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Aerodynamic drag reduction by heat addition into the shock layer for a large angle blunt cone in hypersonic flow

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Reduction in aerodynamic drag for a large angle blunt cone flying at hypersonic Mach number by heat addition into the shock layer is demonstrated in HST2 hypersonic shock tunnel. The heat addition is achieved by the exothermic reaction of chromium atoms ablated from the stagnation region of the chromium coated blunt cone with the atomic oxygen behind the shock wave. The measurements show about 47% reduction in the drag coefficient for a 60° apex angle blunt cone in a Mach 8 flow of 3.4 MJ/kg specific enthalpy. The reduction in drag is measured using the accelerometer based force balance system and the heat addition into the shock layer is identified by the surface mounted thin film heat flux gauges and the corresponding movement of the shock wave is visualized by schlieren pictures. © *2008 American Institute of Physics*.
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Enhanced wave drag is the penalty paid for adopting blunt body configurations to reduce the aerothermal loads on space vehicles traveling at hypersonic speeds. In order to overcome the large drag force encountered by the high speed vehicles, many schemes have been proposed and analyzed both numerically as well as experimentally. Most of these drag reducing schemes have been investigated and implemented predominantly in supersonic regime. In recent times we have been investigating the application of these drag reducing schemes to blunt body configurations traveling at hypersonic Mach numbers using hypersonic shock tunnels.[1–4] These schemes include a forward facing aerospike mounted at the stagnation point of the blunt body,[1] opposing supersonic gas jet ejecting from the stagnation point of the model in hypersonic flow,[2] deposition of energy into the hypersonic flow upstream of the stagnation point of the model,[3] and adding a stepped afterbody at the base of the model.[4]

Although these techniques have shown an appreciable reduction in the wave drag, their application to practical systems is inhibited by the enhancement in system complexity. In order to overcome this problem, we have developed a novel drag reduction technique in which the drag reduction is achieved by adding heat into the shock layer in front of the blunt cone.[5,6] The heat is added through the exothermic reaction of the ablated atoms from the nose portion of the model coated with thin film of appropriate material. The aim of this letter is to report the experimental results of the wave drag reduction achieved using the proposed new technique for a 60° apex angle blunt cone flying at hypersonic Mach number. The change in the drag coefficient is measured using an accelerometer based balance system and the heat addition due to the exothermic reactions is measured using surface mounted platinum thin film heat flux gauges and the corresponding displacement of the shock wave is measured using schlieren technique.

The experiments for drag reduction study are carried out in the HST2 hypersonic shock tunnel,[7] which consists of a stainless steel shock tube of 50 mm internal diameter connected to a convergent divergent conical nozzle of 300 mm exit diameter. The driver and driven sections of the shock tube are separated by an aluminum diaphragm. Three pressure sensors are mounted along the length of the shock tube, on the driven section side, for the measurement of shock speed and the stagnation pressure at the entry to the nozzle. The Mach 8 hypersonic flow from the nozzle goes through a 450 mm long test section of 300×300 mm^2 square cross section. The specific freestream enthalpy of the flow in the shock tunnel can be varied by choosing the metal diaphragm of appropriate thickness. The current set of experiments was performed at two flow enthalpies of 2.3 and 3.4 MJ/kg and the typical freestream conditions for 3.4 MJ/kg flow are given in the Table I.

A 60° apex angle blunt cone model having 70 mm base diameter and bluntness ratio (defined by the ratio of nose diameter to base diameter) of 0.857, as shown in Fig. 1, was used to demonstrate the proposed drag reduction technique. The model was equipped with an internally mounted accelerometer based force balance system having rubber bushes to provide free floating condition during the test time.[8] The force balance was calibrated using an impulse hammer to obtain system transfer function. Platinum thin film gauges coated on 5 mm thick thermally insulating material MACOR were flush mounted on the model to measure the heat flux on the wall of the model during the hypersonic flow. The flow fields around the model in the test section were visualized using the schlieren visualization technique.[9] The schlieren images were recorded using a high speed camera with highest frame rate of 0.2×10^6 frames/s (Vision Res. Inc., USA). The flowfields were recorded at the acquisition rate of

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TABLE I. Freestream conditions of the current set of experiments in HST2 shock tunnel.

Freestream Mach number M_∞	6.9
Freestream static pressure P_∞ (kPa)	0.654
Freestream static temperature T_∞ (K)	322.0
Freestream stagnation pressure (kPa)	4052
Freestream stagnation temperature (K)	2850.0
Freestream stagnation enthalpy (MJ/kg)	3.4

10 000 frames/s in the current set of experiments. After completing the set of force and heat transfer measurements, the blunt cone was coated with 95% pure chromium before repeating the measurements. The chromium is a hard metal with a melting point of 2180 K and is an exothermic material having heat of vaporization of 339.5 kJ mol^{-1}. The basic blunt cone model was made of aluminum alloy and the 10 μm thick chromium was coated on the model using electrolytic deposition technique.

