjamin 1989; Jacobs and Budzinski; 1991), infrared absorption and emission (Houas 1988), holography (Stearman 1989), and x-ray absorption (Bonazza and Sturtevant 1991).

2. Numerical simulations

Numerical simulations of the RM problem have been performed with a variety of techniques: two-dimensional calculations using purely Eulerian meshes (Besnard 1989; Wehner 1989), Eulerian meshes with interface tracking, Eulerian meshes with adaptive mesh refinement (Rupert 1989, 1991), arbitrary Lagrangian Eulerian meshes (Rauenzahn 1989; Griswold 1991), semi-Lagrangian meshes with interface tracking (Cowperthwaite 1989), and front-tracking methods (Glimm 1991); three-dimensional calculations using Eulerian codes (Cowperthwaite 1989; Wehner 1991).

All the calculations assume inviscid fluids. Mesh size limitations restrict the type of perturbations that can simulated. In general, a single wavelength or only a small number of wavelengths are used, with a_0/λ ranging from 0.3 to 7%. The meshes are defined in such a way as to ensure a good resolution of all the initial wavelengths. However, as the perturbation crosses through a nonlinear stage into the fully turbulent regime, smaller scales develop and eventually cannot be resolved. Adaptive-mesh and interface-tracking schemes are least susceptible to this loss of resolution but are limited nonetheless by the growing size of the problems versus the finite size of computer memories.

A few calculations have been initiated with small random perturbations (Besnard 1989) but present problems of convergence.

2.1 Simulations of single- and multi-wavelength perturbations

The single-wavelength calculations are in good agreement. A set of problems was run for air→He at M = 1.24, air→SF_6 at M = 1.32, Ar→He at M = 3.45 and He→Ar at M = 2.77, where M is the Mach number of the incident shock. The M = 1.24 case was a simulation of one of Benjamin's experiments. The simulations showed a quasilinear growth after passage of the incident shock, as well as after the first reflected shock (Fig. 2, Rupert, 1989). The calculated growth rate just after passage of the incident shock through the interface ranges from 75 to 80 m/s and was obtained by determining the growth of the layer containing a 5:95 ratio, per volume, of the constituents. (Note that this definition corresponds to ~1.98 times the amplitude for a sinusoidal perturbation.) This

