SUPERSONIC FLOW DIAGNOSTICS USING OPTICAL NOZZLES

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ABSTRACT

An investigation of axisymmetric glass blown supersonic nozzles for flow and surface property optical measurements is presented. The flow field is measured by Background oriented Schlieren (BOS) along with 1 test vehicle (wedge) and side wall pressure is measured via binary Pressure Sensitive Paints (PSP). The nozzle is made of borosilicate glass and the shape was designed both with Method of Characteristics (MOC) and the Rao approximation. The inlet stagnation pressure varied from 3.04 atm to 9.19 atm. Shock structures were observed at the leading edge of the wedge shape and downstream of the vehicle body at high inlet pressures. The walls show low Cp values and a sudden jump at the end of the expansion zone. BOS ability to see large density gradients such as shock waves happen in the nozzle. Preliminary PIV and Shadowgraphs have been included to give a sense of free steam Mach number for the PSP testing.

INTRODUCTION

Analysis of supersonic and hypersonic flow structures pose some of the most difficult problems for researchers and scientists in modern times. Being able to visualize flow structures can provides strong opportunity to understand the complexities associated with supersonic and hypersonic flow structures. Designing testing methodologies in order to properly visualize the flow in the most realistic manner possible could be considered more important than testing itself. In order to provide non-intrusive measurement techniques, certain methods have been implemented by researchers to complete diagnostics. Analyzed in this report is PSP and BOS along with preliminary PIV and Shadowgraphs (PSV). With these testing methodologies, optical access is required in order to visualize that flow. In order to tackle this, the idea of using a glass, bell shaped supersonic nozzle was designed and implemented. The purpose of this study is to determine the efficacy of using such glass blow supersonic nozzles to be able to conduct advanced diagnostics of supersonic flow and surface interactions.

A Laval nozzle was originally designed for the purpose of steam turbines, but quickly became a way to create supersonic flow [1]. For this flow to happen smoothly, without shocks or other abnormalities, a perfect gas, must isentropically converge and expand, where at the throat of the nozzle, the Mach number must be equal to 1 [2]. In order to achieve this ideal expansion, it is important to use appropriate pressure ratios between the expanded pressure and the stagnation pressure of the upstream, otherwise shocks will occur causing the flow to no longer be isentropic and cause the flow to be subsonic [2]. Several methods have been developed to create smooth and even flow through nozzle shapes in order to get high speed flow [3, 4, 5, 6].

Advanced flow diagnostic tools were used to non-intrusively visualize the flow in for the case of this experiment. Primarily used was BOS and PSP. PSP has been shown to be capable of showing pressure distributions along surfaces in contact with flow and can also show shocks or expansion waves surface footprints that could be present in such flow conditions. [7, 8, 9 ,10]. BOS has also been shown to visualize density gradients in images [14]. Due to the sudden change in density across a shock wave it is possible to use BOS to see the shock waves in a wind-tunnel [15]. PIV and Shadowgraphs were used preliminarily in this study. Both methods have shown success at collecting qualitative and quantitative data that can be used in high speed flow research [11, 12, 13].

EXPERIMENTAL SETUP

i) Nozzle/Blowdown Design

The nozzles used for this experiment were M=2 and M=5. The way the nozzles were utilized was by creating a blowdown to atmosphere system were upstream there would be a high-pressure tank. This would be opened using a large diameter solenoid valve to match the 2" inlet diameter of the nozzle. The nozzle would be clamped to the inlet tube by a rubber exhaust clamp rated to handle high pressures.

In order to generate the isentropic flow required for this experiment both the Rao approximation, MOC and isentropic flow calculations were used to determine ideal contraction/expansion ratios. Based on the 2 inch outlet diameter that was used, the throat diameter was determined to be approximately 1.19" and for the M=2 nozzle. The inlet compression ratio was deemed acceptable for flow traveling greater than M=0.2. For the second nozzle it utilized an area ratio of 25. While this would be ideal for Mach numbers reaching 5, the lack of sufficient upstream heating, and low downstream pressure make it not possible to achieve that. It was still used due to its probability of being able to generate large density gradients for BOS testing.

ii) PSP

PSP was utilized in order to view surface pressure on a 2 test objects and nozzle walls to help visualize pressure changes [10]. The test objects tested was both a wedge of approximately 11-degree deflection to the flow. The second was a special designed "insert" that was modeled to be the shape as the interior of the nozzle for measurements. This was done in order to highlight the efficacy of the glass nozzle used in the experiment, allowing for easy PSP measurements. The objects were made using a ProJet MJP 2500 with a material choice of VisiJet Armor (M2G-CL). This would allow for a high-quality painting surface, and the strength and toughness to survive in hostile testing environments. These can be seen in Figure 1 through Figure 3.

