

High speed schlieren facility for visualization of flow fields in hypersonic shock tunnels

K. Satheesh, G. Jagadeesh* and K. P. J. Reddy

Department of Aerospace Engineering, Indian Institute of Science, Bangalore 560 012, India

The time-dependent evolution of flow around a 120° blunt cone model with a base radius of 60 mm has been visualized at Mach 8.8 and 9.2 using the newly established high speed schlieren facility in the IISc hypersonic shock tunnel HST2. The establishment and termination process of hypersonic flow in the shock tunnel is visualized using both argon and air as test gases. The experimental shock stand-off distance around the blunt cone matches well with the results from the computational fluid dynamics study.

Keywords: Blunt cone model, high speed schlieren facility, hypersonic shock tunnel.

MOST of the proposed Indian space missions in the next 20 years falls in the hypersonic flight corridor. Unlike the sub-sonic/sonic flight missions, the hypersonic flight domain continues to be an area where there are more questions than answers. This is primarily because of the inherent complexities in the flow aerothermodynamics around vehicles at speeds exceeding Mach 5. Unique flow features like thick shock layers, chemically reacting boundary layers, dissociated high-temperature flows, strong entropy gradients and viscous interactions dominate the hypersonic flight regimes. Notwithstanding the great progress made in computational fluid dynamics in recent years, careful experiments in the ground-based test facilities continue to be the only way for understanding the complexities of hypersonic flows around vehicles. However, since the power required for simulating an air flow varies as the cube of the velocity, it is virtually impossible to run ground test facilities for longer durations in the laboratory. Hence short-duration (few milliseconds) test facilities like hypersonic shock tunnels are routinely employed for simulating hypersonic flows around bodies in the laboratory. In fact, hypersonic shock tunnel is the only facility wherein one can simulate the flight Mach number, Reynolds number and the total energy content of the flow around bodies.

Both shock tunnel¹ and free piston-driven shock tunnels have been exhaustively used in the High Enthalpy Aerodynamics (HEA) Laboratory at the Indian Institute of Science (IISc), Bangalore for hypersonic flow research. The electrical discharge-based flow visualization tech-

nique^{2,3} was established for visualizing the shock wave around bodies in the IISc shock tunnel. This technique has also been successfully used to investigate the effect of test gas on the shock stand-off distance⁴. However, one of the major limitations of this technique is that it is possible to take only one snapshot of the hypersonic flow during the entire steady-state flow duration. As a consequence it is not possible to clearly quantify the dynamics of hypersonic flow evolution process in the shock tunnel. Proper understanding and precise characterization of the tunnel starting and flow termination processes are vital for accurate shock tunnel testing. In this backdrop a research programme has been initiated in the HEA Laboratory to establish a dynamic hypersonic flow field visualization tool that can be used to precisely map the short-duration shock tunnel flows. This article describes details of the high-speed flow visualization studies carried out in the IISc hypersonic shock tunnel along with important results. A 120° blunt cone model with a base radius of 60 mm has been used in the study to standardize and then integrate the new flow diagnostic tool with the hypersonic shock tunnel.

Experimental facility

Currently, three shock tunnels HST2, HST3 and HST4 have been commissioned and are fully operational in the HEA Laboratory, IISc. With these facilities one can simulate a range of stagnation enthalpies (0.7–20 MJ/kg) over bodies at different Mach and Reynolds numbers. The HST2 shock tunnel (Figure 1) operating in either the straight through mode or reflected shock mode with a Mach number range of 5.75 to 12, can simulate flow enthalpy up to 4.0 MJ/kg. The shock tunnel consists of a stainless steel shock tube of 50 mm diameter connected to a convergent–divergent conical nozzle of 300 mm exit diameter. The hypersonic flow goes through a 450 mm long test section of 300 × 300 mm square cross-section before entering the 1000 mm diameter dump tank. The driver and driven sections of the shock tube are separated by a metallic diaphragm of appropriate thickness and the shock tube and the nozzle are separated by a thin paper diaphragm. The flow Mach number in the test section is varied by changing the throat portion of the nozzle. Any desired test gas like argon or carbon dioxide can be filled in the driven section of the shock tube so as to simulate different gaseous atmosphere over bodies at hypersonic speeds.

