ISSN 2250-3153

Design and Analysis of Metallic Thermal Protection System (MTPS)

Suneeth Sukumaran*, Dr.S.H.Anilkumar**

* Mechanical Engineering, Jyothi Engineering College, Cheruthuruthy, Thrissur
** Mechanical Engineering, Sree Chithra Thirunal college of Engineering, Trivandrum

Abstract- The thermal protection system used in the study is an active type structure (withstand both thermal as well as structural loads) in the form of metallic corrugated sandwich. In GPP like ANSYS and NASTRAN (using 2-D heat transfer equation) have ability to do thermal analysis in component level but the customized special software(using 3-D heat transfer equation) have capability to do thermal analysis of assembled structures by giving basic properties (ρ,c,k) of each component. But the main intricacy is the variation of Thermal Contact Conductance (TCC) at metal to metal contact portions of the brazed components. In this work contains transient thermal analysis of a unit cell of MTPS and a parametric study by changing TCC value and finally reach an appropriate value and validated with available experimental value and Compared it with a casting model (no TCC) and collected the thermal data and transfer to ANSYS model. Finally carry out both thermo-structural analysis in ANSYS and bring out the capability of thermo-structural analysis of ANSYS with the support of existing customized software for evaluation of thermal field.

Index Terms- Metallic Thermal protection systems (MTPS), Transient thermal analysis, Thermal Contact Conductance(TCC)

I. Introduction

Space vehicles that enter a planetary atmosphere like the Space Shuttle Orbiter require the use of a thermal protection system (TPS) to protect them from intense aerodynamic heating. The aerodynamic heating is generated at the surface of an entering object due to the combination of compression and surface friction of the atmospheric gas. The thermal protection systems used on the Space Shuttles are reinforced carbon/carbon (RCC) at the nose and wing leading edges, high and low temperature reusable surface insulation (HRSI, LRSI) used to cover the major portion of the Shuttle windward side, advanced flexible reusable surface insulation (AFRSI) and coated nomex felt reusable surface insulation (FRSI) for the leeward side. While not much can be done with respect to replacing RCC other than develop new materials, there is good scope for developing new structures to replace the LRSI tiles,AFRSI, and FRSI which occupy the major portion on the Shuttle as shown in Figure (1). For commercial viability, the TPS must contribute to minimizing life cycle costs to enable delivery of commercial payloads at reasonable cost. For military applications, the TPS must enable high performance, rapid response, and rapid turnaround under adverse conditions. The most extensive experience with reusable TPS is with the ceramic tile and blanket TPS on the Space Shuttle orbiter. Although the orbiter TPS does an excellent job of protecting the vehicle from aerodynamic heating, more than 40,000 work hours are typically expended to refurbish and inspect the TPS between flights.

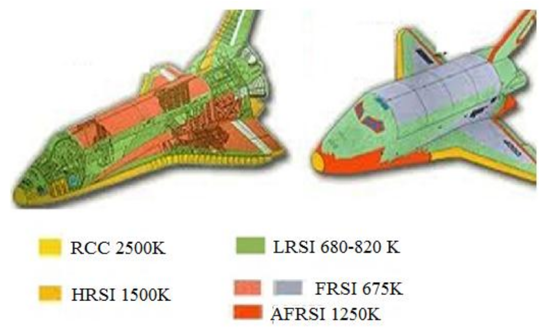

Fig (1).TPS distribution

The launch cost for the space shuttle increases by about $10,000 [1] for every pound of launch weight. So to keep space expedition economically viable in 21st century we need to decrease the cost of launching a space craft. One of the most expensive systems of a space vehicle is the Thermal Protection System (TPS), which protects the vehicle from the high thermal loads during re-entry; therefore it deserves some special attention. TPS are designed to protect the structure of atmospheric space vehicles from the extreme temperatures arising due during atmospheric re-entry.

A variety of reusable TPS concepts are being developed to address the requirements of future Reusable Launch Vehicle (RLV).The TPS used in the present study was corrugated core sandwich Metallic Thermal Protection Systems (MTPS). The corrugated core sandwich structure has more damage tolerant properties and load bearing capacities [2]. It is an Integrated Metallic Thermal Protection System (IMTPS), means withstand both thermal as well as structural loads.