Once all the parts were printed an 'ISSI Inc.' screen layer was applied to the surface of interest in order to create a strong base layer to later have the PSP applied to. Once applied it was placed in a vacuum oven for 4 hours at 90 deg C to cure. The type of paint used for this preliminary PSP results, was an ISSI binary PSP. This was applied on top of the screen layer, and then cured at 70 deg C to remove temperature sensitivity. Binary PSP was selected due to it using a reference signal, which helps remove reading changes due to rapid fluctuation of temperature during experiment. A 550 nm filter was applied to the camera to capture the proper signal ranges. The final PSP coated objects can be seen in Figures.

To create the pressure maps 3 different images were gathered at two different signal frequencies, a light off, a wind off and a wind on image. These 3 types of images were collected at both a reference signal and primary signal. Due to current operating constraints certain levels of data, both average and instantaneous imaging were able to be captured.

iii) BOS

Shadowgraphy was used as another method to visualize flow in the glass nozzles. In order to image the shadows, a LaVision ImagerLX camera was utilized. For the setup in this experiment the camera was imaging at 30Hz. A high intensity light was used behind a speckled sheet of paper in order to have the camera focus on.

The image used was from a paper on speckle texture image generator and the algorithm to generate can be found there [16]. It should be noted in the case of this experiment, the more refined and less distortion there was with the image sheet, the better the results would turn out Figure 4 shows the setup that was used.

In order to process the data LaVision Davis 10 was used in PIV processing mode to determine the pixel shift and map the pressure gradient. It should also be noted Matlab software does exist and will show some trends, but usually at the expense of visual resolution.

iv) Other Methods

Early in the development some preliminary PIV was taken in order to try and validate Mach number and tunnel velocity. In figure 5 a basic setup of a PIV system similar to that used in the experiment can be seen. The laser sheet was placed in the center of the nozzle to view the centerline velocity. The laser used for this experiment is a double pulsed Nd:YAG laser (NewWave MiniLase-III) pulsing at 15 Hz with a power of 100 mJ/pulse at a wavelength of 532 nm. The laser beam was altered using a cylindrical and spherical lenses to make sure it was a sheet with a thickness of less than 1mm. In order to seed the flow hollow spheres were placed at the exit of the pressure vessel to get a basic feel for the flow field. The flow could be visualized in the lab by using a La Vision Imager LX 2M camera which has a resolution of 1608x1208. Data was processed using Davis 10.

Shadowgraphy was used as another method to visualize flow in supersonic and hypersonic conditions and can be seen in figure 6. This was done using similar pieces of equipment as before. In order to image the shadows, a LaVision ImagerLX camera was also utilized. The camera was imaging at 30Hz during the wind-tunnel operation. To illuminate the wind-tunnel, a high intensity light used for a high-speed camera was used.

RESULTS AND DISCUSSION

Using a binary PSP from ISSI yielded some interesting results. Consistently shown across the several tests was a strong subsonic trend, indicating a non-ideal pressure ratio, below 3.74 atm. For the wedge it started to have supersonic flow Cp trends above 3.74 atm showing a supersonic pressure map on the shape of the wedge, with a high pressure on the leading edge and sharp decrease immediately after, a possible indication of potential oblique shock onset at the leading edge of the wedge. The higher the inlet stagnation pressure, the stronger the trend was, as seen in figure 7 and 8. Finally, in figure 9 the change in average pressure was able to be mapped through a single run. It was observed that for the first 32 frames there was still that supersonic flow trend of a high pressure on the tip and a sharp decrease on across the rest of the geometry indicating for this pressure having about a 3 second testing time.

Figure 10 through figure 14 show the pressure trend at the wall ranging from 3.06 atm and 9.19 atm. As the inlet stagnation pressure increased the Cp would drop along the insert. Also, it was observed in figure 12 the pressure contour trend starts to change a bit more at the edge of the insert, with a very large and sudden jump in Cp occurring. Currently it is hypothesized that supersonic flow is consistently achieved once operated with an inlet pressure above 5.10 atm. Results will need to be compared to PIV or Shadowgraphs, in order to view what the sharp change in Cp is. While more testing will be completed involving the PSP, it should be noted so far, the optical access nozzle used in this test provides a very strong platform for testing.

BOS testing was able to visualize the density gradient that occurred in wind tunnel testing for the glass nozzle shape. The two regions looked at was the onset of expansion, after the throat and the end of the expansion to try and visualize shock waves. The 1 test vehicle did not indicate shock waves from the ramp, but from the bolt attaching it, cased normal shock waves to form seen in figure 15. It should be further looked into with PIV or other shadowgraph methods to validate. When testing the blunt object a bow shock appeared to form in front of the object, despite being hard to fully visualize. This can be seen in figure 16.

Preliminary PIV (Figure 17) and Shadowgraphy (Figure 18) that have been taken seem to show unsteady normal shock formation in the nozzle prior to the test object. This is likely due to in the tests using low stagnations pressures causing the flow to not be able to isentropically expand, i.e. the nozzle was over expanded. Since hollow spheres were used as well in the test, they have large particle diameters and low relaxation times causing them to not track the flow well. Despite that it seems that flow was seen at about M=1.2 in that tests, and resultant velocity after the "shock" seems to correspond well with the normal shock equation. The shadowgraph taken was for similar testing conditions and an unsteady vertical line is able to be seen through the test as shown by figure 18.

