Originally published in *Proceedings of the Fifth International Workshop on Compressible Turbulent Mixing*, ed. R. Young, J. Glimm & B. Boston.
ISBN 9810229100, World Scientific (1996).

Effect of Membrane on Measurements of Turbulent Mixing in Shock Tubes*

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Abstract. Experiments measuring the time development of shock-wave induced turbulent mixing between two gases initially separated by a thin membrane have been performed in many laboratories. The main purpose of the experiments is comparison with Richtmyer-Meshkov instability theory. This comparison assumes that the membrane has no effect on development of the mixing.

We have performed similar experiments in which membranes of different thicknesses were placed between two volumes of air. Series of schlieren photographs were taken using a copper-vapor laser pulsed at a rate of 10000 pulses per second and a shutterless rotating-prism camera. A *mixing region* developed and grew with time, despite the fact that only one gas was present. We have measured the dependence of the *mixing width* on membrane thickness. The existence of a membrane-induced *mixing zone* means that membrane effects must be accounted for in comparing theory and experiment.

1 Introduction

Acceleration of two fluids of different densities into each other by a shock wave leads to the Richtmyer-Meshkov hydrodynamic instability [1],[2]. The time-development of this instability has been studied both theoretically and experimentally for a wide variety of geometries and initial conditions. Most of the experiments have been performed in shock tubes, with the two fluids separated by a thin membrane. Usually the membrane is planar, and the instability is initiated by random perturbations (e.g., [2]). In some experiments an initial perturbation, usually sinusoidal, is imposed on the membrane (e.g., [3]).

*We are grateful to D. Hirshler for his technical contributions to all parts of the research and to D. Shvarts and G. Ben-Dor for their valuable advice.

There is disagreement among results from different groups who have performed nominally similar experiments [4], [5]. Various explanations have been given for these differences (e.g., [6]); it is widely agreed that the cause of the disagreements probably lies in experimental artifacts and in interpretation of the photographs. We have attempted to resolve these differences by eliminating two of the possible sources of error. In order to eliminate errors due to experiment-to-experiment irreproducibility, we have used a repetitively pulsed laser together with a rotating-prism camera to photograph the entire time-development of the instability in a single experiment. In order to eliminate photograph-to-photograph variations and operator bias in the measurement of the mixing zone width, we have used computerized image analysis.

2 Experimental Apparatus and Technique

The experiments are performed in a 7.5 meter-long horizontal double diaphragm shock tube with an 8×8 cm^2 cross section. A thin membrane separates the two gases. The development of the mixing region induced by the shock wave is measured by photographing a series of schlieren pictures using a copper-vapor laser pulsed at a rate of 10000 pulses per second and a shutterless rotating prism camera. The photographs are analyzed using computerized image analysis. Figure 1 is a schematic diagram of the experimental apparatus. A short description of the experimental apparatus and technique follows; a detailed description will be published elsewhere.

The shock tube is similar to those described in many previous papers. A thin membrane is placed between the shock tube and the test section, and is shattered by the shock wave, beginning the mixing process. The length of the test section is determined by positioning a rigid end wall at a variable distance from the membrane. Windows are built into the side walls of the test section. Their height is the entire 8 cm height of the section; their length is 20 cm, beginning at the membrane. The test section is filled with gas to a pressure of one atmosphere, equal to that in the shock tube.

The membrane is prepared by dropping a small amount of a solution of a monomer in a thinner onto the surface of a water bath, and then lifting the thin polymerized membrane layer off the water using an 8×8 cm^2 frame. The frame is then placed in the proper position in the shock tube. The membrane thickness is approximately proportional to the concentration of monomer in the solution. The thickness is measured by weighing the membrane and using the known area and density. There is an estimated error of 10% in the thickness calculation resulting from uncertainty in the density.