The model was mounted across the hypersonic flow along with the Pitot probe in the test section of the HST2 shock tunnel. Consistency of all the results, with and without chromium coating, was ensured by repeating many experiments and the average values of the measured parameters are presented in this communication. The theoretical estimate of the drag coefficient for the blunt cone in Mach 8 flow is calculated using the following empirical relation:[10]

$$C_D = \left(0.0016 + \frac{0.002}{M^2}\right)\delta^{1.7} + C_{L\alpha}\alpha^2,$$

where C_D is the drag coefficient, $C_{L\alpha}$ is the lift coefficient at the angle of attack α, δ is the semiapex angle of the blunt cone, and M is the flow Mach number. For the present blunt cone model at zero degree angle of attack in the Mach 8 hypersonic flow, the estimated drag coefficient is 0.53. The experimental value of the drag coefficient for the model in the test flow was determined from the measured model acceleration due to the induced wave drag using the deconvolution procedure described earlier.[8] The deconvoluted drag force signals for the model with and without chromium coating are shown in Fig. 2 for the flow enthalpy of 2.3 MJ/kg. It is seen from this figure that the drag force is not affected by the presence of chromium plating. The drag coefficient measured using these signals is 0.58, which matches very well with the theoretically estimated value.

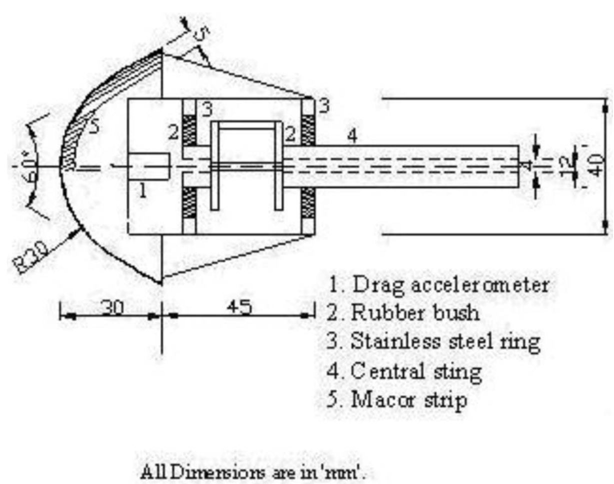

FIG. 1. Schematic diagram of the 60° apex angle blunt cone model fitted with an accelerometer based balance system and thin platinum film heat transfer gauges.

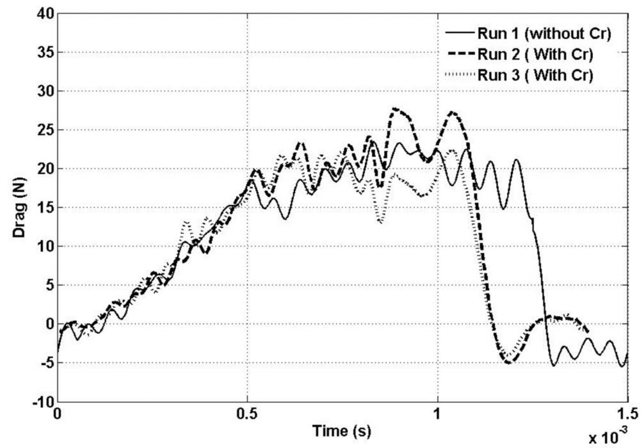

FIG. 2. Measured drag signals for the 60° apex angle blunt cone with and without chromium plating in Mach 8 hypersonic flow with a specific enthalpy of 2.3 MJ/kg.

The experiments were repeated for the flow enthalpy of 3.4 MJ/kg and the measured drag force signals are presented in Fig. 3. The measured drag force for the blunt cone with and without chromium plating shown in Fig. 3(a) clearly indicates the substantial reduction in drag force due to the presence of chromium plating. The reduced drag coefficient of 0.31 estimated from the measured drag force for the chromium plated blunt cone is 47% lower than the corresponding coefficient for the blunt cone without chromium coating. Hence the presence of chromium coating has resulted in the net reduction in drag coefficient by 47%. In order to understand the phenomenon of drag reduction and the sequence of events during the process of drag reduction, the measured drag signal is plotted in Fig. 3(b) along with the total pressure signal measured by the pitot probe mounted in the test section along with the blunt cone. It is seen that the flow takes about 500 μs to reach steady state and it remains steady for about 1 millisecond. The drag force also follows similar trend and reaches the value identical to the blunt cone without chromium plating but reduces suddenly to a lower value after about 300 microseconds and remains steady for the rest of the test time. This sudden drop in the drag force is due to the onset of exothermic reaction of chromium atoms ablated from the model surface with the atomic oxygen present in the shock layer. The presence of substantial percentage of atomic oxygen in the shock layer is evident from the composition of the test gas presented in Table II, which is estimated using the computational code GASEQ for the tunnel operating conditions listed in Table I. The release of heat into the shock layer by the exothermic reactions enhances the shock layer temperature and reduces the pressure and the density behind the shock wave, which results in the reduction in drag force as seen Fig. 3(b). The addition of heat into

