Shock tube Richtmyer-Meshkov experiments: inverse chevron and half height

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Abstract

This paper reports results from two Richtmyer-Meshkov instability (RMI) shock tube experiments. The first features an inverse chevron perturbation and the second consists of a half height dense gas region.

The experiments were conducted on the AWE's 200 x 100 mm shock tube with a shock Mach number of 1.26 (70kPa overpressure). Both configurations involved a three zone test cell arrangement of air / dense gas / air all initially at atmospheric pressure. Using sulphur hexafluoride (SF_6) as the dense gas yielded an Atwood number of 0.67. Gas separation was by means of profiled windows and fine wire meshes supporting microfilm membranes. Visualisation of the mixing was by laser sheet illumination of the dense gas seeded with an olive oil aerosol. A pulsed laser allowed a drum camera to record over 50 images of the mixing process augmented by an Intensified CCD (ICCD) camera capturing a single image per experiment.

The inverse chevron was on the downstream membrane with a central obtuse angle of 157° and amplitude 20mm. This is complimentary to the chevron presented at the previous workshop (Smith et al., 2001) and is related to the inclined interface experiments initiated at the 5th meeting of this workshop (Bashurov et al., 1995).

The half height experiment was significantly different from previous experimental configurations which involved perturbations on otherwise plane interfaces. In this case the central, dense gas region of the test cell was filled to halfway (100mm high) with seeded dense gas. The interfaces to either side feature microfilm membranes and were plane, whereas the top interface was membraneless and is nominally plane. This then introduced a Kelvin-Helmholtz instability to the experiment.

Sample laser sheet images from each experimental configuration are compared to corresponding code images from the AWE TURMOIL 3D LES model. A qualitative comparison between experimental and code images is presented. Quantitative analysis in the form of line-outs through both sets of images are included and substantial agreement on large scale features is demonstrated.

A time sequence is included on this proceedings CD/DVD for each experiment to allow improved visualisation of the mixing history.

Introduction

This paper reports some of the latest results from the AWE linear shock tube programme of mix experiments, the inverse chevron and half height experiments. A brief description of the each experiment is given. Sample results from each are reported and compared with results from the TURMOIL 3D code and some sample analysis data is included. Some conclusions are drawn from the work and future work is proposed.

The AWE shock tube is a 200 x 100 mm rectangular shock tube which can achieve a maximum shock overpressure of about 230kPa which gives a shock Mach number of 1.73. In these experiments a 70kPa overpressure shock with Mach number 1.26 was used.

Inverse Chevron Experiment

The inverse chevron was a Richtmyer-Meshkov experiment investigating the mixing at both interfaces of a dense gas region bounded on either side by air. A large perturbation was added onto the downstream interface of a dense gas region. The perturbation amplitude was 20mm offset by 10mm so as to maintain the same volume of dense gas as in the unperturbed case, see figure 1. The perturbation stretched across the whole width of the shock tube making the experiment essentially 2D 'on average'. The dense gas was sulphur hexafluoride giving an Atwood number of 0.67 for the experiment. The SF_6 was constrained, prior to shock arrival, by the use of microfilm membranes supported on fine wire meshes. The meshes on both interfaces were made from horizontal and vertical 25µm wires with 4mm spacing giving a total flow blockage of 1.25%.

