# EXPERIMENTAL STUDY OF THE RICHTMYER-MESHKOV INSTABILITY ON INCLINED INTERFACE

An Undergraduate Research Scholars Thesis

by

CHRISTOPHER MICHAEL MCDONALD

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Approved by
Research Advisor: Devesh Ranjan

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Major: Mechanical Engineering

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# ABSTRACT

Perturbed Interface Creation on an Inclined Interface. (May 2013)

Christopher Michael McDonald
Department of Mechanical Engineering
Texas A&M University

Research Advisor: Dr. Devesh Ranjan
Department of Mechanical Engineering

The RichtmyerMeshkov instability (RMI) is a hydrodynamic instability resulting from an impulsive acceleration of a density gradient. This instability was first described in the theoretical work of Richtmyer [2], and later in the experimental work of Meshkov [3]. The two primary ingredients for the RMI are an impulsive acceleration which takes the form of an instantaneous pressure gradient, and a fluid interface which generates a density gradient that is misaligned with the pressure gradient. To further our investigation of the RMI an initial condition experiment needed to be conducted. At the Texas A&M Shock Tube and Advanced Mixing Lab (STAML) there is a Mach 3 capable shock tube, used to study the RMI. It was necessary to study the initial conditions of the interface to understand its effects on the development of the RMI at post-shocked times. From this we were able to determine characteristic flow qualities present on the interface prior to the shock. Within the initial conditions investigation was a qualitative study conducted to determine the vorticity of the interface. The vorticity study was to show how much energy the shock wave deposits, and aid in development of a controlled perturbation of the interface. In the case of the qualitative vorticity study, little was learned due to problems encountered involving Particle Image Velocimetry (PIV) imaging. However, a method for controlled perturbation techniques was discovered involving the flow characteristics at the interface.

# DEDICATION

I dedicate this research to my parents. Without their continued suppport this opportunity would not have been possible.

# ACKNOWLEDGMENTS

I would like to thank Jacob McFarland, and Dr. Devesh Ranjan for there tremendous support and friendship. Their teaching has been paramount to the production of this thesis and my improvement as a student and person.

I would aslo like to acknowledge Tammis Sherman and Dr. Duncan MacKenzie for their support of standardizing the Undergraduate Research Scholars thesis through the use of LaTeX.I would also like to thank Sarat Kuchibhatla for his help with LaTeX.

# NOMENCLATURE

| | |
|---|---|
| RMI | Richtmyer-Meshkov Instability |
| KHI | Kelvin-Helmholtz Instability |
| ICF | Inertial Confinement Fusion |
| RTI | Raleigh-Taylor Instability |
| 2D | Two Dimensional |
| 3D | Three Dimensional |
| STAML | Shock Tube & Advanced Mixing Lab (Texas A&M) |

# CHAPTER I

# INTRODUCTION

The two primary ingredients for the RMI are an impulsive acceleration which takes the form of an instantaneous pressure gradient, and a fluid interface which generates a density gradient that is misaligned with the pressure gradient. The vorticity deposited by the RMI stretches and deforms the fluid interface, increasing the surface area for diffusion, and leading to rapid mixing of the fluids. The amount of vorticity depends on the strength of the incident shock wave and the gradient of the density between the two fluids. The difference between the densities of the fluids is therefore important in predicting the growth of the RMI, and is described by the non-dimensional parameter known as the Atwood number. The Atwood number is a dimensionless density ration of the two fluids. The RMI has become increasingly important in many areas of scientific research such as supersonic combustion, where the RMI can be used to increase fuel and air mixing [4], and stellar phenomena like supernovae, where inclusion of RMI models has been shown to be necessary to accurate modeling of these phenomena [5]. The area where most RMI research is currently being directed toward is inertial confinement fusion (ICF). To further our investigation of the RMI it is necessary gain a greater understanding of the initial conditions present on the interface, and determine a method to perturb the interface in a repeatable manner.

The vorticity deposited by the RMI stretches and deforms the fluid interface, increasing the surface area for diffusion, and leading to rapid mixing of the fluids. The amount of vorticity depends on the strength of the incident shock wave and the gradient of the density between the two fluids. The difference between the densities of the fluids is therefore important in predicting the growth of the RMI, and is described by the non-dimensional parameter known as the Atwood number. The Atwood number is a dimensionless density ratio of the two fluids. The RMI has become increasingly important in many areas of scientific research such as supersonic combustion, where the RMI can be used to increase fuel and air mixing

[4], and stellar phenomena like supernovae, where inclusion of RMI models has been shown to be necessary to accurate modeling of these phenomena [5].