II .GEOMETRY OF CORRUGATED SANDWICH MTPS

The Corrugated sandwich MTPS used for the present study consists of: (i) top face sheet, (ii) bottom face sandwich, (iii) truss-core and (iv) thermal insulation. Metallic sheets are used for the first three items. Ceramic insulation in the form of fibers is filled inside the truss core space and the sandwich core to block the heat flow from top to bottom face sheet as shown in the figure(2) the MTPS is of one storied construction. The main design constraint of MTPS is back wall temperature of Sandwich structure should be less than 375K for all re-entry space vehicles at a required duration of 1000s of the flight during the re-entry phase and this can be achieved by filling "SAFFIL" like insulation material inside the truss core.

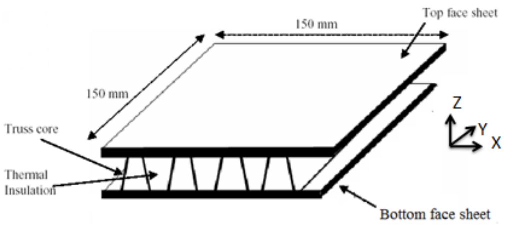

Fig (2). Geometry of MTPS

The structure is symmetric with respect to vertical plane (Z-plane).So one unit cell of 37.5 x 37.5 x 20 mm is considered to obtain the thermal field data. The one unit cell of corrugated sandwich MTPS is shown in Figure (3).

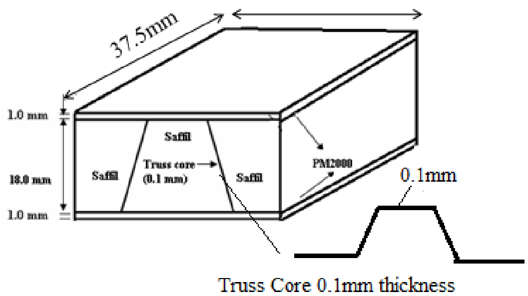

Fig (3) Unit cell of MTPS

The panel is constructed of three materials (i) PM2000 for top face sheet (1.0 mm thick), truss Core (0.1mm thick) and bottom face of top sandwich (1.0mm thick). This model is made by fixing corrugated web to the top and bottom face sheet by the process of brazing.

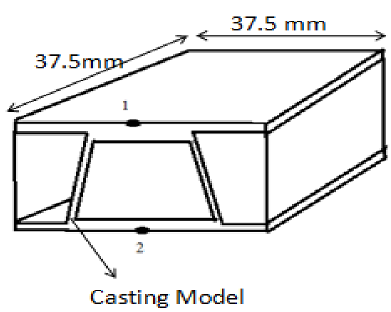

Fig (4).Casting Model

The figure (4) shows a casting model. In this model the web portion is made by casting with TFS and BFS as single volume. In casting model Back wall temperature is very high.

III .FINITE ELEMENT MODELING OF MTPS

This paper presents a three dimensional finite element method based thermal modeling of a metallic thermal protection system (MTPS).Analytical solutions are not possible with this type of heterogeneous construction since it is a non-linear transient problem. The formulation uses three types of element: (i) shell element for metallic parts, (ii) 3-D solid element for insulation and (iii) interface element for heat flow between metallic skins and insulation. Then conducted transient thermal analysis and collected thermal field data at each time step. Polynomial approximation is used to represent the through thickness temperature profile in shell elements and transfer these temperature values to ANSYS model to conduct thermo-structural analysis because stresses are considered equally important as the temperatures. Any structural failure due to high stresses may call for replacement of failed ones, before the next launch. Three types of elements: (i) 8-node shell element, (ii) 20-node solid element and (iii) 8-node interface element are employed. Shell elements are used in the metallic parts (top face sheet, truss core, top and bottom face sheets of sandwich). Solid elements are used for the insulation parts, both in truss core space and core of bottom sandwich. Interface elements are used in:

(i) Between face sheets and truss core sheets (metal-metal contact) and
(ii) Between face sheets and Saffil insulation

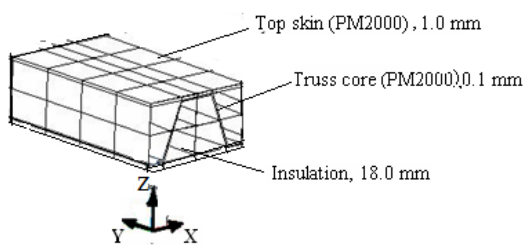

Fig (5).Finite element Modeling

The modes of heat transfer are: (i) conduction through places of direct contact, (ii) conduction through the medium filling the interstitial space,(iii)re- radiative heat transfer across the interface. The heat flow through a common surface between two contacting surfaces is modeled using the concept of interface element. The aerodynamic heating ceased after 640s is shown in heat flux trajectory (Appendix) but the heat transfer was not ceased .After 640S radiative heat transfer would be take place so give additional time up to 5640 S for heat transfer ceasing. The emissivity value used in the analysis is 1.The element exists at (i) metal to metal contact (ii) metal to saffil contact.