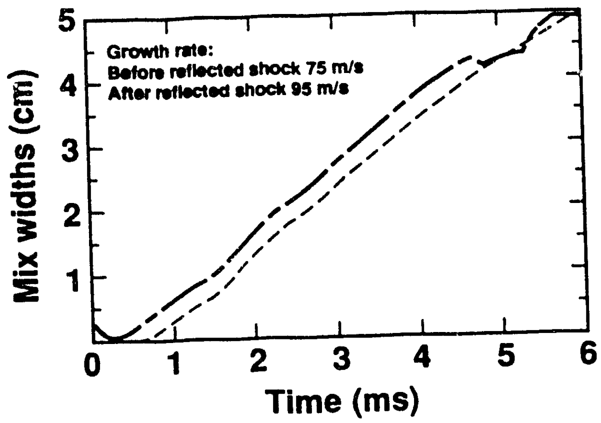


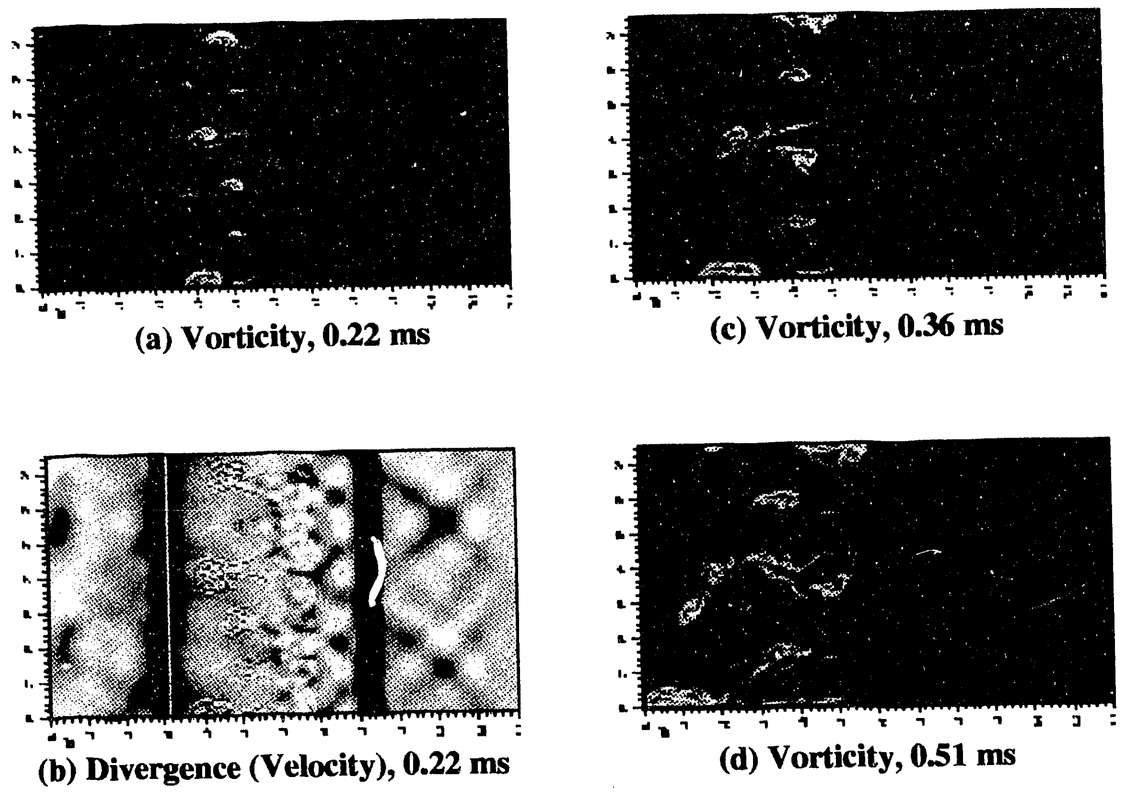
Figure 2. Numerical simulation of single (- -)- and multiple (- — -)-wavelength perturbation growth at an air/He interface subjected to a Mach 1.24 shock incident from the air side. The growth rate is almost constant after both incident shock and reshock.

rate compares well with a prediction of 83 m/s based on Richtmyer's formula, but it is much larger than the experimental value of 38 m/s. Because the initial conditions of the calculations and the experiments were identical, the discrepancy cannot result from the fact that the perturbation rapidly reached a nonlinear phase.

The influence of the membrane is difficult to simulate; because its density greatly exceeds that of the gases, its inclusion in the calculations necessitates both an extremely fine mesh and a simulation of the strength of the membrane material. In attempting to include it in the calculations, researchers usually resort to simulating it with a dense "gas" layer. Benjamin (1991) reports the results of such a calculation and concludes that the membrane should have a negligible effect.

The remaining obvious possible source of differences between calculations and experiments is the boundary layer, which is ignored in most calculations, where the shock tube's walls are treated as reflecting boundaries. This aspect of the problem was studied by Cloutman (1990), who used both no-slip and slip conditions at the walls. His results indicate little difference in the growth rates in the bulk of the flow, although additional vorticity was generated at the walls in the no-slip case. Thus the puzzle remains unsolved. Better ways of treating membranes and boundary layers need to be implemented, and simulations of the experiments without a membrane also need to be performed.

Results from simulations of the Benjamin problem, using an AMR code, are shown in Fig. 3 (Rupert,1989) for a multi-wavelength initial perturbation. Here, the evolution of the vorticity is shown at various times after arrival of the reflected wave at the interface. For the earliest time, the divergence of the velocity is also shown and displays, to the right of the interface, the location of the primary shock after it has been transmitted through the interface, reflected off the end wall, and retransmitted through the interface. Relative to the interface perturbation, the shock is almost flat. The secondary shock reflected off the interface is seen on the left of the interface and is also rather flat. Throughout the flow field can be seen a complex pattern of expansion and compression or shock waves resulting from the reflection and refraction at the interface of the incident shock and shocks reflected from the end wall. The near planarity of the strongest shocks results from the coalescence of the curvilinear shocks transmitted through the wavy interface. The vorticity, however, is seen to be concentrated at the interface, primarily at the tips of the spikes of denser fluid. As the perturbation grows, vortex pairing occurs, creating larger-scale structures. The successive shocks reflected off the end wall cross the interface area and increase the vorticity.