This experiment will allow us to further study the RMI, which arises when a shock wave interacts with an interface separating two different fluids. Any perturbation present on the interface will be amplified following the refraction of the shock. The mechanism for the amplification of perturbations at the interface is baroclinic vorticity generations resulting from the pressure gradient of the shock wave and the density gradient of the two gases on either side of the interface [6]. A key element of this project will be the controllability and repeatability of the perturbations of the interface. Without the ability to reproduce or make measurable alterations the relationship between the induced perturbation and the resulting baroclinic vorticity generations will be difficult to distinguish. Controlled perturbations of the interface increase the surface area of the interface exposed to the shock front. It seems reasonable to assume the increased surface area will lead to greater mixing of the fluids.

The mixing width, the region that lies between 5 and 95 percent contours of the mole fraction, is the length of the interface at time, t, after the shock wave has struck the interface is a method of measuring the extend of mixing used by many experimentalists studying similar phenomena. The perturbation will likely increase the shear stresses experienced by the interface leading to a greater mixing width. In ICF, the fuel target interfaces, such as the interface between the ablative outside layer and the frozen DT fuel [7]. The RMI causes mixing causes mixing between these layers which reduces the temperatures and pressures achieved in the fuel target and lowers the fusion yield [6]. The interface perturbation studies will aid our understanding of the issues surrounding fusion.

# CHAPTER II

# METHODS

## Experimental Design

The shock tube at the Texas A&M University STAML facility measures approximately 9 meters long with a 11.4 cm square cross-section. The shock wave is generated by rupturing a diaphragm with high pressure one side (referred to as the driver section) and atmospheric on the other. The shock wave is then allowed to travel approximately 7.5 meters to develop a planar shock front. This planar shock development segment is referred to as the driven section. The shock wave then enters the bottom of the driven section referred to as the test section of the tube, a 2 meter section with windows positioned as desired to capture the appropriate image. Figure II.1 may be seen to show the sections of the shock tube.

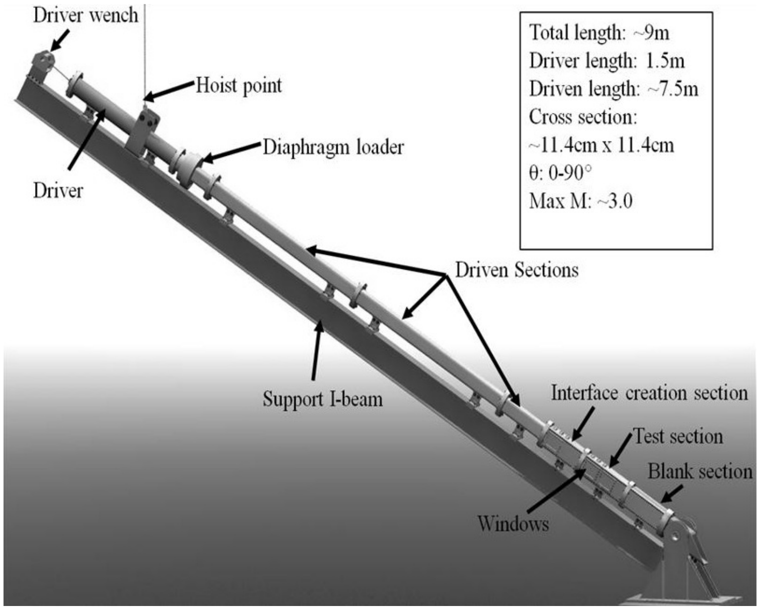

Fig. II.1.: Display of the STAML shock tube courtesy of Jacob McFarland.

The tube is designed to study the result of a shock wave traveling through a fluid interface of two gases. One of the key features of the shock tube is its variable inclination capability, which causes the misaligning of the density and pressure gradients; density referring to the interface of the two gases, and pressure referring to the shock front. The valves are positioned so that when the tube is at 60 degrees the valves are perfectly horizontal, so the interface may use gravity to become less diffuse, instead of being perturbed by it, causing an unrepeatable perturbation. This misalignment may be viewed in Figure II.2. In our current setup, nitrogen is used in the driver section to burst the diaphragm, and in the driven section very near atmospheric pressure. The nitrogen in the driven section is infused with glycerin smoke, referred to as fogged nitrogen so that it may be seen in the images captured in the experimental section. The fogged nitrogen enters the driven section through a valve located near the diaphragm loader, whereas the carbon dioxide enters through a valve located at the bottom of the tube in the test section. Only a small part of the experimental section is filled with the fogged nitrogen, with the rest being filled by carbon dioxide. The two gases meet, or interface, at a chosen location determined by the positioning of two gas exit valves, where the gases are allowed to freely exit creating a flat interface, also seen in Figure II.2. The fogged nitrogen is illuminated by a laser plane entering the through the bottom of the shock tube through the unseeded carbon dioxide.

