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Heat Shielding Analysis of a Hypersonic Aerospace Vehicle Structure

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Abstract

Hypersonic cruise vehicles are fly at Mach numbers of above five (≈7) and the aerodynamic heating would be severe. Hypersonic Vehicles encounter a severe hazardous environment such as extremely high temperature plane to aerodynamic heating, fluctuating pressures, stresses for which the structures are to be designed and fabricated to withstand these environments to protect various electronic items like guidance, control and instrumentation systems housed in the vehicle structure. High temperature of the order of 1500^0C and above during the hypersonic flight causes enormous thermal stresses. Inconel-617 is a Nickel based alloy. Hence Inconel-617 is employed as a sandwich material. Theoretical & ANSYS modeling analysis have been done for both, the square and hexagonal honeycomb panels of Inconel-617 material have been performed to suit the hypersonic flight conditions. The honeycomb structures are built from thin walled metal sheets. These structures as a part of the airframe outer cover provide thermal protection to the interior parts mounted inside the vehicle. This paper is to perform geometrical (shape) analysis of different candidate honeycomb cells that have the same effective density but different geometrical shapes. To perform heat-transfer analysis of hypersonic aerospace vehicle structure with different honeycomb cell geometry.

Key words: hexagonal core, square core, Inconel617 sandwich structure, Adhesive, ANSYS

1 Introduction

Hypersonic flight vehicles such as the Space Shuttle orbiter are subjected to severe aerodynamic heating during flight missions. Flight vehicles have large number of electronic and other systems which need to be protected against high temperatures in their performances which should not be deteriorated during flights to achieve the specified performance. A thermal protection system (TPS) made of low–thermal conductivity materials are used to insulate primary structures from overheating so that the vehicle can operate within the design temperature limit. The honeycomb construction provides low density and low thermal conductivity through the TPS thickness. The super alloy TPS is capable of functioning at high temperatures because of improved conductivity performance. A TPS is exposed to high temperatures on the outer surface and to relatively lower temperatures on the inner surface facing the cooler substructures, which protects the internally housed items.

Sandwich panels are used for design and construction of lightweight transportation systems such as satellites, aircraft, missiles, high speed trains. Structural weight saving is the major consideration and the sandwich construction is frequently used instead of increasing material thickness, honeycomb are made of very thin material. They reduce the weight, while providing the structural rigidity. This type of sandwich construction consists of two thin facing layers separated by a core material. Potential materials for sandwich facings are aluminum alloys, high tensile steels, titanium, inconel-617 and composites with composites with honeycomb cores and a suitable matrix depending on the specific mission requirement. Several types of core shapes and core materials have been applied to the construction of sandwich structures. Among them, the honeycomb core that consists of very thin foils in the form of hexagonal cells perpendicular to the facings is the most popular.

Honeycomb sandwich structure as shown in Fig.1 are currently being used in the construction of high performance aircraft and missiles and are also being proposed for construction of future high speed vehicles. The design of a vehicle for high speed flight must be supported by structural temperature predictions and the amount of heat transferred through the exterior panels during flight. In order to predict these quantities, it is necessary to have knowledge of the heat transfer characteristics of the honeycomb panel.

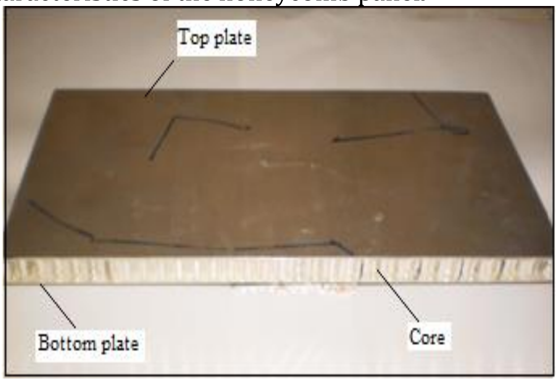

Fig.1 Honeycomb sandwich structure

2 Honeycomb Structures

A typical cross sectional view of sandwich structure consists of two thin, high strength face sheets bonded to a thick, light weight core as shown in Fig.2. Face sheets are rigid and core is relatively weak and flexible, but when combined in a sandwich panel they produce a structure that is stiff, strong and lightweight. In structural sandwiches, face sheets are mostly identical in material and thickness and they primarily resist the in-plane and bending loads. These structures are called symmetric sandwich structures. However, in some special cases face sheets may vary in thickness or material because of different loading conditions or working environment.