(a) Vorticity, 0.22 ms

(c) Vorticity, 0.36 ms

(b) Divergence (Velocity), 0.22 ms

(d) Vorticity, 0.51 ms

Figure 3. Numerical simulation of the evolution of a multiple-wavelength perturbation growth at an air/He interface subjected to a Mach 1.24 shock incident from the air side. (a), (c), and (d): Vorticity maps at various times, showing vorticity concentrated near the tips of the air spikes and vortex pairing at late time. (b): Map of the divergence of the velocity at the same time as in (a). It shows an almost planar transmitted and reflected shock, in spite of the proximity of a highly distorted interface.

From such calculations, the Reynolds stresses can be computed as a function of the position along the shock tube axis, and the turbulent energy (as the integral of the Reynolds stress tensor trace) is determined as a function of time. As Fig. 3 implies, the turbulent energy is concentrated in the mixed layer. As the first shock crosses the interface in these calculations, which neglect viscosity, turbulent energy is generated, diffuses, and decays slowly. At the arrival of the second shock, the turbulent energy increases by more than a factor of 10 as energy is transferred from the shock to a pre-existing turbulent region (Fig. 4, Rupert, 1991). In essence, the energy transfer is now more a result of small, random density fluctuations than of large density differences caused by different gases. Similar results were extracted from all numerical simulations.

An important result of the 2-D simulations is the late-time RM growth rate's sensitivity to the initial conditions. This result marks a break from RT instability, where asymptotic growth rate has been shown both experimentally (Read 1984) and numerically (Youngs 1984) to be independent of the initial perturbation. Caution must be exercised, however, in extrapolating these findings to all situations because, in most experiments and simulations, the distance between the interface and the end wall was so short that the mixed layer was not fully turbulent before arrival of the reflected shock.

