# Simulations and Experimental Investigation of the Inclined Interface Richtmyer-Meshkov Instability

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## 1 Introduction

The Richtmyer-Meshkov instability (RMI) [1, 2], forms when a shock wave interacts with a misaligned density gradient created by a fluid interface. This instability can be viewed as the result of baroclinic vorticity (eq. 1) generated at the interface from the misalignment of the pressure and density gradients. The strength of the RMI is dependent on the strength of the pressure and density gradients, described by the Mach number and Atwood number (eq. 2) and the angle between them.

$$\frac{D\vec{\omega}}{Dt} = \vec{\omega} \cdot \vec{\triangledown}\vec{u} + \nu \triangledown^2 \vec{\omega} + [\frac{1}{\rho}\vec{\triangledown}\rho \times \vec{\triangledown}P]_{baroclinic\ term} \tag{1}$$

$$A = \frac{\rho_h - \rho_l}{\rho_h + \rho_l} \tag{2}$$

The RMI has been found to be important in many applications such as supersonic combustion [3] and supernovae formation [4], but has received much attention due to its role in inertial confinement fusion (ICF). The RMI occurs at the interfaces of the DT fuel target causing mixing of the high density, high temperature core with surrounding material and greatly reduces the fusion yield [5]. The RMI has been studied extensively in experiments and simulations using various methods to produce the misaligned density gradient and pressure gradient.

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R. Bonazza and D. Ranjan (eds.), *29th International Symposium on Shock Waves 2*,
DOI: 10.1007/978-3-319-16838-8_59

In this paper, an integrated experimental and computational study is presented for an inclined interface RMI. In the case of an inclined interface problem, the amount of vorticity deposited on the initial interface, can be easily controlled by changing the inclination angle, without changing the Mach number (pressure gradient) or Atwood number (density gradient). The inclination angle can be adjusted experimentally by changing the inclination of the shock tube containing the fluid interface. This provides an easy-to-control, clean and repeatable interface for studying the RMI problem. It should be noted that by changing the inclination angle, we only alter the amplitude-to-wavelength ratio of the perturbation present at the interface.

## 2 Experimental Apparatus

Experiments were performed with the Texas A&M Fluid Mixing Shock Tube (figure 1). This facility is capable of inclination angles from 0° to 90°, incident shock wave Mach numbers up to 3.0 in air and Atwood numbers from ∼0.2 to ∼0.9. The shock tube is approximately 8.7m long with a modular design to allow it to be reconfigured for a wide range of experiments. The test section contains the eight optical access points for visualizing the interface and the valves necessary for creating the interface by the co-flowing method. This method creates a gas interface with minimal diffusion by flowing the heavy and light gases from the top and bottom and then bleeding them off at the interface where they mix through suction slots.

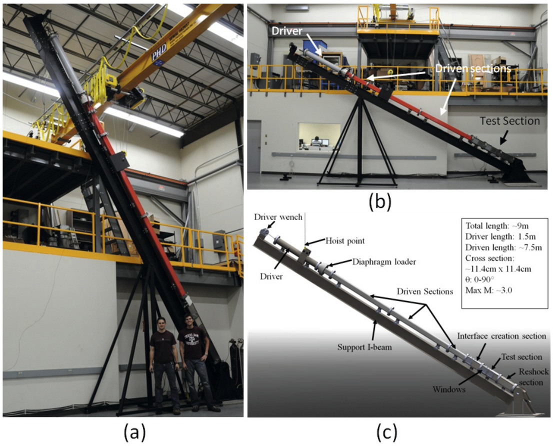

**Fig. 1** The Texas A&M University Advanced Fluids Mixing Shock Tube Facility. (a) The shock tube inclined at 60°, (b) The shock tube is inclined at approximately 30° with the main sections labeled. (c) An illustration of the shock tube at 30° with all sections labeled.

The timing of the diagnostic systems is initiated by 2 dynamic pressure transducers located at the end of the driven section which initiate high precision counter timers to trigger the laser and camera system. Imaging can be obtained through two primary methods: Mie scattering using a 532nm wavelength laser and fog droplets for seeding, or laser induced fluorescence using a 266nm wavelength laser and acetone vapor as a tracer. For this paper, the Mie scattering method will be used for visualization of the interface and for particle imaging velocimetry (PIV). Glycerin fog particles with a diameter of approximately 0.2-0.3$\mu$m were seeded in the light gas. A dual–cavity New Wave Research Gemini PIV laser capable of providing 200mJ per pulse at 532nm was used to illuminate the fog particles. High quantum efficiency TSI Inc. Powerview Plus 2 MP cameras were used for interface visualization images, and a TSI Inc. Powerview 1.4 MP camera with short frame straddling time was used for PIV images.