CONCLUSION

The current experiments have demonstrated that PSP and BOS can be applied in order to visualize the flow through 2 glass nozzles at high speeds.

First a wedge shape was utilized to show PSP, and furthermore BOS was used to try and visualize free stream properties. The wedge shape with binary PSP was able to indicate supersonic trends along the wedge. Furthermore, the contour was able to visualize the flow along the walls of the Mach 2 nozzle. There appeared to be a sharp increase in pressure right after the expansion which needs to be investigated further to see if normal shock is forming or noise.

BOS was able to show large density gradients when testing the wedge object and blunt object. The wedge appeared to not cause any shock waves or significant changes in the density, but the bolt holding it on seemed to cause a shock wave that was seen. The blunt object also appeared to have a bow shock occur off the front of it. BOS overall seemed an effective method of viewing data, but more should be taken to get clearer results.

More work will need to be done in order to confirm these results such as using better PIV/shadowgraph results. Shadowgraphs will have to be more carefully planned to help deal with optical distortion that will occur inside the nozzle, but should also be used to see if similar trends can be followed. PIV will require a better seeding system so that homogenous seeding will happen through the nozzle.

References

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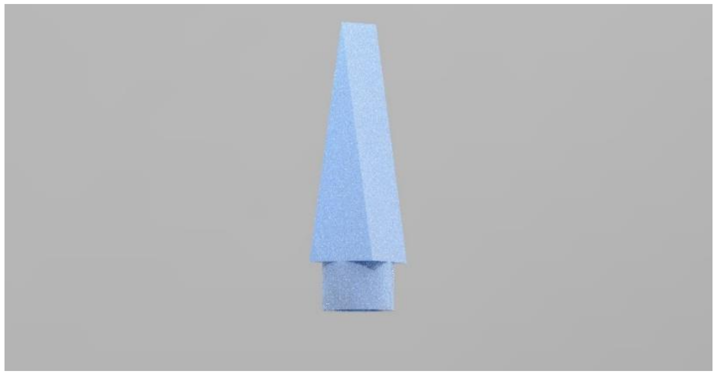
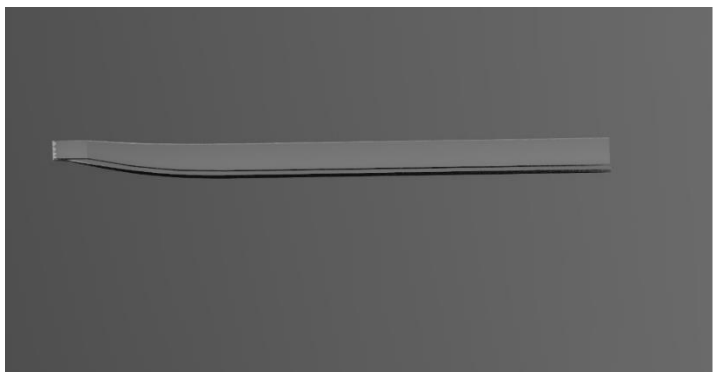
Appendix I: Figures



(a)



(b)

Figure 1: 3D printed test objects (a) Wedge along with the (b) 3D printed wall contour map.

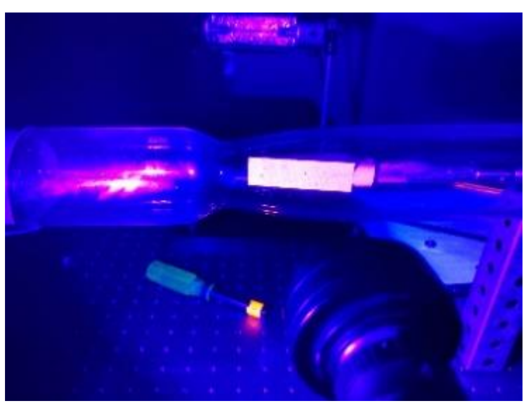


Figure 2: 3D printed Wedge test object in nozzle for testing.

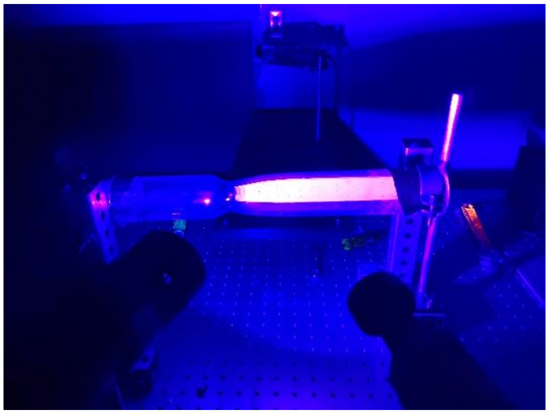


Figure 3: 3D printed wall contour test object.