Parametric study for arriving at an optimum configuration can be achieved by using this Software by varying the thickness, heat flux, material without actually conducting the test.In the present study concept of Thermal Contact Conductance (TCC) have been included in the modeling for making it close to reality. Thermal Contact Conductance exists between bodies in contact whether they are of similar or dissimilar materials. The contacting surfaces correspond to the sides of two adjacent elements. Three combinations are possible in MTPS. (i) shell-solid (ii) solid-shell (iii) shell-shell. Since high temperatures are involved material properties becomes function of temperature that is also considered in the analysis. Figure (6) Shows typical temperature profiles on either side of interface with a temperature drop (ΔT) across the interface.

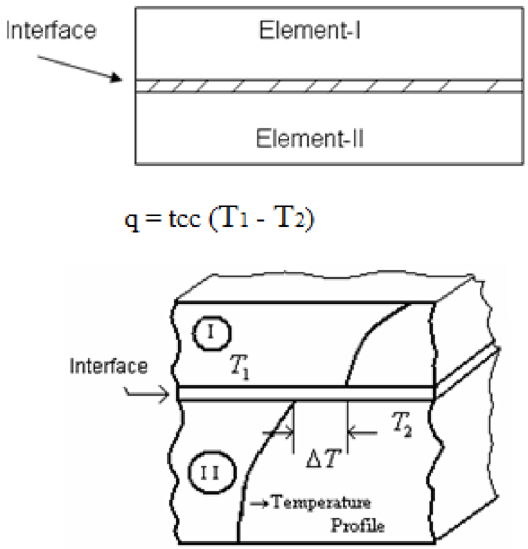

Fig (6) .Typical temperature profile

The heat flux passing through the interface is expressed as [4].

$$q = tcc(T_1 - T_2) \qquad (1)$$

Where T_1 - temperature on the bottom surface of medium – I and T_2 - temperature on the top surface of medium- II , tcc - thermal contact conductance, the value of which is difficult to specify. An experimentally evaluated one is more appropriate. But experiments have to be conducted for the specific combinations and statistical values have to be obtained. Alternately reasonable values may be obtained from existing literature (TCC=5 x 10^{-4} W/ mm^2K).In the study conduct transient thermal analysis by four TCC value(5 x 10^4 ,3x 10^{-4} ,1 x 10^{-4} ,0.5 x 10^{-4} W/ mm^2K) and find thermal datas up to 1000 seconds.

The thermal load is applied on the top surface. It is uniformly applied on the surface, the intensity varies with time. In addition to thermal load mentioned above, re-radiation heat loss condition is applied on the top surface. Also convective heat loss is applied on the top surface, after aerodynamic heating is ceased. The convective heat transfer is hc= 6.5 x 10^{-6}W/mm^2 [5].The time varying heat flux load (MACH12 trajectory) and thermal properties are shown in (Appendix).

IV .RESULTS AND DISCUSSION

The figure (7) shows positions for Temperature measurement. The transient thermal is carried out for four Thermal contact conductance (TCC) value and find temperature at top and bottom face sheet.

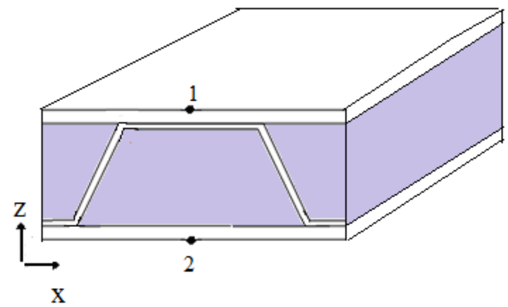

Fig (7) Positions for Temperature Measurement

Table 1 Selected location across MTPS

Position	Details
1	Outer surface of top PM 2000 skin, z = 20 mm
2	Bottom of PM2000 sheet (back wall), z =0.0 mm

A. *Transient Thermal Analysis Results*

The 4 TCC values are 1) A= 5 x 10^{-4} W/ mm^2K 2) B=3 x 10^{-4} W/ mm^2K 3) C=1x 10^{-4} W/ mm^2K 4) D=0.5 x 10^{-4} W/ mm^2K