## 3 Simulation Conditions

The simulations were performed using the ARES code developed at Lawrence Livermore National Laboratory. ARES is an Arbitrary Lagrange Eulerian (ALE) code with adaptive mesh refinement (AMR) capabilities. Both viscosity and diffusion models were applied in these simulations [11]. The diffusion model included enthalpy diffusion. The simulations were initialized with the conditions shown in figure 2 where the computational domain extends from 0cm and 250cm. All boundaries were no slip, and shock–reflecting, where the upstream boundary contained a source term to sustain the shock wave. The initial diffusion thickness was set to 1mm to approximate the experimental conditions and the highest refinement mesh size was 282$\mu$m.

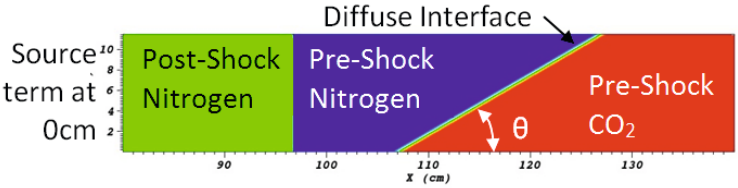

**Fig. 2** Density plot from simulations showing the initial conditions

## 4 Experimental Procedure

The RMI experiments presented here are for A Mach 1.55 accelerated $N_2$ over $CO_2$interface with an inclination angle of 60° ($\eta/\lambda \sim 0.3$). The interface was generated by flowing $N_2$ into the tube from just below the diaphragm and $CO_2$ in from the bottom of the tube and allowing them to vent from the tube at the interface. Fog particles were mixed with incoming $N_2$ in a settling chamber containing a stirring device to ensure fog particles are well dispersed. Flow rates of the $N_2$ and $CO_2$ were measured and set to approximately 8L/min and 3L/min respectively. The tube was allowed to fill for 20 minutes or 3 complete fills, until a uniform fog seeding was attained. The incident shock wave Mach number was set to 1.55 using a 0.03 inch thick polycarbonate diaphragm. The driver was filled with gas to a pressure below its static rupture point. Then a fast acting solenoid boost valve was used to break the diaphragm within 400ms of triggering. The interface valves are closed after the boost valve is actuated and before the shock reaches the test section. A detailed analysis of the impact of valve timing on the interlace was performed to determine the proper timing.

## 5 Results

A time series of processed experimental images obtained using the Mie scattering techniques is shown in fig. 3. The development of three distinct vortices can be seen by time 2.91ms. The secondary and tertiary vortices merge by time 5.09ms. This time is just prior to reshock and shows small Kelvin-Helmholtz (KH) vortices developing on the primary vortex due to the high shear. An image of the interface after reshock shows the interface has inverted and many smaller scale structures have developed which has increased the mixing of the two fluids. The effect of reshock is discussed in detail in the complementary paper presented in this symposium Inclined Interface Richtmyer-Meshkov Instability: Reshock Study. A comparison of simulations and experimental results is presented in fig. 4. The simulation approximates the overall form of the interface well, but shows an interface which is growing faster initially and has a slightly higher bulk velocity. This is likely due to the presence of the suction slots which can reduce the shock strength as it transmits into the $CO_2$. Also, the boundary layers are laminar in the simulation and therefore do not grow as large. These boundary layers can have an effect on the bulk velocity of the interface. Figure 5C shows that the small KH structures were not resolved by the simulation as they require scales below the smallest mesh size. Another distinct difference is that the secondary and tertiary vortices do not merge in the simulations. The merging of these vortices is believed to be a function of the initial departure from a planar interface which was not modeled in the simulation.