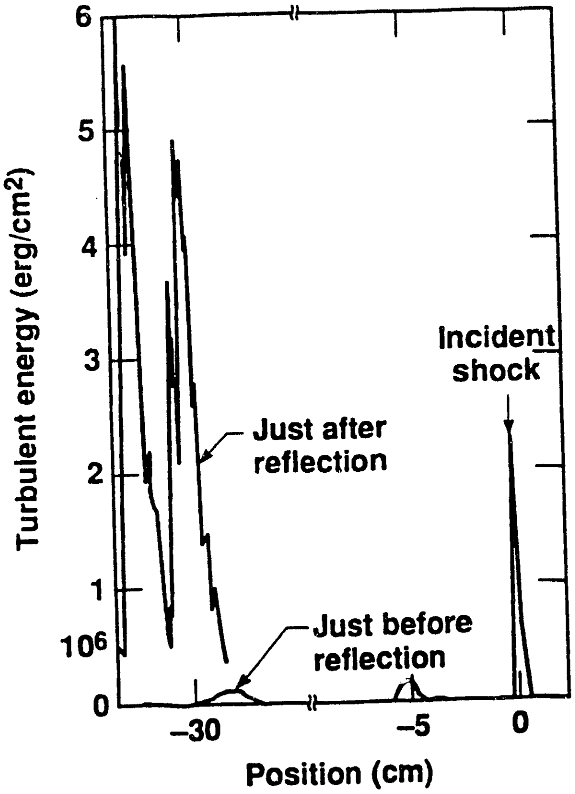
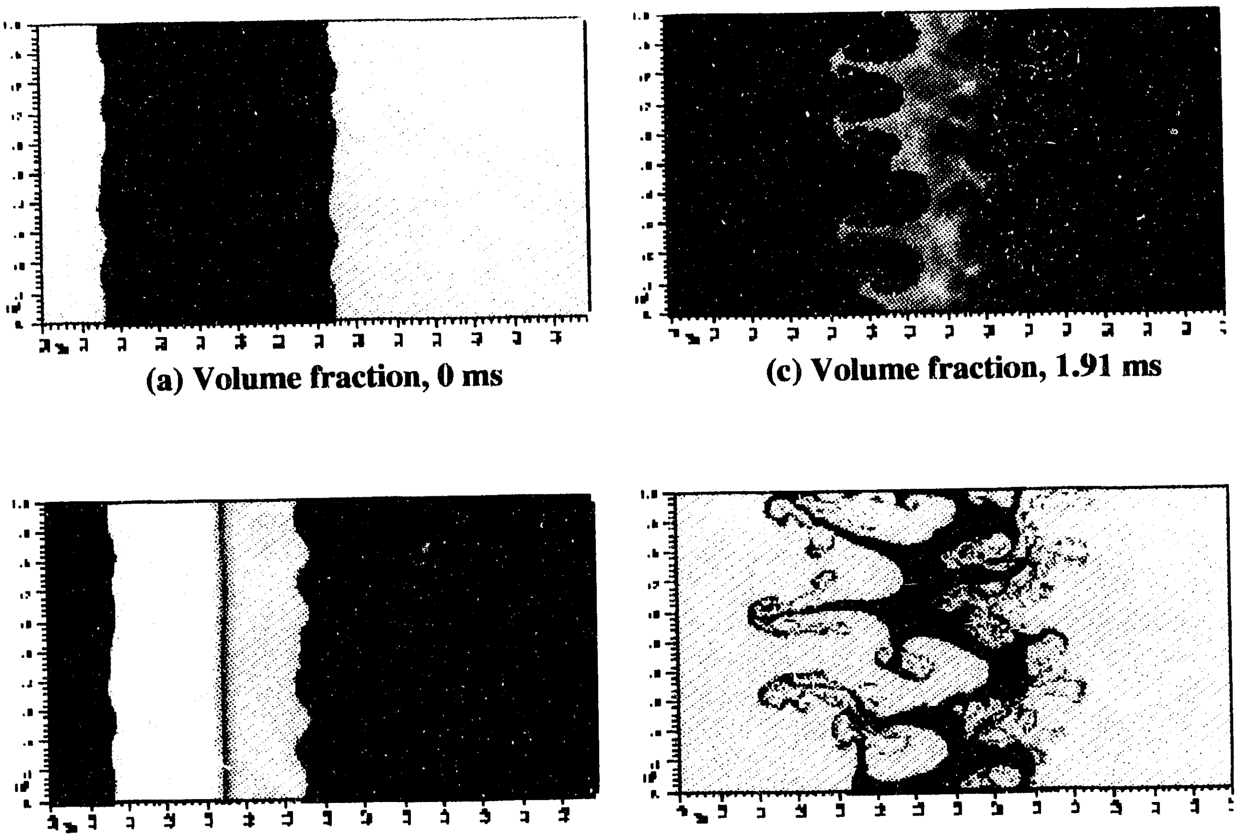


Figure 4. Snapshots of the turbulent energy at various times, resulting from the interaction of a Mach 2.7 shock in He incident on an Ar/He interface. Numerical simulations were performed with a single-wavelength perturbation. Following shock passage and turbulence generation, the turbulent energy diffuses across the inter-face, and the total energy decreases slightly. The reflected shock results in a 20× increase in total turbulent energy.

2.2 Simulation of a perturbed gas layer

Yang and Zabuski (1989) simulated gas layers for tilted planar interfaces. Here, simulations of a gas layer with interfaces normal to the shock-tube axis and comprising multiple-wavelength small-scale initial perturbation are presented (Rupert, 1989). This simulation was performed with an Adaptive Mesh Refinement code developped by Colella (Puckett, 1989). The configuration studied was proposed by Youngs. A weak shock, at M = 1.23, is incident from air into an R22 (refrigerant) layer. The first interface, I_1, traversed by the shock is therefore RT unstable, while the second, I_2, is RT stable. Figure 5(a) shows the initial interface shape, with identical perturbations. In Fig. 5(b), the shock is halfway within the layer. The perturbation has grown on I_1, but it is still nearly linear. In Fig. 5(c), I_2 has reversed phase and has reached a highly nonlinear configuration, while I_1 is starting to show vortex pairing or mode coupling. At this point, the shock reflected off the end wall has just crossed the layer so that I_1 is RT stable and is changing phase, the mushroom heads are flattening, and I_2 is RT unstable and is continuing to grow. Little cross coupling is apparent between the interfaces at this point. In Fig. 5(d), the coupling between the interfaces is visible, although the layer has not yet broken through. The attempt of the highly complex shape of I_1 to change phase has led to a turbulent configuration.

