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Engineering Note

Effectiveness of Aerospike for Drag Reduction on a Blunt Cone in Hypersonic Flow

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I. Introduction

IMPOSED bluntness at the nose of a hypersonic vehicle is necessary to alleviate the oncoming heat load. However, increased wave drag is the immediate consequence of the forced bluntness. Hence, research in the field of hypersonics is always centered on the reduction of wave drag encountered by the space vehicles during their ascent phase. Most of the drag-reduction techniques are directed towards modifying the flowfield ahead of the stagnation point. Among the drag-reduction techniques, retractable spike is the simplest and is an easy-to-implement technique; hence, the forward-facing aerospike technique has attracted many researchers to consider various issues. Various configurations of aerospikes were assessed by Menezes et al. [1] to arrive at the best configuration for drag reduction on a 120 deg apex angle blunt cone, and a flat-disc-tipped aerospike of unity L/D (spike length-to-cone base-diameter ratio) with a disc diameter of $\frac{1}{4}D$ was observed to be the most efficient drag-reducing agent. Therefore, a similar flat-disc-tipped aerospike configuration is considered in the present study to evaluate its effect on drag of a 120 deg apex-angle blunt cone under various total-enthalpy conditions. An accelerometer-based force balance was used to measure drag on the model in a conventional hypersonic shock tunnel, IITB-ST (Indian Institute of Technology Bombay—Shock Tunnel), at low-enthalpy conditions (1.1 ± 0.02 and 1.5 ± 0.03 MJ/kg), and high-enthalpy tests (5 ± 0.44 MJ/kg) were conducted on the same model in a free-piston-driven hypersonic shock tunnel, HST3. Flowfield modifications brought about by the disc-tipped spike were expected to depend on the total enthalpy of the flow, as such a dependence was observed in the case of drag-reduction studies using a fluidic spike [2]. Details of the experimental methodology and the results are presented in the following sections.

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II. Test Facilities, Model, and Force Balance

Experiments at lower enthalpies were carried out in a conventional hypersonic shock tunnel, IITB-ST, which is driven by a 51-mm-diam shock tube that operates by rupturing an aluminum diaphragm. A conical converging–diverging nozzle of 300 mm exit diameter is connected to the end of the shock tube. The nozzle produces a hypersonic flow of Mach number 8 into a 450-mm-long test section of 300×300 mm square cross section. The freestream conditions simulated in IITB-ST at enthalpies of 1.1 and 1.5 MJ/kg are given in Table 1. Experiments at a higher enthalpy were carried out in a free-piston-driven shock tunnel, HST3, which consists of a 10-m-long, 165-mm-i.d. compression tube equipped with a piston weighing 20 kg, a 4.4-m-long, 39-mm-i.d. shock tube, a convergent–divergent Mach 8 conical nozzle, and a $300 \times 300 \times 450$ mm rectangular test section connected to a dump tank. The freestream conditions simulated in HST3 at an enthalpy of 5 MJ/kg are also listed in Table 1.

In the present studies, the blunt-cone apex angle was chosen to be 120°, as a high-apex-angle configuration generates a high wave drag and hence is a better configuration for demonstrating substantial drag reduction. This specially designed 120° apex angle blunt-cone model has a base diameter of 60 mm. A flat aerodisc with a diameter of one-fourth the blunt-cone base diameter was attached to the tip of a cylindrical spike such that the length of the spike assembly was 60 mm (equal to the blunt-cone base diameter). The entire model assembly was fabricated out of an aluminum alloy. Weight of the model is 166 g without the spike and it increased to 170 g with the spike. The test model was provided with a sufficient space on the inner side for holding the accelerometer balance. Schematic of the test model assembled with the force balance is shown in Fig. 1. The balance consists of a rubber bush attached to the model through a metallic ring. The bush on the inner side is in turn attached to a central sting that is used for the purpose of mounting the model in the tunnel. The rubber bush provides a free-floating condition during the test, since the resistance offered by the bush during the short run time is negligible [3]. A miniature uniaxial accelerometer (PCB 353B17 with 10 mV/g sensitivity) was mounted inside the model along its axis to measure the axial acceleration experienced by the model during the test.

Dynamic calibration of the force balance was carried out to get the system characteristics in the form of impulse response function. This calibration is essential, as the sudden application of the aerodynamic load vibrates the mounting system and damping of these vibrations may take a longer time than the test time of impulse facilities [4]. The test model integrated with the force balance was mounted at a 0 deg angle of incidence in the test section for these calibration experiments. An impulse hammer (PCB Piezotronics) with a metallic tip was used to apply an impulse at the nose of the test model. The principle of this dynamic calibration is in Fig. 2, where $u(t)$ is the input or the applied load, $y(t)$ is the output (acceleration signal), and $g(t)$ is the impulse response function. The input and the output are related by the following equation:

$$y(t) = \int_0^t g(t-\tau)u(\tau)\,\mathrm{d}\tau \tag{1}$$

where t is time and τ is time-variable. The applied (input) load and the obtained acceleration (output) were used to get the impulse response function of the model assembly using Fourier transform method. The time history of the applied aerodynamic load can be obtained using the experimentally acquired acceleration signal and the known impulse response function.