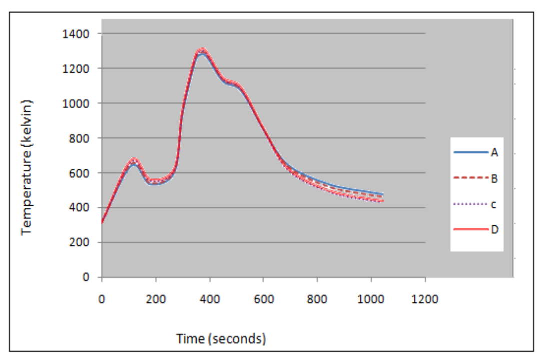

Fig (8) Top face sheet temperature for Different TCC

The variation of TFS and BFS temperature for different values of TCC are shown in Fig (8&9). For a MACH12 heat flux history (Appendix) the heat transfer through thickness from TFS to BFS was affected by TCC value .So the TFS temperature shows not much difference but BFS temperature shows much difference as shown in Fig(8 &9). This transient thermal analysis for different TCC value shows the maximum temperature value which is most close to experimental value is for TCC= 0.5 x 10^{-4} W/ mm^2K .For this TCC value the maximum temperature at top face sheet is 1312K (at 370 seconds) and maximum temperature at bottom face sheet is 601K (840 seconds) and conducted transient thermal analysis of a casting model (NO TCC) to find the importance of thermal contact conductance.

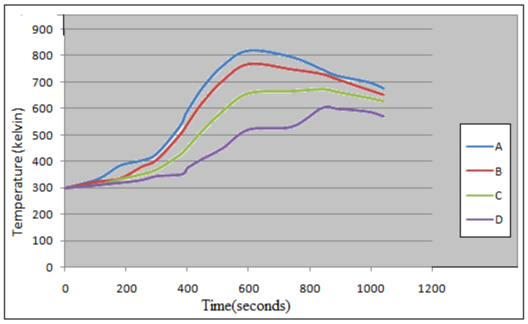

Fig (9).Bottom face sheet temperature for Different TCC

Table 2 Comparison of Temperatures

	Maximum Temperature(K)	Maximum Temperature(K)	
	Experimental	Special software(TCC=0.5 E-04)	Difference (K)
TFS	1295	1312	17
BFS	575	601	26

In this model there is no need for giving thermal contact conductance at metal-metal contact part because corrugated web is made as a single volume with top and bottom face sheet. The Variation of top face sheet and bottom face sheet temperatures of brazing model and casting model (TCC=1) is shown in Fig (10) and Fig (11) respectively.

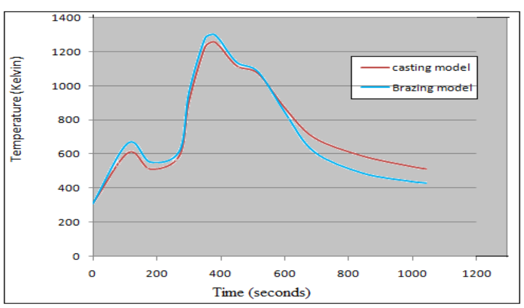

Fig (10) Variation of TFS temperature

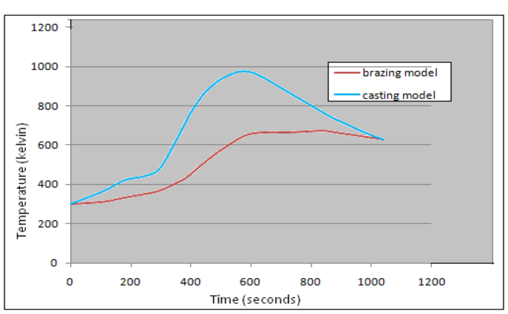

Fig. (11) Variation of BFS temperature

The maximum TFS temperature for casting model is 1260K (t=370 seconds) and for brazing model is 1304K (t=370 seconds), i.e. temperature difference of 44K. The maximum BFS temperature for casting model is 976K (t=575 seconds) and brazing model is 667K (t=620 seconds).