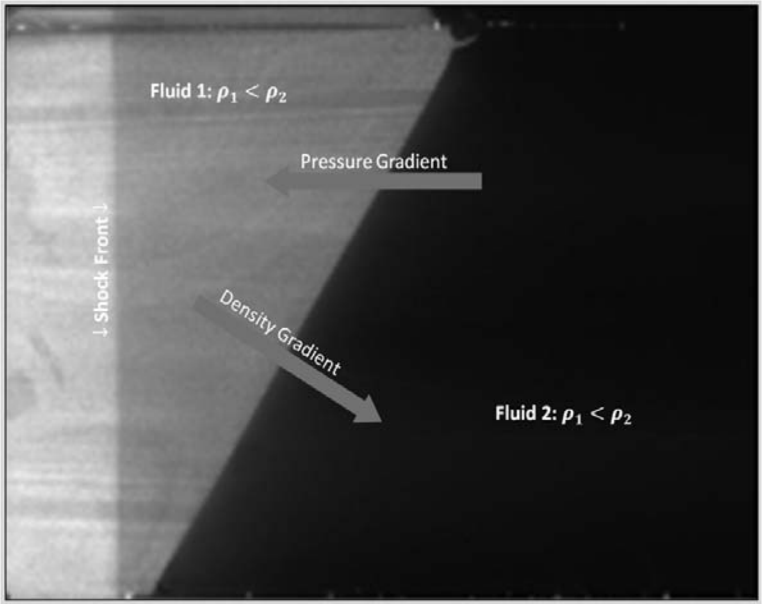

Fig. II.2.: Image of the shock wave front just before it interacts with the interface, highlighting the misalignment of the pressure and density gradients.

Figure II.2 also shows the planar shock front. When the shock front interacts with the interface it passes straight through, at approximately Mach 1.6 with the current experimental setup. At those supersonic speeds the effect experienced by the shock wave as it travels through the interface is infinitesimal, and therefore considered zero. The interface however, is instantly accelerated to 250 m/s, and begins to mix. At a window positioned further down the test section, an image is captured showing the development of the interface. An example of such an image may be viewed in Figure II.3.

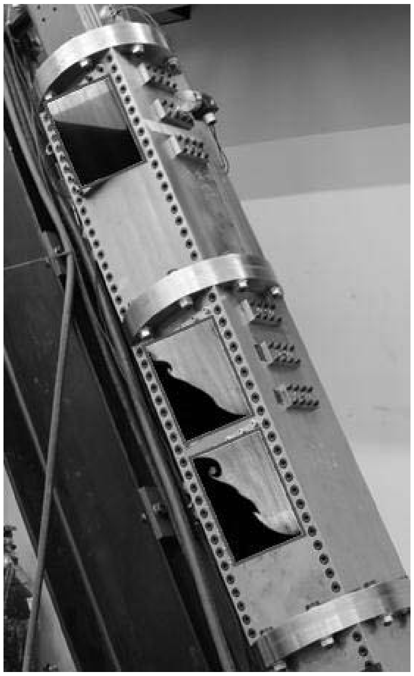

Fig. II.3.: Displays the progression of the interface right before the shock wave interacts with the interface at t=0 s, at t=2.51 s, and t=3.42 s.

In Figure II.3, the procession of images displayed were captured from three different experiments and placed in their current arrangement as a visual to display the progress of the interface as it develops. Assuming the top image of the shock front is time zero, the middle image is captured at 2.51 ms, and the last image at 3.42 ms.

The images in Figure II.3, were taken with a PLIF camera using the mie-scattering technique. For the initial conditions study, a PIV setup was necessary. PIV is an optical method of flow visualization to obtain velocity measurements. A PIV setup measures the velocity of tracer particles, in this case the tracer particles were the fog in the nitrogen, by taking two images very close together. The nitrogen entrained with the fog is illuminated to illuminate the particles. The motion of these particles from one image to the next is used to calculate the speed and direction of the flow. The time between these two images was 2 s, which was determined by a PIV rule of thumb calculation based on the velocity of the interface.

## Problem

Much of the RMI research being done today is done for the continued development of ICF technology. Laser technology has finally reached a point where generating the energy required for ignition is no longer an issue. What remains to be refined is the sustainability of the reaction. Fluid instabilities within the reaction arise causing premature energy dissipation before the critical temperature is reached. Among these instabilities are the RMI and the KHI. The shock tube at the STAML facility is on the forefront of RMI variable inclination research. The inclination of the shock tube is one type of perturbation that may be induced. However, the production of a second perturbation on top of the inclination is necessary to advance the fields scope. When the hydrogen isotopes that make up the fusion fuel pellet in an ICF reaction are ignited, many perturbations are present in the chaotic reaction that ensues. The closer the STAML shock tube can mimic those perturbations, the sooner a solution to the fusion problem will be reached. By studying the initial conditions the present on the interface pre-shock and post-shock the amount of vorticity deposited by the shock wave may be calculated.

