

Parametric Study to Determine Best Model for Use in Studying RCS Shock Wave Interactions

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Abstract

In an effort to obtain a precision landing for Mars landers, it is important to use reaction control system (RCS) jets in order to control the trajectory of an entry vehicle traveling through atmospheric regions where aerodynamic control surfaces are ineffective. Experimental work involving RCS interactions is highly requisite in order to validate computational code and give greater physical understanding. In this paper, a parametric study conducted to assist in gaining data on the interactions of RCS is outlined. In this parametric study, two models of the Mars Science Lander (MSL) are placed in a wind tunnel at different Mach numbers at different angles of attack. The flow field around the model is illuminated using a Tesla coil. Pictures were taken of the different setups and are compared here to determine the robustness of the model design under the different conditions. The comparison is used to determine the model and set up for the experiments that will be used in conjunction with PLIIF in order to gain better physical and quantitative understanding of the RCS jet interactions. The pictures obtained show the interactions of the bow shock off the model with the barrel shock created in the free expansion jet.

Introduction

Precision landing for MSL is an important step in preparation for manned missions to Mars. Current Mars landers have a footprint on the order of 100's of kilometers. However, with the MSL, plans are to achieve a footprint of a radius 10 km within target range.¹ With that such capability, the contributions to science on Mars can be enhanced in looking at geographically interesting areas without risking the safety of the mission.² This is critical in regarding human space missions when larger space crafts and the risk of human life will require even more accuracy in landings, called pinpoint landing.² One of the mechanisms that will allow for precision landing is

reaction control system (RCS).³ RCS is utilized during entry in less dense atmospheric conditions when aerodynamic control surfaces have no effect. The RCS fires any combination of eight jets on the surface of the backshell to create moments that allow for banking of the vehicle in guided descent. Although RCS have been used on the Space Shuttle Orbiter and the Apollo spacecraft, in light of the Mars missions, RCS have proven problematic.^{4,5} One of the current problems with RCS though is the inability to understand exactly the contribution that the RCS makes to the movement of the spacecraft.³ Firing the RCS jet on the backshell creates an adverse pressure differential that can negate any positive pressure the jet is intended to create, which could possibly steer the aircraft more off course. Thus, a better understanding of RCS interaction plays an important role in the design of RCS on the MSL so that it can achieve its goal of precision landing.

This paper outlines a parametric study involving visualizations of the interactions between the bow shock off an MSL model and the barrel shock of the wind tunnel, to determine the robustness of the model design regarding size and test Mach number.

In future work, the model will be plumbed with internal hardware to allow for an RCS jet on the windward side at an angle of attack in order to obtain qualitative (visualizations) and quantitative data for the interactions between the RCS jet and the shocks off the model. Quantitative data include velocity flow fields, density flow fields which will then be used to obtain pressure and force measurements in order to understand the moments and forces acting on the MSL during RCS firing. The data will also be used validate computational code developed at NASA Langley Research Center and the University of Michigan. The further study involving the plumbing of the MSL model will utilize a method of measurement known as Planar Laser Induced Iodine Fluorescence (PLIIF).

In this paper, background for the usefulness of the PLIIF method will be touched on briefly followed by a brief overview of the entire research effort. Following that, an explanation is given of the

set up of the lab for this current parametric study, the design of the model and the methods used to obtain visualizations for 2 and 1.5 cm models placed in Mach 10 and Mach 12 (also limited Mach 8) conditions at both 0 and 20 degrees angles of attack. The results will be then given with an explanation and comparison of the visualizations and discussion of best test parameters for the final study.

Background

PLIIF Measurement Method:

PLIIF is a method developed and used at the University of Virginia for the past twenty years. In this method, flow is seeded with iodine particles. A narrowband transition line from a 514.5 nm argon ion laser is collimated into a laser sheet through the flow. The iodine particles fluoresce and images are taken with a CCD camera at different points that allow for a two-dimensional resolution of the flow. From the images, qualitative understanding of the flow can be obtained. Furthermore, at each point in the flow, quantitative data can be obtained and evaluated to obtain velocity, density measurements for the flow field.^{6,7} Due to its ability to obtain both qualitative and quantitative results; this method is highly advantageous particularly in gaining better understanding about the interactions in physically complex interactions. [more sources here]

Overview:

In the overall research, the parametric study discussed here will be used to determine a best sized model for the analysis of RCS interactions in a hypersonic low density, low temperature wind tunnel. The model used is designed after the Mars Science Lander, which will be launched in 2009. From the parametric study, a model will be chosen for use in gaining better understanding of the RCS interactions. The chosen model will be put in the free expanding jet wind tunnel and, using PLIIF, will obtain qualitative pictures of the shock interactions on the MSL model with the RCS jet both on and off. Furthermore, quantitative results will be obtained to gain a velocity profile of the flow field as well as density profile which will be used to gain better understanding of the pressures and force moments acting on the back shell of the RCS when it is firing. The data obtained from both the qualitative and quantitative data will be compared to CFD models developed at the University of Michigan by Iain Boy and his students. The data will be used for CFD code validation at NASA-Langley as well in order to better understand the interactions.

Parametric Study:

In this parametric study, in order to gain better understanding of the actual model set up, two models of 1.5 cm and 2 cm were built. Due to spatial resolution as well as fidelity to the actual MSL design, the larger model is preferable. However, due to the freely expanding jet wind tunnel, in which the local Mach number increases in distance from the orifice, larger model can plug the flow for smaller Mach numbers and can create bow shocks off the model that interact with the barrel shock of the wind tunnel, and consequently the Mach stem. If this interaction occurs, then unwanted sub-sonic regions can occur around the model which does not sufficiently simulate entry conditions and is difficult to compare computational code to. As a result, of the model size complications, different Mach numbers were also compared. For computational and experimental purposes, higher Mach numbers for RCS are desired. However, again to better understand how robust the model is and the possible interactions between the shocks and the Mach stem, it is necessary to examine the model in the wind tunnel both faster and slower than the desired Mach 10 flow condition. Further, for computational purposes it is important to take measurements both at the trim angle of attack as well as the zero degree angle of attack. Overall, this parametric study which examines model size, Mach number and angle of attack for future interaction studies, will be used to determine the overall robustness of the model.

Experimental Set Up:

The wind tunnel for the experiment is a low density, low temperature wind tunnel using a freely expanding jet through an orifice⁸. Based on Ashkenas and Sherman's work which details the Mach number conditions and the length based upon the ratio of the inlet pressure to the back pressure in the vacuum vessel, distances for the interested Mach numbers were calculated. The equation used is as follows in which gamma is 1.40, A is 3.65 and x_0/D is 0.075 for nitrogen conditions⁹:

$$M = A \left(\frac{x-x_0}{D} \right)^{\gamma-1} - \frac{1}{2} \left(\frac{\gamma+1}{\gamma-1} \right) / A \left(\frac{x-x_0}{D} \right)^{\gamma-1} \quad (1)$$

Results for Mach 8, 10, and 12 and their corresponding distances from the orifice plate to the leading edge of the model are shown in Table 1 below:

Table 1: Mach number and corresponding distance from the orifice plate (to leading edge of model)

Mach Number	Distance (mm)
8	16.67
10	27.50
12	42.03

A vacuum for the wind tunnel vessel is pulled by three pumps – a Stokes MicroVac Pump, a Roots Rotary Vane Booster Pump, and a Roots Rotary Vane High Pressure Pump - to achieve back pressures around 280 mTorr at a total pressure of 1.8 atm^{6,8}.

Visualizations are obtained using an Electro-Technic High Frequency generator which uses a high voltage and small current to ionize the air around in the wind tunnel chamber, causing the flow to become a deep pink purple color. The ionized air allows for visualization of the bow shock off the model interacting with the barrel shock. Pictures of the interactions were taken using a digital camera at different exposures.

Results and Discussion:

Images for Mach 8, 10 and 12 for the smaller model set at a twenty degree angle of attack are shown in Figures 1 through 3. It is important to note for the images that the three dimensional shock interactions illuminated by the Tesla coil are captured in a two dimensional image by the digital camera. Thus, the images are not planar spatially resolved. However, in examining the bow shock off the model and the outermost shock line from the barrel shock, one can make comparisons for the smaller model with respect to the different Mach numbers.