The light source for the schlieren photographs is a copper-vapor laser which produces 30 nsec long pulses with a repetition rate of 10000 per second and an energy of approximately 0.5 mj per pulse. Only the green (511 nm) line of the output is used. The timing of the laser pulses is not synchronized with the shock wave. The 3 cm diameter

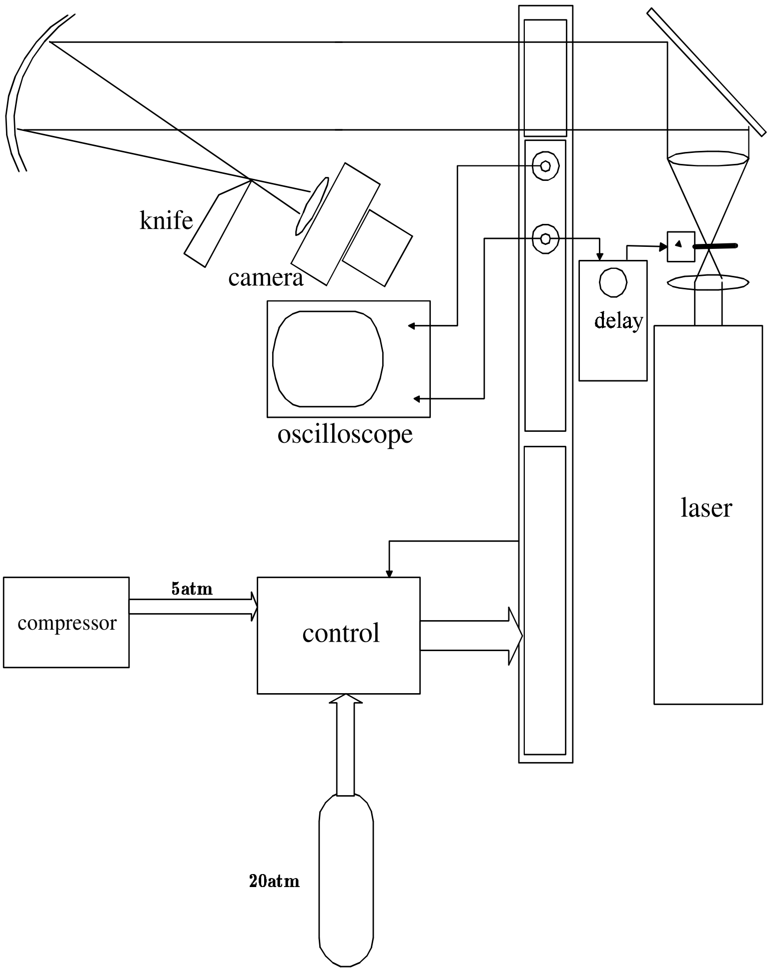


Figure 1: Schematic diagram of experimental apparatus.

laser beam is expanded by a telescope to 8 cm in order to fill the test section window. A shutter at the focus of the telescope blocks the beam except for a very short time during the experiment. The parallel laser beam passes through the test section and is focused by a concave mirror onto a knife edge and then imaged onto the detector.

The detector consists of a shutterless rotating prism camera. The rotating prism is enclosed in a drum whose circumference is equal to the length of a 36-exposure roll of 35 mm film. The prism rotation speed ensures that one complete rotation corresponds to about 30 laser pulses. Since the camera is shutterless, the laser shutter serves to prevent *double exposure*, where a second set of pictures overlays the first set.

Figure 2(a) shows part of a series of pictures from a single experiment in which the shock wave passes from air to helium. A two cm-long arrow is pasted on the outside of the experimental section downstream from the membrane. It appears in the upper right corner of each picture. The dimensions, position and orientation of the arrow serve as calibrations for the set of pictures. The sharp dark line in the center of picture A is the incident shock wave. The reflected shock wave is seen in pictures C and D. The mixing zone is the dark band which appears on the right of picture A. In subsequent pictures it grows in width and moves left, until it reaches a nearly constant position in pictures E and F. The boundaries of the dark band are not well defined, making it difficult to measure the width of the band accurately, reproducibly and without operator bias.