To study the initial conditions of the interface to understand its effects on the development of the RMI at post-shocked times, in was necessary to develop a PIV imaging system capable of producing adequate seeding, achieving high quality image resolution, and accurate determinations of time between the two captured PIV images. The foremost of these, adequate seeding, provided the most difficulty. The fog is produced by a fog machine through which nitrogen flows, from glycerin. The fogged nitrogen is then made uniform in a mixing chamber before it enters the shock tube. There was a delicate balance that had to be struck to qualify the seeding as adequate. If the seeding was too dense, the PIV analysis yielded few vector results, unable to distinguish between tracer particles. If the seeding was not dense enough, the PIV analysis was not able to differentiate between the carbon dioxide and the nitrogen sides of the interface, yielding incorrect vectors. Achieving high image resolution in a PIV sense refers to the general focus of the camera as well the cameras ability to distinguish tracer particles capable of creating a quality PIV image. Determining the appropriate time was an iterative process. During the initial condition study prior to the passing shock, the flow was slow enough to develop a delta that was appropriate for the flow speed after several PIV processing trials. The post-shock initial condition time was determined by using the pre-shock to post-shock flow velocity ratio.

# CHAPTER III

# RESULTS

## Intial Conditions

The pre-shock initial conditions describe the state of the interface prior to interacting with the shock wave. A sequence of 20 images was captured, each separated by 100 ms. As seen in Figure III.1, the flow of the fogged nitrogen may be observed flowing out of the two valves located, in this orientation, at the top and bottom of the figure where the fogged nitrogen meets the carbon dioxide (the carbon dioxide is not seen because it does not have tracer particles). To align with the statement in the experimental setup, Figure *** was rotated 60 degrees clockwise during the actual experiments.

The intensity of the fogged nitrogen per pixel is approximately 267 according to Insight 3G, whereas the carbon dioxide is approximately 47. This is a decent representation of a favorable intensity ratio, resulting in a decent PIV vector density. It may be noted that the flows velocity was determined to be 0.85 cm/s on average. Within the image you may notice a structure in the top of the picture. This is due to the changing of diaphragms, which allows air to mix with the fogged nitrogen. It is a problem that is typically solved by allowing the air to be pushed down the tube and out the interface valves. At the same time the fog density was increasing over time. However, challenges faced during the PIV setup, referred to earlier, made it difficult to obtain adequate fog density forcing sometimes premature image sequences to be taken before the structures dissipated. This was done in order to capture the appropriate tracer density of the fogged nitrogen.

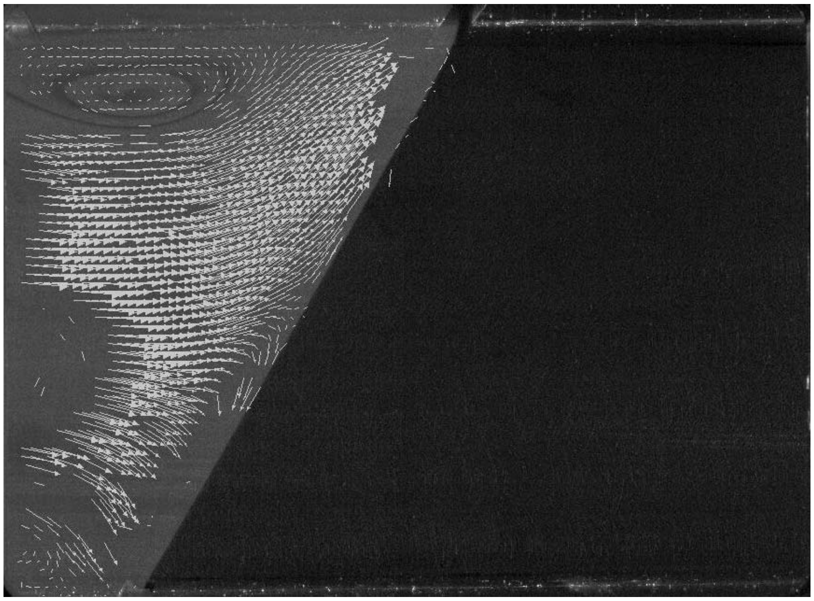

Fig. III.1.: PIV image of the pre-shock initial conditions before the interface valves are closed, 200 ms after the shock wave program has been initiated.