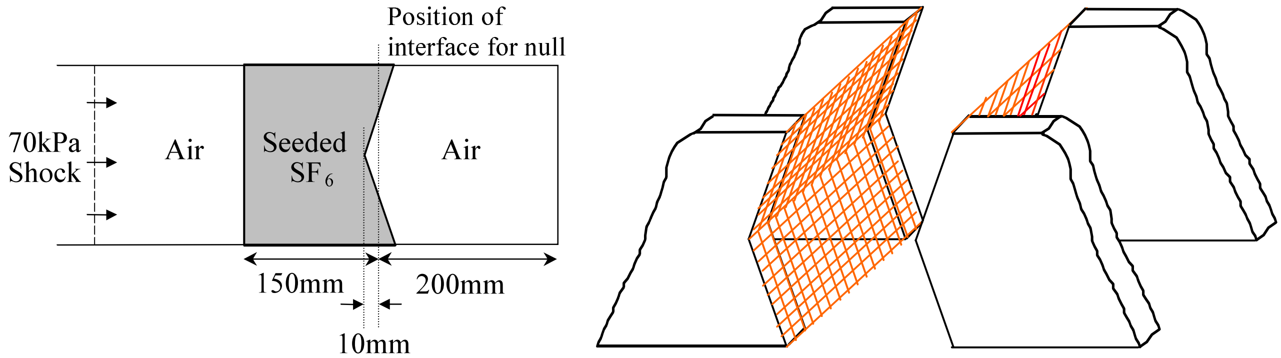
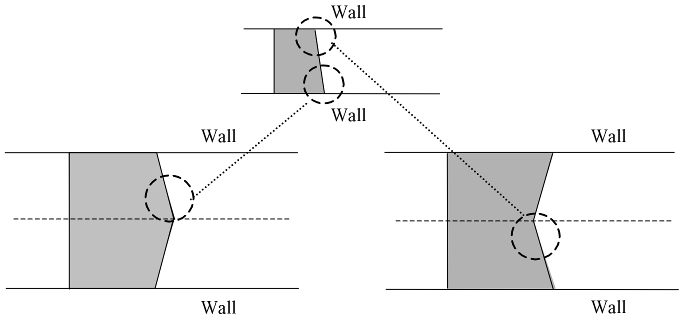


Figure 1. Schematic of inverse chevron perturbation and illustration of wire mesh formation.

The Chevron experiments (Smith et al., 2001) were conceived as a progression of the work of Meshkov et al (Bashurov et al., 1995) on an inclined interface experiment presented at a previous meeting of this workshop and subsequently used as a test problem. Taking advantage of a larger shock tube the inverse chevron and the previous chevron perturbations use a plane of symmetry to remove the constraining effect of one wall, figure 2.



Previous Work Current Work

Figure 2. Illustration showing the inclined interface (top), the previous, chevron, work (bottom left) and the current, inverse chevron, work (bottom right).

Figure 3 illustrates the test cell and diagnostics as set-up for an experiment. The shock entered from the left. A pulsed laser was used to form a sheet, approximately 2mm wide and the full height of the test cell, which entered through a transparent window in the end plate of the test cell. Membrane A and B constrain the SF_6 and separate it from the air. The SF_6 was seeded with an olive oil aerosol to scatter the laser sheet illumination into a camera set at 90° to the test cell. Both electronic and film cameras were used.

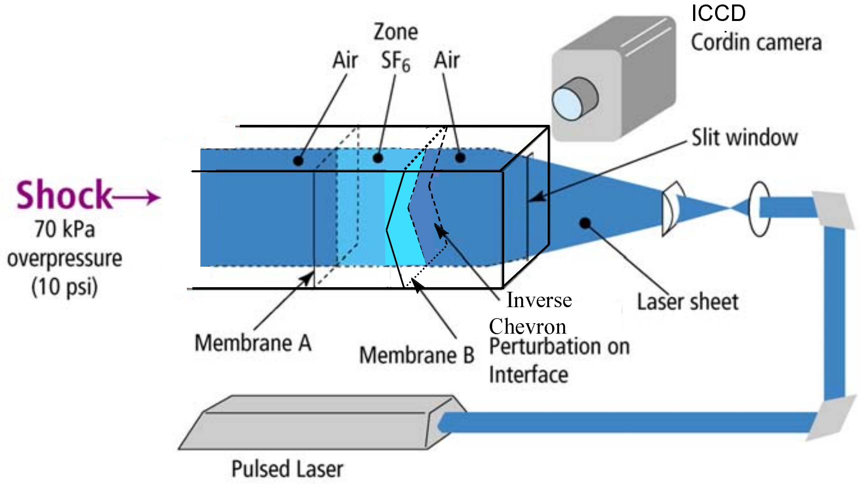


Figure 3. Schematic of experimental set-up.

TURMOIL 3D

The aim of this work was to further the understanding of turbulent mixing and to validate David Youngs' TURMOIL 3D mix model. TURMOIL is a semi-Lagrangian Large Eddy Simulation where the x-direction mesh moves with the mean fluid velocity. The test cell was modelled by 20.10^6 cells; 400 x 320 x 160 (length: height: depth), shown in figure 5. A random initial perturbation, wavelength 0.5 to 5cm and RMS amplitude 0.01cm, was applied to the air / SF_6 interfaces to provide an initial seeding condition and to simulate the effects of the meshes.