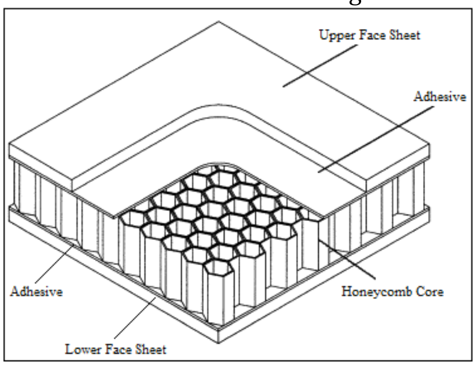

Fig.2 View of honeycomb Sandwich structure

2.1 Honeycomb Core

The purpose of the core is to increase the flexural stiffness of the panel. The honey comb core as shown in Fig.3, in general the core has low density in order to add as little as possible to the total weigh of the sandwich construction. The core must be stiff enough in shear and perpendicular to the faces to ensure that face sheets are constant distant apart to present their detachment. In addition the core must with stand compressive loads without failure.

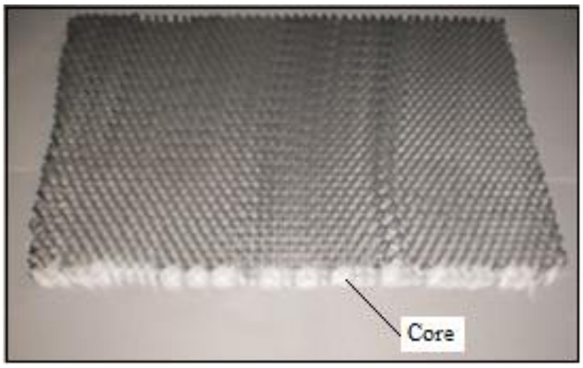

Fig.3 Honeycomb core

2.2 High Temperature Adhesives

High Temperature Adhesives find its application mainly in aerospace industries. A number of adhesives available can operate at high temperatures than epoxies and phenolics. These adhesives are really expensive and require high cure temperatures, sometimes complicated cure schedules.

3 Material Properties

The honeycomb panel material was modeled as a sandwich structure with three layers through the thickness. For Inconel-617 honeycomb panel material is Inconel-617. These properties are summarized in Table. 1

Table- 1 Honeycomb Panel Material Properties

S.NO	PROPERTIES	INCONEL-617
1	Thermal Conductivity (W/m°c)	28.7
2	Heat Transfer Coefficient (w/m^2-k)	40
3	Poisson ratio	0.30
4	Density (kg/m^3)	8360
5	Specific Heat (j/kg-k)	662
6	Thermal Expansion (m/m-°c)	$16.3x10^{-6}$

4 Concept of Sandwich Structures

A sandwich structure consists of three main elements, two outer faces, or skins, and a centre core as shown in Fig. 4; the outer faces typically consist of a stiffer, higher density material in comparison to the inner core. Practically any structural material can be used for the faces depending on the purpose of the sandwich construction.

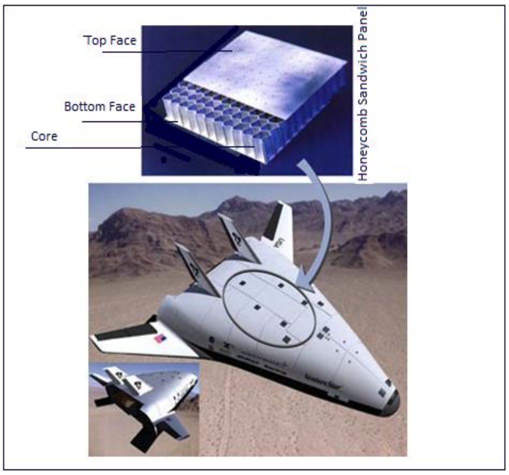

Fig.4. .X-33 reusable launch Vehicle

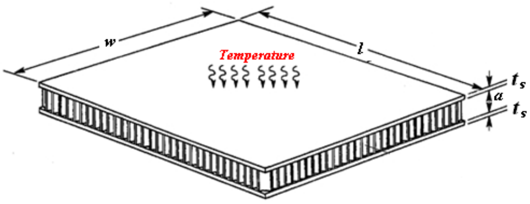

Fig.5 Honeycomb sandwich thermal protection system (TPS) subjected to heating over entire upper surface.

Fig.5 shows a honeycomb-core sandwich thermal protection system panel subjected to transient surface temperature, over its entire outer surface. The thermal protection system panel is rectangular with a side length –***l*** & width-**w**, and is fabricated with two identical face sheets with a thickness of t_s and honeycomb core with a depth of **a**. For a given material, the overall heat-insulation performances of the honeycomb thermal protection system panel depend on the thickness of the face sheets, depth of the honeycomb core, thickness of the honeycomb cell walls, and size and shape of the honeycomb cells.