In Figure III.1, the elapsed time 200 ms as compared to Figure III.2, taken at 600 ms. The sequence of images was started with the same program, altered of course, as used when shock wave experiments are ran. From analysis of the shock wave program, it was determined that the interface valves closed at approximately 325 ms after the beginning of the imaging sequence. The valves close immediately before the shock wave passes them in order to keep the system closed. It may be seen in Figure III.2 that the interface valves have closed by noticing the small structure developing at the top valve.

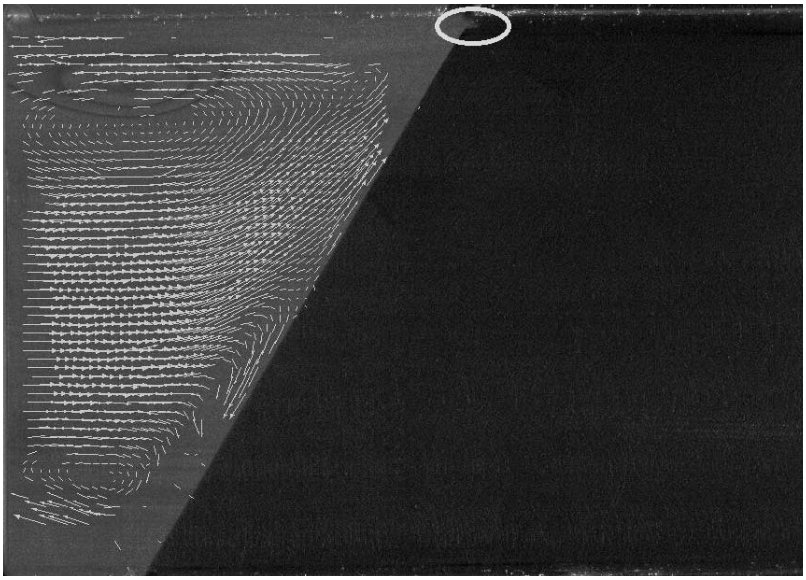

Fig. III.2.: PIV image of the pre-shock initial conditions after the interface valves are closed, 600 ms after the shock wave program has been initiated.

It was important to understand how the interface develops after the valves closed, so that the timing could be refined, closing the interface valves later, closer to the passing of the shock wave. By decreasing the time between the closing of the valves and the passing of the shock wave, the interface had less time to develop unwanted perturbations. Though perturbations are, as mentioned before, an area of interest, they are not wanted when they are not being sought.

## Vorticity

To determine the vorticity deposited by the interface, PIV images at the interface are needed pre-shock and post-shock. Using an image processing software such as MATLAB the image may then be processed to determine the vorticity in each. By finding the difference between the post-shock and pre-shock vorticity, the vorticity deposited by the shock wave is known. The determination of vorticity from an image is heavily dependent on the quality of the PIV vectors obtianed from experimentation, which has many difficulties as discussed earlier in the Problem section. Figure III.3 clearly demonstrates the issues had with the PIV system.

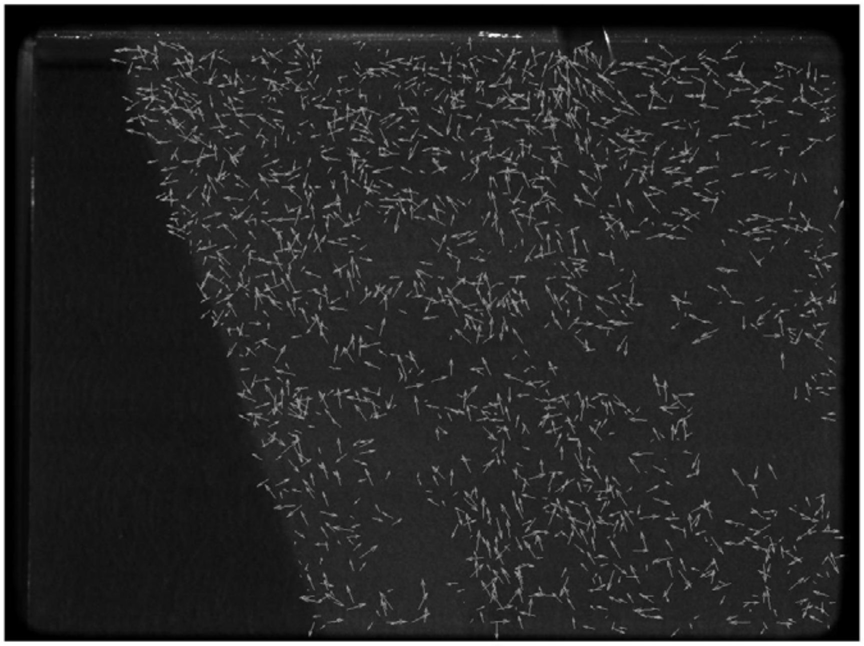

Fig. III.3.: PIV image of the post-shock initial conditions after the interface valves are closed and the shock wave has passed, 0.68 ms after the shock wave passed the dynamic pressure transducers located 15 cm before the interface.