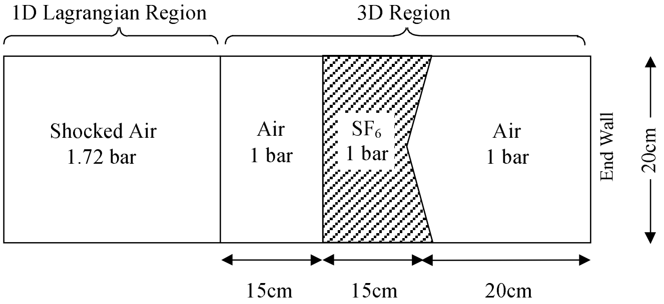


Figure 5. Illustration of the initial conditions for the TURMOIL 3D simulation.

Comparison

Figure 6 shows a qualitative comparison between experimental images and results from the TURMOIL 3D. The code results, as previously reported (Holder et al, 2003), have been post processed with a Monte Carlo code to include the effects of multiple scattering. The images on the left of figure 6 are eight sample experimental images from the 50 images recorded in a single experiment. The first image shows the initial conditions with the perturbation defined by the membranes. On shock arrival the upstream membrane is fragmented. At 0.5ms after shock arrival at the upstream membrane the shock is approximately half way through the dense gas region. The shock progresses through the dense gas compressing it and exits into the air. It reflects from the end wall at around 1.3ms at which time phase inversion of the perturbation has produced an almost plane interface. At 1.9ms the reflected shock is passing back through the SF_6 and the perturbation has inverted to a chevron with the beginnings of a central dense gas jet visible. At 2.2ms the jet is growing and air voids are forming along the top and bottom walls. These features all continue to grow and at 4.0ms, the end of the experiment, the central jet has impacted the end wall and flattened out along it and the air voids are close to breaking through into the upstream air region.

There is very good agreement in the shock position for both the incident and reflected shocks. At 1.3ms the growth of the central jet is in good agreement as it is at 1.9ms. Good agreement is also seen in the later time images with the size and position of the dense gas jet and the air voids which are pushing back into the dense gas. At 4ms the shape and size of the jet and air voids agree well.

The 50 images from a single experiment can be put together to form a time sequence (available on this proceedings CD/DVD) to enable improved visualisation and understanding of the mixing occurring in the experiment. As in all images in this presentation the shock enters from the left and the laser sheet from the right.