5 Honeycomb Cells Dimensions

The geometrical analysis of honeycomb cells with different geometry (hexagon & square shapes) is adopted. Fig.6 shows two types of honeycomb cell geometry to be analyzed. The honeycomb cell wall thickness for the first two types is *t(c)*. The first type is a right hexagonal cell with identical side lengths of b_1. The second type is a square cell with side lengths of b_2, which is modified from the right hexagonal cell by reducing the bonding interface length to a minimum of $\sqrt{2}\, t_c$. The size, d(i) (i=1,2) of each type of honeycomb cell is defined as the maximum diagonal of the cell cross section. The size of honeycomb cells types 1, 2, are adjusted to have the same effective density (that is, $\rho_1 = \rho_2$). Honeycomb structures are composed of plates or sheets that form the edges of unit cells. These can be arranged to create, square and hexagonal.

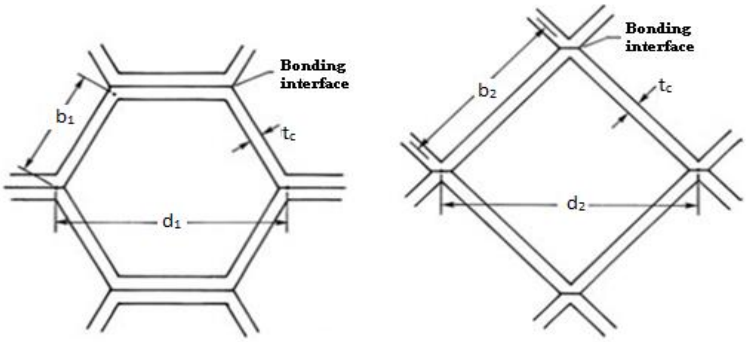

Fig.6 (a) Right hexagonal cell.(b) Square cell

5.1 Numerical Input Values

A typical candidate Thermal Protection System (TPS) structures has the following dimensions are given:
l = 115 mm, w = 85 mm, d_1 = 7 mm, d_2 = 7.42mm, b_1 = 3.5 mm, b_2 = 5.25 mm, t_s= 0.7 mm, a = 15 mm, t_c = 0.005 mm

