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# Heat flux characteristics within and outside a forward facing cavity in a hypersonic flow

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ABSTRACT

A forward facing cavity effect on heat flux variations inside the cavity and over the nose surface is studied over a typical projectile geometry using the shock tunnel experiments. The flow oscillation will tend to oscillate the shock, which in turn varies the heat flux over the nose surface as well as inside the cavity. The higher length to diameter (L/D) ratio of the cavity plays an important role in nose surface heat flux reduction and investigated for L/D = 1, 2 and 3 by a uniquely designed model. The cavity flow oscillation period is determined, using the base pressure and surface heat transfer signals measured inside the cavity with reference to the pitot probe steady test time and shock oscillation period. The frequency analysis for oscillations is performed using the fast Fourier transformation. Experimental results showed that, the mean nose surface heat flux reduced by ≈4.6% to ≈7%, ≈6% to ≈8% and 3% to ≈31.4 and the mean shock standoff distance ($l$) is increased by ≈13%, ≈25% and ≈35% for L/D = 1, 2 and 3 configurations respectively with reference to the baseline geometry (without cavity geometry). As L/D increases, the nose surface location on which the heat flux reduction is observed moves towards the cavity lip and more surface area is covered with lower heat flux. Cavity region heat flux variations are studied by incorporating the thin film sensors over the cavity surface and it is observed that, a significant ≈32.5% to ≈36%, and ≈28% to ≈58% lower mean heat flux for L/D = 2 and 3 respectively with reference to the baseline geometry stagnation point heat flux.

## 1. Introduction

Hypervelocity projectiles operate with large penetration depths into armour due to their very high kinetic energy at impact, where the nose experiences high heating rate during hypersonic conditions. In the flight regime of 1.5–4 km/s, the projectile nose tip experiences severe heating rate that may cause shape change due to ablation. At its peak, the raised stagnation temperature can easily melt the influenced nose surface and produces unacceptable perturbations in the aerodynamics and the flight path. There is a need to develop innovative and effective active or passive techniques to reduce tip heating rates. Recently researchers have reported that, by introducing an axial cavity in the nose region of a hypersonic vehicle can substantially reduce the peak heating. Strong pressure oscillations are generated within the cavity to induce bow shock oscillations which provide the cooling mechanism. Schematic of such projectile nose without and with a cavity used in the present study is shown in Fig. 1(a) and (b) respectively.

### 1.1. Background and brief review

Research progress of experimental investigations on drag and heat reduction are by several kinds of mechanism, namely the forward-facing cavity, the counter flowing jet [1,2] and array of micro jets [3,4], the aerospike [5,6], the energy deposition [7,8] and their combinational configurations, and the combinational configurations [9] include the combinational opposing jet and forward-facing cavity concept [10] and the combinational opposing jet and aero spike concept [11]. These techniques are broadly classified as passive, semi-passive and active cooling [12] and reviewed each mechanism in detail by Zhen-guo Wang et al. [13].

Focussing the current investigation on heat flux characteristics by forward facing cavity mechanism following literatures are briefly reviewed. Cooper et al. [14] measured the heat transfer rates at the stagnation point of a concave hemispherical nose and found that steady flow heat transfer coefficients were 20–50% of the heat transfer coefficients associated with the convex nose shape at Mach numbers of 1.98 and 4.95. Hopko and Strauss [15] observed that the heating at the

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**Nomenclature**

| | |
|---|---|
| L | length of the cavity in mm (It is measured from the lip to the base of the cavity) |
| D | diameter of the cavity in mm |
| $l$ | average shock standoff distance in mm |
| L/D | ratio of cavity length to cavity diameter |
| X/R | ratio of axial length along the nose surface to radius of the nose surface |
| $P_\infty$ | freestream static pressure in Pa |
| $T_\infty$ | freestream static temperature in K |
| $\rho_\infty$ | free stream density of the air in kg/m$^3$ |
| $M_\infty$ | freestream Mach number |
| $Re_\infty$ | freestream Reynold number in million/m |
| $U_\infty$ | freestream velocity in m/s |
| $H$ | enthalpy in MJ/kg |
| $\dot{q}_{(t)}$ | heat flux in W/cm$^2$ |
| $\alpha$ | thin film temperature coefficient of resistance in K$^{-1}$ |
| $\beta$ | backing substrate material property (Is equal to $\sqrt{k\rho c}$ in Ws$^{1/2}$/m$^2$ K |
| k | thermal conductivity of the substrate material W/m K |
| $\rho$ | density of the substrate material kg/m$^3$ |
| c | specific heat of the substrate material in J/kg K |
| S | nose surface thin film sensor denoted by 1, 2…8 |
| s | cavity thin film sensor denoted by A, B, C and D |
| $E(t)$ | change in volts measured by thin film sensor in volts |
| $E(f)$ | initial thin film sensor voltage in volts |
| $\Delta V$ | change in voltage in volts |
| $V_o$ | initial voltage of the thin film used in the calibration in volts |
| $\Delta T$ | change in temperature in K |
| $f$ | frequency of shock oscillation in Hz |
| $\gamma$ | ratio of specific heats, |
| R | gas constant in J/kg K |
| T$_o$ | stagnation temperature inside the cavity in K |
| rms | root mean square |

stagnation point is reduced to one eighth of the heating for convex noses at Mach number of 8 for a 30$^0$ blunted cone with concave nose shape. Stallings and Burbank [16] also observed a significant reduction in the stagnation point heat transfer rates for concave hemispherical noses for steady-state flow conditions as compared with convex nose shapes.

