Convergent Shock Tube: New Design, First Results

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Abstract.

This paper reports on the progress of the AWE convergent shock tube (CST) project. The latest results from the old CST are presented and some of its limitations noted. A triangular notch perturbation experiment was presented at the last meeting of this workshop (Holder et al. 2003), an improved set of experimental results is presented and compared to results from the TURMOIL3D large eddy simulation (LES). The limitations of the old CST were used as a basis for its redesign

Details of the new design are discussed to illustrate the problems highlighted in conducting experimental work with the CST. Some information on the manufacture of the new facility is discussed focusing on areas where machining limitations had a potential to compromise the design and the solutions found.

Commissioning of the new facility is discussed and comments made on its performance and operational issues.

1. Introduction.

The AWE Convergent Shock Tube (CST) was initially designed as a compressed air driven two-dimensional shock tube. This original design had many problems with shock formation and has evolved over the years through various design changes to be driven by the detonation of an oxy-acetylene mixture which is ignited by a set of 30 miniature spark plugs. This version of the shock tube is shown in figure 1. Recent developments have advanced the design of the shock tube into a demonstrably working facility in which Richtmyer-Meshkov Instability (RMI) mix experiments can be performed in cylindrically converging geometry at Mach numbers of 3-4.

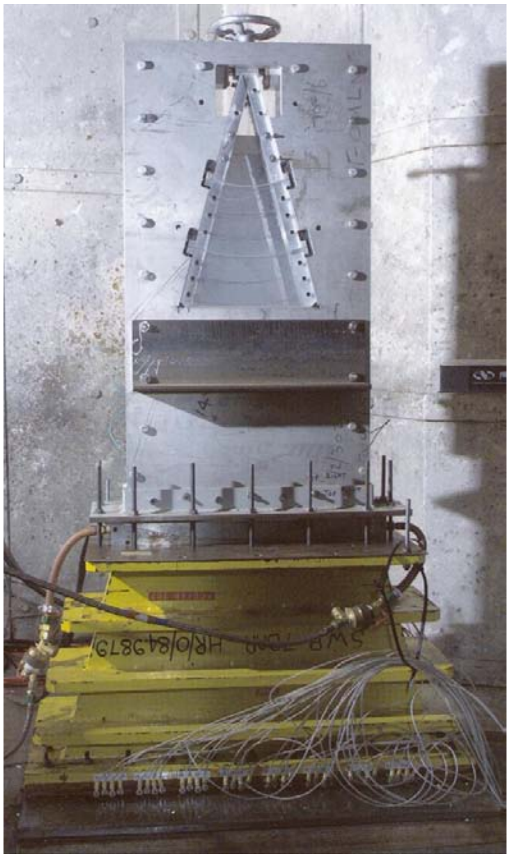


Figure 1. Photograph of old CST.

The method in which the shock tube has been changed over the years has been by replacing, or modifying, different sections whilst still using the remaining components. This has led to a facility which has proven the feasibility of the experimental configuration but has resulted in an overcomplicated design consisting of poorly fitting parts which is very difficult and time consuming to assemble. A new convergent shock tube has now been built which is much easier to assemble and use. It has been designed specifically, to tight tolerances, to facilitate assembly of the experimental test cell for firing and has been built as an integrated unit. It has also been designed such that no single part is heavy enough to require mechanical lifting aids during assembly, further increasing speed and ease of use.

2. Results from Feasibility Studies.

Results from notch experiments performed using the old shock tube design have been presented previously (Holder et al. 2003). These results, however, showed a leak in one of the microfilm membranes used to constrain the dense gas, which degraded the experimental images. Further experiments have now been performed and have provided significantly improved results. A schematic of the experimental set-up for these experiments is shown in figure 2. This shows the dense gas region, bounded by cylindrically curved microfilm membranes supported on fine wire meshes, with air on either side. A triangular notch perturbation is superimposed on the upstream interface, across the whole width of the test section, formed by shaped test cell components and wire meshes. A plug of radius 20mm is inserted into the apex of the test cell to prevent excessively high pressures when the shock reaches the apex.