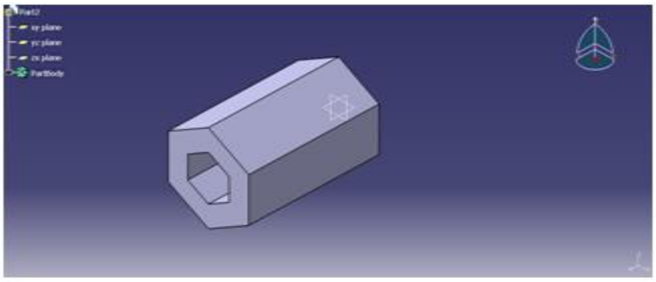

Fig.7 Modeling of Hexagonal Honeycomb Cell

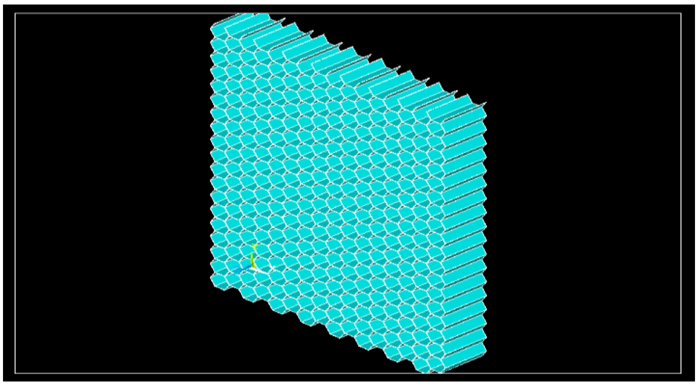

Fig.8 Pattern of Hexagonal Honeycomb cells

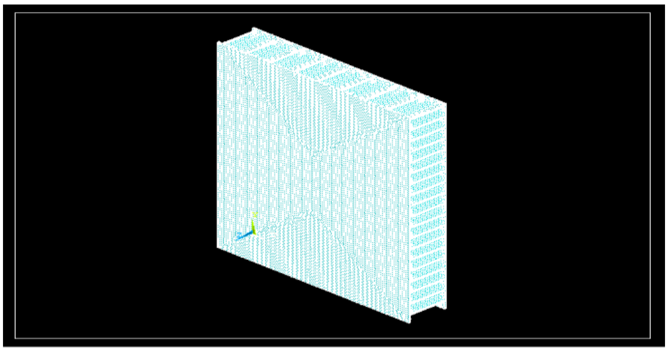

Fig.9 Meshing on Hexagonal Cell

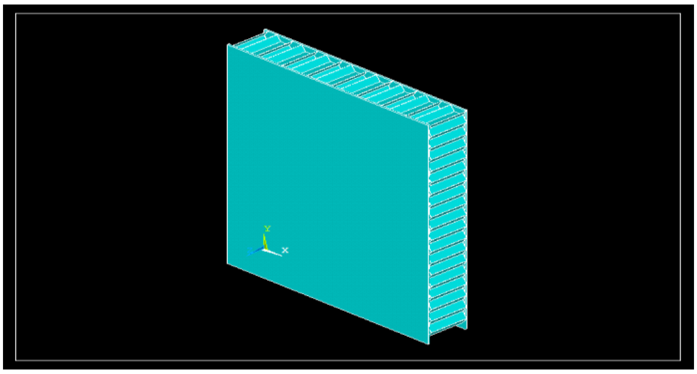

Fig.10 Assembly of Hexagonal Honeycomb cells with structure

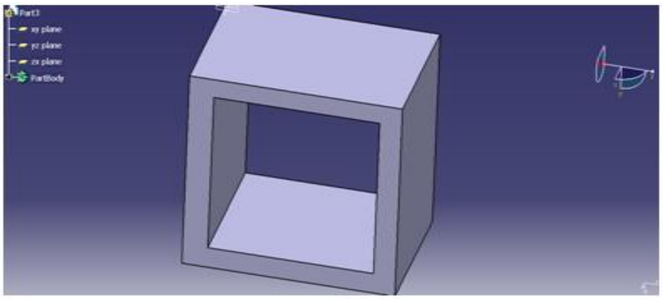

Fig.11 Modeling of 3D-square honeycomb cell

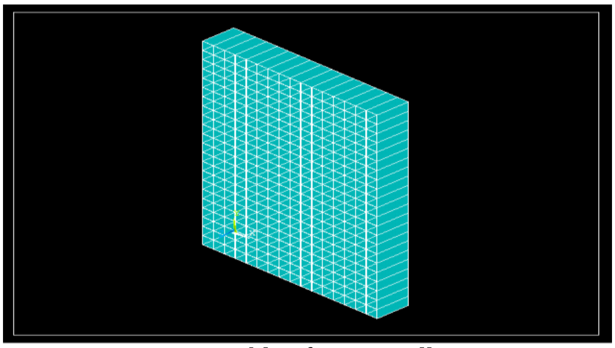

Fig.12 Assembly of square cell

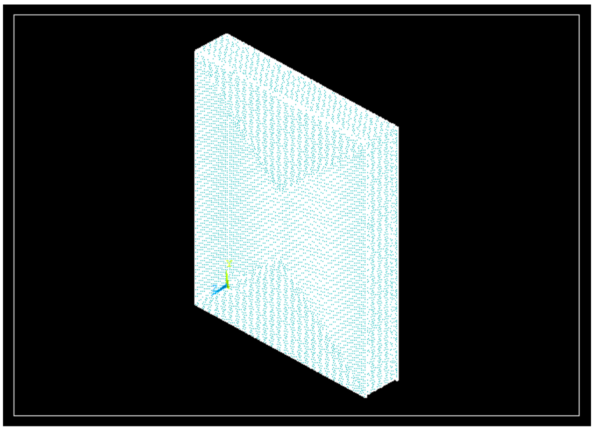

Fig.13 Meshing on square Structure

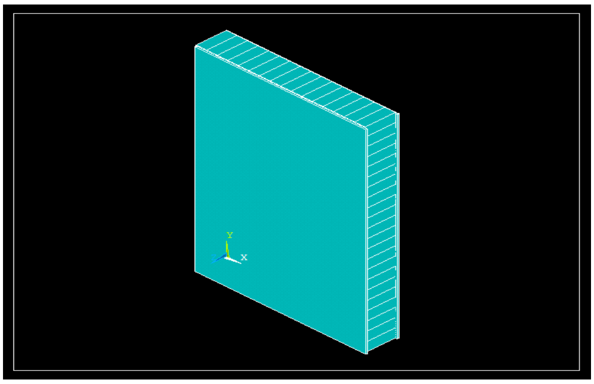

Fig.14 Assembly of square structure with panels

6 Analysis of Honeycomb Sandwich Structure

Heat transfer analysis calculates the temperature distribution and related thermal quantities in the system or component .In general, the heat transfer in honeycomb sandwich panels is a result of (1) conduction of heat in the cell walls, (2) radiation interchange within the cell, and (3) convection of heat through the air contained back side of the panel. However, this work is concerned with sandwich panels in which the primary modes of heat transfer are due to conduction in the cell walls and radiation exchange within the cell. For most honeycomb cores used in the fabrication of sandwich panels, it can be shown that the heat exchange by convection and conduction within the air contained in the cell is negligible compared to conduction in the cell walls and radiation within the cell.

6.1 To simplify the analysis, the following assumptions are introduced.

First, honeycomb cells have the same effective density but different geometrical shapes are considered (i.e., hexagon & square shapes).