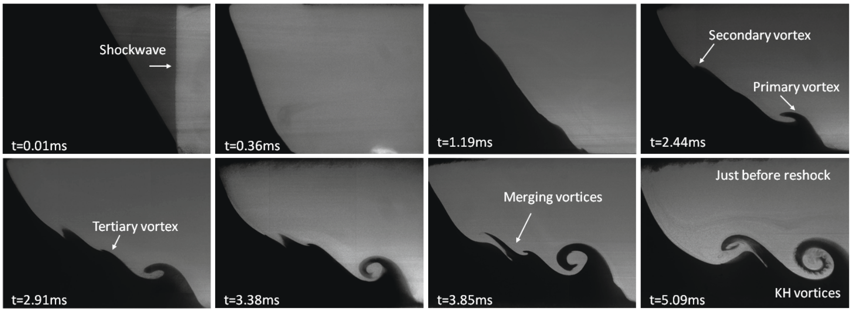

**Fig. 3** Time series of Mie scattering images of the inclined interface RMI

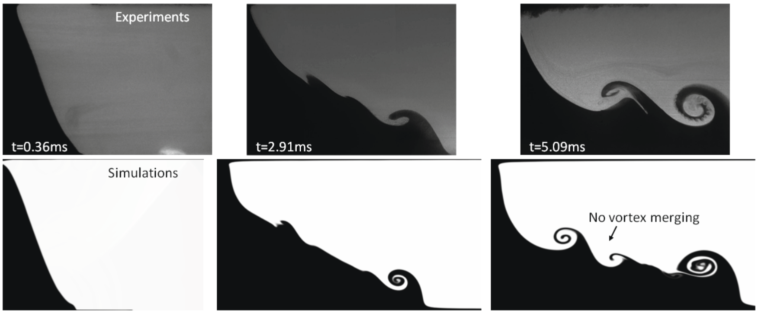

**Fig. 4** Comparison of experimental images and simulation plots. Images are centered at the same location but widths vary to show the full interface in the simulation plots.

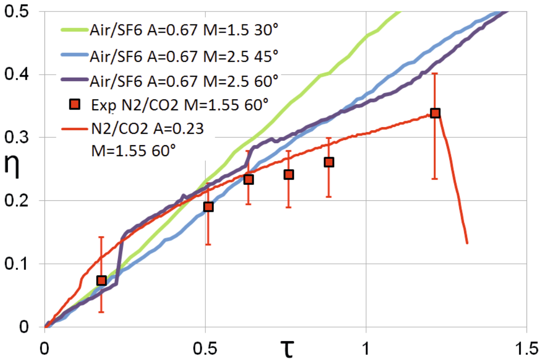

**Fig. 5** Non-dimensionalized mixing width plotted for the experiment, simulation of the experiment, and three other simulation at various Mach numbers (M), and angles (A), for an air over $SF_6$ interface.

The mixing width of the interface was measured as the distance between the 5% and 95% contours of either species. This was accomplished by reducing the experimental images to binary images based on the gradients which located the interface. The average species concentration was then found by averaging the images along the shock tube width at each x location. The mixing width was also measured for the simulation results at a much higher temporal resolution. The mixing widths were non-dimensionalized using the inclined interface scaling method. This method is explained in detail in the authors previous works [6, 7], and in brief, accounts for variation in the Atwood number, inclination angle, and incident shock wave Mach number. The non-dimensional mixing width is plotted for the experiment, and simulation as well as a sample of simulations at a higher Atwood (∼0.67), number, and varying angles and incident shock Mach numbers in fig. 5. This plot shows that the simulation only over predicts the mixing width by a small amount which is within the experimental error. It also shows that the scaling method collapses the initial growth well with the results of the simulation at varying conditions. At late times the growth rates diverge as the interface growth rate asymptotes just before reshock.

## 6 Conclusions

Experimental and computation results were compared for the inclined interface Richtmyer-Meshkov instability at a 60° inclination angle, a Mach 1.55 incident shock wave, and a $N_2$ over $CO_2$ interface (A$\sim$0.23). Analysis of the initial condition over several experiments show a highly repeatable incident shock speed of 542m/s, and interface position. Mie scattering images show the evolution three strong vortices, two of which merge at late times. The primary vortex develops secondary KH instabilities due to its high shear which have never been resolved in simulations before. A comparison with simulations shows that qualitatively the larger flow field is very similar but that the simulations over predict interface speed, and growth, and do not predict the merger of vortices at late time. This is likely due to the departure of the experimental initial condition from the ideal planar interface. Mixing width measurements were made from experiments and simulations and show good agreement between the simulations and experiments on this measurement.

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