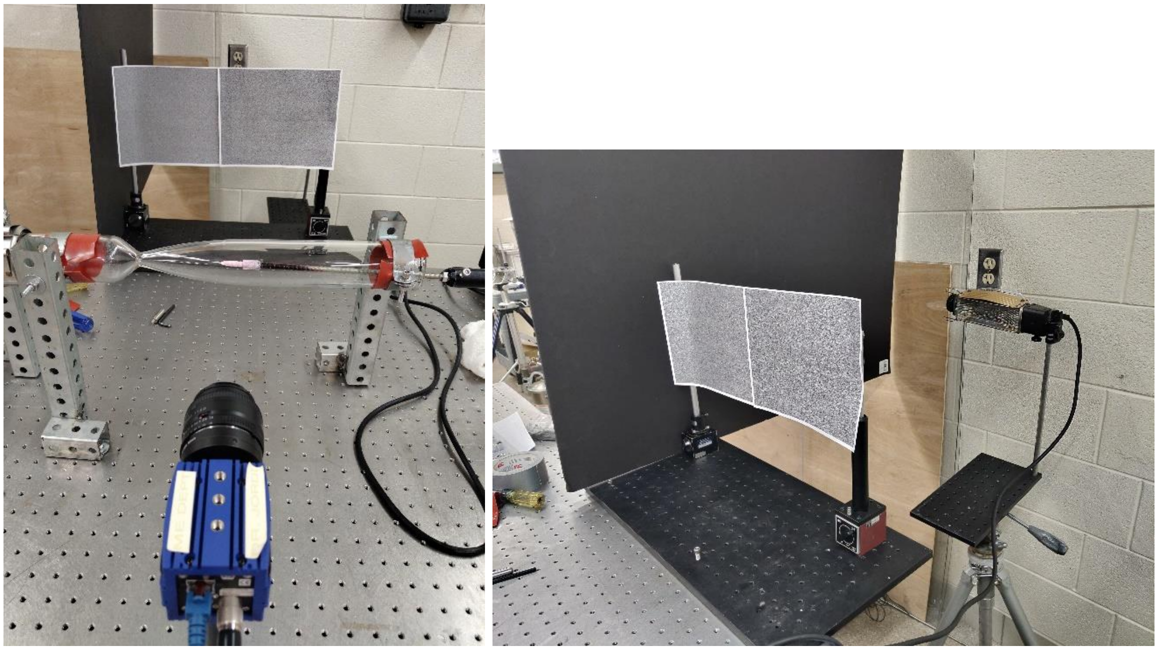


Figure 4: BOS setup used for this experiment.

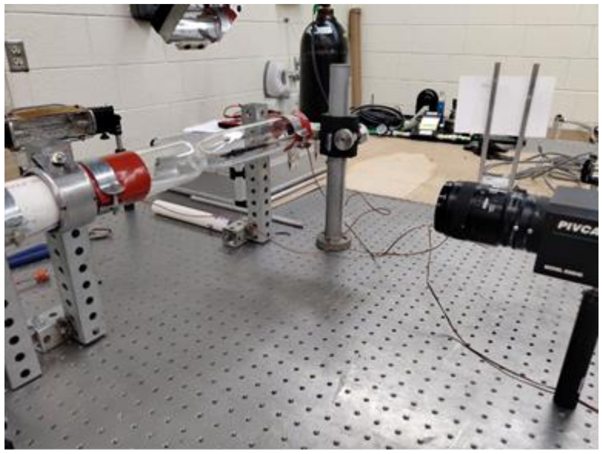


Figure 5: Preliminary PIV setup used for data collection.

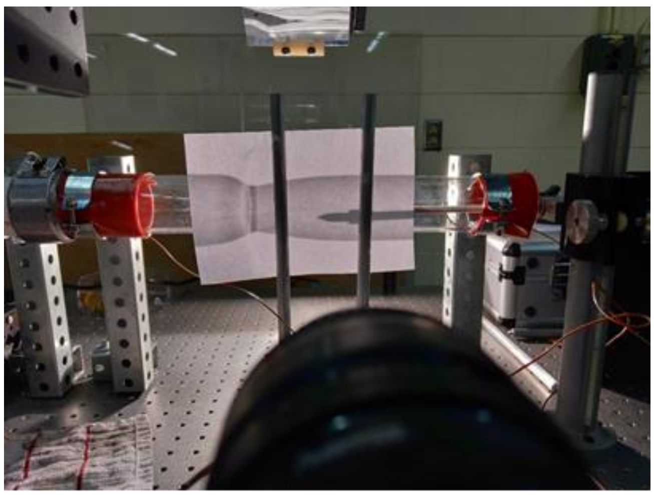


Figure 6: Preliminary Shadowgraphy Setup used for data collection.