B. *Thermo-Structural Analysis*

Stresses are considered equally important as the temperatures any structural failure due to high stresses may call for replacement of failed ones, before the next launch. The shell element used in the special purpose software give top and bottom temperature of each node other than mid surface temperature because of interpolation function used in the software. So it is easily to use solid element for modeling of TFS and BFS in ANSYS and give proper thermal gradient by giving top bottom node temperature. Transfer the nodal temperature in the special software to ANSYS model. The elements used in ANSYS are SHELL93 (web) and SOLID45 (TFS and BFS).The saffil insulation is not considered in the structural modeling because Saffil cannot take structural loads and the structural properties are not taken into consideration. Transfer the nodal temperatures at t=376 seconds (TCC=1) from special software to ANSYS with reference to the material property data (Appendix).The Figure (12) shows thermal distribution at t=376s in ANSYS.

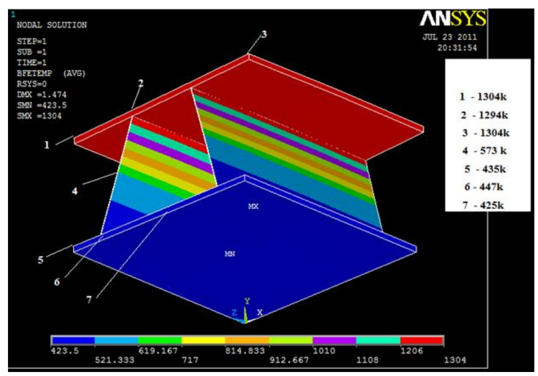

Fig (12).Temperature distribution at 376s (TCC=1)

The maximum temperature in TFS is at 376seconds (1034K) and temperature in BFS is 425K.Then constrained displacements for all nodes in the four sides of BFS and conducted the static type analysis give stresses due to temperature.

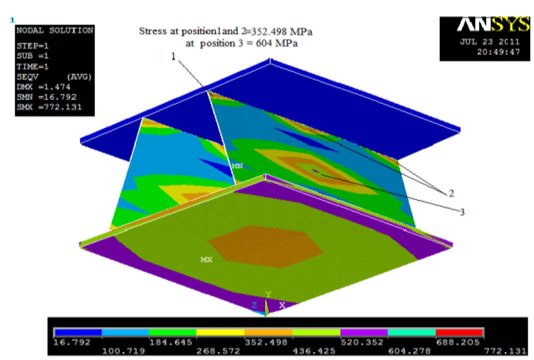

Fig (13) Von-Mises Stress

Figure (13 &14) shows the Von-Mises Stress distribution. The Figure (13) shows the stresses at position1 and position2 are 352.492MPa and at position3 is 604 MPa. The stress values exceed the safe limit according to allowable stress value at the corresponding temperature (Appendix).Figure(14) shows the stresses at position 4,5,6 is 772.131MPa which exceed the allowable stress limit.

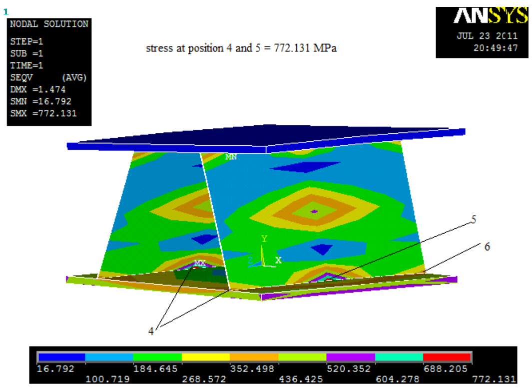

Fig (14). Von-Mises Stresses

V. CONCLUSIONS

A transient heat transfer analysis of MTPS followed by structural analyses has been carried out to bring out intricacies of associated with TCC. Thermal contact conductance which is a parameter that determines the heat transfer across the two different surfaces that are brazed together is varied from 0.5E-4 to 5 E-4 W/mm²K and thermal profile across MTPS. It is interesting to note that for a heat flux history with maximum value of 0.18W/mm² and for TCC= 0.5E-4 W/mm²K the maximum back wall temperature of the MTPS is predicted as 601K at 840s as against maximum respective value of 575K at 704s. As TCC value increases the back wall temperature increases and for TCC = 5 E-4 W/mm²K, it is obtained as 835K at 590s. When compared to the limit case of an integral MTPS (casted), the back wall temperature becomes 976K at 575s as expected.

Structural analysis results on MTPS indicated that for 100kPa load corresponding to a thermal profile for TCC=1E-4 W/mm²K, the critical buckling load as 0.356kPa with web of the truss core in bending mode. Based on the von -misses stress the truss core has a maximum stress 772MPa (476K) as against the strength of 520MPa. It is concluded that a locally the stresses are exceeding the limit. However, for a distance of 5mm away from the maximum stress zone, the value becomes 510MPa (501K) with a positive margin.

