

ANALYSIS OF BLUNT NOSE CONE WITH ULTRA HIGH TEMPERATURE CERAMIC COMPOSITE TPS MATERIALS

N.Sreenivasa Babu¹, Dr. K. Jayathirtha Rao²

Associate Professor, Aeronautical Engg. Dept, Gurunanak Engineering College, Ibrahimpatnam, Hyderabad, India¹

IDST consultant, RCI, DRDO, Hyderabad, India²

Abstract: Aerodynamic drag and heating are the crucial in the thermal stability of hypersonic vehicles at various speeds. The latest developments in the design of nose cone structure demands an effective Thermal Protection System (TPS) meets the need of the space research technology. In this research a typical nose cone with different Ultra High Temperature (UHT) ceramic composite TPS materials like Hafnium diboride (HfB₂) and zirconium diboride (ZrB₂) is analyzed and compared for its effective protection against transfer of heat into the structure. A naval model is designed for from the concepts of blunt nose cone and analyzed with the commercial software. A typical quad 4 node element is adopted to perform thermal analysis in ANSYS software and the simulated results are validated with numerical solutions. Existing ablative materials like SLA-561V, SIRCA and AVCOAT are having the heat flux ranges up to 110 W/cm² and temperatures ranging up to 2000°C and need of new materials and its reliability are focused in this research.

Key words: Thermal Protection System, Thermal stability, blunt nose cone, UHT ceramic Composite.

Nomenclature:

T	: temperature in °k
N	: shape function in terms of temperature
k ^e	: characteristic matrix N/°k
k _x	: thermal conductivity in (W/mm-K)
E	: Young's modulus in N/mm ²
1/m	: Poisson's ratio
ρ	: density of the material in kg/mm ³
α	: heat transfer film co-efficient (°k ⁻¹)
P	: perimeter of the element in mm
f ^e	: forcing function matrix in N

I. INTRODUCTION

In the recent years space vehicles like rockets, reentry vehicles regardless their unique designs needed control surfaces at hypersonic speeds. Low-radius leading edges are subject to much greater aerodynamic heating than blunt edges, such as those on the Space Shuttle, and they thus will reach temperatures that may exceed 2000°C during reentry. Available thermal protection materials will not survive such extreme temperatures and new materials are required for advanced thermal protection systems. Thus they need advanced and latest ultra high temperature ceramic materials [2006] used as a TPS layers which have high resistance in heat and oxidation. Ronald Loehman, Erica Corral, Hans Peter Dumm, Paul Kotula and Raj Tandon described the qualities of Hafnium diboride (HfB₂) (melting temperature of 3250°C) and zirconium diboride (ZrB₂) (melting temperature of 3246°C) [1] for their existence in proving the further research activities of the hypersonic re-entry vehicles. TPS has not only to resist high temperature and oxidation properties but also should have thermal shock property which can improve by improving fracture properties of the materials. Thermal shock stability for ZrB₂-SiCp-Graphite (ZSG) and ZrB₂-SiCp-AlN (ZSA) was investigated by Baoliang Liu, Jianguo Wang and Guoqian Liu [2011]. The surface cracks appeared after it was cooled from 1200°C due to thermal shock instability of the material. Residual flexural strength of ZSA was improved by crack healing after it was cooled from 1450°C. However, no surface crack appeared for ZSG after water quenching test and it provided a potential method for improving thermal shock stability of zirconium diboride ceramic matrix composites by introducing proper quantities of graphite [2]. The sphere-cone is a spherical section with a frustum or blunted cone attached. The sphere-cone's dynamic stability is typically better than that

of a spherical section. With a sufficiently small half angle and properly placed center of mass, a sphere-cone can provide aerodynamic stability from Keplerian entry to surface impact [2009]. The "half-angle" is the angle between the cone's axis of rotational symmetry and its outer surface, and thus half the angle made by the cone's surface edges. "SLA" in SLA-561V stands for "Super Light weight Ablator". SLA-561V is a proprietary ablative made by Lockheed Martin that has been used as the primary TPS material on all of the 70 degree sphere-cone entry vehicles sent by NASA to Mars. SLA-561V begins significant ablation at a heat flux of approximately 110 W/cm², but will fail for heat fluxes greater than 300 W/cm². The Mars Science Laboratory (MSL) aero shell TPS is currently designed to withstand a peak heat flux of 234 W/cm². Phenolic Impregnated Carbon Ablator, Silicone Impregnated Reusable Ceramic Ablator (SIRCA), AVCOAT are also existed but the field demands for the new materials [3-4]. A typical design is adopted in evaluating the performance of blunt nose cone at hypersonic speeds with different materials and mode shapes also determined in acoustic nature considering the temperature effect on the surface [2013] for its feasibility for further studies [5]. Based on the same design a spherical blunt nose cone is chosen with TPS layer in the present analysis with two different ceramic materials.