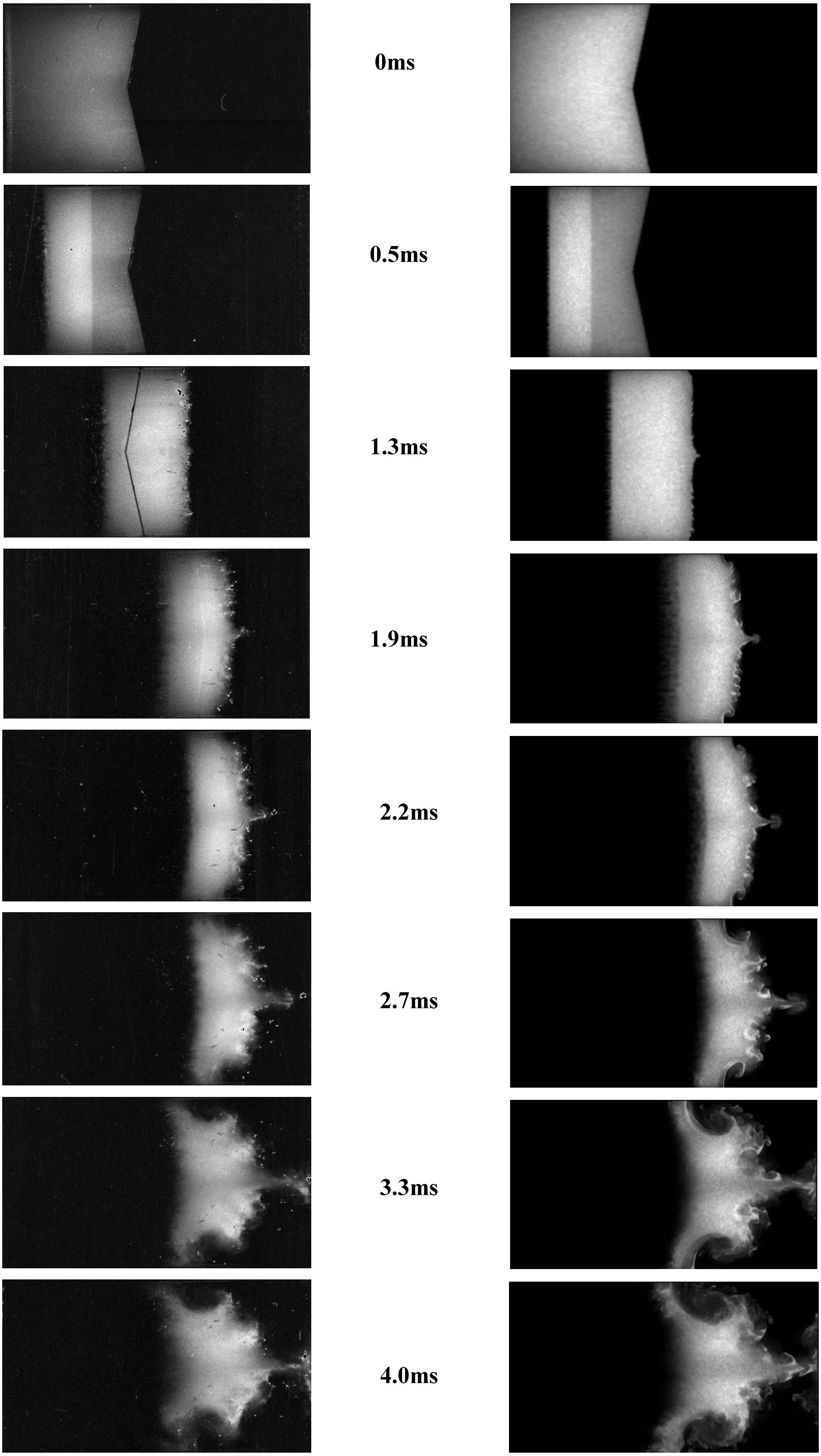


Figure 6. Sample results for experiment (left) and code (right).

Figure 7 shows a sample of the analysis carried out on the experiment and code images. It involved taking and comparing several lineouts for each image. Included is an Intensified CCD (ICCD) image to illustrate the difference and improved agreement between the ICCD experimental images and the code due to the improved resolution and dynamic range of digital cameras over film. Most notably it can be seen that the upstream boundary of the dense gas region in the film image is at approximately 200mm whereas in both the code and ICCD images it is at around 175mm. There is generally a good agreement in size and position of features in all the frames analysed.