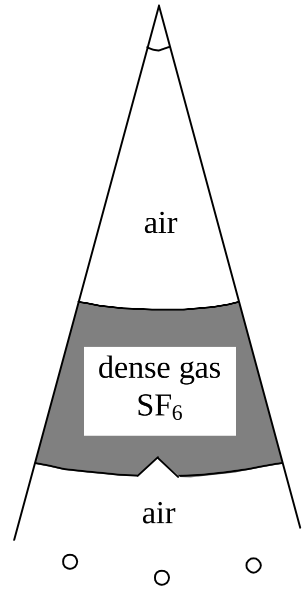


Figure 2. A schematic representation of the notch experiment.

Visualisation of the experiment was by shadowgraph imaging using a copper vapour laser, pulsed at 15kHz, and recording the images on a rotating drum camera. This set-up allows capture of fifty images per experiment. Figure 3 shows a selection of the fifty shadowgraph images recorded from one such experiment. The early time images show the dense gas interface and notch perturbation at the bottom of the image and the shock passing through the dense gas region. A vortex action around the notch perturbation causes a characteristic mushroom shape to form on the dense gas interface. The shock passes through the SF_6 and into the air region in the apex at around 1.07ms. At 1.33ms the shock reaches the apex of the shock tube, by this time an air void has formed in the centre of the dense gas region and dense gas jets are pushing up the walls of the tube towards the apex. Maximum compression of the dense gas is at approximately 1.87ms, at this time the gas is compressed to approximately $1/40^{th}$ of its initial volume.

3. TURMOIL3D LES.

CST experiments are performed to further our understanding of turbulent mixing phenomena. The results also provide data for the validation of the TURMOIL3D mix model developed at AWE. TURMOIL3D is a semi-lagrangian, large eddy simulation (LES) in which, when run using cylindrical polar co-ordinates, the r direction mesh moves with the mean fluid velocity. The test cell is modelled by 1.10^7 cells; 344 x 200 x 140 in the 3D region, as shown in figure 4. Random initial perturbations are added to the gas interfaces to simulate the effects of the fine meshes and microfilm membranes used in the experiments to constrain the dense gas.