II. PROBLEM DESCRIPTION AND METHODOLOGY

The co-ordinates for the development of blunt cone profile is taken into consideration with respect to the tangency point and in which the basic size of the nose cone is given in key points as (11.55,0), (76,0), (76,37), (13.7833, 7.66), (10.95, 4.3), (76,38.5), (10.95,5.8), (9.75,4.3), (10.55,0). Base material for the nose cone is carbon epoxy and the TPS materials are Hafnium diboride (HfB₂) and zirconium diboride (ZrB₂) and their properties are as listed in Table: 1 [4] for performing the analysis. A layer of 1.5 mm is taken for the analysis purpose for each of the TPS material.

Table: I Material properties

	Carbon epoxy composite	Hafnium diboride (HfB ₂)	Zirconium diboride (ZrB ₂)
E (N/mm ²)	1.81e5	0.75e5	4.2e5
1/m	0.36	0.37	0.34
ρ (kg/mm ³)	1.7e-6	10.5e-6	6.085e-6
α (°k ⁻¹)	2e-6	7.6E-6	8.3e-6
k (W/mm-K)	7e-3	62e-3	70e-3

III. FEM MODELING

The FEM model is generated from the key points as furnished in the problem description. In the context of the model the actual model follows the steps of operations like from points to lines, lines to areas and free meshing methodologies available in the software. An axisymmetric model is chosen for the better approach to the solution as the time and data storage can be promisingly minimized with such model. The end boundary conditions are chosen based on the realistic nose cone structure of hypersonic vehicle and later thermal analysis is performed.

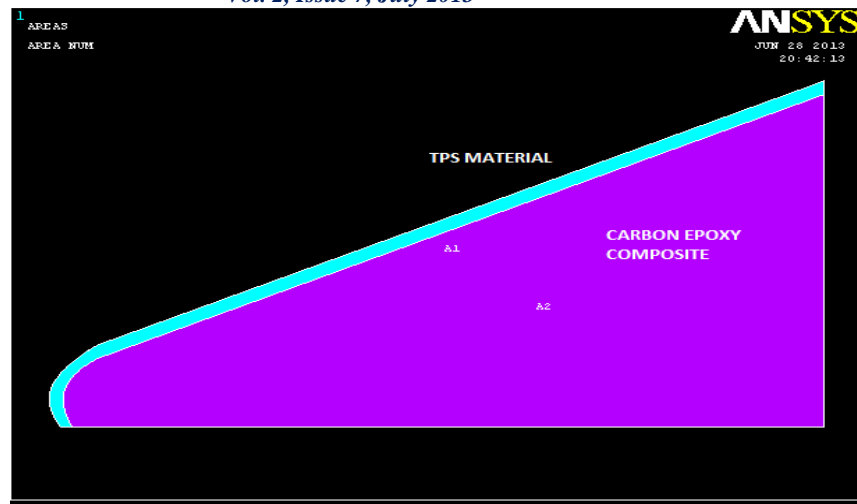


Fig. 1 A typical blunt nose cone 2D profile with TPS Layer

IV. MATHEMATICAL MODELING

V.

A simple mathematical model is adopted for the validation of the actual conditions of the composite structure for its thermal analysis from the fundamentals of FEM procedures. A cantilever beam with two materials is an acceptable model to satisfy the problem. The governing equation for this condition with an isotropic body with temperature-dependent heat transfer has the form of global equations for the domain can be assembled using connectivity information. Shape functions N_i are used for interpolation of temperature inside a finite element as per equation (1) is given by[6]

$$T(x) = N_1(x)T_1 + N_2(x)T_2 \tag{1}$$

Where $T(x)$ is the temperature at the required position, N_1 and N_2 are the shape functions which will be defined in terms of temperature, T_1 and T_2 are the temperatures at that locations. To simplify the above equation in mathematics, evaluate the shape functions as per equation (2) is given by

$$N_1 = 1 - \frac{x}{L} \quad \text{and} \quad N_2 = \frac{x}{L} \tag{2}$$

Where L is the length of the element and x is the distance from the reference point.