Second, the effect of internal radiation turned out to be much smaller than that of conduction for the present TPS core geometry, hence radiation can be negligible.

Third, the thermal properties of the materials used do not change with the temperature.

Fourth, there is no convection heat transfer inside the panel, as the experiment will take place inside a still environment. Convection heat transfer is considered for backside of the panel.

Fifth, the heat transfer functions are nonlinear due to the thermal radiation mode. With these assumptions, a one-dimensional transient heat analysis can be used to determine the temperature difference.

6.2 Heat Transfer Analysis

Heat transfer is a science that studies the energy transfer between two bodies due to temperature difference. Conductive heat transfer analysis on honey comb sandwich panels and the tiny volume inside each honeycomb cell, convection heat transfer of the interior air mass were neglected. This section studies the effect of honeycomb cell geometry on the heat- shielding performance of the TPS panel. Before doing analysis to mesh the model so that the effectively find the change in temperature at each and every point. Perform heat transfer analysis under transient state condition.

6.3 Transient Thermal Analysis

Transient Thermal Analysis determines temperatures and other thermal quantities that vary over time. Engineers commonly use temperatures that a transient thermal analysis calculates as input to structural analysis evaluations.

A transient thermal analysis follows basically the same procedures as a steady state thermal analysis. The main difference is that most applied loads in a transient thermal analysis are functions of time. To specify time-dependent loads, use both the function tool to define an equation or function describing the curve and then apply the function as a boundary conditions or divide the load –versus –time load into load steps.

7 Inconel-617 Hexagonal Honeycomb Sandwich Structure

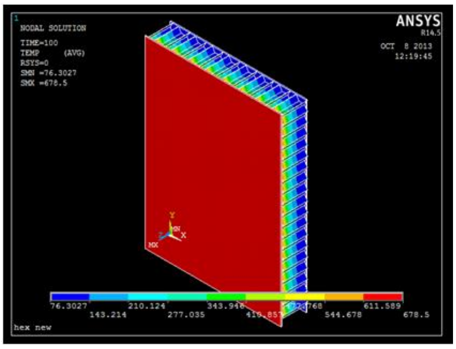

Fig.(a) 100 sec

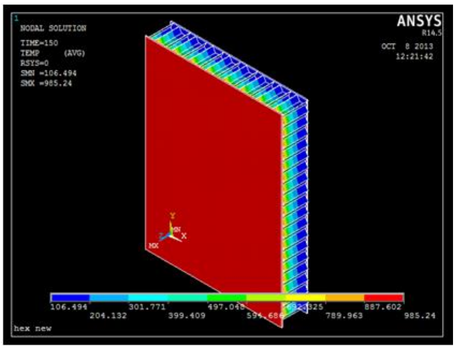

Fig. (b) 150 sec

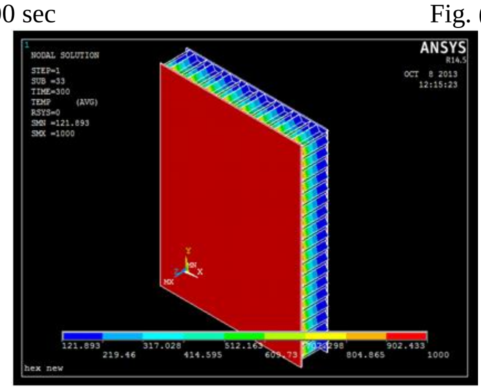

Fig.(c) 300 sec

Fig.15 Temperature distribution with respect to time

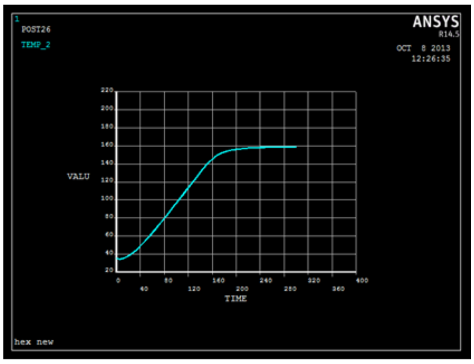

Fig.16 Time vs Temperature for bottom plate of Inconel- 617 hexagonal structure.