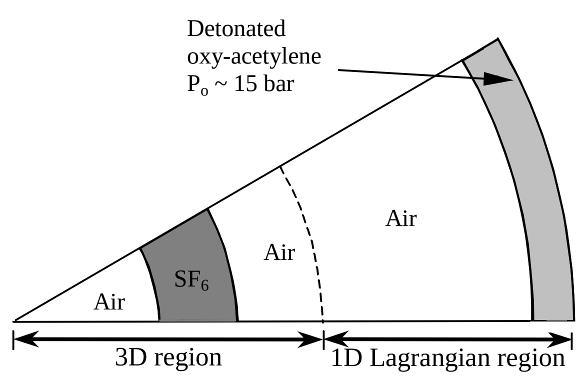


Figure 4. Illustration of code regions

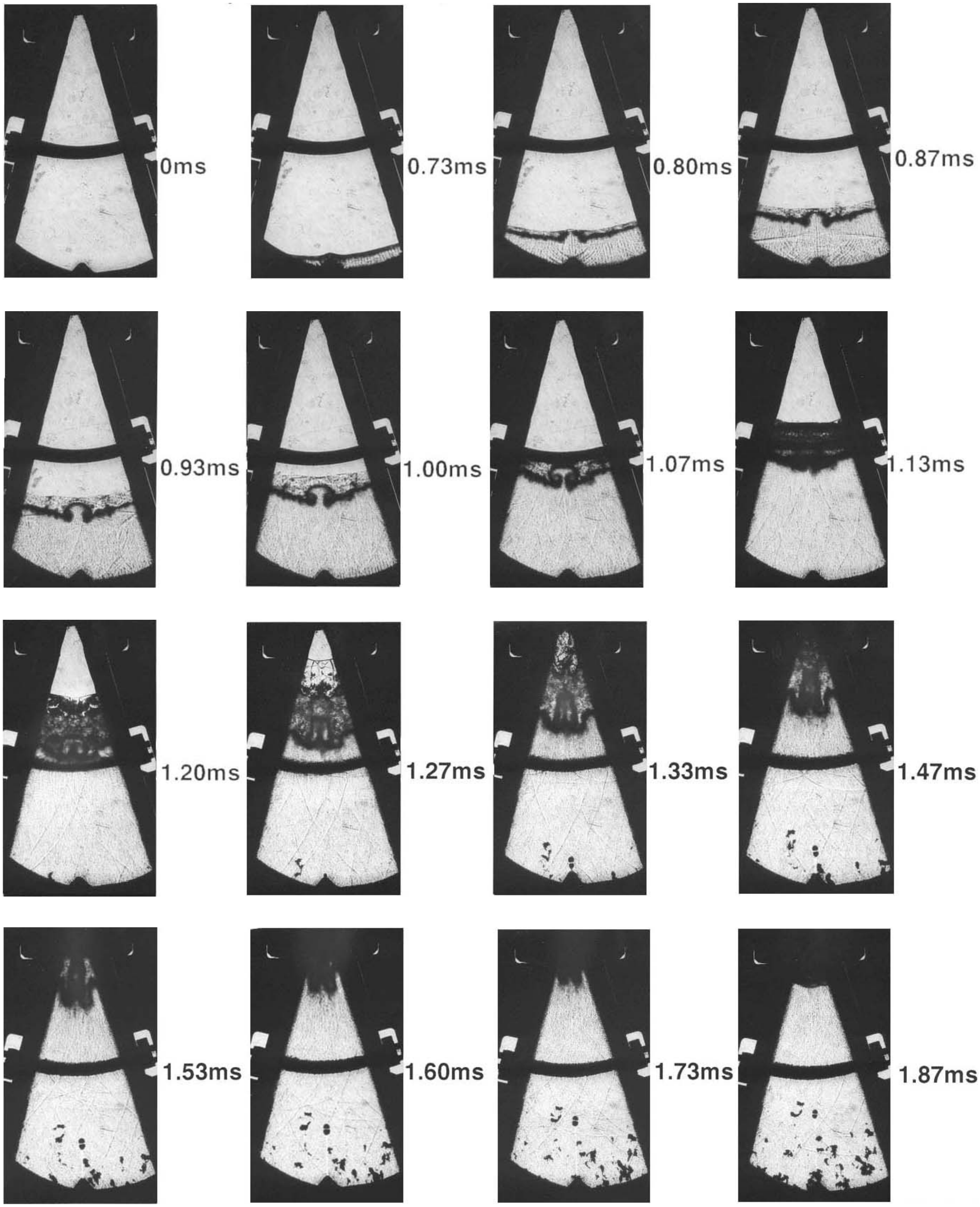


Figure 3. Improved results from the notch experiment performed using the old CST

4. Comparison of experimental and code results.

Figure 5 shows a comparison of experimental and code results for 4 different times. On the left is an experimental shadowgraph image and on the right two code images showing volume fraction and mean density respectively. The 1.19ms image shows good agreement of gas position, shock position and the size and shape of the vortices forming on the lower gas interface. As time progresses to 1.45ms the shock position is still in good agreement but the gas position in the code images has begun to lag behind that of the experiment.