*For correspondence. (e-mail: jaggie@aero.iisc.ernet.in)

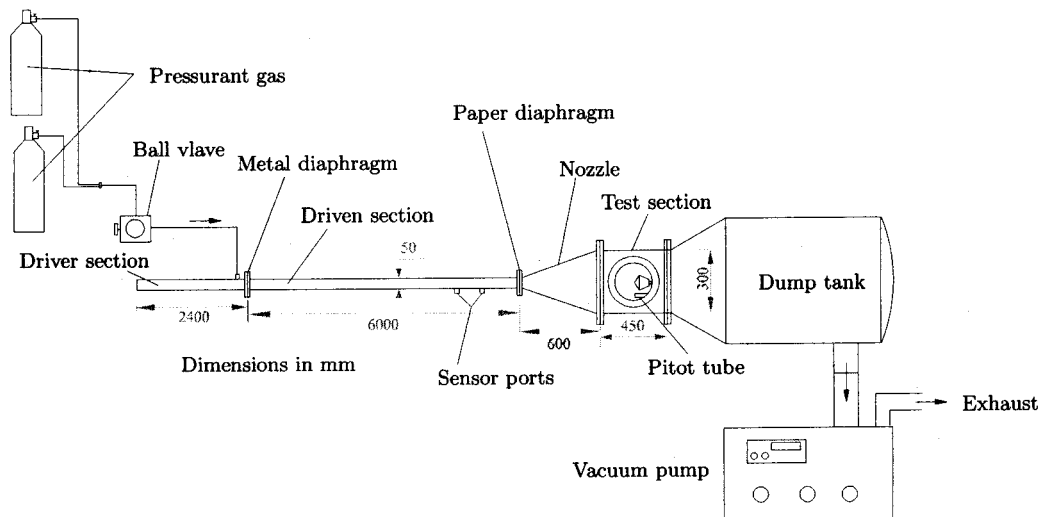


Figure 1. Schematic diagram of the HST2 facility.

Table 1. Typical shock tunnel experimental conditions in the present study

No.	M_∞	P_∞ (Pa)	ρ_∞ (kg/m ³)	T_∞ (K)	u_∞ (m/s)	Re	Test gas
R1	9.2	48.9	0.0029	58.7	1413	$1.0927e^6$	Air
R2	8.8	600	0.045	64	1340	$12.47e^6$	Argon

∞ , Free-stream condition; M , Mach number; P , Static pressure; T , Static temperature; ρ , Density; u , Velocity; Re, Reynolds number.

In the present experiments carried out in a hypersonic shock tunnel HST2, air and argon are used as the test gases to simulate two different free stream conditions that are shown in Table 1. In recent times we have been evaluating the possibility of using concentrated electrical energy as a means to reduce the aerodynamic drag of vehicles flying at hypersonic speeds. In these types of experiments it is necessary to evaluate the thermal effects of energy deposition on the hypersonic flow field. In order to evaluate the suitability of shock tunnel to carry out these kinds of novel experiments, in the present study we have selected both argon (monatomic) and dry air (diatomic) as test gases. Condition 1 corresponds to the tunnel operation in the reflected mode with dry air as test gas and condition 2 refers to the straight through mode of operation of the tunnel with argon as the test gas. Successive evacuation of air in the driven section of the shock tube followed by filling up of argon is important to ensure hypersonic argon jet in the test section during tunnel operation. Because of the variation in the coefficient of specific heat and local acoustic speed in argon environment, for the same ratio of driver to driven section operational pressure differential higher Mach number flow can be simulated in the tunnel. The conditions mentioned in Table 1 can be repeated within $\pm 5\%$.