Table 1 Freestream conditions (typical) of hypersonic shock tunnels

	Hypersonic shock tunnel		
	IITB-ST	IITB-ST	HST3
Freestream static pressureP_∞, kPa	0.041 ± 0.001	0.089 ± 0.004	0.284 ± 0.02
Freestream static temperatureT_∞, K	79 ± 1.4	113 ± 2.6	316 ± 24.7
Freestream Mach numberM_∞	8 ± 0.15	8 ± 0.09	8 ± 0.2
Freestream stagnation enthalpyH_0, MJ/kg	1.1 ± 0.02	1.5 ± 0.03	5.0 ± 0.44

III. Results and Discussion

Experiments were conducted in IITB-ST at 1.1 and 1.5 MJ/kg stagnation enthalpies, during which the model was mounted at a 0 deg angle of incidence. Experiments without spike were conducted before the drag-reduction experiments. The impulse response function obtained from the calibration experiments was operated on the acceleration signals acquired during the tests, to recover the drag force on the model. Having recovered the drag force, the coefficient of drag C_d can be calculated using a simple relation:

$$C_d = \frac{D}{\frac{\gamma}{2} P_\infty M_\infty^2 A} \tag{2}$$

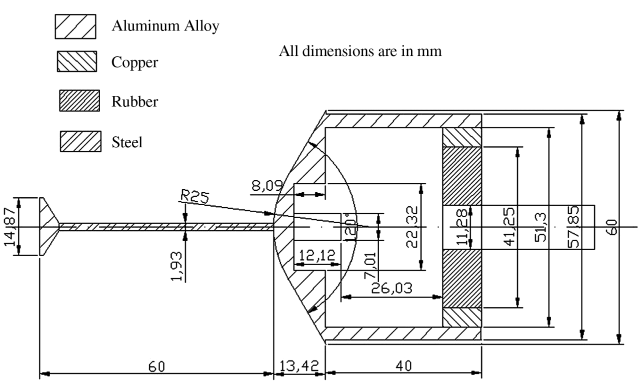

Fig. 1 Schematic of the test model assembly with accelerometer balance.

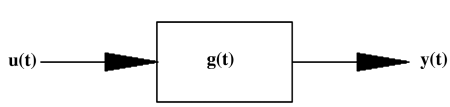

Fig. 2 Principle of dynamic calibration for linear systems.

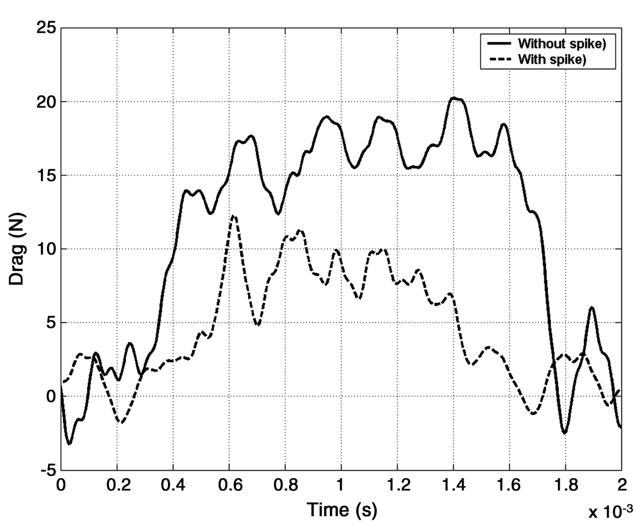

Fig. 3 Recovered drag signals without and with spike.

where D is the recovered drag force; P_∞ and M_∞ are the freestream static pressure and Mach number, respectively; γ is the ratio of specific heats of the test gas; and A is the reference area for the drag coefficient. For the present model, A is taken as the base area of the blunt cone. The measured drag coefficient for the model without spike at lower enthalpies is 1.32 (± 0.04 for 1.1 MJ/kg; ± 0.07 for 1.5 MJ/kg). Repeatability and consistency of these measurements have been confirmed by conducting a set of experiments. The tests at 5 MJ/kg stagnation enthalpy were conducted on the same model at a 0 deg angle of incidence in the free-piston-driven shock tunnel HST3. The same impulse response function as described above was used to recover the drag force from the axial acceleration signal. Repeatability and consistency have been observed in these measurements too. The experimentally obtained drag coefficient for the high-enthalpy test is 1.26 ± 0.07. Theoretical drag coefficient for the model, based on modified Newtonian theory [5], including the centrifugal force effects, is estimated to be 1.36. This estimation indicates a close agreement of the experimental data with the theory.