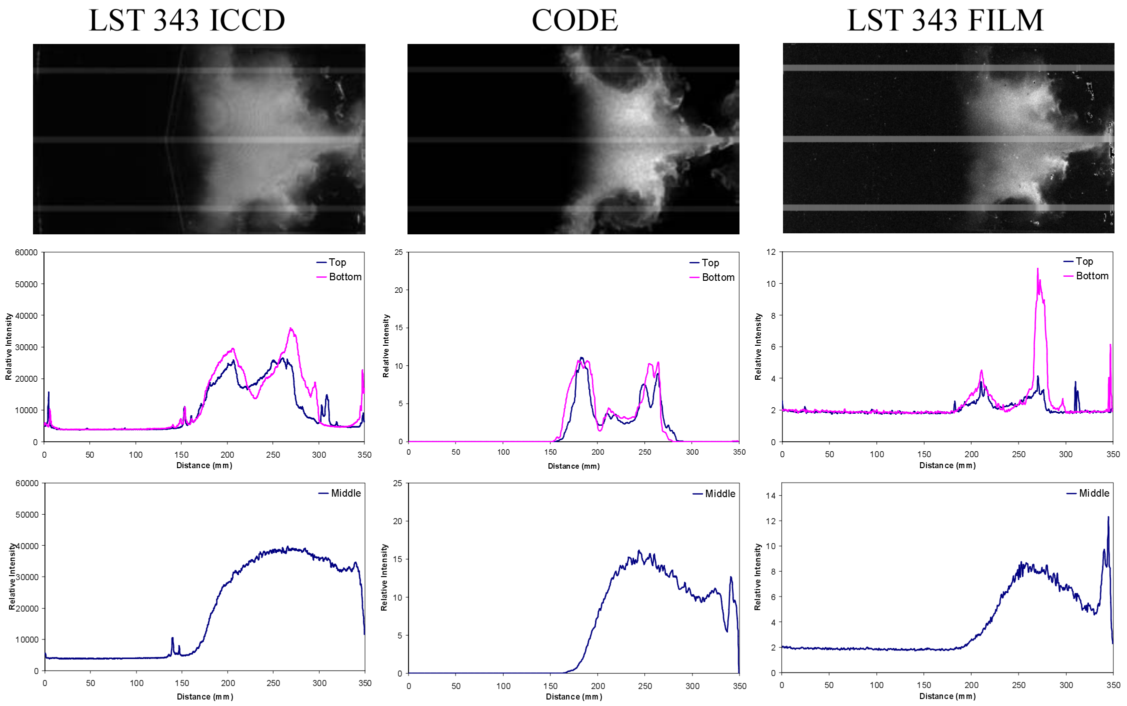


Figure 7. Sample analysis at 4.0ms for the inverse chevron.

Half Height Experiment

Figure 8 shows a schematic of the half height experiment, which differs from the usual perturbed interface experiments conducted on the shock tube. Here the dense gas region only extended to half the height of the test cell with a membrane-less horizontal interface. As the shock passes through the air above the SF_6 there is a Kelvin-Helmholtz instability across the horizontal interface superimposed on the Richtmyer-Meshkov instability across the to vertical interfaces. Otherwise the general experimental set-up is the same as shown previously in figure 3.

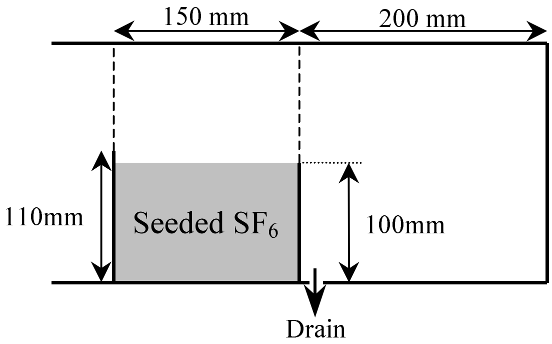


Figure 8. Schematic of half height set-up.

To achieve a half height gas fill and complete drainage of excess gas the upstream membrane was 110mm high and the downstream 100mm, thus all the excess dense gas from purging fell into the end section and hence out the drain hole. The drain hole (7mm by 80mm) was left open throughout the experiment, but is considered to have had little effect on the mixing process.

TURMOIL 3D

Again this experiment is used to validate the TURMOIL 3D code. This was set-up as before, however here there were more horizontal zones to accommodate the gas regions extra travel. Thus zoning in the 3D region was 640 x 320 x 200.

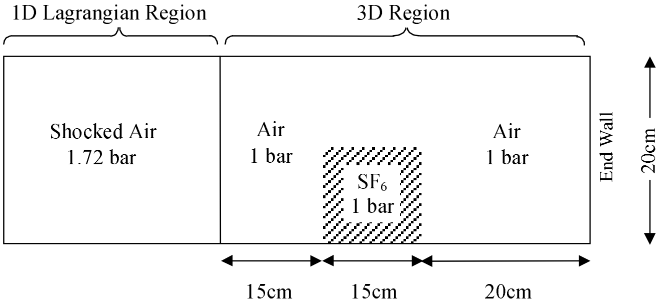


Figure 9. Illustration of the initial conditions for the TURMOIL 3D simulation.

Comparison

Figure 10 shows some sample results from a single experiment compared with the equivalent results from TURMOIL 3D, again the code results have been post-processed to include multiple scattering effects. The first four frames show the shock progression. The shock velocity in the air is approximately twice that in the SF_6 hence the shock in the air races ahead creating the Kelvin-Helmholtz shear and forming a diagonal shock which propagates down into the dense gas as seen in the illustration, figure 11. The upstream corner of the dense gas is dragged up and pulled along rolling up into a vortex caused by the flow behind the air shock. This comparison shows very good agreement for these first four frames in both shock position and extent of the curl on the upstream interface (if one allows for the slight time discrepancies).