We have therefore developed a computerized image analysis technique. The region of interest in the picture is scanned digitally. A histogram is made of the number of pixels within the region as a function of gray scale. Most of the pixels are either very dark (within the dark band) or light (outside it), leading to a double-humped histogram. The pixels corresponding to the minimum between the two humps are defined as the boundary of the dark band. The number of pixels within this boundary are counted; the area is normalized using the arrow.

3 Experimental Results

The growth of the mixing zone width in Figure 2(a) is qualitatively similar to that measured for air-helium mixtures in references [4] and [5]. In attempting to reproduce this result we have found that the measured growth rate depends strongly on membrane preparation. In order to separate membrane effects from mixing zone growth due to the Richtmyer-Meshkov instability, we studied the effect of membrane thickness on the measured widths. In particular, we have placed air on both sides of a planar membrane. Obviously, there is no hydrodynamic instability in this case, but we have observed a *mixing zone* which grows with time.

Figure 2(b) shows a series of pictures from one such experiment. The conditions of the experiment are similar to those described for Figure 2(a), but both sides of the membrane consist of atmospheric-pressure air. The pictures are also qualitatively

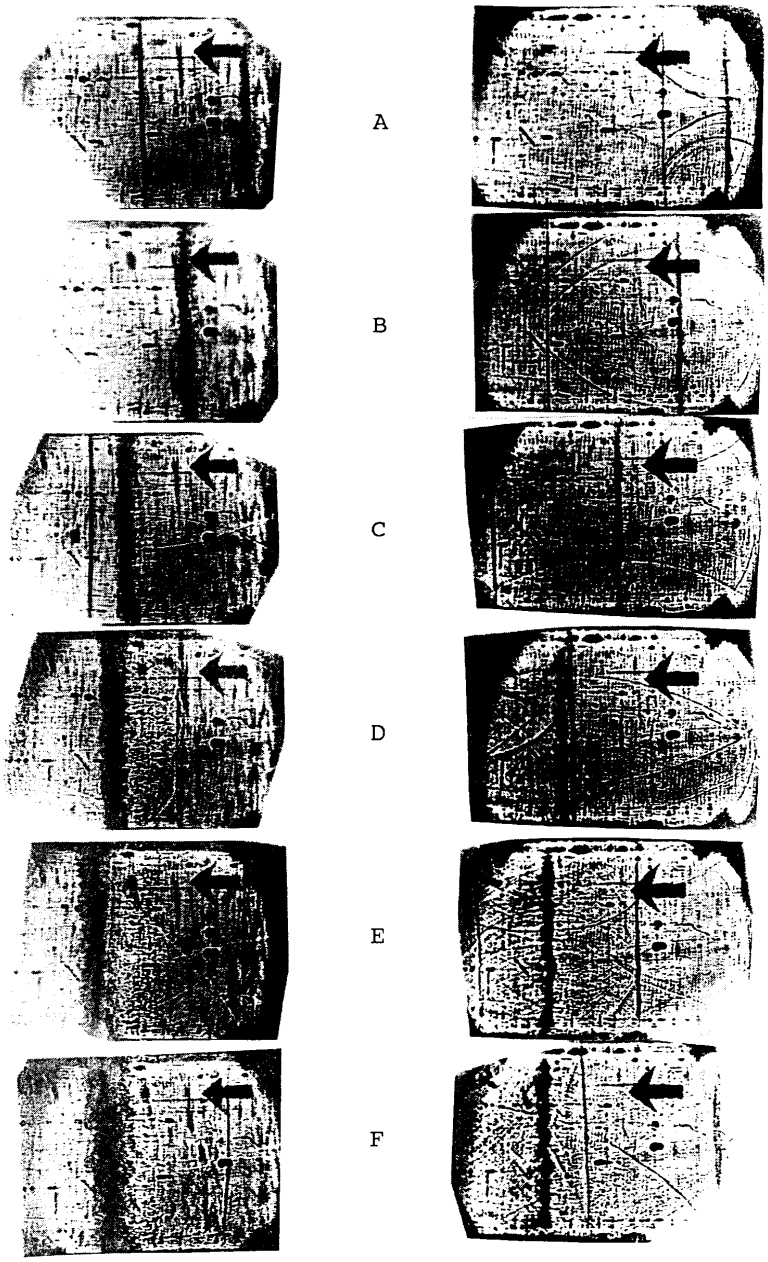


Figure 2: Series of schlieren photographs from single experiments. The pictures are separated by 100 μ sec. (a) Air-to-helium. (b) Air-to-air.