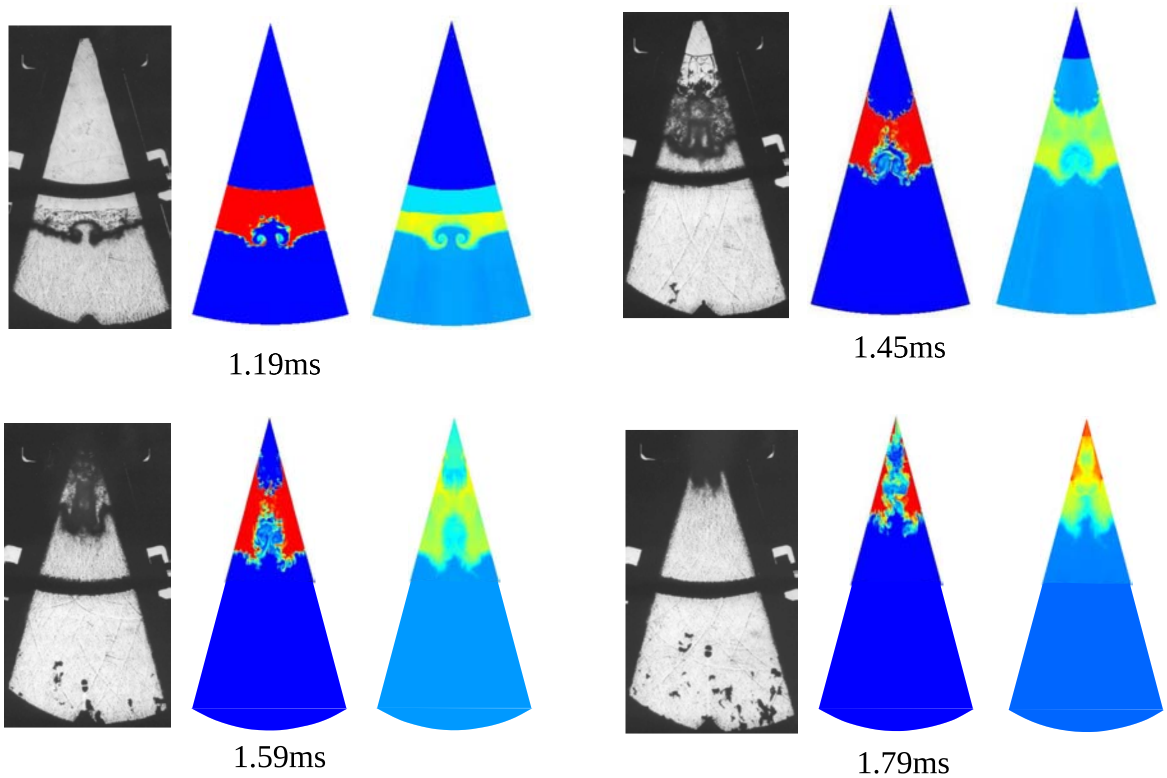


Figure 5. Comparison of Experimental and code results at selected times.

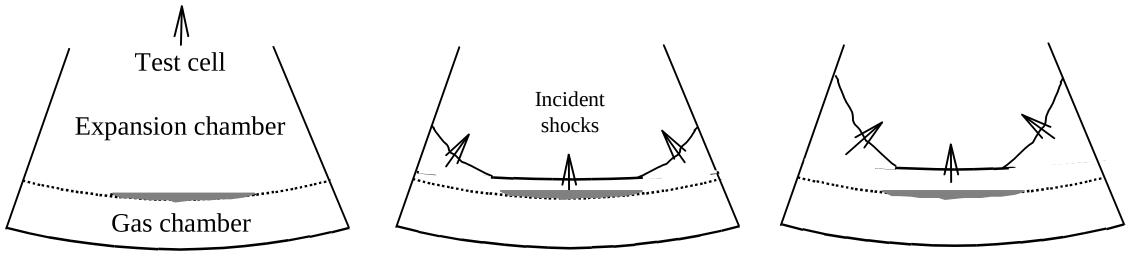
The later time images are comparable in the positions of the central air void, the dense gas jets towards the apex and the air jets along the walls of the tube. The code images do, however, continue to lag behind the experimental images showing much less compression of the dense gas. This is thought to be due to uncertainties in the Equation of State (EOS) for SF_6 which is not well defined at high temperatures and pressures. It is intended to use Xenon gas in future experiments as the EOS for Xenon is more accurately defined. Time sequences of the fifty images from a single experiment and from a code calculation are available on this CD, these allow improved visualisation of the mixing process.

5. New Shock Tube Design

This section describes some of the shortcomings of the old CST design and how the new CST has been designed to overcome these, both in the ease of handling, due to a weight reduction and some new design features to ease assembly.

5.1 Overall design.

The old CST was designed to operate vertically with the test cell and apex at the top and the detonable gas chamber at the bottom. This design meant that if there was a leak in one of



(a) Pre-detonation: showing leaked dense gas sitting on the diaphragm (shaded region)

(b) Post-detonation: showing shock in the centre slowed by passage through leaked dense gas

(c) Shock propagation showing how shock reflections and Mach stems are initiated

Figure 6. Illustration of how a dense gas leak leads to non-ideal shock formation

the microfilm membranes in the test cell during dense gas fill it could not be detected until the results were analysed and incorrect shock profiles were identified. A leak would allow dense gas to fall down through the main body of the shock tube and rest in a ‘puddle’ on the curved foil constraining the detonable gas at the bottom of the shock tube. This puddle would have a flat surface, meaning it would be deeper in the centre of the tube than at the edges. When the shock passes through this dense gas it travels through a thick layer at the centre and only a small amount at the edges causing extra curvature of the shock leading to internal reflections and formation of Mach stems as illustrated in figure 6. The new design, shown in figure 7 has overcome this by inverting the shock tube meaning that any dense gas leakage will be towards the apex and will be visible in the shadowgraph or laser sheet images of the test cell. It was thought that, if a leak did occur, this might also produce an interesting experiment with two dense gas regions.