When the air shock passes over the downstream interface position a similar vortex is created there. Due to the presence of three components of the incident shock and the diffraction of the air shock around the dense gas region there is no single reflected shock, but a multitude of shocks reverberating around the test cell. Hence the next four frames are taken at the arbitrary times of 1, 2, 3 and 4ms. A gross overturning motion and general lifting of the dense gas region is clearly evident and the SF_6 is lifted to the full height of the test cell at 3ms. A number of vortices are also evident but these are better defined in a time sequence of the images from a single experiment which highlights the vortices and the main swirling, overturning motion. Good agreement is achieved in these later frames with position and shape of the bulk gas region. Also close agreement is achieved in the general form of the smaller scale features especially the form of the large curl over and the mushroom jet at the bottom. However the code shows the mushroom shaped dense gas jet to be angled upwards while the experiment is not – this could be due to the drain hole being left open.

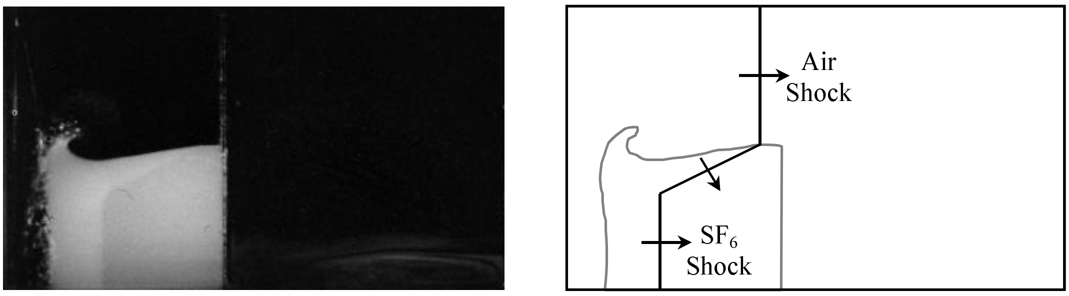


Figure 11. Experimental image and illustration of shock positions at 0.4ms.