Dynamic schlieren set-up in IISc shock tunnel

The schlieren imaging technique⁵ is a widely used method for visualizing inhomogeneities in transparent gaseous

medium. This technique works by making use of the refraction of light due to the spatial variations in the refractive index of the media under study. Here a parallel beam of light is allowed to pass through the test area, after which it is focused on a knife edge. Due to the inhomogeneities in the media, light from different parts of the test area will be refracted by different amounts and thus will not focus at the same point. The knife edge then selectively blocks the light rays coming from different parts of the test area, depending on the orientation and the amount of refraction undergone by the light rays. As a result of this selective blockage of light, the inhomogeneities (density changes) in the test area show up as intensity gradients in the resultant image, the contrast (fractional change in intensity with respect to the background intensity) of which at a point is directly proportional to the density gradient at the corresponding point in the test flow¹. A 'z-type' schlieren set-up (Figure 2) was used for visualization of the hypersonic flow field, wherein a pair of concave mirrors of focal length of 96" are used to obtain the parallel beam of light and then for focusing it on the knife edge.

In most conventional systems a camera with film or a digital camera is used to record the schlieren images. While for long-duration experiments the speed of the camera is a trivial issue, for short-duration experiments like in shock tunnels, the type of the camera plays a vital role. Even in cases where we need to record only a single snapshot of the event during the shock tunnel testing, it is not possible to click the camera manually since the time

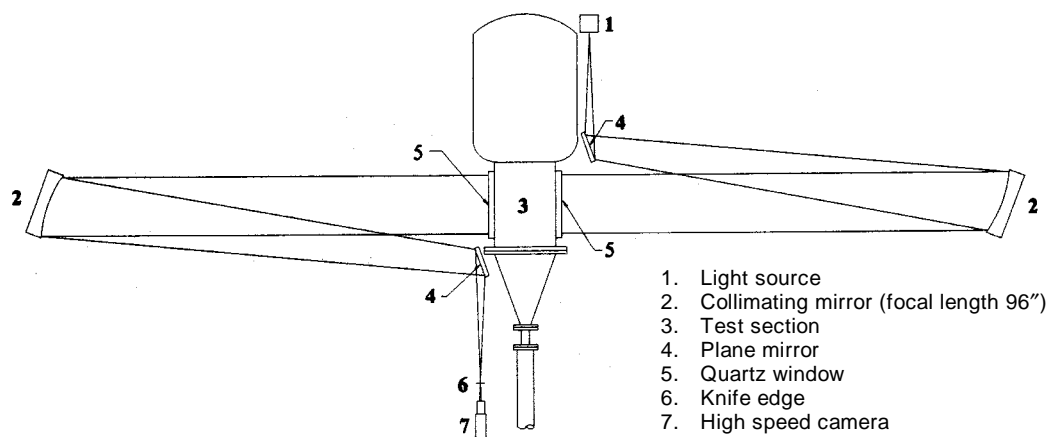


Figure 2. Schematic diagram of the high speed schlieren visualization set-up used in the present experiments.

available to us is only 1 or 2 ms. This implies that we either use a stroboscopic light flash and synchronize the same with the physical event by keeping the camera in the classical B exposure setting or go in for a high speed camera with electronic gating facility. Because of the low values of flow density in the shock tunnel, even these kinds of single shot recordings need high speed films with typical speed of ASA 1400 and above. However, using ordinary camera we will not be able to dynamically monitor the evolution of hypersonic flow in the shock tunnel. The only way of monitoring the dynamics of hypersonic flow in a shock tunnel within 1 or 2 ms is using a high speed digital camera with reasonable resolution at high speeds as the recording medium along with appropriate accessories.