8 Inconel-617 Square Honeycomb Sandwich Structure

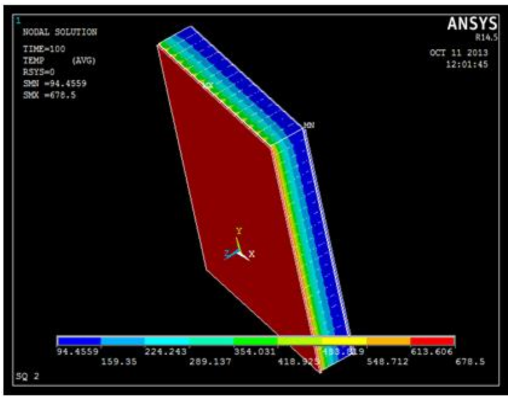

Fig.(a) 100 sec

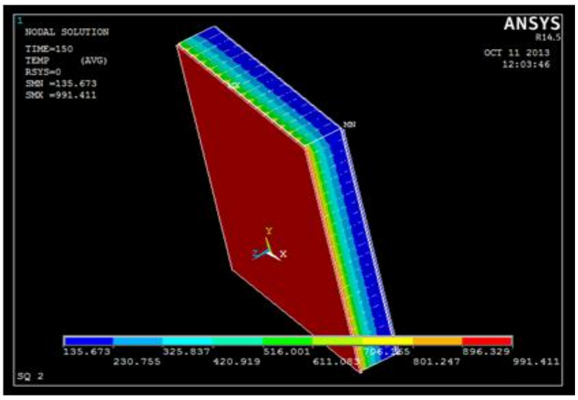

Fig. (b) 150 sec

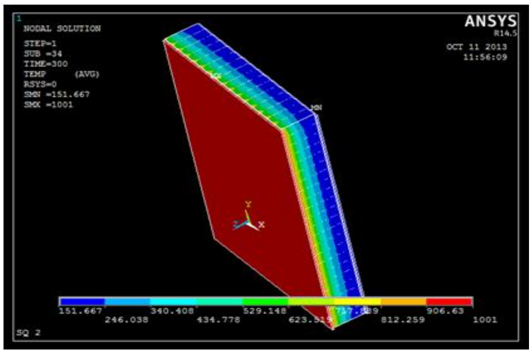

Fig.(c) 300 sec
Fig. 17 Temperature distribution with respect to time

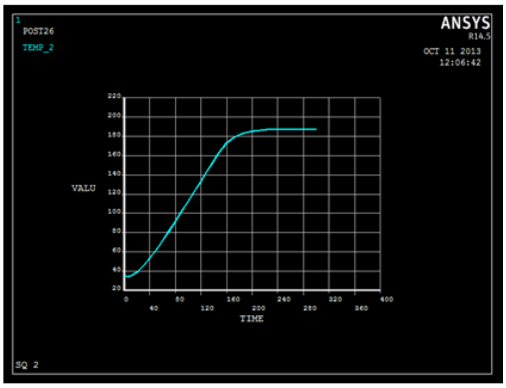

Fig. 18 Time vs Temperature for bottom plate of Incone- 617 square structure.

9 Theoretical Analysis

A honeycomb sandwich surface area A, volume v, densityρ, Thermal conductivity k, Specific heat c_p and initial temperature t_∞. At time t=0, the body placed into a medium at temperature T_0 and heat transfer takes place between the body and its environment, with a heat transfer coefficient h. For the sake of discussion, we assume that $T_0>T_\infty$, but the analysis is equally valid for the opposite case. We assume lumped system analysis to be applicable, so that the temperature remains uniform within the body at all times and changes with time only, T = T(t).
During a differential time interval dt, the temperature of the body rises by a differential amount dT.
Writing the energy balance of the solid for the time interval dt ca be expressed as

Heat energy lost at the surface of the body = Rate of change of internal energy of the body

$$- hA(T - T_\infty)\, dt = \rho V c_p dT \text{----------------------}(1)$$

Equation written in the following form

$$\frac{dT}{T - T_\infty} = -\frac{hA}{\rho V C_p} dt$$

This expression can be rearranged and integrating temperature T and the time t

$$\int_0^t \frac{dt}{T - T_\infty} = -\frac{hA}{\rho V C_p} \int_0^t dt$$

$$\log (T-T_\infty) = -\frac{hA}{\rho V C_p} t + C_1$$

The integration constant C_1 is evaluated from the initial conditions $T=T_i$ at t=0 T_i symbolizes the body temperature at the commencement of the heating process.

Therefore C_1= log $(T-T_\infty)$ and hence

$$\log (T-T_\infty) = -\frac{hA}{\rho V C_p} t + \log (T-T_\infty)$$

$$\text{or} \quad \log \frac{T-T_\infty}{T_i-T_\infty} = -\frac{hA}{\rho V C_p} t$$

$$\text{or} \quad \frac{T-T_\infty}{T_i-T_\infty} = \exp\left(-\frac{hA}{\rho V C_p} t\right)$$

$$or \quad \frac{T-T_\infty}{T_i-T_\infty} = e^{-hAt/\rho V C_P}$$

10 Results and Discussion

The effect of honeycomb cell geometry on the heat-insulation performance of a super alloy TPS has been investigated. The results of heat-transfer, of super alloy honeycomb TPS panels are presented in the following sections.