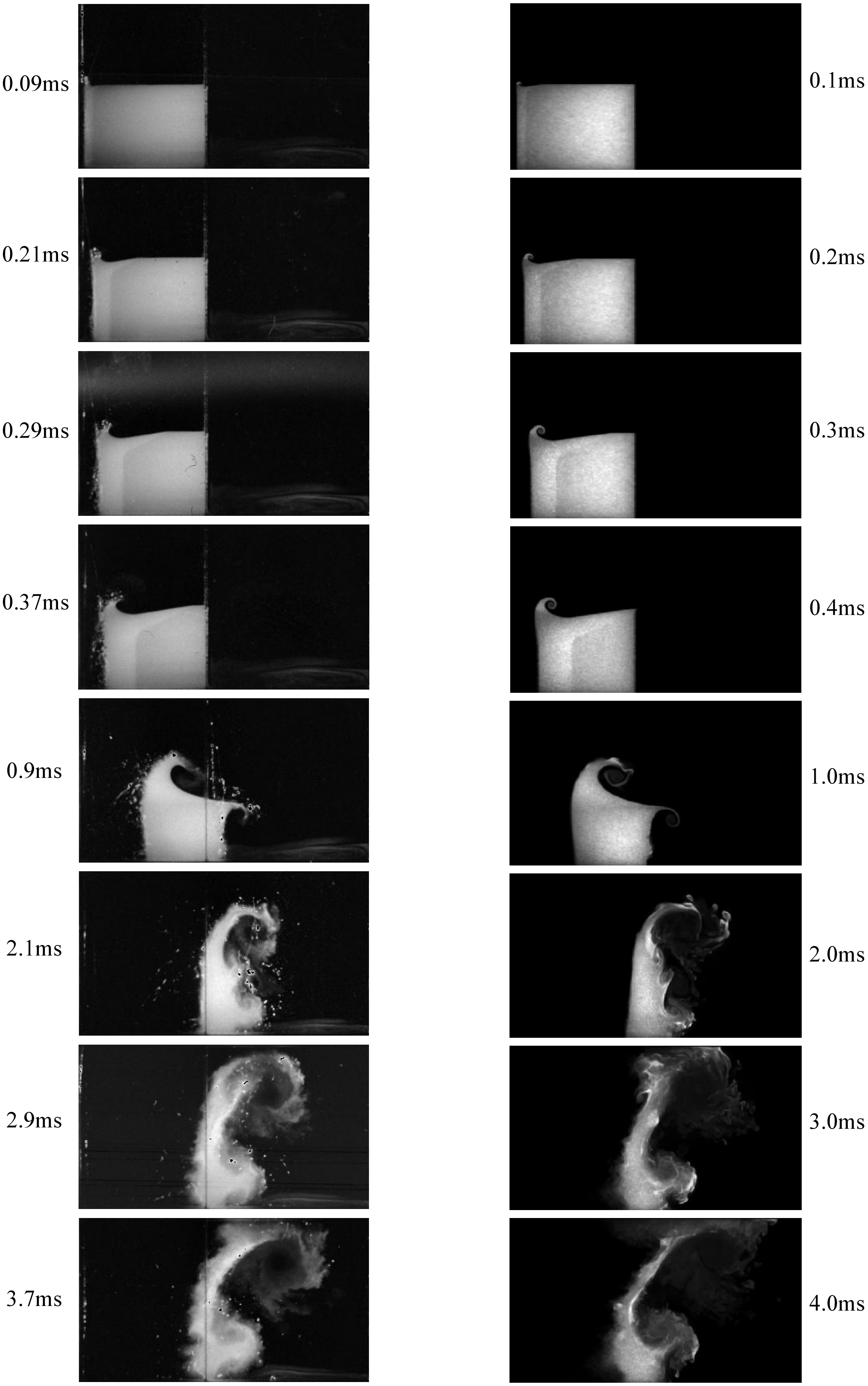


Figure 10. Sample results for experiment (left) and code (right).

Sample Analysis

Some sample lineouts, figures 12 and 13, illustrate the good agreement in modelling the experiment in size and position of the bulk gas region. However a slight discrepancy can be seen in the definition of the incident shock in the code when comparing the lower two graphs in figure 12. This suggests that we are not accurately modelling the multiple scattering with our Monte Carlo code. This is currently being investigated.

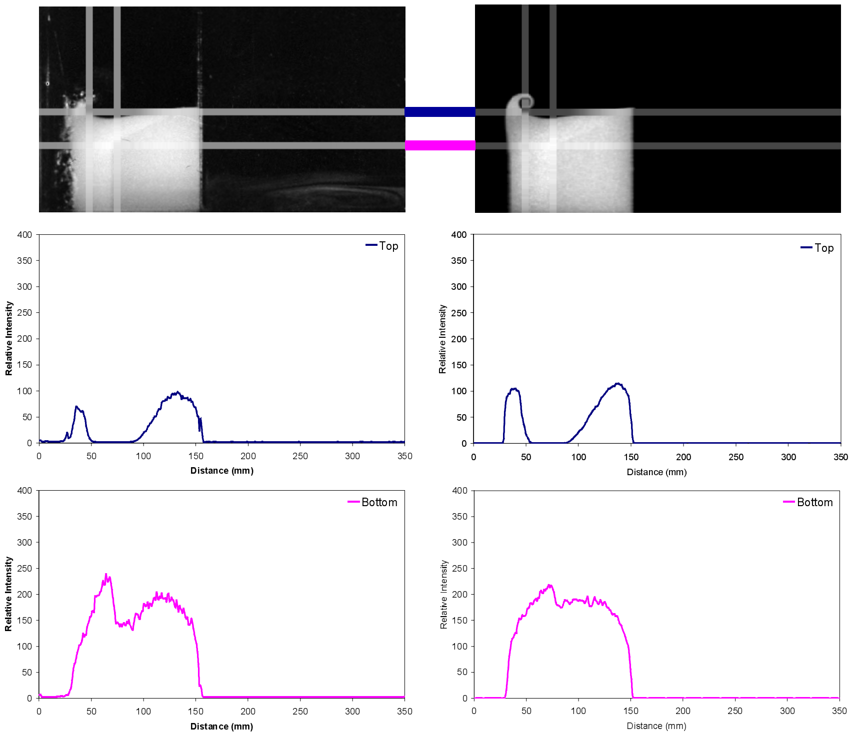


Figure 12. Lineout analysis for the half height experiment (left) and code (right) at 0.4ms.