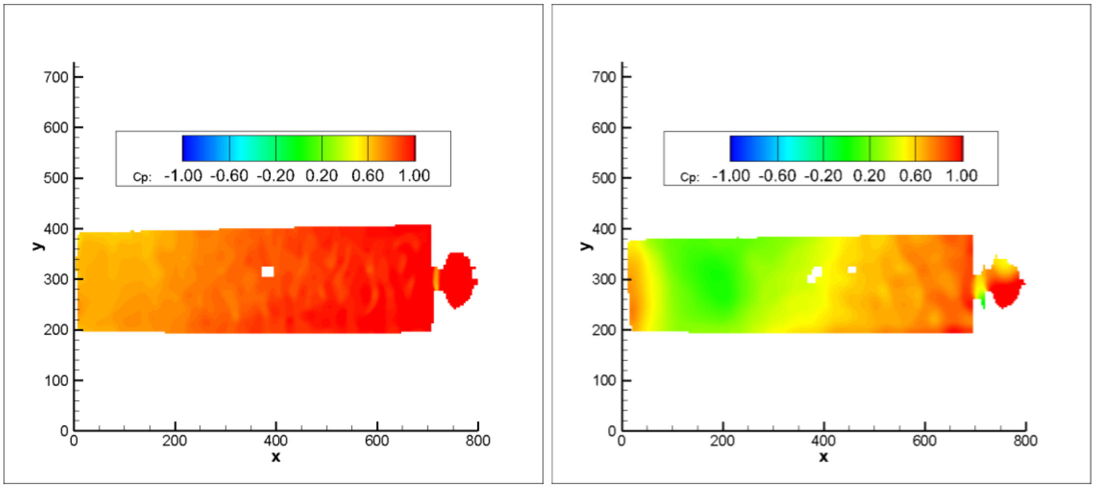


Figure 7: Cp across a wedge in the center of a nozzle at 3.05 atm (left) and 3.74 atm (right).

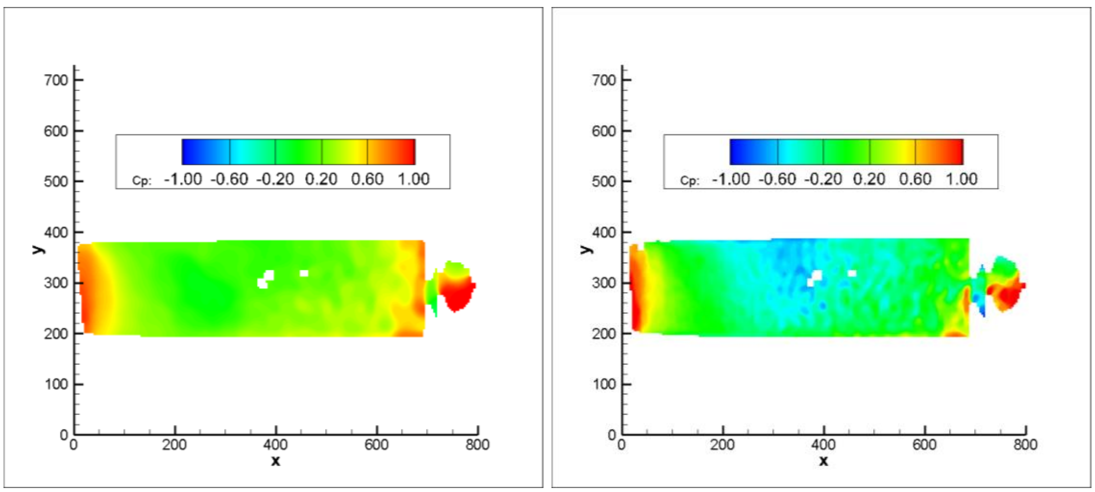


Figure8: Cp across a wedge in the center of a nozzle at 4.42 atm (left) and 5.10 atm (right).

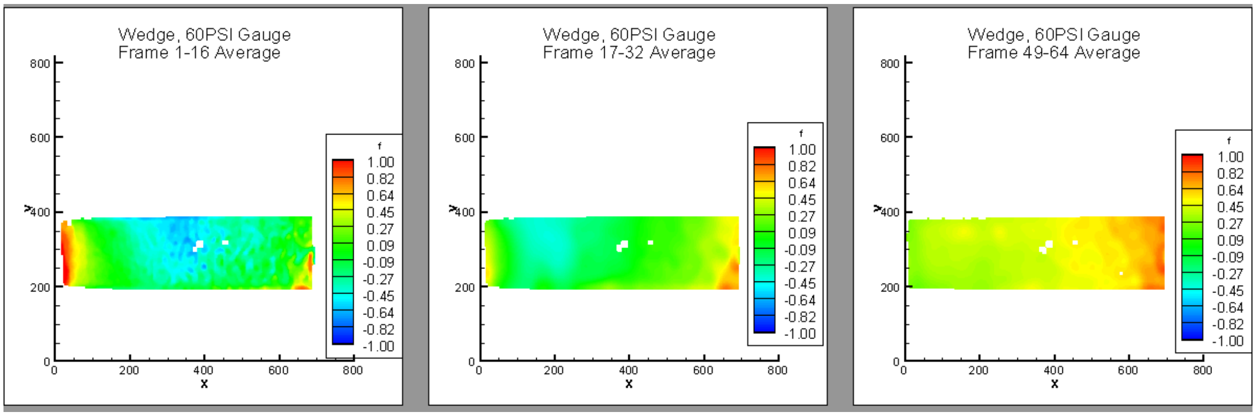


Figure 9: Fluctuation of average pressure map over the course of a run of the wind-tunnel.