10.1 Heat Transfer

Fig.19 shows the linear time history of the temperature input to the top plate, and the time histories of the temperatures at the bottom plate for different cell geometry. The difference between the top plate and the bottom plate temperatures, ΔT is the measure of the heat-shielding performance of the TPS. Namely, the larger the ΔT values of the better the heat-resisting performance. Therefore all cell geometries reaches maximum at approximately 154 sec, then decreases only slightly with the increasing time, *t*. The bottom plate temperatures for all cell geometries are nearly the same, indicating that the TPS heat-shielding performance is relatively insensitive to the shape change of the honeycomb cell (under the same effective density). The right hexagonal cell has the lowest heat-shielding performance (the lowest), and the square cell has the highest heat- shielding The effect of internal radiation turned out to be much smaller than that of conduction for the present TPS core geometry.

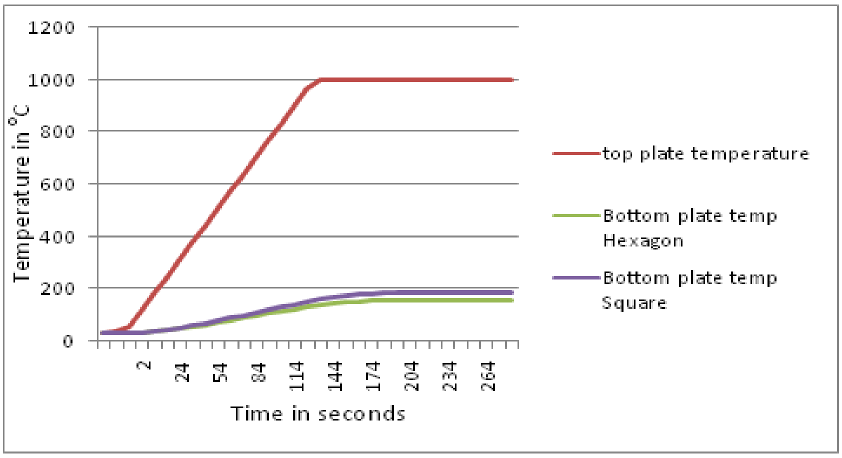

Fig.19 Effect of honeycomb cell geometry on the heat-insulation performance of super alloy honeycomb TPS panel

Table-2 Inconel-617 Hexagonal Honeycomb Sandwich Structure

TIME	TP Temp	BP Temp ANSYS	Δt-ANSYS	BP Temp Theoretical	Δt-Theoretical
1	35	34.838	0.1613	35	0
2	41.5	34.669	6.831	35	6.5
5	61	34.294	26.7059	35.0007	25.9993
14	119.5	35.537	83.963	35.0433	84.4567
24	184.5	39.345	145.154	35.3317	149.1683
34	249.5	44.842	204.657	36.165	213.335
44	314.5	51.452	263.047	37.8402	276.6598
54	379.5	58.782	320.717	40.6017	338.8983
64	444.5	66.576	377.923	44.622	399.878
74	509.5	74.667	434.832	50.0003	459.4997
84	574.5	82.950	491.549	56.7702	517.7298
94	639.5	91.355	548.144	64.9112	574.5888
104	704.5	99.839	604.660	74.3614	630.1386
114	769.5	108.373	661.127	85.0294	684.4706
124	834.5	116.94	717.56	96.8047	737.6953
134	899.5	125.527	773.973	109.566	789.934
144	964.5	134.086	830.414	123.19	841.31
154	1000	141.826	858.174	137.551	862.449
164	1000	147.598	852.402	152.532	847.468
174	1000	151.517	848.483	168.022	831.978
184	1000	154.081	845.919	183.919	816.081
194	1000	155.736	844.264	200.132	799.868
204	1000	156.799	843.201	216.579	783.421
214	1000	157.481	842.519	233.189	766.811
224	1000	157.918	842.082	249.899	750.101
234	1000	158.199	841.801	266.657	733.343
244	1000	158.378	841.622	283.419	716.581
254	1000	158.493	841.507	300.146	699.854
264	1000	158.567	841.433	316.81	683.19
274	1000	158.615	841.385	333.385	666.615
284	1000	158.645	841.355	349.853	650.147
294	1000	158.664	841.336	366.198	633.802
300	1000	158.673	841.327	375.942	624.058

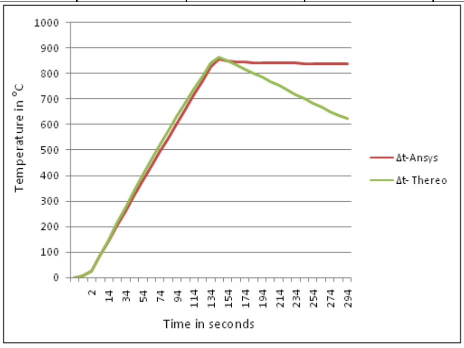

Fig. 20 Heat insulation performance of Inconel-617Hexagonal honeycomb sandwich Structure