Finally the conduction and convection problem solution may also can be taken the form as,

$$[k^{(e)}] = \frac{k_x A}{L} \begin{bmatrix} 1 & -1 \\ -1 & 1 \end{bmatrix} + \frac{hPL}{6} \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \tag{3}$$

The forcing function can be written as

$$\{f_h^{(e)}\} = hPT_a \begin{Bmatrix} \int_0^L N_1 dx \\ 0 \\ \int_0^L N_2 dx \\ 0 \end{Bmatrix} = \frac{hPT_a L}{2} \begin{Bmatrix} 1 \\ 1 \end{Bmatrix} \tag{4}$$

and finally the problem solution can takes the form

$$\{k\}\{T\} = \{f\} \tag{5}$$

VI. RESULTS AND DISCUSSIONS

A 2D model is analyzed for its steady state heat transfer analysis by using Newton Raphson model at Mach number 10 for hypersonic environment and the surface temperature is taken as 2478°k and boundary temperature of 298°k [3]. A total number of 1157 elements are taken for its final solution convergence.

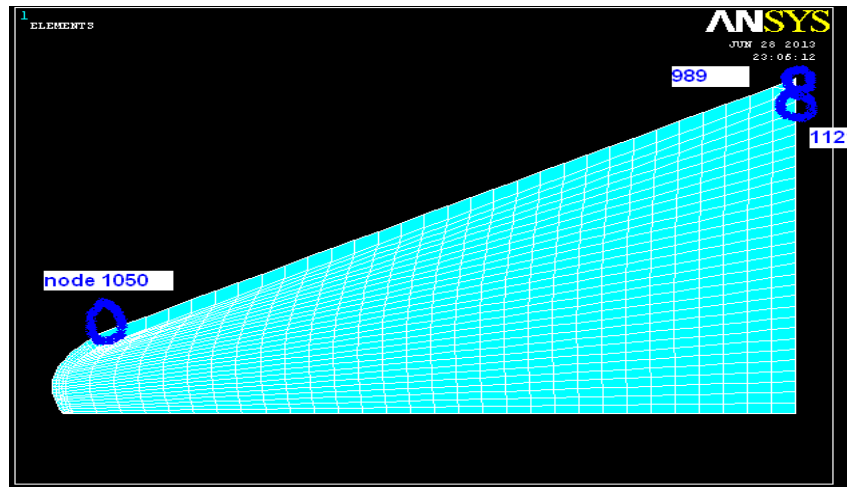


Fig. 2 Node 989,1050 & 1121 locations

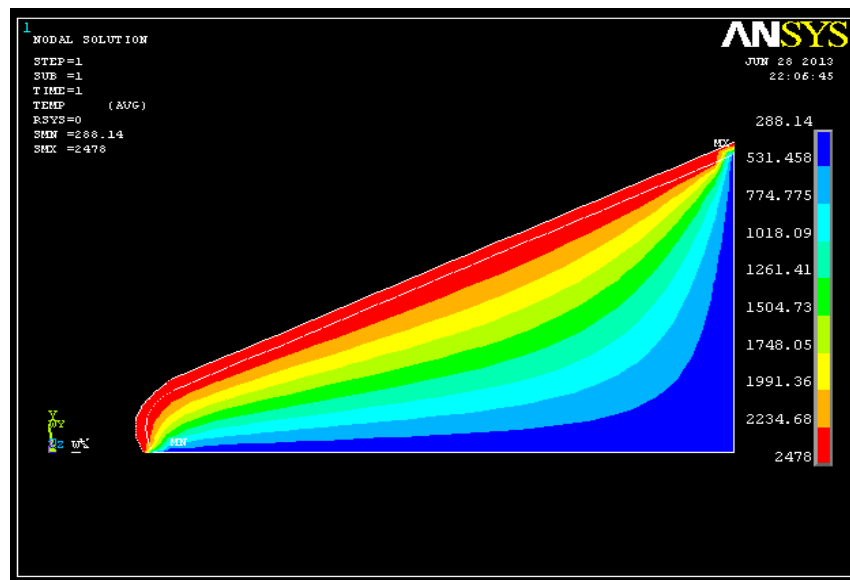


Fig. 3 Temperature distributions for HfB2 material

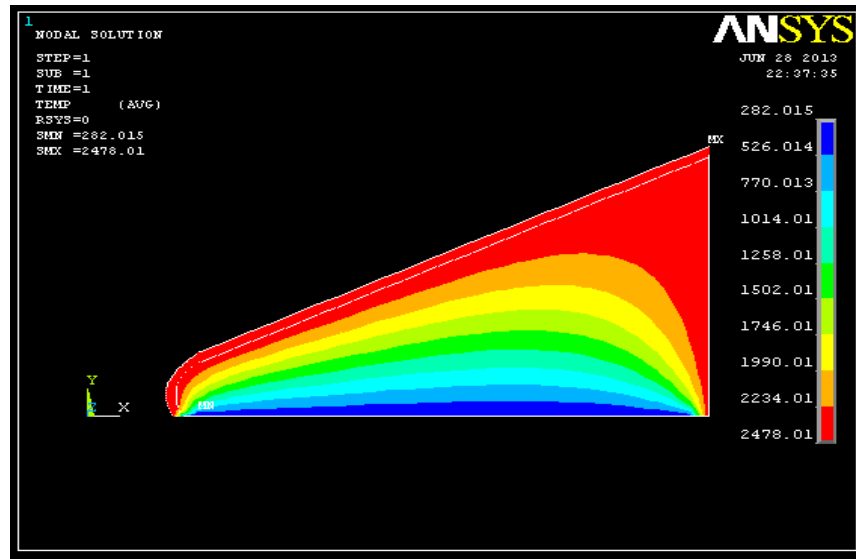


Fig. 4 Temperature distributions for ZrB2 material

Table II HfB2 material results

At Node numbers	Temperature in °K	Thermal gradient (°k/mm)	Thermal Flux (W/mm ²)
1050	2478	-10.755	0.627
1121	1196.36	-250.790	4.496
989	2411.58	-81.905	-2.141

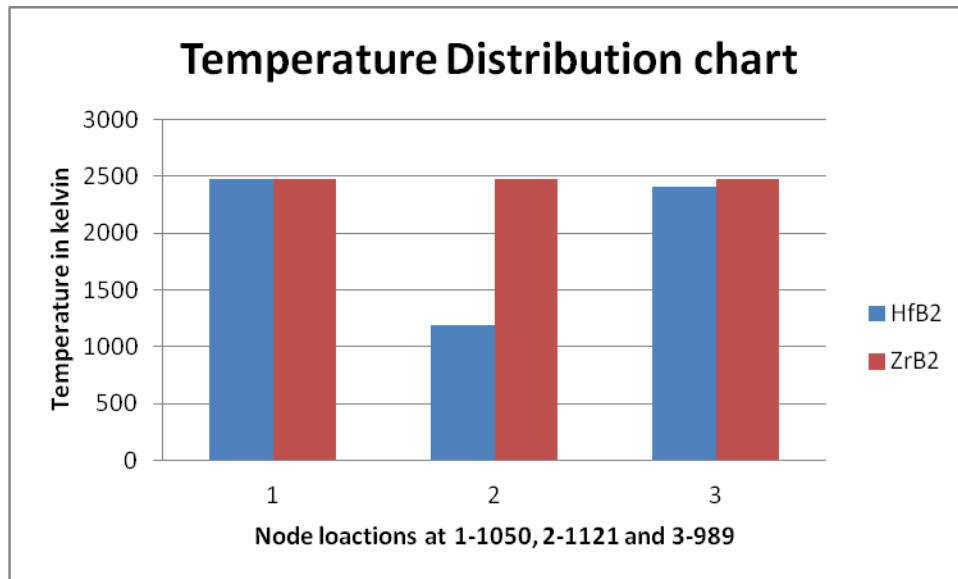
Table III ZrB2 material results

At Node numbers	Temperature in °K	Thermal gradient (°k/mm)	Thermal Flux (W/mm ²)
1050	2478	-7.438	0.6258
1121	2478	-0.0021	-0.0018
989	2478	0.0055	-0.000315

