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Experiments on a Blunt Cone Model in a Hypersonic Shock Tunnel

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Abstract

The experimental investigation on a 60^0 apex-angle is carried out to study feasibility of simultaneous measurement of drag and aerodynamic heating in a shock tunnel. A three-component accelerometer balance system is used to measure the drag whereas platinum thin film gauges are used for heating rate measurements on the surface of the blunt cone model. Since every ground test and flight test data have unique test conditions, so the importance of simultaneous measurement is realized by measuring both drag and heating rates under unique test conditions during gas injection at the nose of a blunt cone model flying at Mach 5.75, in a IISc hypersonic shock tunnel (HST2). In addition, flow visualization experiments are also conducted on the blunt cone model using electric discharge technique.

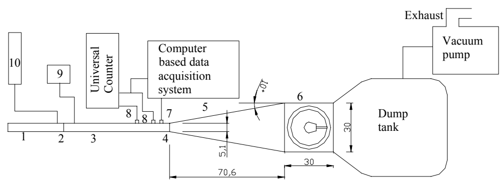
Introduction

The aerodynamic drag and heating are the two dominating features in the design of hypersonic vehicles. The aerodynamic heating increases as the cube of the velocity whereas the aerodynamic drag increases as the square of the velocity [1]. The heating problems are reduced to some extent by employing the large angle body configurations, but then the drag increases. In the context of model geometry, the stagnation point aerodynamic heating varies inversely as the square root of nose radius [1]. So the larger is the nose radius, lower is the aerodynamic heating and vice versa. Many variations of the aerodynamic shapes were studied to address the issues of heating and drag. Among the most recent advances, is the Jupiter re-entry vehicle (45^o semi-apex angle blunt cone model with bluntness of 0.352) and Mars pathfinder vehicle (70^o apex-angle sphere-cone model with bluntness of 0.5). The ballistic range of tests conducted on Jupiter entry vehicle configuration (Galileo probe) highlight the importance of aerodynamic drag [2] whereas the Mars entry configuration [3] highlights the importance of aerodynamic heating tests. The surface heat transfer rates over 140^0 blunt cone configurations are also routinely measured in impulse types of testing facilities [4, 5]. These reports in the literature address the importance of aerodynamic heating and drag independently because the model size doesn't allow implementing requisite instrumentation for simultaneous measurements. Moreover, unique test conditions can not be repeated in short duration testing facilities if the drag and heating rates are measured independently.

Severe aerodynamic heating during re-entry, is another concern for designing hypersonic vehicle which in turn decides the requisite thermal protection system (TPS). Hence, simultaneous measurement of aerodynamic heating and drag on blunt cone models with a feasible thermal protection will address some of the issues in a hypersonic flow fields. A novel method was proposed by Menezes et al. [6] by using a forward facing retractable aero-spike for reducing the wave drag for blunt-nosed bodies flying at supersonic and hypersonic speeds. It was shown that by incorporating suitable geometry of aero-spikes the flow field around the blunt cone can be modified. However, the spike becomes hot and ablates as a result of large stagnation temperature, hence requires frequent replacement or active cooling. One of the alternate solutions is to achieve similar effect using a forward facing gaseous jet. In the present paper, the experimental investigations are carried out on a 60^0 apex-angle blunt cone model to explore the effectiveness of forward facing gaseous jets on aerodynamic flow field modification where the effect of drag and heating rates are predominant under a given test condition. In particular, the model is designed such that both drag and surface heat transfer rates can be measured simultaneously. In addition, flow visualization study using electric-discharge technique is attempted to understand the shock structures in the hypersonic flow field. All the experiments are carried out at flow Mach number of 5.75 in IISc hypersonic shock tunnel HST2. Moreover, the data for surface heating rates and drag are presented for unique test conditions which not only cost effective but also saves time.

Experimental Facility

The experimental investigations are carried out in the HST2 hypersonic shock tunnel, shown schematically in Figure 1.



1. Driver section
2. Aluminum diaphragm
3. Driven section
4. Paper diaphragam
5. Conical nozzle
6. Test section
7. Location of pressure transducer
8. Thermal sensors ports for shock speed
9. Driven section vacuum pump
10. Pressurized driver gas cylinder

Figure 1: Layout of IISc hypersonic shock tunnel, HST2.