This inverted design also lowers the optical axis for the laser beam diagnostics to only approximately 50mm above the floor. This was previously around 1.5m above the floor in the old design which is not good laser practice as this is near to eye level.

Figure 7. New CST on support stand

5.2 Detonable Gas Chamber.

The gas chamber of the old CST was designed relatively recently, when it was decided to change from using spark gaps to miniature spark plugs, and much of this design has been retained in the new CST build. The gas chamber consisted of front and back plates with grooves machined into them to locate a rolled steel plate to house the spark plugs. The only disadvantage of this design was that there were a lot of joints that were all possible leakage paths and required sealing. The new design (detailed in figure 8) is made of only two pieces. A milled body including the back plate, sides and curved spark plug plate and a flat front plate with a groove to locate it to the body. This method of a ‘body’ and ‘front plate’ has been used wherever possible throughout the design to reduce the number of possible leakage paths and to speed up assembly of the shock tube.

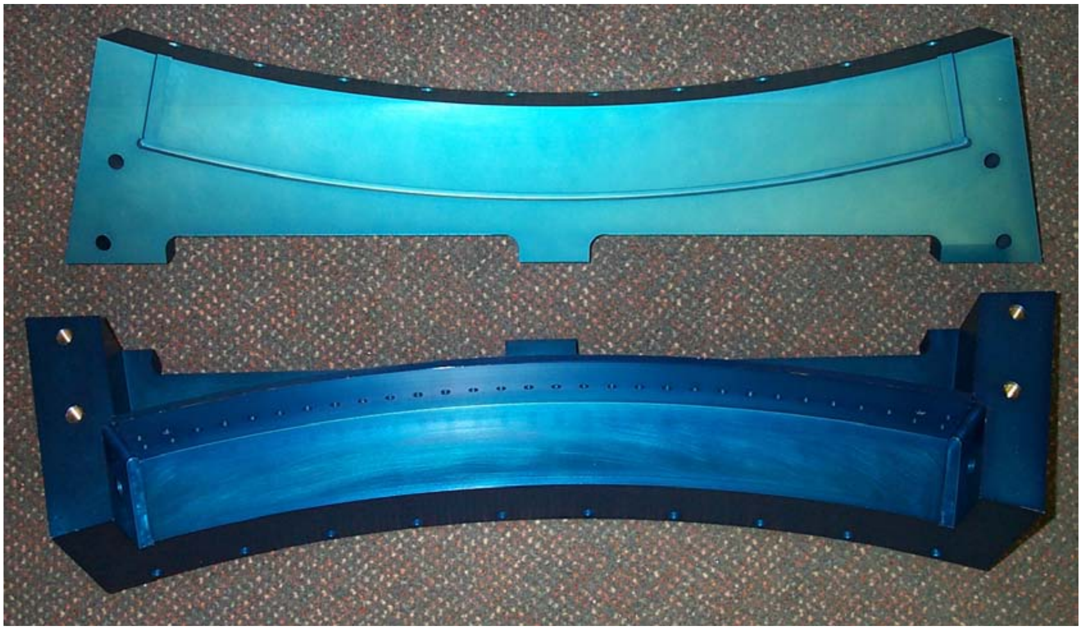


Figure 8. Two components of the detonable gas chamber

The other major alteration to the design of the gas chamber is the method in which the porous gas diffusers are located. Previously they were glued in place with small spacers behind them to allow the gas to flow through. This was difficult and time consuming to assemble and so was changed to using steel holders to locate them, which slide into a groove in the end of the gas chamber.

5.3 Main Body.

The main body of the old CST was made from two square flat plates of aluminium with two large triangular spacers to separate them and to form the correct inner dimensions. This resulted in a lot of unnecessary material making the body of the shock tube heavy which required the use of mechanical lifting aids. The new design has removed the unwanted material and used a milled body and front plate design, where the back and sides are milled out of one piece of aluminium and a separate flat front plate affixes onto this. This has made the main body much lighter than the previous design and does not require mechanical aids to lift, it easing assembly.

Another significant feature of the new main body design is the addition of two lines of pins along the top face, which adjoins the detonable gas chamber (figure 9). Previously wires used to support the foil constraining the detonable gas mixture (and fragment it upon firing) had to be laboriously glued into place individually. These pins now allow the wires to be directly applied to the main body and held in place prior to assembly. Also visible in figure 9 is an O-ring groove, this O-ring will improve the sealing between the main body and the detonable gas chamber.