In an ideal scenario it is better to use a light source which is capable of giving short duration (10 or 20 μ s) light pulses and then synchronize the same with a high speed camera and the shock tunnel operation for high resolution schlieren images. However, this arrangement will be complex and here it is rather difficult to achieve satisfactory synchronization with shock tunnel operation because of non-compatible inherent delays in the electronic hardware accessories. Hence in the present experiments we have used a Phantom 7.2 high speed camera (Ms Vision Research, USA) that is capable of recording 6688 frames per second at full resolution of 800×600 pixel using SR-CMOS imaging array. As we keep increasing the recording speed the pixel resolution reduces and hence for the given condition, we have to optimize the operational conditions of the camera. This camera has the continuous adjustable resolution feature that enables us to enhance the speed of the camera with adjustable 16×8 pixel increments. In the present experiments, the schlieren images have been recorded by operating the camera at a speed of 10,000 frames per second with a resolution of 450×450 pixels. The Standard 300 W North Star lamp with C-Clamp base, is used as the continuous light source. Operation of the camera was synchronized with the shock tunnel flow using a trigger pulse generated by the pres-

sure sensor located at the end of the shock tube. The light is switched on before the experiments and only the camera is triggered to synchronize with shock tunnel experiments.

Results and discussions

The schlieren images recorded by the high speed camera during the experiment reveal the various features of the shock tunnel flow. Figure 3 is a set of sequential photographs recorded during a typical shock tunnel experiment. The hypersonic flow field around the blunt cone during the nozzle starting time, steady test flow and the termination is clearly seen in these images. The nozzle starting time shown in the sequential schlieren images compares well with the pitot pressure measurements (Figure 4) in the test section, which also takes about 600 μ s to reach a steady state.

The pitot pressure measurement indicates the presence of a steady flow for about 1 ms, which in turn is taken as the useful test duration of the facility; however, the shock structure in the schlieren images remains unaltered for almost 3.6 ms. This could be explained with reference to Figure 5 which shows the time variation of the ratio of pitot pressure (P_{02}) to the stagnation pressure (P_{01}). This pressure ratio, which is a unique function of the Mach number and the specific heat ratio of the test gas remains steady for more than 3.5 ms. As a result, the free stream Mach number also remains invariant for that duration. The shock structure being mainly dependent on the free stream Mach number, also remains unaltered during this period, as seen in the schlieren images. Even as the flow Mach number remains unaltered for 3.5 ms, other flow properties such as the free stream density, static pressure, etc. begin to drop after remaining constant for a period of 1 ms. Also, from Figure 4 it is clear that both the reservoir and pitot pressures in the test section start decreasing after remaining steady for about 1 ms. Once the total pressures drop, it heralds the termination of the test time in the

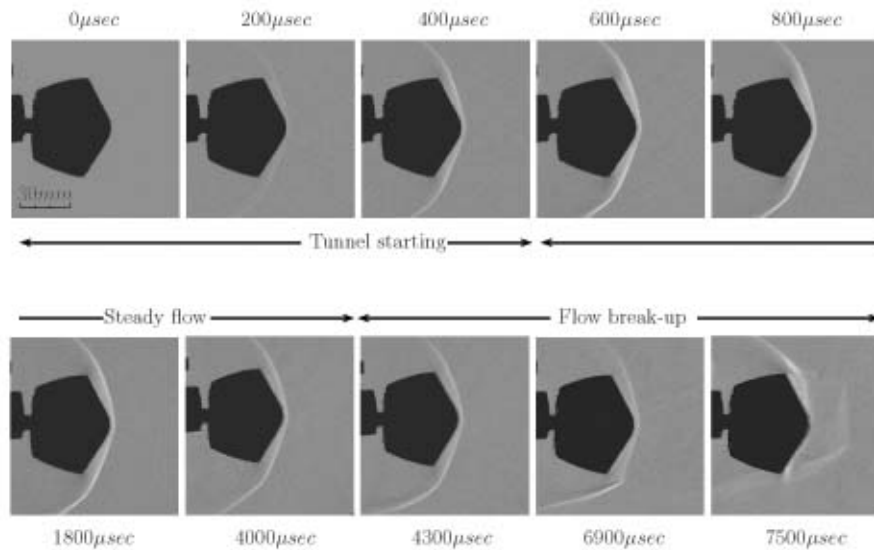


Figure 3. Dynamics of shock tunnel flow evolution corresponding to condition R1.