For all three images, the shape of the barrel shock remains mostly constant, with the shock expanding outward from the nozzle and curving around the model. The Mach stem also occurs in mostly the same location for all three Mach numbers. Thus the shock of most interest in these images is the bow shock off the leading edge of the model. In the Mach 8 set up, the barrel shock on the lee side of the model comes off at just a slight angle. This angle increases with Mach number. Thus the barrel shock and bow shock interact much further away from the nozzle with increasing Mach number. The lee ward side of the model though, while valuable to note, will not be of primary interest in the experiment.

For the windward side of the model, which is of great interest, for Mach 8 set up, the shock wave curves out from the model before bending back toward the model and interacting with the barrel shock somewhere along the Mach stem. For the Mach 8 set up, the shock appears to interact around the triple point located on the Mach stem. With increasing Mach number, the shock wave does not extend as far out from the model before bending around the model. Furthermore, the barrel shock, bow shock interaction occurs along the Mach stem but further inward, away from the triple point.



Figure 1: Mach 8, 1.5 cm model, 20°

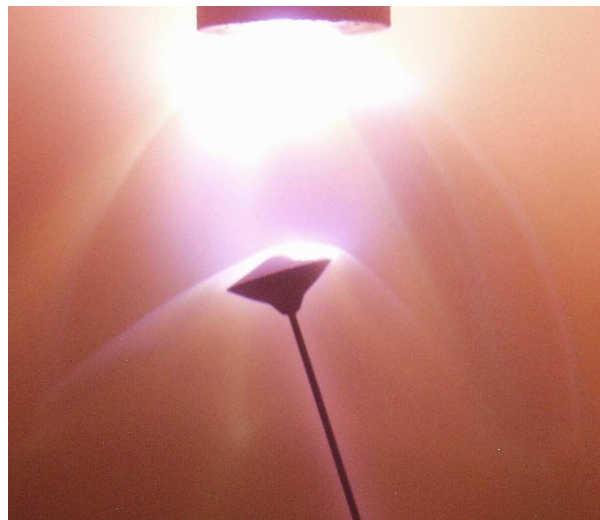


Figure 2: Mach 10, 1.5 cm model, 20°

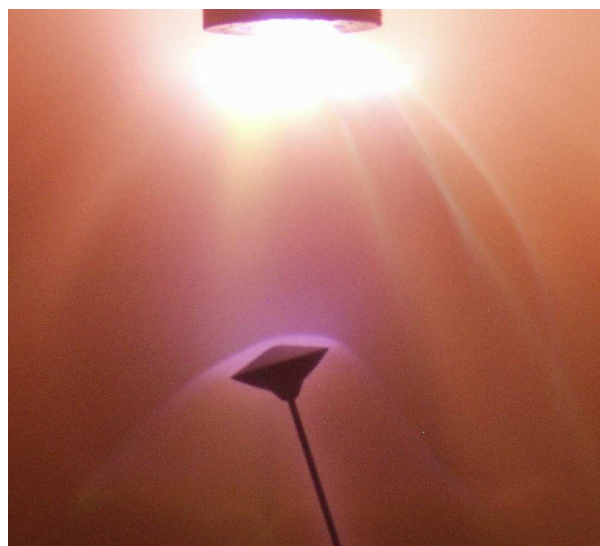


Figure 3: Mach 12, 1.5 cm model, 20°



Figure 6: Mach 8, 1.5 cm model, 0°

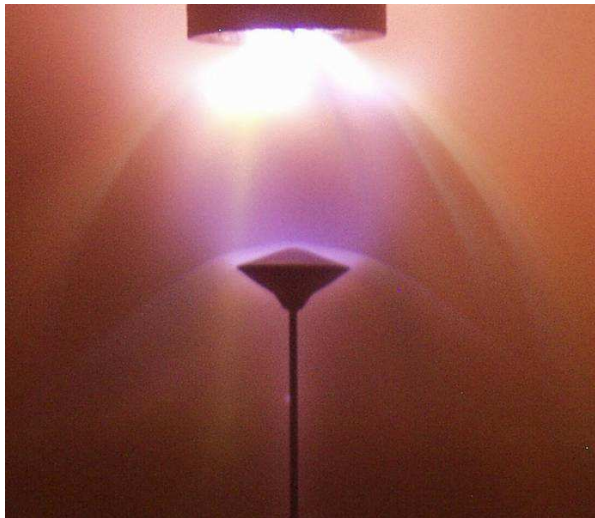


Figure 7: Mach 10, 1.5 cm model, 0°

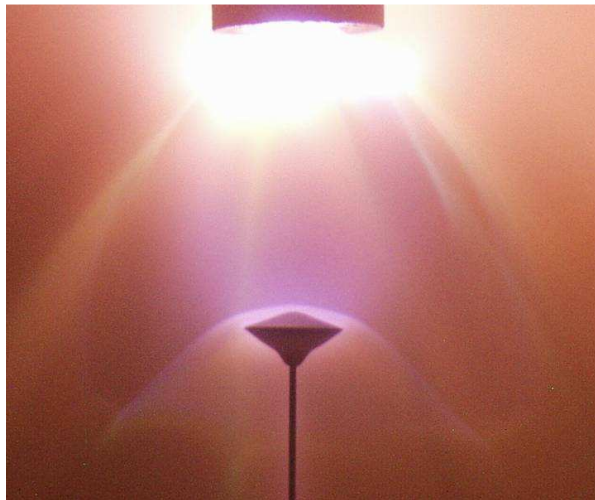


Figure 8: Mach 12, 1.5 cm model, 0°