It comprises of a shock tube, a conical nozzle, square test section and a dump tank along with a high efficiency vacuum pumping system. The tunnel is capable of producing a reservoir enthalpy up to 4.0 MJ/kg and has an effective test time of about 800 μs. The hypersonic flow goes through a 450mm long test section of 300mmx300mm square cross section before entering the 1000mm 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. Typical test conditions achieved in HST2 shock tunnel are listed in Table 1.

Table 1: Nominal test conditions in HST2

Driver gas	Nitrogen and helium
Primary diaphragm thickness	1mm and 1.5 mm
Shock Mach number, M_s(± 2.5%)	2.1 to 3.6
Stagnation pressure, P_o (± 8%)	220 to 1030 kPa
Stagnation enthalpy H_o(± 10%)	0.70 to 1.6 MJ/kg
Free stream Mach number M_∞ (±2%)	5.75
Free stream static pressure P_∞ (± 5%)	0.18 to 0.85 kPa
Free stream static temperature, T_∞(± 9%)	90 to 210 K
Free stream unit Reynolds number, $R_{e\infty}$ (± 16%)	~ 10^6 (m^{-1})

Measurement of Drag and Aerodynamic Heating Rates

The phenomenon of forward facing gaseous jet as a means of flow field modification is explored by measuring drag and surface heating rates around a blunt cone model flying at Mach 5.75 in HST2 shock tunnel at 0^0 angle of attack. The 60^0 apex-angle blunt cone with bluntness of 0.857 is shown in Figure 2 whereas the photograph of the model is shown in Figure 3.

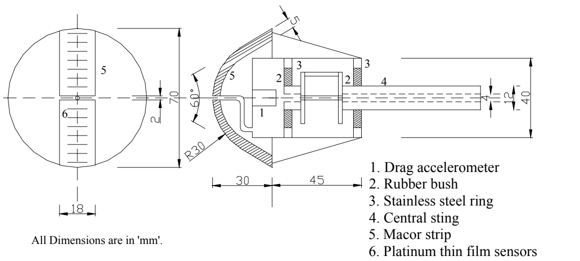


Figure 2: A 60^0 apex-angle blunt cone model fitted with an accelerometer balance system and platinum thin film gauges for simultaneous drag and heat transfer measurements

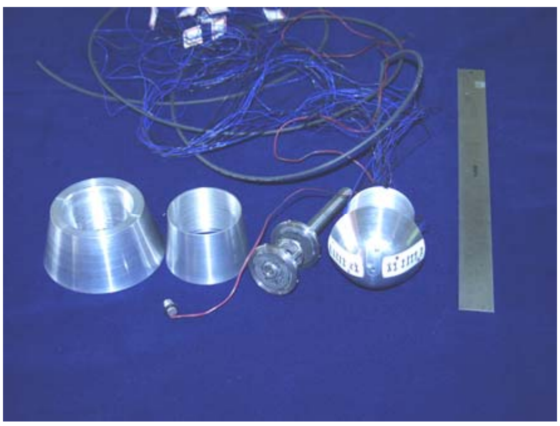


Figure 3: Photograph of the 60^0 apex-angle blunt cone model along with an accelerometer balance system and platinum thin film gauges for simultaneous drag and heat transfer measurements.

The gases under atmospheric conditions are injected into the hypersonic flow through a hole of 2 mm diameter at the nose of the model. A flexible pipe connected to this hole passes internally along the hollow sting that in turn is connected to the tunnel port. The aerodynamic drag over the model is measured using the three-component accelerometer balance system whereas the platinum thin film sensors deposited on the Macor insert measures convective heating rates. The basic principle of measurement of aerodynamic forces and surface heating rates are highlighted by Sahoo et al. [7] and Jagadeesh et al. [5], respectively. Because of having a hole of 2 mm diameter at the nose of the model, it is almost impossible to mount the heat transfer gauges at the stagnation point. However, the heat transfer gauges mounted closest to the stagnation point is at the location of (s/R_n) as 0.3333 where s is the arc length on the cone surface measured from geometric stagnation point and R_n is nose radius. This is again based on the minimum thickness of the Macor for which one-dimensional heat conduction equation can be assumed.

The test model (Figure 2 and 3) is used to study the phenomena of forward facing gaseous jet during shock tunnel testing at 0^0 angle of attack under two different stagnation enthalpy conditions at Mach 5.75. Four different gases (air, argon, carbon dioxide and helium) are injected into the hypersonic stream through a hole of 2 mm diameter at the nose of the model. The operating pressure ratio ensures choked mass flow rate at the nozzle exit plane.