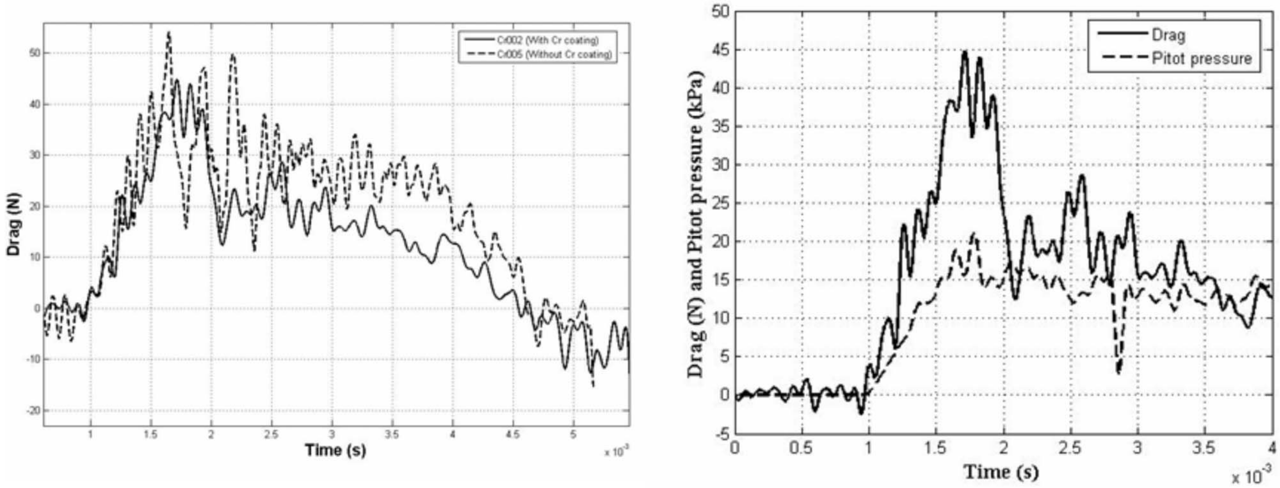

FIG. 3. Measured drag signals for the blunt cone model with and without chromium plating in Mach 8 hypersonic flow with a specific enthalpy of 3.4 MJ/kg (a) and the drag signal for the chromium plated model with the Pitot signal (b).

the shock layer is evident from the heat transfer signal shown in Fig. 4, measured using the platinum thin film gauge mounted close to the stagnation point. It is seen that the measured heat transfer rate matches very well with the theoretically estimated value of about 75 W/cm^2 based on the Fay and Riddle expression.[11] However, appreciable jump in the heat flux is seen after about 1.5 ms which synchronizes with the drop in the drag signal seen in Fig. 3(b), indicating the onset of exothermic reactions. Hence from these experiments, it is concluded that the measured reduction in drag force is due to the release of heat energy into the shock layer by the exothermic reaction of chromium atoms ablated from the model surface with the atomic oxygen behind the shock wave at high specific flow enthalpy in hypersonic flow.

The reduction in pressure in the shock layer is accommodated by the movement of the shock wave away from the body surface which can be identified by measuring the shock stand-off distance. This is verified by measuring the shock stand-off distance from the schlieren pictures of the blunt cone model with and without chromium plating in Mach 8 flow of 3.4 MJ/kg specific enthalpy. One of the schlieren pictures recorded using high speed camera at a framing rate of 10 000 frames/s is shown in Fig. 5. The measured shock stand-off distance for the model with and without chromium plating during the steady flow (after about 800 μs from the start of the flow) in the test section is shown in Fig. 6. From this figure it is very clear that the shock wave in front of the 60° apex angle blunt cone has moved away from the body surface for the model with chromium plating after the onset of the exothermic reactions.

The physical processes taking place during the entire flow duration can be understood by comparing the temporal behavior of drag and Pitot signals presented in Fig. 3(b) and the heat transfer signal presented in Fig. 4. It is seen that after the commencement of the flow, the accelerometer in the test model and pressure sensor in the Pitot take about 500 μs to reach steady state value while the heat transfer sensor, because of its lower response time, reaches the steady state value much faster. From Fig. 4 it is seen that the heat release due to the onset of exothermic reactions occurs after about 500 μs (around 1.5 ms on time scale) and the drag accelerometer takes about 300 μs to respond to the corresponding reduction in the drag force as seen in Fig. 3(a). The reduced drag remains constant until a few hundred microseconds beyond the steady flow time due to its slow response time.