Images for the smaller model at Mach 8, 10 and 12 at zero degree angle of attack are shown in Figures 6 through 8. These interactions behave much as expected for a bow shock off the model, with the bow shock bending more around the model at higher speeds. For increasing Mach numbers as well, the bow shock/barrel shock interaction occurs further downstream. The Mach stem for the barrel shock does not become apparent until at higher speeds of Mach 12.

Images for the larger model at speeds of Mach 10 and 12 as measured from the model's leading edge at a twenty degree angle of attack are shown in Figures 4 and 5.

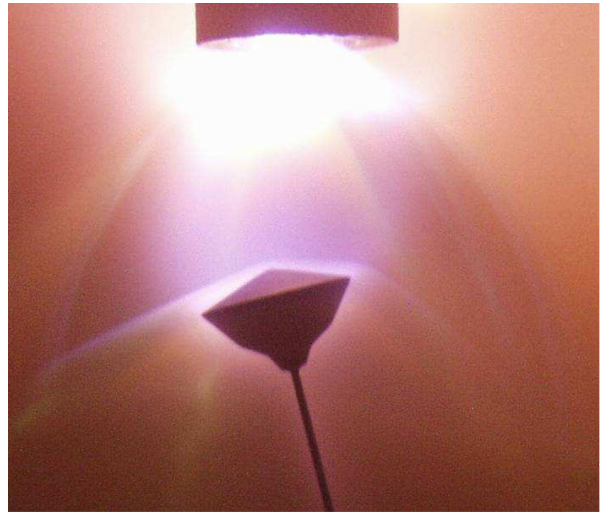


Figure 4: Mach 10, 2 cm model, 20°

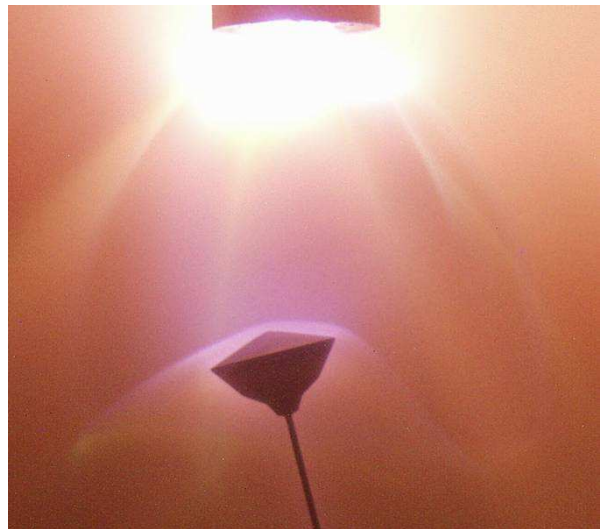


Figure 5: Mach 12, 2 cm model, 20°

For the larger model, the shock waves exhibit the same characteristic behavior as shown with the smaller model. For increasing Mach numbers, on both sides of the model, the shock wave extends less from

the model before curving down toward the model. The bow shock, barrel shock interaction again occurs somewhere along the Mach stem. It is important to note, however, that because of the larger size of the model, the Mach 10 bow shock looks much like the Mach 8 bow shock off the smaller model. This would indicate another variable – that with a larger model, the bow shock does not bend around the model as much. This larger model draws the bow shock/barrel shock interaction closer to the Mach stem. Problems in experimentation can occur if the bow shock sticks to the triple point on the Mach stem so that the bow shock is not simply influenced by the model but by the barrel shock as well. This would create an un-realistic picture of the interactions that exist in free flow for the Mars Science Lander since such interactions can create unnatural regions of subsonic flow.