Although this simulation involves a layer and (at late stages) cross coupling between the interfaces tends to influence the evolution of the interfaces, these results illustrate (in greater detail than the preceding simulations) the nonlinear phase of perturbation growth. Indeed, here, the end wall is sufficiently far from the interfaces to allow them to evolve to a highly nonlinear phase before the reflected shock arrives. Simulations of this kind, with a single interface, still need to be performed in order to study the question of sensitivity to initial conditions.



(a) Volume fraction, 0 ms

(c) Volume fraction, 1.91 ms

(b) Log density, 0.22 ms

(d) Volume fraction, 2.55 ms

Figure 5. Numerical simulation of an R22 layer in air, with multiple-wavelength perturbations of the layer boundaries. Incident shock Mach number was 1.23. (a) The initial volume fraction of air. (c) and (d) The volume fraction after the incident and reflected shocks have crossed the layer. (b) The density distribution when the incident shock is still within the layer.

2.3 Three-dimensional simulations

Two-dimensional calculations have been quite helpful in understanding the evolution of shocked interfaces. However, because part of the mixed layer develops turbulent characteristics, it is probable that the 2-D growth rates do not exactly reflect the real 3-D growth observed in the experiments. Several researchers (Cowperthwaite 1989; Sahoda 1990; Wehner 1991) have attempted to follow the evolution of the perturbations in 3-D.

Even to a larger extent than 2-D simulations, 3-D simulations are limited by the number of mesh zones that can be used, but progress has been made, particularly in the computation of single-wavelength perturbations. A simulation of the experimental configuration in which a cylindrically corrugated membrane separates the gases would require a 3-D calculation wherein a single wavelength is imposed in one direction and small random perturbations are superimposed in the perpendicular direction. Because of the small number of zones available, such random perturbations cannot be well resolved. Thus, 3-D simulations tend to be conducted with either a cylindrically symmetric, single-wavelength perturbation (Sahoda and Wehner) or the product of single wavelengths in two orthogonal directions (Cowperthwaite and Wehner). Calculations for a random perturbation have been reported by Youngs (1990) for the milder case of RT instability.

Cowperthwaite's results indicate a higher growth in 3-D than in 2-D after multiple reshocks but appear to give the same growth rate after the incident shock and the first reflected shock. These results are in conflict with Wehner's, who in first analysis, finds slightly lower growth rates. Differences in the type of initial perturbations may account for the different results.

3. Modeling

The most important result of studies of RM instability is to provide a data base against which simple models can be calibrated and verified. Indeed, full 3-D simulations of astrophysical problems, or miniature ICF targets, are quite expensive in money, time, and computer memory. While a few cases can be run, it would be prohibitive to investigate a large number of scenarios to reach an acceptable configuration. Hence, much emphasis has been placed on developing models that can describe the evolution of shocked interfaces in terms of basic hydrodynamic equations, supplemented by 1-D evolution equations of a small number of additional variables.

The linear phase of perturbation growth can be described by Richtmyer's equations for the width of the mixed region. His formalism has been extended to describe the nonlinear evolution of a random perturbation. Several such extensions have been proposed (Crowley 1983; Neuvazhaev 1981; Gauthier and Bonnet 1990). In general, these equations include Richtmyer's terms, where a/λ is replaced by an (adjustable) constant, and a drag term that comprises a scale length. The principal differences between such models is the implementation of the scale length. Two phase models are also used to describe the nonlinear interpenetration of the materials.

The turbulent phase has been modeled with variants of a $k\varepsilon$ model. Simple models include equations for the turbulent energy and its dissipation rate, with some closure model (usually in the form of diffusion terms). More sophisticated models retain additional moments of the fluctuating components.