The nature of flow and the heat reduction mechanism for the nose with forward facing cylindrical cavity are explained by many investigators. Engblom et al. [17,18] showed that for the deep forward-facing cavity in hypersonic flow, the cavity flow oscillates at its natural frequency. By the motion of the bow shock the mean stagnation temperature of the airflow into the cavity is reduced and the heat reduction benefit appears to increase with mean bow shock speed. Sambamurthi et al. [19] and also Heubner & Utreja [20] observed that the cooling effect is caused by the bow shock wave oscillation which is produced by the oscillation of the stagnant cavity fluid. Silton et al. [21] using the experimental results with the computation analogy showed that, for sufficiently deep cavities the local heat fluxes were reduced everywhere on the surface when the strong longitudinal pressure oscillations within the cavity induce large bow shock oscillations. Recently, Saravanan et al. [22] experimentally observed a reduction of 35–40% in surface convective heat transfer rates for a missile shaped body with a nose cavity located in the stagnation region at a freestream Mach number of 8. Seiler et al. [23] studied the heat flux inside the cavity for a blunt nose projectile equipped with nose cavity at Mach 4.5, for smaller L/D geometries (L/D = 0.085, 0.266) and reported that the deepest cavity has the lowest heat flux. Lu and Liu [24] showed numerically that the deeper the cavity, the smaller is the heat flux and the mean heat flux increases along the body surface to reach a peak value near the sharp edge and then fall sharply. Using the ellipsoid cavity Rajesh [25] simulated the flow and reported that greater reductions in aerodynamic heating is achieved for deeper cavities. Using the opposing jet with forward facing cavity combination is analysed numerically by Hai-Bo Lu et al. [26] and reported that, the opposing jet thermal protection system has a more powerful cooling capability; the aerodynamic heating is reduced at each point of the outer body surface of the nose-tip.

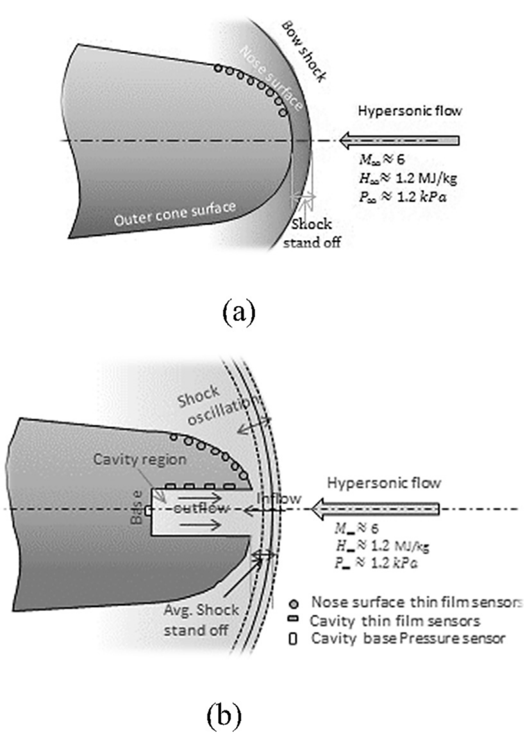


**Fig. 1.** Projectile nose schematic diagrams.

With the given back ground, researchers have reported that the forward facing cavity mechanism significantly reduces the heat flux over the nose surface at higher L/D conditions. In such situation, determining the heat flux variations inside the cavity region is very important from the application perspective. At hypersonic flow conditions experimental studies inside the cavity including the nose surface heat flux analysis for higher cavity lengths are not abundant in the literature. The objective of this investigation is to study the heat flux variations in the cavity region as well as over the nose surface (i.e., outside the cavity) for higher L/D configurations and comparing with respect to blunt cone having a hemispherical nose without a cavity geometry (baseline geometry having L/D = 0) under hypersonic flow condition using shock tunnel experiments.

The current experiments are mainly focussed on the variation of L/D parameter, to account the cavity effect, varying from 1 to 3 for a cylindrical cavity geometry. These are in deep and very deep geometries and insensitive to the free stream disturbance as reported by Ladoon et al. [27], and Yuceil & Dolling [28]).

## 2. Methodology

### 2.1. Experimental facility

This paper presents result from an experiments carried out using Hypersonic Shock Tunnel-2 (HST-2) facility at Laboratory for