Images for the Mach 10 and 12 conditions for the 2 cm model at zero degree angle of attack are shown in Figures 9 and 10.

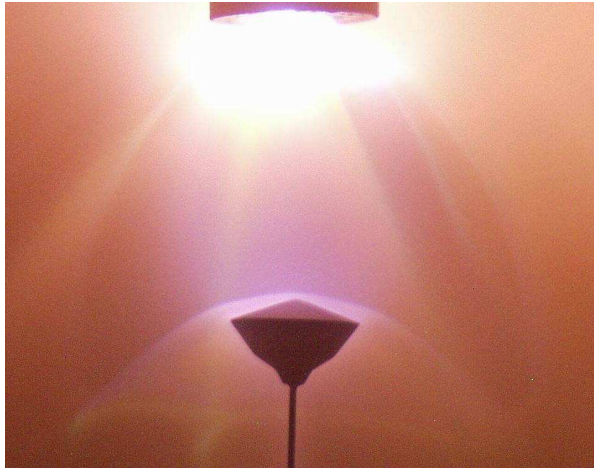


Figure 9: Mach 10, 2 cm model, 0°

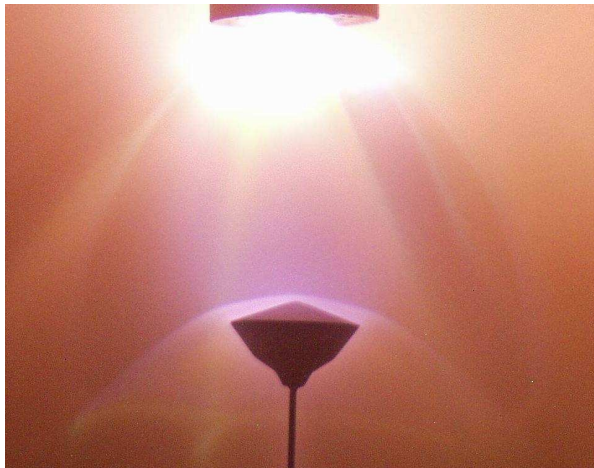


Figure 10: Mach 12, 2 cm model, 0°

For the zero degree angle of attack, the bow shock behaves as expected around the model. With increasing speed, the bow shock more closely follows the shape of the model as was seen before with the smaller model. However, there are also differences between the model size and bow shocks. With the larger model, although the shape of the bow shock looks very similar for both the larger and the smaller model, the bow shock/barrel shock interaction with the larger model occurs upstream of interaction seen for the smaller model. This moving upstream of the Mach stem can be perceived as a potential problem with the Mach stem occurring much sooner and thus creating subsonic regions that can affect the bow shock interactions. For purposes in studying the interactions in order to gain better physical understanding with the RCS, this could have a noticeable affect.

In order to better understand the RCS interactions, it is important to have the bow shock off the model represent physical reality as much as possible. Thus, it is important for the bow shock to be affected as little as possible by the barrel shock. In light of this, a more conservative approach of using the smaller 1.5 model would be advisable. However, as long as the experimentation is completed at higher Mach numbers, at an angle of twenty degrees angle of attack, the larger model should be adequate. Since the larger model will give better resolution for the RCS interaction and gives greater fidelity to the actual MSL, this larger model is desired for the experiments to examine RCS interactions.

Conclusion

In this paper, a parametric study was completed to determine model size that will be used in the investigation of RCS interactions. The understanding of these interactions is important in validating computational code as well as giving greater physical understanding of the phenomena that the MSL will experience during entry into the Martian atmosphere. After examining the images obtained for two model sizes at two angles of attack each at two or three Mach numbers, one can conclude that the larger model will be adequate for the purposes of the experiment, considering that results for the model at Mach 10 is of greatest interest. The larger model will be plumbed with an RCS and will be used with a PLIIF method of experimentation to obtain qualitative and quantitative results for the RCS interactions.

Acknowledgements

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