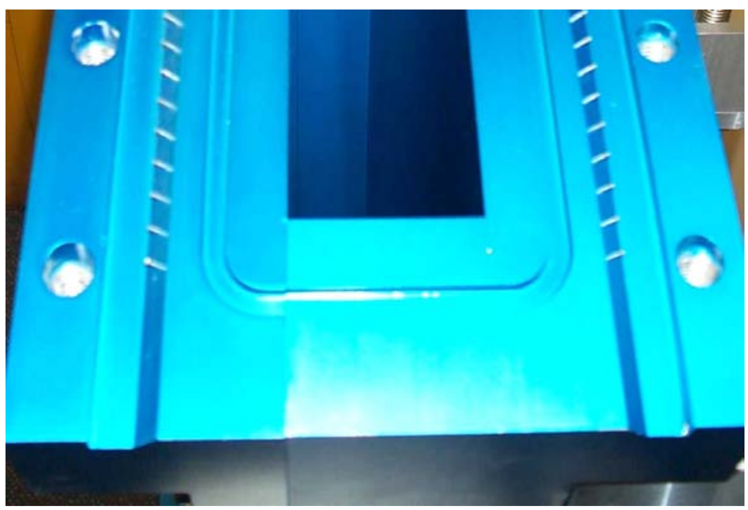


Figure 9. Top surface of the main body showing pins and O-ring groove

5.4 Test Cell.

The test cell has been completely redesigned in the new build of the CST. Previously it was made of three sections each with perspex windows at the front and back and aluminium spacers at the sides. Assembling these parts to fit together and to get the correct internal dimensions was virtually impossible. Also there was no location between the test cell and the main body, the test cell was aligned by eye and then 'wedged' into place using two steel wedges.

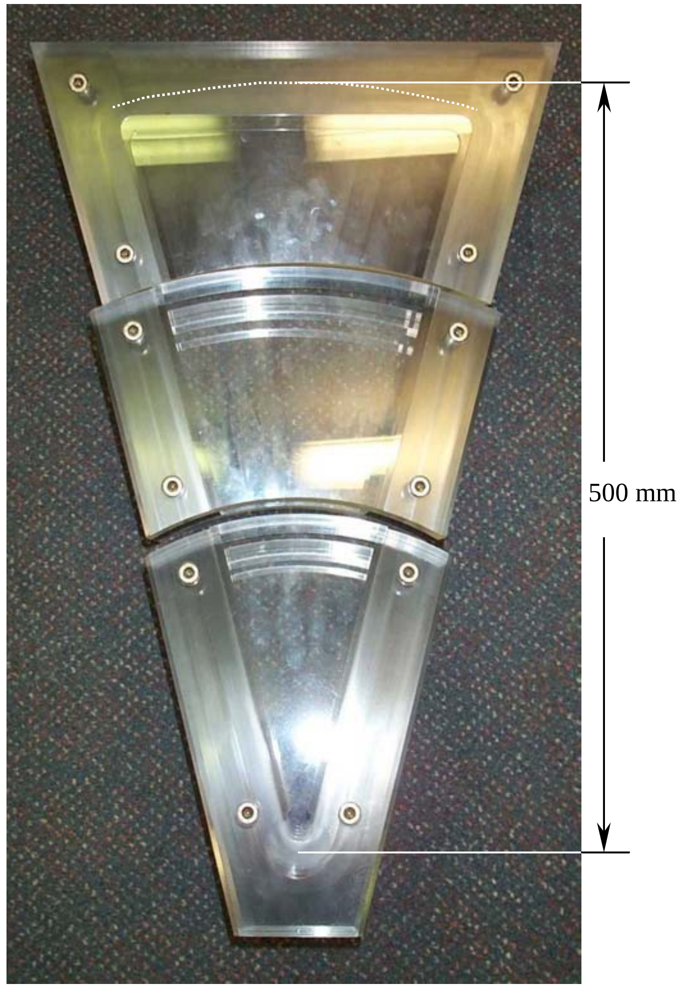


Figure 10. Test cell Cassette components.

The new test cell has been designed to be directly analogous to that of the AWE linear shock tube. It consists of three inner components which make up the 'cassette' (figure 10) roughly similar to the old test cell design, which is then fitted into a steel frame. The main advantage of this design is that the perspex windows need only four bolts to secure them during assembly reducing the stresses in the perspex due to machining. The main strength of the test cell is provided by the steel frame which, when assembled, clamps the perspex windows tightly along their edges.