Experiments with the spike on the nose of the model were conducted under the same test conditions as mentioned in Table 1. Drag force on the spiked body was also recovered using the same impulse response function. Typical axial force signals on the model with and without spike are shown in Fig. 3. The measured drag coefficients in the presence of aerospike, based on Eq. (2), are 0.55 ± 0.02, 0.57 ± 0.029, and 0.53 ± 0.031, respectively, for the stagnation enthalpies in increasing order. The variation of drag coefficient with freestream stagnation enthalpy is shown in Fig. 4. Reductions of 58% ± 0.25, 56% ± 0.1, and 58% ± 0.14 in drag have been observed for stagnation enthalpies of 1.1, 1.5, and 5 MJ/kg, respectively. The percentage reduction in drag coefficient due to the presence of the spike with respect to various freestream stagnation enthalpies is shown in Fig. 5. A drag reduction of 55% was observed by Menezes et al. [1] for a 120 deg apex-angle blunt cone of bluntness ratio (defined by the ratio of nose diameter to base diameter) 0.25 with the same aerospike configuration. Those experiments were conducted at a freestream Mach number of 5.75 and a stagnation enthalpy of $\sim$1.2 MJ/kg. Changes in the flowfield of the model were

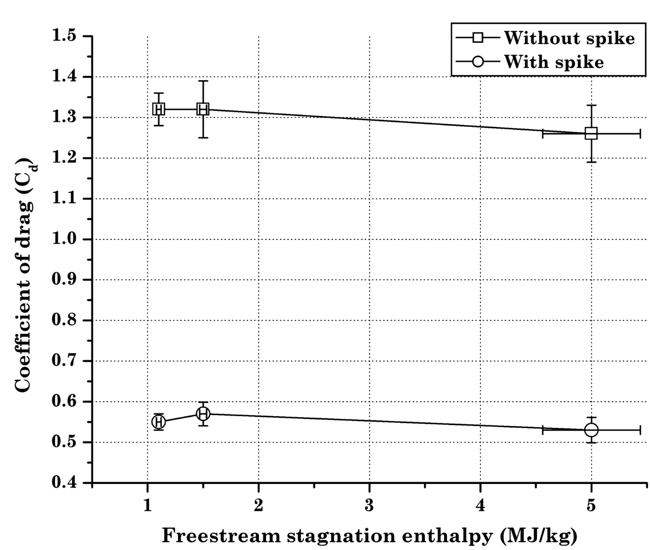

Fig. 4 Variation of drag coefficient with freestream stagnation enthalpy.

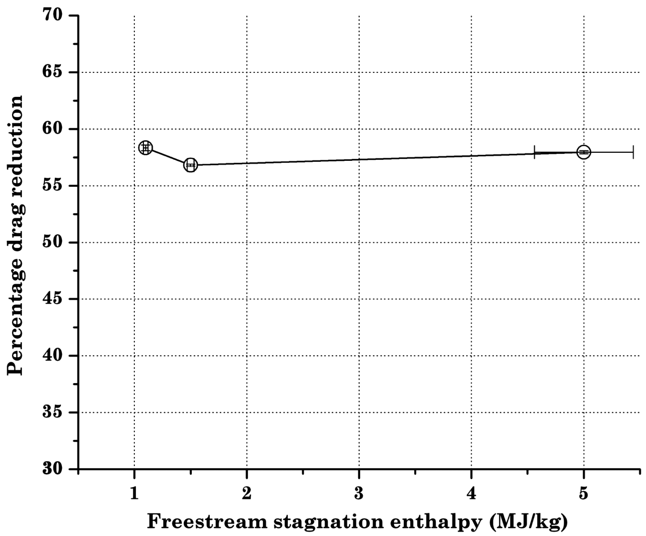

Fig. 5 Percentage drag reduction for various freestream stagnation enthalpies.

expected with a change in stagnation enthalpy. However, the encouraging fact about these results is that the blunt-cone model with a flat-disc-tipped aerospike mounted at the stagnation point gives a consistent average drag reduction of 57% for a gamut of stagnation enthalpies. This percentage drag reduction is also independent of freestream Mach number, which conforms to the Mach-number-independence principle of hypersonic flows. Therefore, the effectiveness of the present disc-tipped spike assembly in reducing wave drag is found to be consistent and independent of stagnation enthalpy and freestream Mach number.

The most probable maximum error in the reported values of drag coefficient (C_d) is estimated to be about $\pm 4.5\%$. This error could be attributed to 1) the error in the data recording systems, 2) the deviation in the accelerometer sensitivities, and 3) the accuracy of the measured freestream dynamic pressure. But the above error is a fixed error that is common for all the measured coefficient of drag values, and hence the drag reduction reported is free of this error, as it is the difference of two C_d values.

IV. Conclusions

Drag measurements were carried out on a 120 deg apex-angle blunt cone without and with a flat-disc-tipped spike, using an accelerometer balance in conventional and free-piston-driven shock tunnels, to check the performance of the spike under varying enthalpy conditions. Presence of the forward-facing disc-tipped aerospike at the nose of the blunt cone consistently reduced the wave drag on the cone by about 57% for various freestream stagnation enthalpies. The present investigations indicate that the effectiveness of the flat-disc aerospike in reducing drag on a 120 deg apex-angle blunt cone is independent of stagnation enthalpy.

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