Table-3 Inconel-617 Square Honeycomb Sandwich Structure

TIME	TP Temp ANSYS	BP Temp ANSYS	Δt-ANSYS	BP Temp Theoretical	Δt Theoretical
1	35	34.844	0.1559	35	0
2	41.5	34.674	6.8259	35	6.5
5	61	34.320	26.6792	35.0006	25.9994
12.59	106.5	35.565	70.9342	35.0253	71.4747
21.55	165	39.634	125.365	35.1969	129.8031
30.92	230	45.885	184.114	35.8323	194.1677
40.48	288.5	53.621	234.878	36.9122	251.5878
50.15	353.5	62.328	291.172	38.9553	314.5447
59.89	418.5	71.656	346.843	42.0612	376.4388
69.66	483.5	81.380	402.119	46.3619	437.1381
79.46	542	91.354	450.645	51.9296	490.0704
89.27	607	101.485	505.515	58.7847	548.2153
99.1	672	111.714	560.286	66.904	605.096
108.9	737	122.005	614.995	76.2307	660.7693
118.7	802	132.334	669.666	86.6802	715.3198
128.6	867	142.688	724.312	98.1694	768.8306
138.4	925.5	153.057	772.443	110.584	814.916
148.2	990.5	163.329	827.171	123.801	866.699
158.1	1010	171.707	838.293	137.813	872.187
168.0	1010	177.557	832.443	152.435	857.565
177.9	1010	181.365	828.635	167.569	842.431
187.8	1010	183.776	826.224	183.12	826.88
197.7	1010	185.288	824.712	199.005	810.995
207.6	1010	186.234	823.766	215.131	794.869
217.4	1010	186.824	823.176	231.462	778.538
227.3	1010	187.193	822.807	247.932	762.068
237.2	1010	187.423	822.577	264.462	745.538
247.1	1010	187.566	822.434	281.035	728.965
257.0	1010	187.656	822.344	297.604	712.396
266.9	1010	187.712	822.288	314.137	695.863
276.8	1010	187.747	822.253	330.592	679.408
286.8	1010	187.769	822.231	347.163	662.837
293.4	1010	187.779	822.221	358.029	651.971
300	1010	187.787	822.213	368.846	641.154

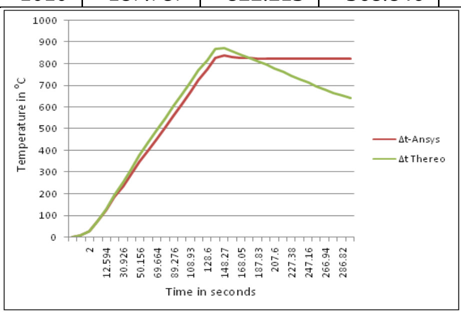

Fig. 21 Heat insulation performance of Inconel-617 Square honeycomb sandwich Structure

10.2. Comparison between Experiment, ANSYS and Theoretical Values

When the heat shielding performance of the honeycomb sandwich panels have been reasonably well-known, good agreement has been obtained between ANSYS, Calculated results. Some success has been attained in determining uncertain structural characteristics by attempting to match calculated and ANSYS results. For the most part, effort has been concentrated on determining the temperature variation of right hexagonal panel and square panel with respect to time. Table.4 shows a Heat shielding performance of TPS honeycomb-panel with different cell geometry. Comparative studies were performed on the heat- shielding characteristics of honeycomb-core sandwich panels fabricated with different geometrical shapes for possible use as wall panels for the hypersonic vehicle. Inconel-617 hexagonal honeycomb structure for heat insulation is better than square honeycomb structure.

Table- 4 Heat insulating performance of TPS honeycomb-panel with different cell geometry

S No	Cell type	Material	Time in sec	Maximum ΔT Values (max. heat shield)	
				ANSYS	Theoretical
3	Right Hexagonal	Inconel-617	154	858.174	862.449
4	Square	Inconel-617	158.16	838.293	872.187

11 Conclusions

Heat-transfer, analysis are performed on a super alloy thermal protection system (TPS) for future hypersonic flight vehicles. Effect of honeycomb cell geometry on the heat shielding performance, are found out. The heat-transfer analysis of the inconel-617 is performed on a super alloy thermal protection system (TPS) for future hypersonic flight vehicles. The heat transfer analysis shows that the Nemonic alloy attains its temperature limit of 1000^0 C at 154 seconds for hexagonal panel and 158 seconds for square panel. . Inconel-617 hexagonal honeycomb structure for heat shielding is better than square honeycomb structure. The heat shielding performance of a honeycomb TPS is insensitive to the shape of the honeycomb cell under the same effective core density, but improves with the core depth.

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