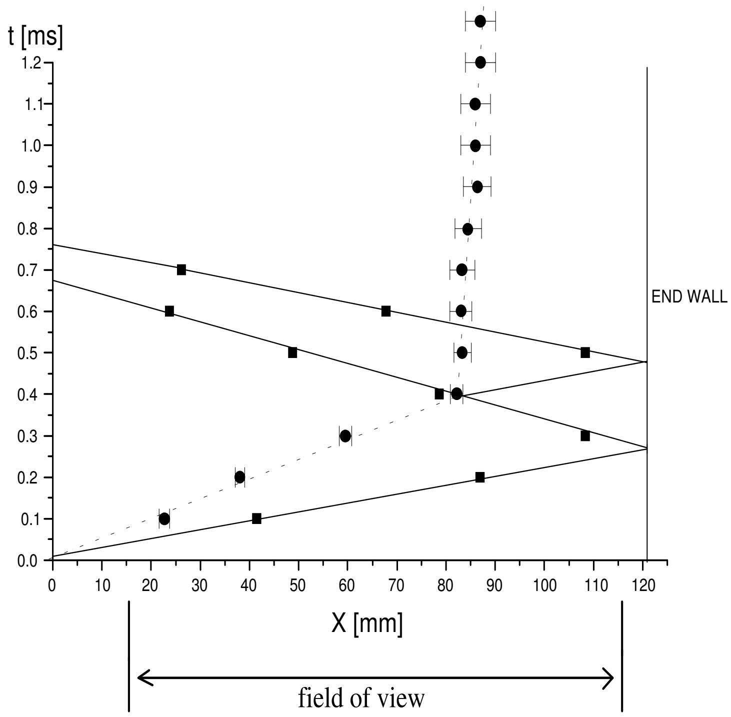
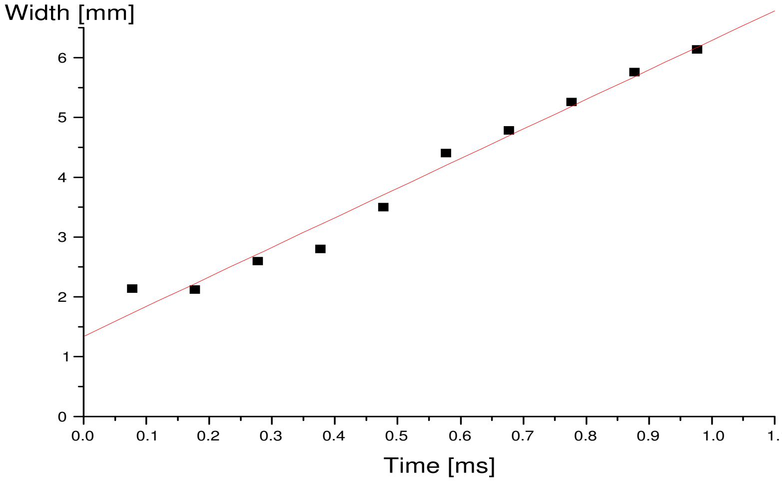


Figure 3: *x-t* diagram of *mixing zone* development for experiment shown in Figure 2(b). Circles represent center of mixing zone; distance between vertical lines is width of zone. Squares represent incident and reflected shock waves.