Present study indicated that the junction where truss core meets the skin needs additional reinforcement in the form of beading and recommended for using C- type channel section at the junction for supporting the truss core.

REFERENCES

[1] Satish K, Oscar M.Matrinez, Christian Gogu, Bhavani V.Shankar, Raphael T.Haftka, (May, 2006), Analysis and Design of Corrugated-Core Sandwich Panels for Thermal Protection Systems of Space Vehicles, AIAA/ASME//AHS/ASC Structures, dynamics And Materials Conference, Newport, Rhode Island.

[2] Blosser, M.L, C.J. Martin, D. Kamran, C.C. Poteet (March, 1998) Reusable Metallic Thermal Protection Systems Development, Third European workshop on thermal Protection Systems, ESTEC, Noordwijk, The Netherlands.

[3] Satish K, Christian Gogu, Bapanapalli, Bhavani V.Shankar, Raphael T.Haftka (April, 2006), Comparison of Materials for Integrated Thermal Protection Systems for Spacecraft Reentry, AIAA/ASME/ASCE/AHS/ASC Structures, dynamics, And Materials Conference, Honululu, Hawaii.

[4] Fukuoka (2005), Luo Xing et al(2008).Multi-Fidelity Analysis of Corrugated-Core Sandwich Panels for Integrated Thermal Protection Systems.. Department of Mechanical and Aerospace Engineering, University of Florida.(50th AIAA/ASME/ASCE/AHS/ASC Structures, Dynamics, and Materials Conference, 4 - 7 May 2009.

[5] Blosser, M.L., Advanced metallic thermal protection systems for reusable launch vehicles, Doctoral dissertation, Dept. of mechanical and aerospace engineering, University of Virginia, May 2000.

[6] Micromechanical Analysis of Composite Truss-core Sandwich Panels for Integrated Thermal Protection Systems.- Oscar Martinez, Satish Bapanapalli, Bhavani Sankar, Raphael Haftka. Department of Mechanical and Aerospace Engineering. University of Florida, Gainesville, Florida 32611-6250. (47th AIAA/ASME/ASCE/AHS Structures, structural dynamics, and Materials Conference Conference1 - 4 May 2006, Newport, Rhode Island). (*www.**aiaa**.org*).

AUTHORS

FirstAuthor –SuneethSukumaran, M.Tech (machinedesign),Assistant Professor,Jyothi engineering college,Thrissur and suneethsukumaranforyou@gmail.com.

Second Author – Dr.S.H.Anilkumar,Ph.d , associate professor and shakumar69@gmail.com.

Correspondence Author – Suneeth Sukumaran, suneethsukumaranforyou@gmail.com, 9496352391.

APPENDIX

Table .3.Transient heat flux loading history

ISSN 2250-3153

No	Time (s)	Heat flux, q (W/mm^2)
1	40	0.015
2	50	0.06
3	70	0.05
4	110	0.002
5	250	0.0
6	330	0.18
7	350	0.175
8	370	0.18
9	430	0.095
10	450	0.09
11	480	0.095
12	570	0.04
13	580	0.015
14	640	0
15	5640	0

Table 4. Thermal properties of PM 2000

Temperature (K)	Thermal conductivity, W/mm K	Density, kg/mm^3	Specific Heat, J/kg/K
300	0.0109	7.18e-06	480
473	0.016		480
773	0.021		610
1023	0.022		680
1273	0.0255		740
1473	0.028		800

Temperature, K	Thermal conductivity, W/mm K	Density, kg/mm^3	Specific Heat, J/kg/K
300	1.1e-05	9.61e-08	900
372	1.21e-05		950
572	1.97e-05		1092
772	3.36e-05		1172
972	5.48e-05		1222
1272	1.02e-04		1260

Table 6.Structuralproperties of PM 2000

Temperature (K)	Elastic modulus, MPa	Poisson's ratio	Coeff. of Thermal Expansion, /0C
300	21.5e04	0.3	10.7e-06
373	21.0e04		12.0e-06
523	19.9e04		12.2e-06
773	17.9e04		12.5e-06
1273	13.5e04		15.1e-06
1450	12.0e04		15.45e-06

Table 7.Allowable Stress of PM2000

Temperature(k)	Allowable Stress(MPa)
300	850
600	425
1200	255

Table 5: Thermal properties of Saffil insulation