TABLE II. Composition of the test gas in the stagnation region behind the shock wave computed using GASEQ for equilibrium temperature and pressure conditions.

Pressure (kPa)	15.86
Temperature (K)	2580.0
Composition (mole fraction)	N_2=0.7387
	O_2=0.1536
	O=0.0626
	NO=0.034 06

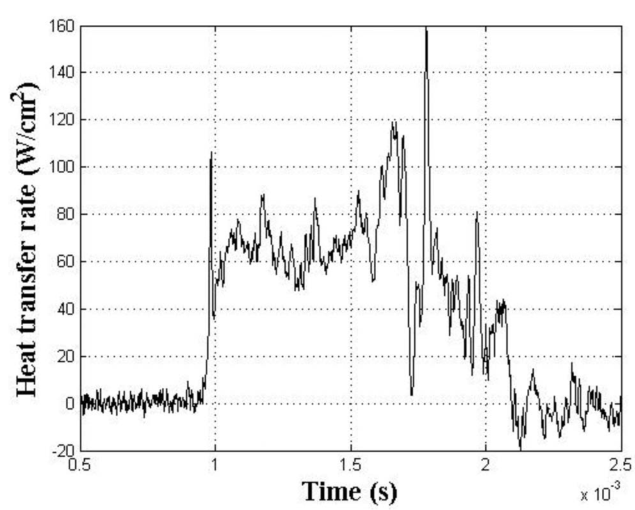

FIG. 4. Stagnation point heat transfer rate signal for the blunt cone model with and without chromium plating in Mach 8 hypersonic flow with a specific enthalpy of 3.4 MJ/kg.

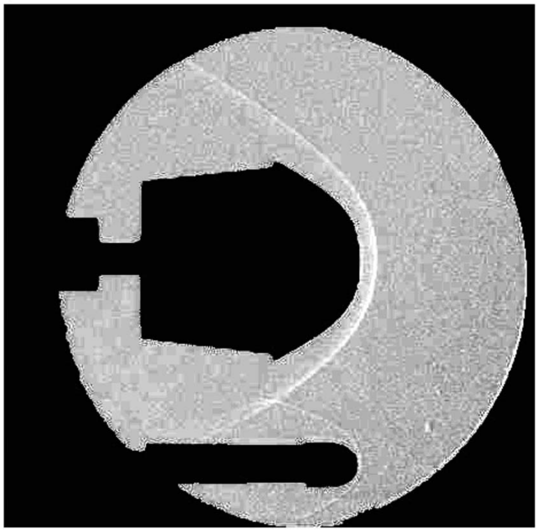

FIG. 5. Schlieren picture of the flow field around the blunt cone model in Mach 8 hypersonic flow in HST2 shock tunnel.

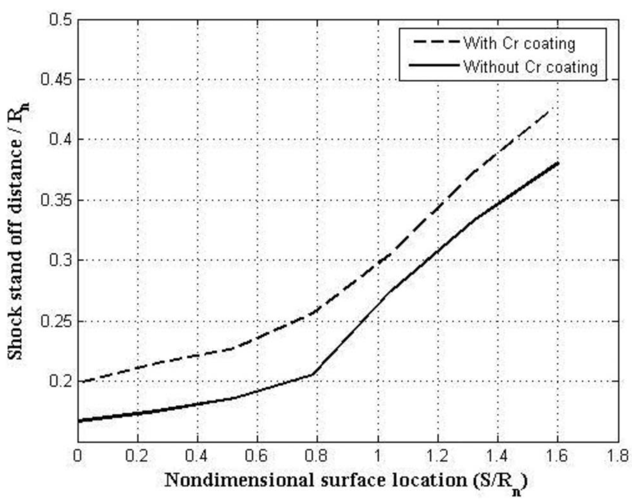

FIG. 6. Measured shock stand-off distance for the blunt cone model with and without chromium plating in Mach 8 hypersonic flow with a specific enthalpy of 3.4 MJ/kg.

About 200 μm after the release of heat into the shock layer, heat transfer rate decreases due to the movement of the shock wave away from the body as shown in Fig. 6.

In conclusion, we have demonstrated the phenomenon of drag reduction due to the addition of heat energy into the shock layer for a large angle blunt cone flying at hypersonic Mach number. The heat addition is achieved by the exothermic reaction of chromium atoms ablated from the chromium plated model surface with the atomic oxygen present in the shock layer in the high enthalpy flow. The experimental data presented in this communication have shown about 47% reduction in aerodynamic drag for a chromium plated 60° apex angle blunt cone in Mach 8 hypersonic flow with 3.4 MJ/kg specific enthalpy.

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