Lack of adequate seeding results in a low quality PIV image as seen in Figure III.3. The intensity readings for an image such as Figure III.3 are not favorable only showing a light to dark ratio of 2. When the light to dark ratio is not above 2, the PIV vectors have a difficult time determining the appropriate direction. An example of a quality PIV image may be seen in Figure III.4.

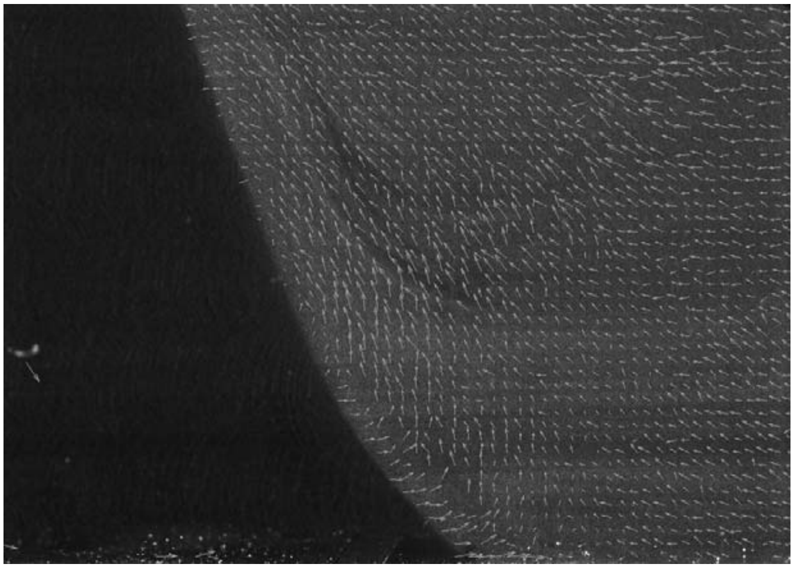

Fig. III.4.: PIV image of the post-shock initial conditions after the interface valves are closed and the shock wave has passed, 0.68 ms after the shock wave passed the dynamic pressure transducers located 15 cm before the interface.

In images such as Figure III.4, the light to dark ratio is approximately 3 to 4, as mentioned earlier in the Initial Conditions. Future work will improve the PIV system,, and develop vorticity models, and also increase the repeatability of PIV imaging as shown if Figure III.4.

### Perturbations

The images of the initial condition interface after closing the interface valves revealed a backflow out of the valves seen earlier in Figure III.2. The backflow is identified by the structure forming at the top interface valve. The PIV vectors at the top and bottom no longer reach into the interface valves, but instead they circulate away from the interface following the same circulation that was present in Figure III.1 before the interface closed. Notice how the vectors in Figure III.2 close to the interface remain parallel to the interface and the interface as well maintains a linear trend. In Figure III.5 however, the vectors now appear to be directed into the interface and the interface also appears to resemble a sinusoidal function.

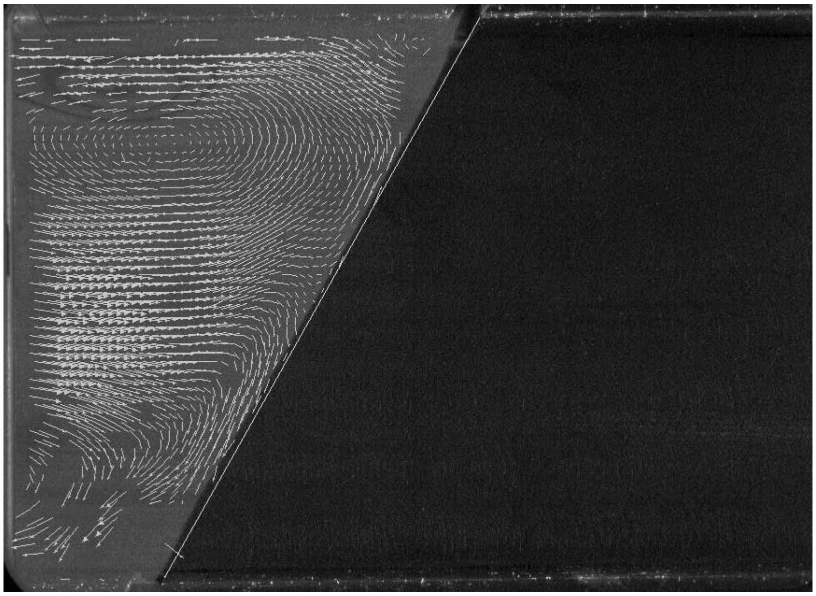

Fig. III.5.: PIV image of the pre-shock initial conditions after the interface valves are closed, 700 ms after the shock wave program has been initiated. The line along the interface serves as an aid to see the perturbations developing.