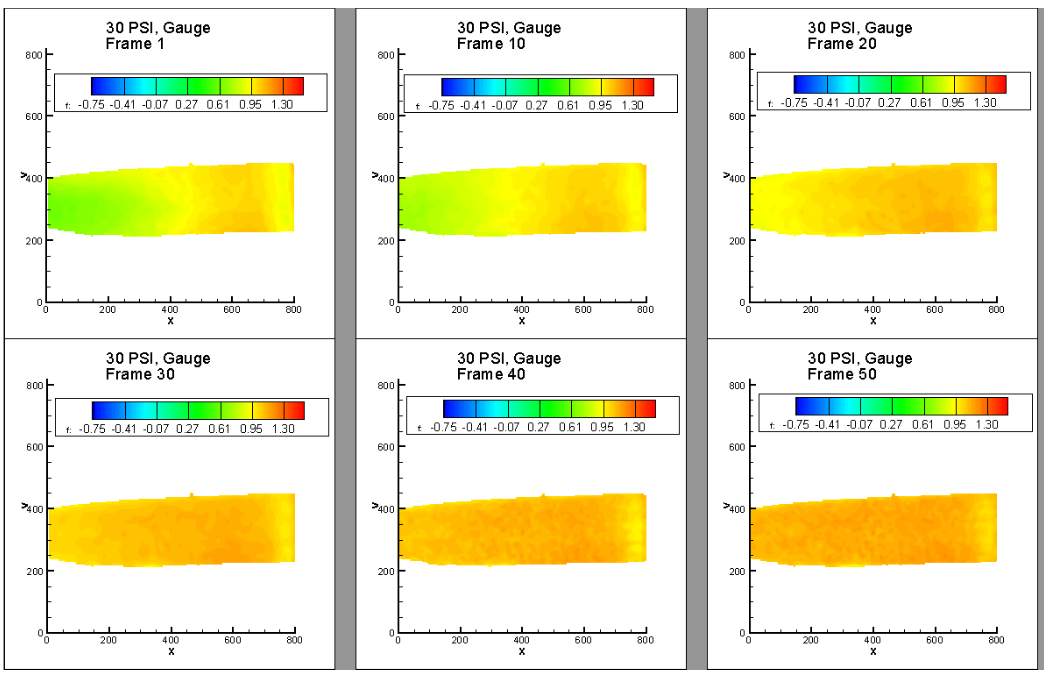


Figure 10: Change of Cp along the wall, at 3.06 atm inlet stagnation pressure.

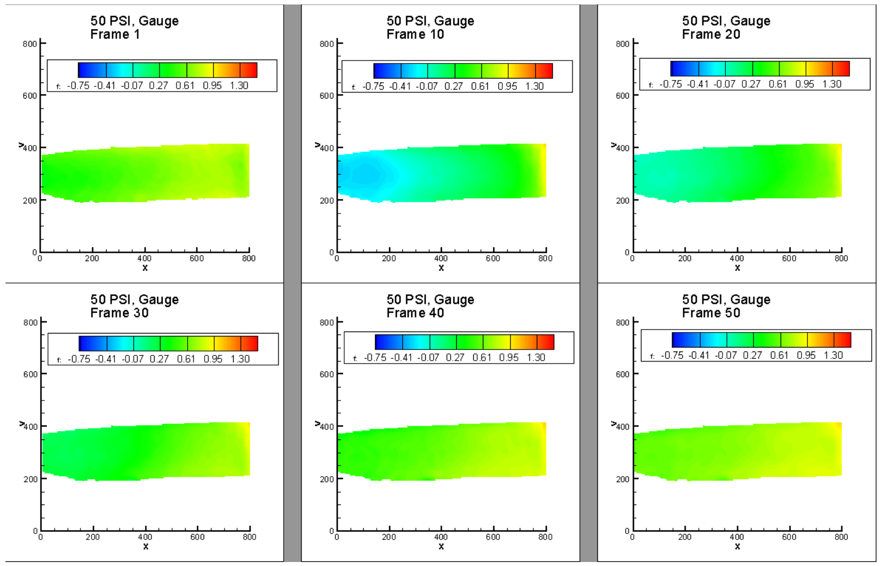


Figure 11: Change of Cp along the wall, at 4.42 atm inlet stagnation pressure.