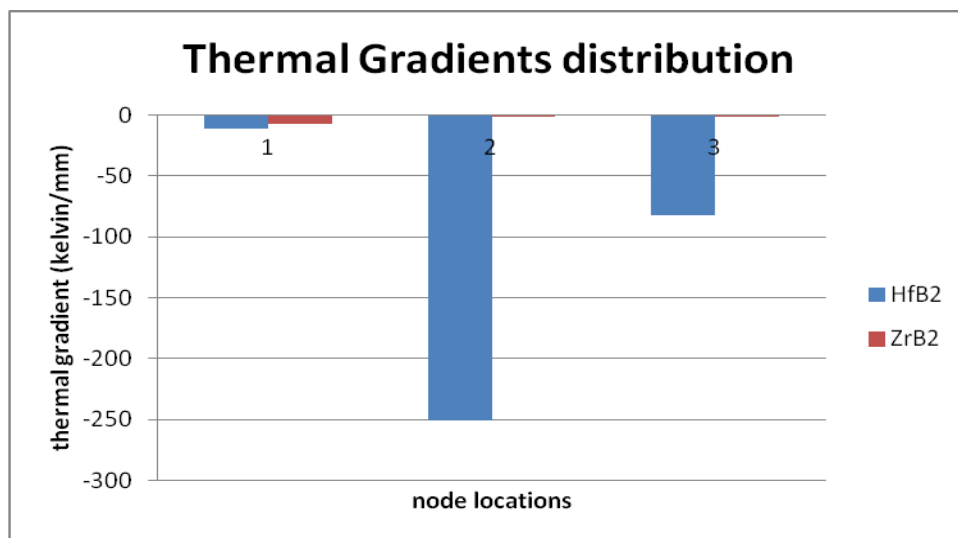
The node numbers are chosen for mathematical solutions at 1050, 989 and 1121 at the radii of the nose cone 5 mm, 37mm and 38.5 mm respectively and the solutions were compared.

Table IV Validations of Results

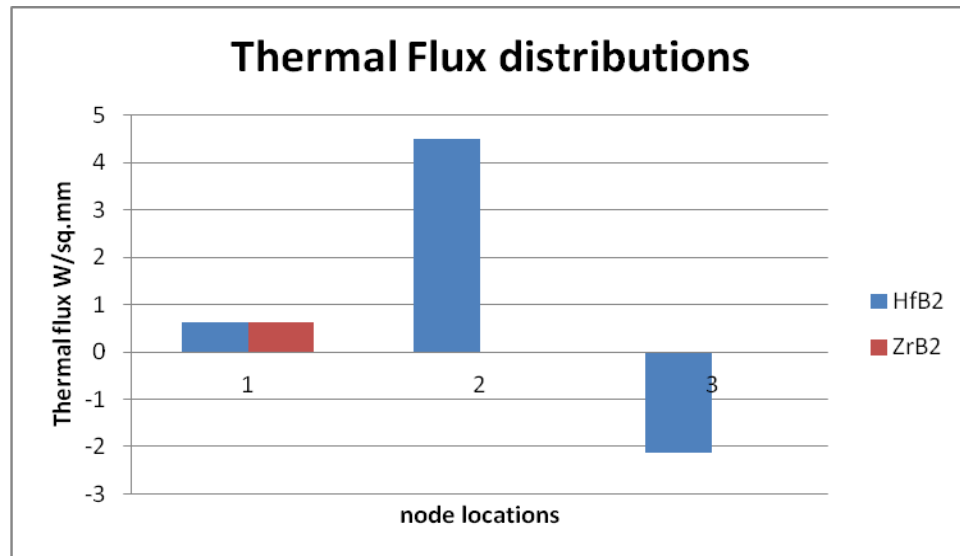
At Node numbers	HfB2 material		ZrB2 material	
	Simulated results Temperature in °K	Mathematical solutions	Simulated results Temperature in °K	Mathematical solutions
1050	2478	2432.9	2478	2432.9
1121	1196.36	1208.1	2478	1208.1
989	2411.58	2398.89	2478	2398.89



Graph. 1 Temperature distribution at nodes



Graph. 2 Thermal gradient distribution at nodes



Graph. 3 Thermal flux distribution at nodes

VII. CONCLUSIONS

- Simulated solutions at various nodes are validated with numerical solutions which are fairly in good understanding and show the feasibility of the problem methodology.
- For the Hafnium diboride material the temperature distribution is from 2478°k to 2411.58°k and the distribution is normal showing the uniformity of the distribution over the entire nose cone as in figure 3.
- But for the Zirconium diboride material the temperature distribution is not same and it is 2478°k at the skin of the TPS layer and shows the resistance of the material in transferring the temperature for the remaining of the nose cone as in figure 4.
- From the simulated results the Hafnium diboride material shows the better distribution pattern and its heat flux values are also in promising levels than Zirconium diboride material.
- This can be further evaluated for the transient thermal analysis which may have additional solutions for the defined problem.

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