A typical temperature-time history and the corresponding numerically integrated heat transfer signals with and without gas injection are shown in Figure 4 and 5, respectively. The force-time history inferred from the drag accelerometer with and without air injection is shown in Fig. 6.

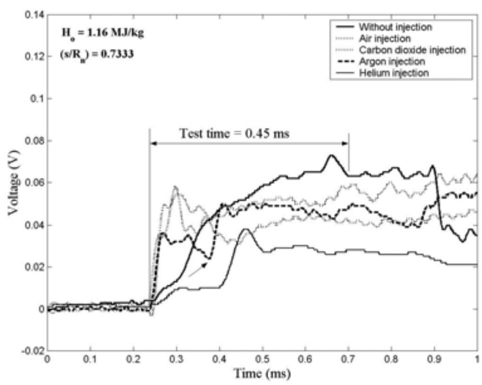


Figure 4: Typical temperature-time history from platinum thin film sensors 'with and without' gas injection.

Maximum reduction in heating rate of about 40 % is observed at the gauge location of (s/R_n)= 0.7333 for stagnation enthalpy of 1.16 MJ/kg with carbon dioxide injection and the corresponding values change to 28 % with helium injection. About 12-25 % increase in the aerodynamic drag coefficient is observed at all enthalpy conditions. The reason for the drag enhancement is because the operating pressure is not adequate enough to produce a gas jet into the oncoming hypersonic flow and thereby forms a thin film around the test model. It leads to 'heat buffer' between the hot air stream and the body which reduces the heat transfer rates substantially. Since, the operating pressure ratio is not sufficient to push the body shock away from the blunt body surface, and hence leads to increase in the gas density due to gas injection in the stagnation region which in turn increases aerodynamic drag. The detail investigation on effectiveness of forward facing gaseous jet on film cooling can be found in Sahoo et al. [8].

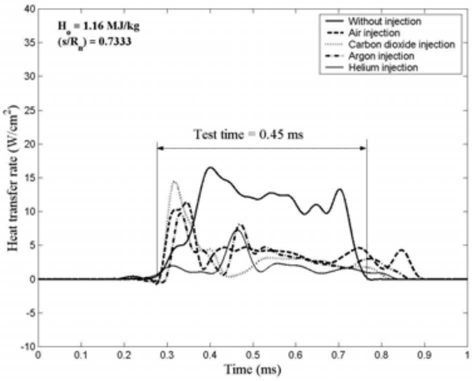


Figure 5: Numerically integrated heat transfer signal for platinum thin film sensors ‘with and without’ gas injection.

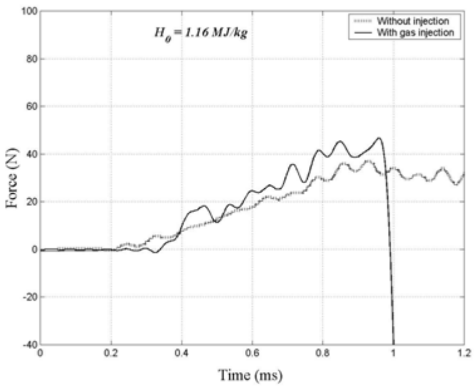


Figure 6: Typical force-time history inferred from drag accelerometer at 0^0 angle of attack.

Flow Visualization Study for Blunt Cone Model

In order to highlight the factual evidence of shock structure with forward facing gaseous jet into the hypersonic flow field, flow visualization study around the blunt cone model is attempted. This would essentially complement the results of simultaneous measurement of drag and surface heating rates. The electric discharge technique [9] is used in the present study to visualize shock structure on the blunt cone configuration. This technique is based on the principle that the intensity of spontaneous radiation emitted by the ion recombination in an electric discharge depends on the gas density and temperature along the discharge path. So when an electric discharge is generated across a shock wave, the light emitted from the shock wave region will be very weak compared to that of free stream and shock layer. Based on the density and temperature difference of the shock layer and free stream, the shock shapes appear in the intensity field and can be captured by taking the photograph of the discharge column.