The upper part of the cassette is made of a milled aluminium body and perspex front window, giving increased strength and defining the dimensions of the test cell accurately. The central dense gas region was required to have perspex windows on both front and back to enable shadowgraph imaging. Thus the design for this consisted of 2 perspex windows separated by aluminium sides similar to the old design.

The apex of the test section went through various design changes. The design from the old CST consisted of two aluminium sides bolted and sealed together at the apex (figure 11a). It was found that the pressure from the shock was sufficient, when reaching the apex, to push these two sides apart causing a leak and loss of compression. The ideal design for the new shock tube is shown in figure 11b in which both sides are manufactured from the same workpiece, this is, however, impossible to machine. The next best thing would be as in figure 11c having a 20mm radius plug at the apex as in the old design, this also impossible to machine.

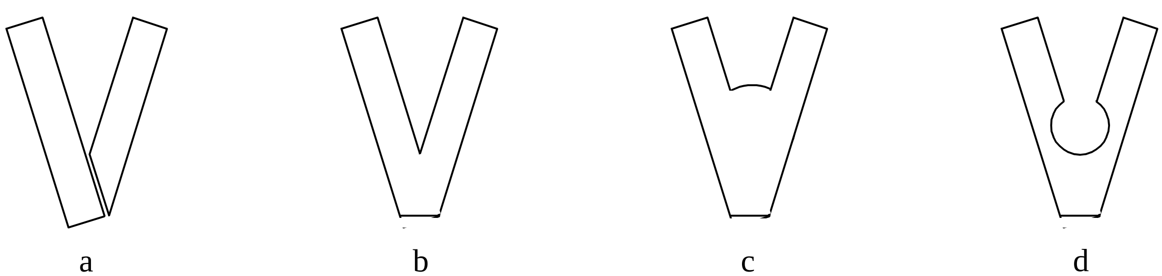


Figure 11. Potential designs for test cell apex

It was intended that laser sheet imaging would be used in the shock tube in the future which allowed this problem to be solved with a novel idea for optical access. This would be through the apex with custom made optics forming a laser sheet ~2mm wide and having a divergence of 30º to fill the inside of the test cell. This has been designed such that the final optic will fit inside a 20mm radius barrel which will slot into a hole left in the test cell apex part, figure 11d.

The three parts of the cassette are secured together with clips along the edges. This cassette assembly is then lifted into the frame body and the front plate of the frame screwed on. Two large diameter pins are incorporated into the top surface of the frame to locate it to the main body prior to firing.

Figure 12. CST support stand with test cell and frame in place.

5.5 Support Stand.

The old CST used the old steel compressed air section as a base, (yellow section in figure 1), which was extremely heavy and difficult to position accurately, this was disposed of in the new design. The new design initially had the main body fixed to a stationary stand and it was thought that a hydraulic pump, or similar, would lift the test section into place prior to firing. This was altered to a relatively lightweight frame design where the test cell was fixed into place and the main body lowered onto it via a stepper motor built into the frame, shown in figure 12. The advantage of this set-up is that the test cell frame is stationary and the optical alignment doesn't require adjustment after setting up each experiment.

6. Conclusions.

Improved results from experiments using the old convergent shock tube have been presented. These results proved the feasibility of performing perturbed Richtmyer-Meshkov instability (RMI) mix experiments in cylindrical geometry at a shock Mach number ≈ 3. A reasonable comparison of the experimental results with those of the TURMOIL 3D calculations has been demonstrated.

Overcoming the initial problems with the old CST enabled a good understanding of the features required in the design of the new build CST. The new CST has been commissioned and has proven much easier and less time consuming to operate with the lighter components, location of all of the separate sections and O-ring seals between the sections all easing assembly. Initial experiments will soon be performed, with no dense gas region present, to analyse the shock profile and velocity. The new design will then be used for RMI mix experiments. It will also allow laser sheet diagnostics to be used, which was not possible using the old design, which will give improved results and allow quantitative analysis of those results.

7. References.

Holder, D.A., Smith, A.V., Barton, C.J. and Youngs D.L., 2003 Mix Experiments using a two dimensional convergent shock-tube. Laser and Particle Beams *21*, 403-409