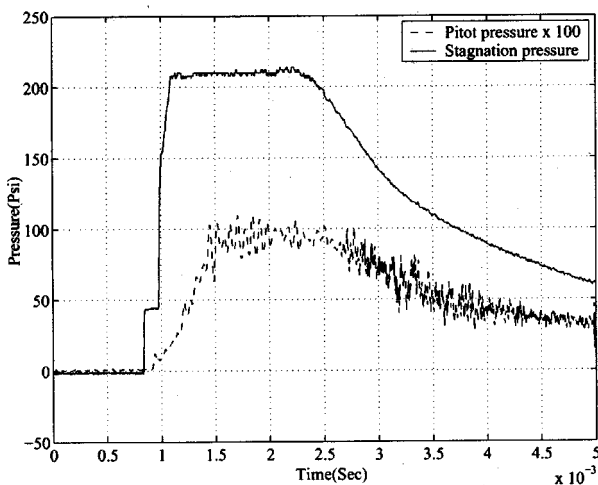


Figure 4. Typical pitot pressure trace recorded for the experimental condition R1 along with the corresponding stagnation pressure variation.

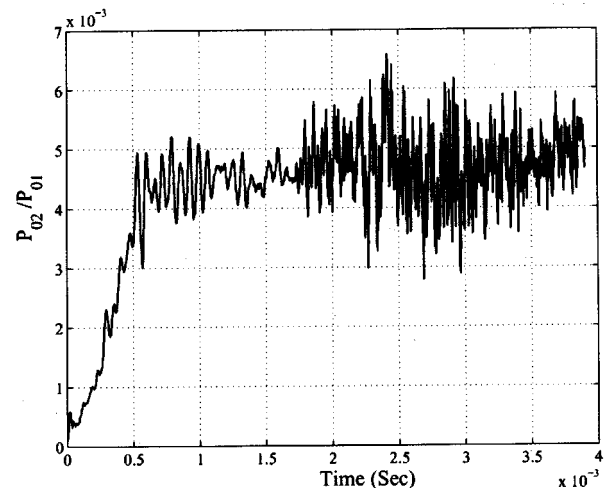


Figure 5. Variation in the ratio of pitot pressure to stagnation pressure for the experimental condition R1.

shock tunnel. Also during the tunnel operation, the dump tank pressure rises gradually and when this value becomes more than that of the free stream static pressure, the disc shocks are generated at the nozzle exit, thus disrupting the hypersonic flow. This phenomenon is also visible in the sequential schlieren images, with the last frame clearly showing the Mach disc formation characteristic of over-expanded nozzle flows. With the successful integration of this high speed flow diagnostic with the shock tunnel, it is now possible to actually see the hypersonic flow during a typical test by which we can easily characterize the flow field around any vehicle.

The shock stand-off distance⁶, especially along the stagnation streamline, is a unique signature of the body geometry and the flow Mach number. In fact, most of the blunt-body hypersonic flow fields are characterized by

the shock stand-off distances ahead of the blunt body. In order to quantify the results from the high speed visualization studies, the shock stand-off distance along the length of the blunt cone was digitally measured from the schlieren images. In order to complement the experiments, the hypersonic flow around the blunt cone was also simulated by solving the Navier–Stokes equation in the axi-symmetric formulation using commercial CFD (Computational Fluid Dynamics) package CFX 5.7. The experimentally visualized bow shock wave in front of the 120° blunt cone model along with the results from the computational study is shown in Figure 6. Variation of the shock stand-off distance along the surface of the blunt cone obtained from both experiments and CFD studies is shown in Figure 7. Agreement between experiments and the CFD study is good. However, about $\pm 10\%$ difference