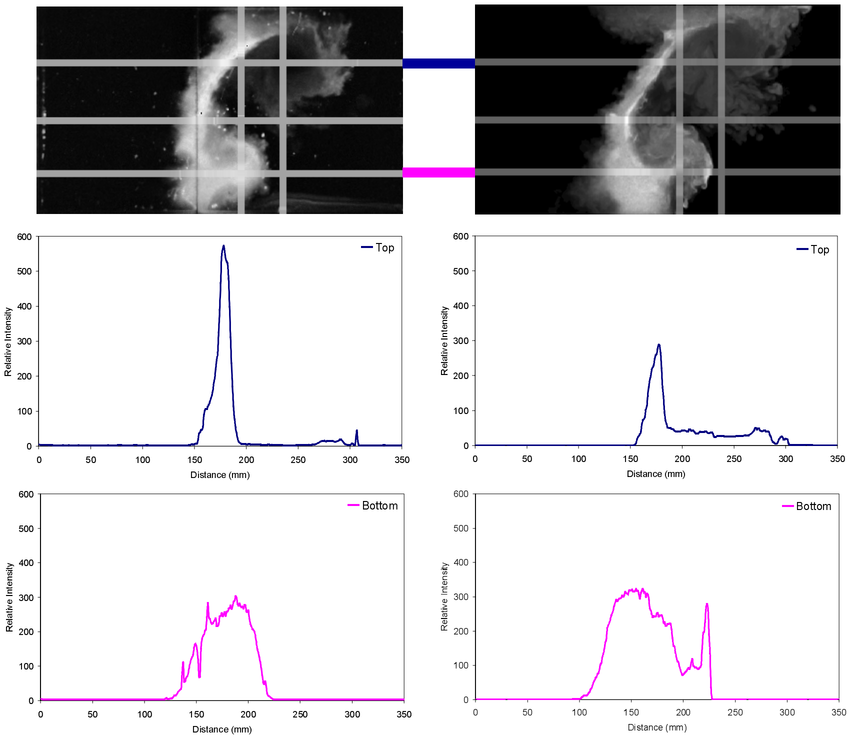


Figure 13. Lineout analysis for the half height experiment (left) and code (right) at 4.0ms.

Conclusion

Inverse chevron experiments have been conducted to complement the chevron experiments reported previously achieving good qualitative agreement with code results. The usefulness of the

Monte Carlo post processing to add multiple scattering to the code results has again been demonstrated. The lineout analysis performed illustrates agreement with code, however this is only semi-quantitative due to the presence of multiple scattering.

Half height experiments have been conducted which superimpose a Kelvin-Helmholtz shear instability on a Richtmyer Meshkov experiment and shown a good visual comparison between experiment and code. A good agreement in shock positions in the early time images has been achieved. The semi-quantitative analysis performed shows good overall results although this has demonstrated problems with the Monte-Carlo multiple scattering code that need to be addressed.

Future work

Further analysis is required to extract more data from the experiment to solve the slight discrepancy in the multiple scattering modelling. Two new ICCD cameras have been integrated into the experiment and to allow full digital recording of future experiments. PLIF (Planar Laser Induced Fluorescence) imaging will soon be implemented to experimentally remove the multiple scattering problem. The new CST, also reported in these proceedings, will extend these studies into 2D geometry at higher Mach numbers.

References

Bashurov, V.V., et al., 1995, Experimental and numerical evolution studies for 2-D perturbations of the interface accelerated by shock waves. Proceedings of the Fifth International Workshop on Compressible Turbulent Mixing.

Smith, A.V., et al. 2001, Shock tube experiments on Richtmyer-Meshkov instability across a chevron profiled interface. Proceedings of the Eighth International Workshop on Compressible Turbulent Mixing.

Holder, D.A., et al. 2003, Shock Tube Experiments on Richtmyer-Meshkov Instability Growth Using an Enlarged Double Bump Perturbation. *Laser and Particle Beams,* Vol. **21**, pp 411 – 418, Cambridge University Press.