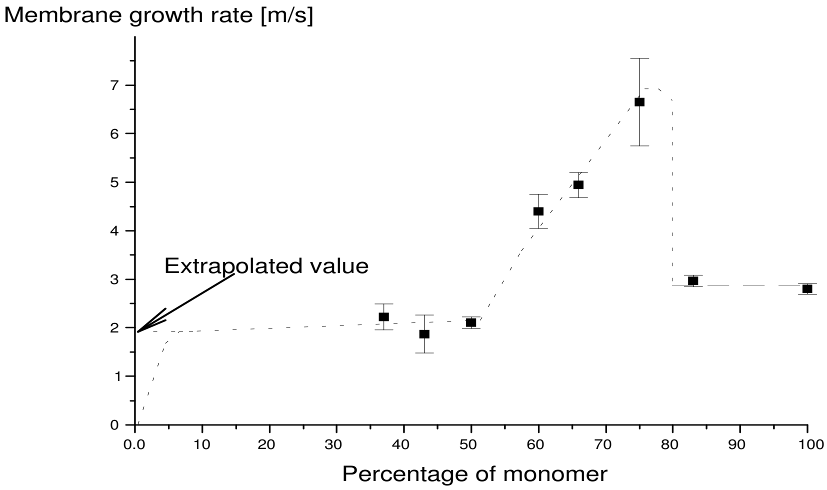
similar to those of Figure 2(a), although the growth of the dark *mixing region* is much slower.

Figure 3 is an x-t diagram of the experiment shown in Figure 2(b). For each photograph, the circle represents the center of the mixing zone, whose width is the distance between the two vertical lines. The squares represent the positions of the incident and reflected shock waves. The dotted and solid lines are drawn to guide the eye. Figure 4(a) is a graph of the mixing zone width as a function of time for this experiment.

We have performed a series of similar experiments using different solution concentrations to form membranes of different thicknesses. Figure 4(b) is a graph of the *mixing zone* growth rate as a function of membrane thickness. It should be noted that the growth rate is quite similar to those measured by other groups for dissimilar gas pairs (e.g., [4], [5]).



(a)



(b)

Figure 4: (a) Graph of *mixing zone* width as function of time from the data of Figure 3. (b) Graph of *mixing zone* growth rate as function of membrane thickness for air-to-air experiments.

4 Discussion

After passage of a shock through a membrane separating two gases, schlieren photography reveals a dark band usually referred to as the *mixing zone* and assumed to represent the zone of turbulent mixing caused by the Richtmyer-Meshkov instability. The measurements performed above, in which air at atmospheric pressure was present on both sides of the membrane, indicate that for this case the dark band is not a refractive index effect, but opacity caused by membrane remnants. We suggest that the dark band observed when dissimilar gases are separated by a membrane is also partly a membrane remnant effect and that development of the Richtmyer-Meshkov instability can only be studied if this effect can be effectively subtracted out.

The series of experiments on membranes of different thicknesses was carried out in order to study the systematics of membrane influence. The shock wave apparently shatters the membrane into small fragments, which attain the velocity of the gas with a range of time constants, probably dependent on fragment size. To an observer photographing perpendicular to the shock direction, the fragments form an opaque band. The band thickness grows as long as different fragments travel at different velocities. For thin membranes, fragments do not interfere with each other, and the growth rate of the opaque band is independent of membrane thickness. For thicker membranes, the density is sufficiently high to cause interference, for example by some fragments moving in the wake of others. These effects broaden the velocity distribution and increase the growth rate of the opaque band. For even thicker membranes, the model of fragmentation into very small pieces is probably invalid, and the opaque band may be caused by larger pieces, whose velocity increases more slowly, reducing the growth rate of the band.

For very thin membranes, the density of fragments should be reduced sufficiently to increase the amount of light transmitted, decreasing opacity, but probably not reducing the growth rate. Extrapolation to zero thickness therefore does not translate to zero growth rate for the membrane fragments, but probably does greatly reduce their influence on mixing zone measurements. Unfortunately, this region is inaccessible to experimental observation as the membranes are too fragile to move intact on the membrane-carrying frame to the shock tube.

The time development of the Richtmyer-Meshkov instability is often studied in shock tubes with two gases initially separated by a thin membrane. In many of these experiments the membrane is planar and the instability is initiated by random perturbations. The existence of a membrane-induced *mixing zone* means that membrane effects must be accounted for in comparing these experiments with theory or numerical simulations.

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