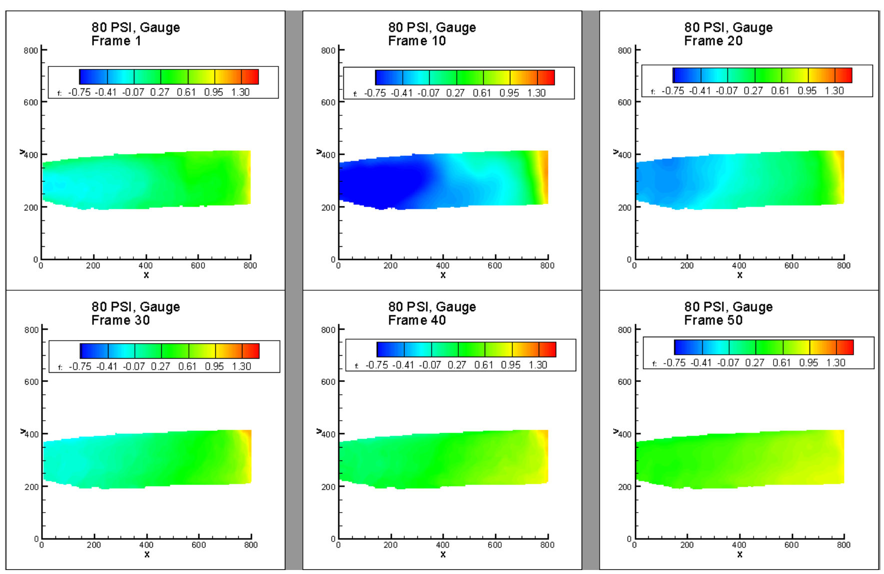


Figure 12: Change of Cp along the wall, at 6.46 atm inlet stagnation pressure.

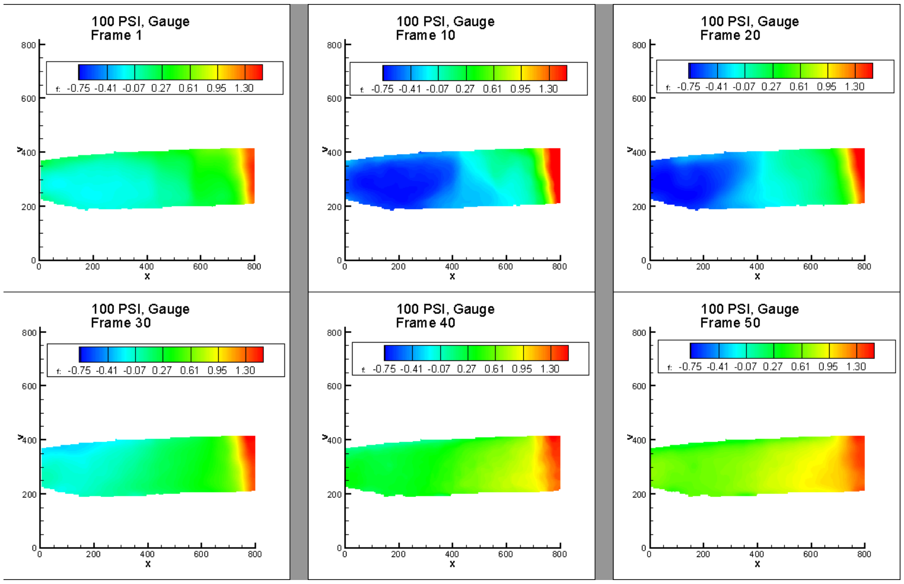


Figure 13: Change of Cp along the wall, at 7.14 atm inlet stagnation pressure.

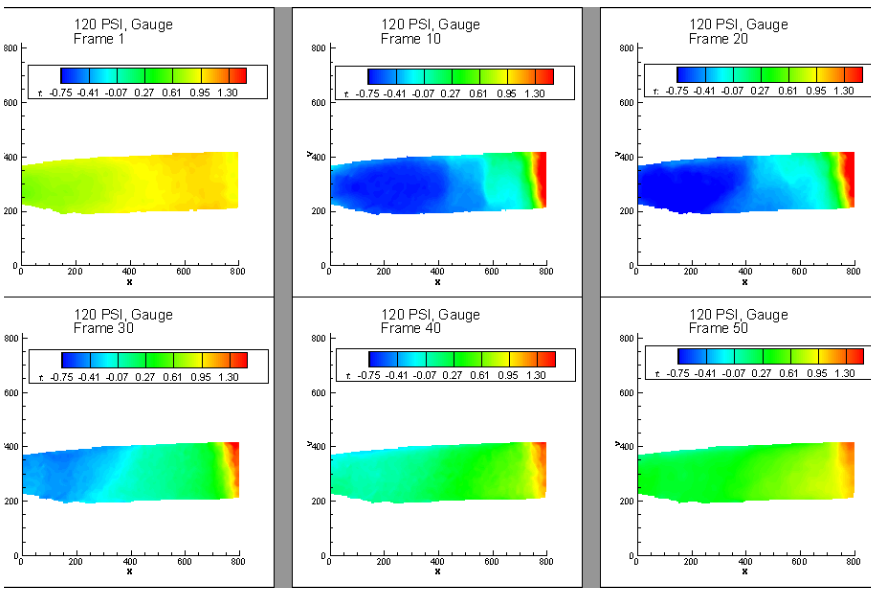


Figure 14: Change of Cp along the wall, at 9.19 atm inlet stagnation pressure.