As the sequence continues on to 900 ms, as seen in Figure III.6, the backflows develop their own circulation on the interface, causing continued perturbations following a sinusoidal pattern. Therefore, this preliminary test shows it may be thought that the two backflows created at the top and bottom interface valves act as two waves traveling along the interface traveling with an initial velocity approximately equal to that of the flow that was exiting right when the interface valves closed.

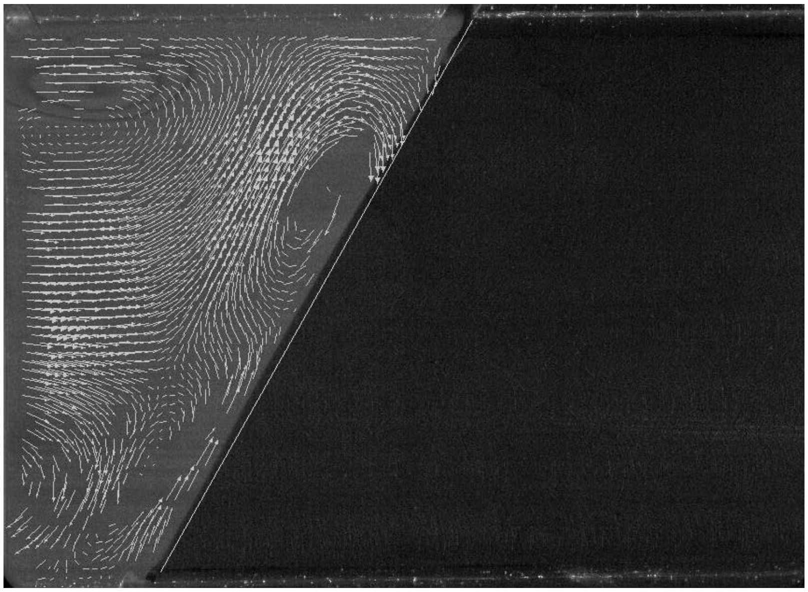

Fig. III.6.: PIV image of the pre-shock initial conditions after the interface valves are closed, 900 ms after the shock wave program has been initiated. The line along the interface serves as an aid to see the perturbations developing.

# CHAPTER IV

# CONCLUSIONS

The pre-shock initial condition images provided insight to the flow characteristics of the interface prior to the passing of the shock wave. The refined understanding of the pre-shock interface will result in better experiments in the future, with the knowledge that the interface began to show signs of deformation within 300 ms of valves being closed. Continued observation revealed a sinusoidal pattern to the deformation of the interface as time went on. Using the PIV images taken just before the interface valves closed, the velocity at the exits may be calculated, and a period established for a cyclical opening and closing pattern to the interface valves. Continuous opening and closing could sustain and even increase the amplitude of the sinusoid on the interface.

The initial conditions investigation was meant to entail a qualitative study to determine the vorticity deposited by the shock wave on to the interface. Due to PIV growing pains little was learned. Furture work in this area will entail a revamping of the particle tracer infusing system, further study on the appropriate displacement of the camera from the interface window, and continued work on refining the laser system.

Future perturbation work at the STAML facility will seek to determine a dynamic model for consistent and repeatable interface perturbation techniques for predicting the multi-mode perturbations that become more prevalent on the interface of the two gases. This model will help us develop new experimentation techniques for the study of the RMI .