Most of these models have been developed to represent RT instability growth and (to the extent that a shock can be thought of as a very large acceleration) are applied to the RM instability as well. This extension does not yield acceptable results if the interface is RT stable. To overcome this problem, Crowley (1988) adds to the pressure gradient an "artificial viscosity" term that is significant only at a shock front and provides a source for the turbulent energy in both RT unstable and stable cases. Such a model can be made to represent shock-tube data quite well, as shown in Fig. 6.

The validity of any model depends on its ability to represent a variety of experiments with the same parameters. Most of the proposed models can be made to match a class of problems such as (1) an interface subjected to a single shock or to multiple shocks, (2) a particular configuration (RT stable or unstable), (3) laser-driven shocks, or (4) shock tubes, but they are not universal. The principal difficulty is that the models describe one or the other phase of the evolution of the interface, whereas all phases are involved in an experiment. Newer models attempt to describe the whole process by retaining both of the equations that describe the nonlinear and the turbulent phases and establishing a consistent link between them. Such models appear to be more reliable, but they are, as yet, too new to have been thoroughly tested. Spectral transport models have also been proposed (Buckingham 1983; Besnard 1991).

In addition to models that can be reduced to 1-D predictions of the state variables in an RM-induced mixed layer, models designed to account for subscale mixing in 2- and 3-D computations are being sought. Here again, most of the work addresses RT instability.

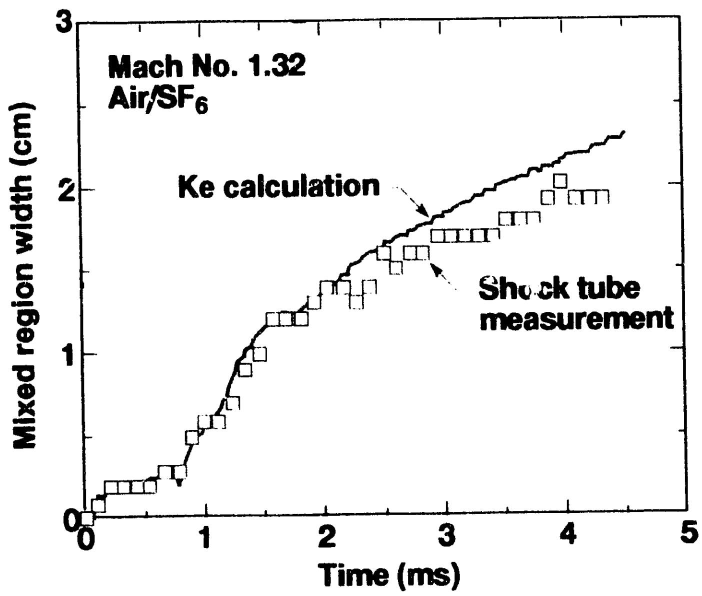


Figure 6. Comparison of experimental data and modeled mix width for a Mach 1.32 shock incident from air into an air/SF_6 interface. A KE model was used with an additional source term to take the shock-induced mixing into account. Model parameters can be selected to match the data quite closely, but they are not universal.

4. Summary

In summary, much has been accomplished in the past decade, but there is still room for exciting research in all aspects of the RM mixing problem. It is important to accumulate a data base of sufficiently different experiments and numerical simulations to help fix model parameters and independently verify their universality. If one is to rely to any extent on numerical simulations, it is also necessary to ascertain their reliability by comparing them with known experimental results before using them to describe situations that cannot be tested in a laboratory.

In the experimental arena, better diagnostics will give more detailed, consistent, and reliable data. Future experiments will need to concentrate on configurations amenable to numerical simulations with well-defined initial conditions, and the effect of extraneous items will have to be quantified.

In the numerical arena, it will be necessary to incorporate all the aspects of the experiments that are being simulated, and 3-D codes should be used more universally, at least until 2- and 3-D results can be reliably correlated.

Models of the mixed region need to be refined to account for all phases of perturbation growth and their transition.

The challenge remains to develop a predictive capability.

5. Acknowledgment

Space limitation precludes an exhaustive list of all the researchers who have contributed to advances in the field of RM induced mixing. Further references can be found in the works cited here.

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