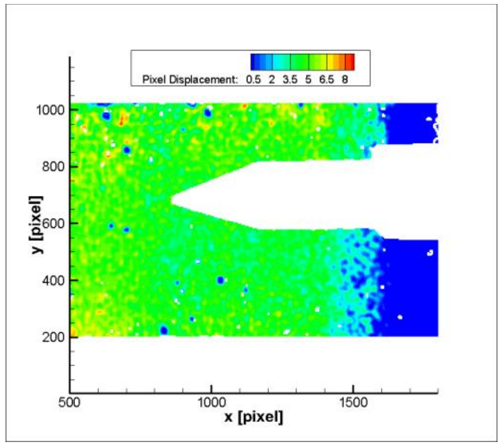


Figure 15: Pixel shift plot for a small wedge shape.

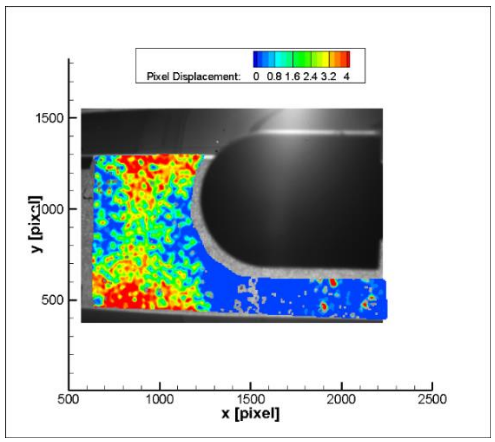


Figure 16: Pixel shift caused by a blunt object.

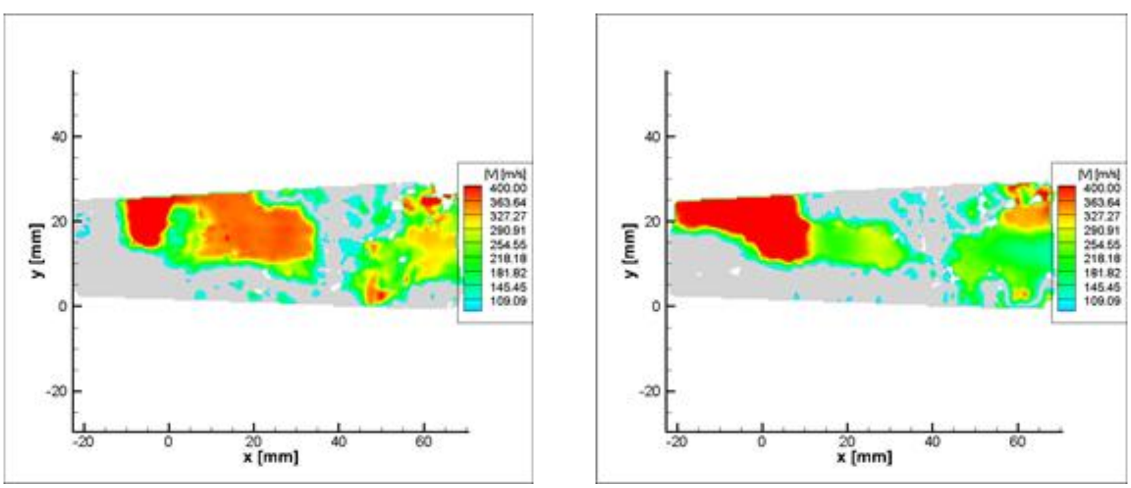


Figure 17: Velocity Contours found using PIV at 2.72 atm inlet pressure.

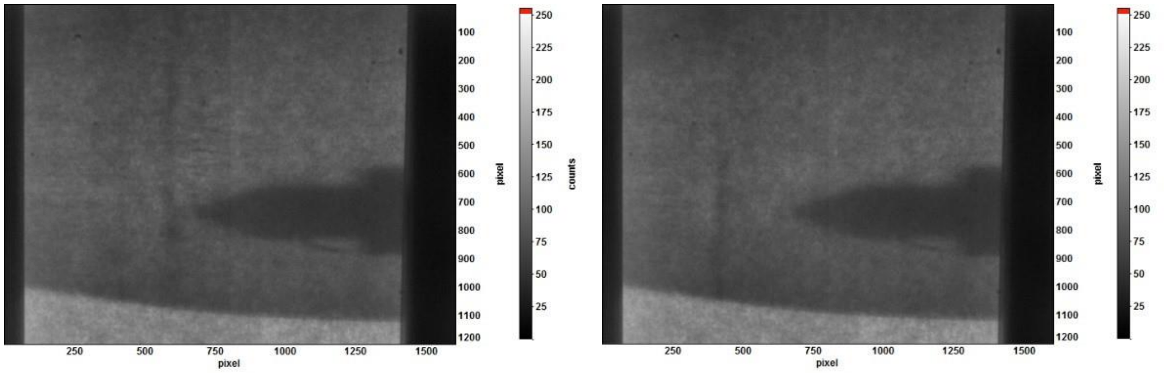


Figure 18: Unsteady shock found using shadowgraphy tests.