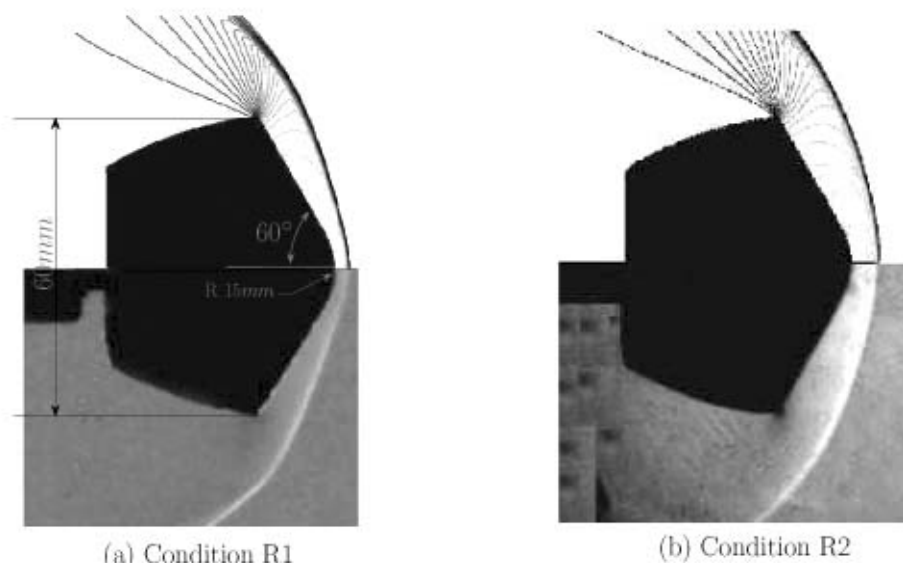


Figure 6. Comparison of experimental and computed shock wave structure in front of the blunt cone.

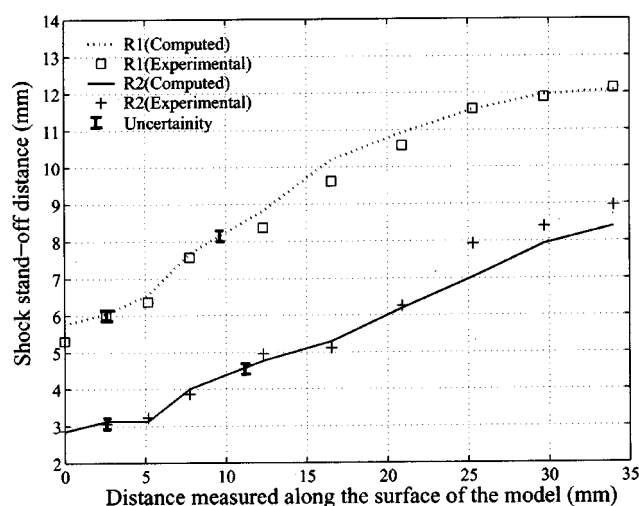


Figure 7. Comparison of the experimental and computed shock stand-off distances along the surface of the blunt cone.

is observed in the measured shock stand-off distance near the corner of the blunt cone model in the argon environment. These differences could be attributed to inadequate resolution of the schlieren system to capture diffused shock structure near the corner of the model, where the flow expands rapidly and the associated problems of simulating accurately hypersonic expanding flows using commercial CFD codes. However, the results from the study certainly reinforce the confidence in the capability of shock tunnels to simulate hypersonic flows around bodies in the laboratory.

Conclusion

With the development of a new ultra-fast flow visualization diagnostic in IISc, it is now possible to capture the

dynamics of the hypersonic flow evolution process in shock tunnels where the typical useful test time is 1 or 2 ms. The time-dependent evolution of the flow around a 120° blunt cone model with a base radius of 60 mm has been visualized at Mach 8.8 and 9.2 in the IISc hypersonic shock tunnel HST2. The schlieren optical technique is used for visualizing the starting and flow establishment characteristics in the shock tunnel using both argon and air as test gases. With the successful establishment of high speed flow visualization tool in the IISc shock tunnel complex, fascinating hypersonic flow problems such as drag reduction using concentrated electrical energy deposition, use of nose cavity for drag reduction in missile-shaped bodies, use of counter flowing air jets for hypersonic drag reduction and characterization of hypersonic separated flows are being currently studied in the HEA Laboratory in IISc.

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Received 10 August 2006; revised accepted 14 November 2006