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# APPENDIX A

# ADDITIONAL INITIAL CONDITIONS IMAGES

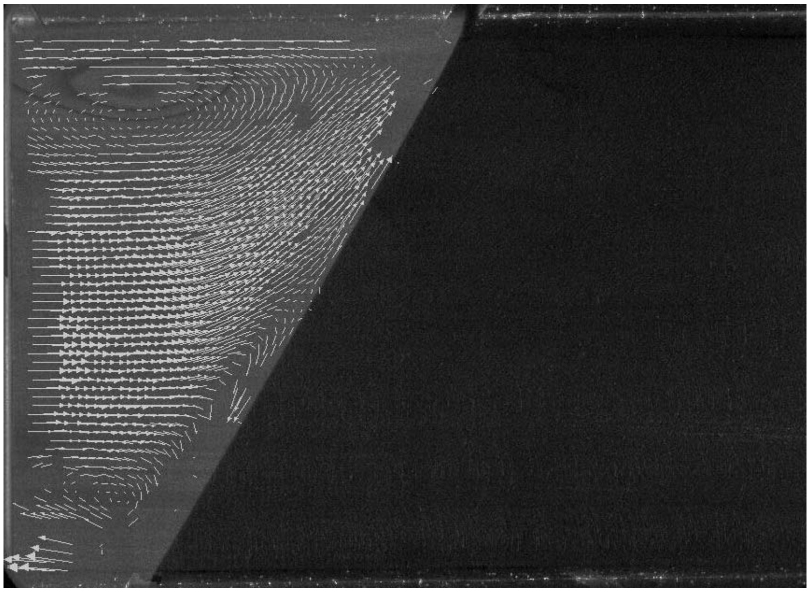

Fig. A.1.: PIV image of the pre-shock initial conditions after the interface valves are closed, 400 ms after the shock wave program has been initiated. The line along the interface serves as an aid to see the perturbations developing.

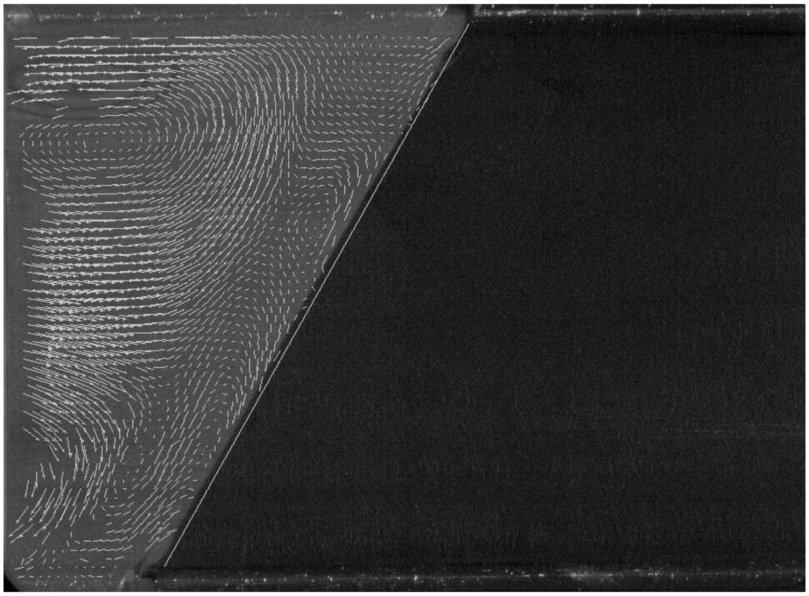

Fig. A.2.: PIV image of the pre-shock initial conditions after the interface valves are closed, 1400 ms after the shock wave program has been initiated. The line along the interface serves as an aid to see the perturbations developing.

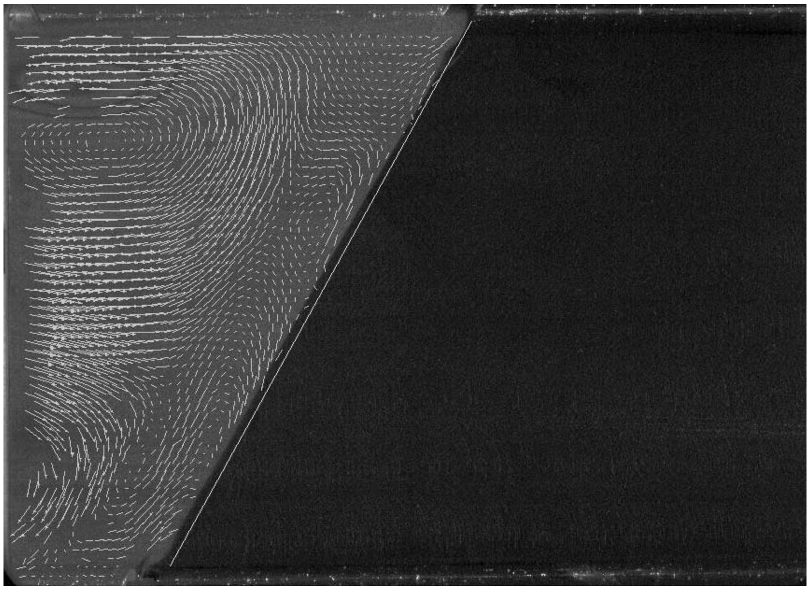

Fig. A.3.: PIV image of the pre-shock initial conditions after the interface valves are closed, 1900 ms after the shock wave program has been initiated. The line along the interface serves as an aid to see the perturbations developing.