The schematic diagram of the electrode arrangement for the 60^0 apex-angle blunt cone with 15^0 flared model, used for flow visualization studies is shown in Figure 7. A 1 mm diameter stainless steel sewing needle with a sharp tip suspended from the roof of the test section is used as a point electrode (+ve) while a 0.5 mm thick copper strip, embedded into the model such that one of its edges is flush with the front surface of the blunt cone, acts as a line electrode (ground). The electrodes are kept about 50 mm apart and operating voltage and current across the electrodes are fixed at 1.8 kV and 1Amp, respectively. A Bakelite hylem blunt cone model is used in the experiments to ensure insulation and also to avoid multiple reflections from the model surface. The application of high DC voltage across the electrodes is controlled by the switching transistor, which in turn is controlled by the triggering pulse from the pulse delay unit [10]. In most of the experiments the duration of the electric discharge between the electrodes is maintained at ~ 2 μs. In order to avoid blockage of the flow in the tunnel test section and to maintain sufficient gap between the model edge and the point electrode attached to the test section wall, the size of the flow visualization test model is scaled down to 42 % of the one used for force and heat transfer measurements while maintaining the geometrical similarity. A SLR camera (Cannon F1.4) operated in the bulb exposure mode using ASA 1600 speed film, which is further boosted to ASA 6400 by appropriate developing technique, is used to capture the photograph. A typical experimental result of the shock shape visualization carried out for the enthalpy conditions of 1.16 MJ/kg is shown in Figure 8 without gas injection.

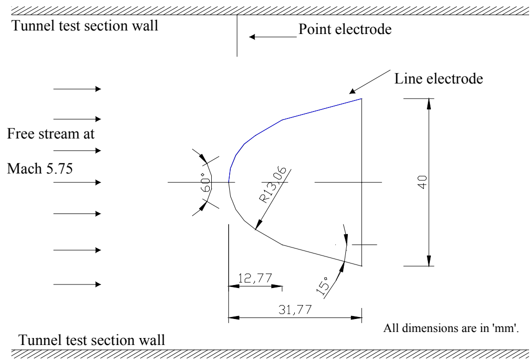


Figure 7: Schematic diagram of blunt cone model with electrode arrangement for flow visualization experiment.

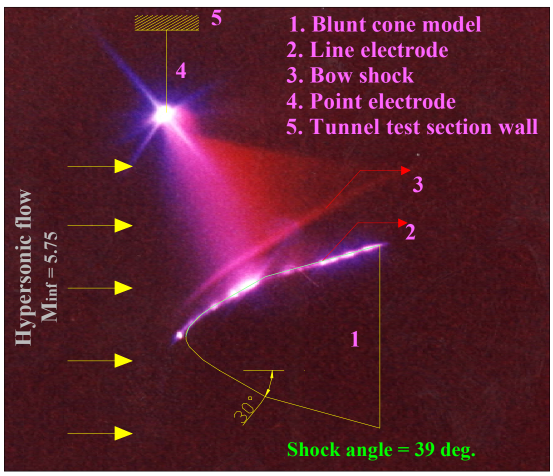


Figure 8: Shock structure around the blunt cone model.

In this picture, the bright lines in the conical portion of the model indicate the shock position. However, the bright lines are not clear in the nose region because the discharge from the point electrode in the test section didn’t strike the line electrode embedded on the nose portion of the model surface. The portion of the body in which the strength of the discharge column is more, appears as bright line and discharge column gets diffused near the spherical portion of the model.

The motivation of flow visualization study undertaken in the current investigation is to observe whether or not the hypersonic flow field gets modified due to gas injection. Unfortunately, the shock shapes could not be captured with gas injection due to several technical difficulties encountered during experiment. In fact, the whole process involves the synchronization of electrical discharge with the establishment of hypersonic flow in the test section with gas injection, controlling the delay and discharge times in the pulse delay unit and most importantly photographic recording during electric discharge. So no other details are being reported here because this method needs further improvements in this area in order to capture shock shapes with gas injection. However, the shock shapes around the blunt cone model without gas injection confirms the hypersonic flow quality in the tunnel.

Conclusions

Simultaneous measurement of aerodynamic heating and drag is carried out for a 60^0 apex-angle blunt cone model to study the effect of hypersonic flow field modification due to a forward facing gaseous jet at the nose of the model. Four different gases (air, carbon dioxide, argon and helium) are injected into the hypersonic flow field at different enthalpy levels. Maximum reduction of surface heating rates of 40% is observed in the vicinity of stagnation point with carbon dioxide injection whereas the aerodynamic drag is enhanced by 12-25%. Flow visualization study is attempted to reveal the shock structure in the hypersonic flow field. Although shock shapes around the test model without gas injection gives a clear picture, but due to experimental difficulty, similar experiments could not be completed with gas injection.

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