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THE DISTRIBUTION OF TEMPERATURE IN THE TILE INSULATING MATERIAL LI900 AT HYPERSONIC FLOW

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Abstract

The paper presents the issue of aerodynamic heating and its effect on flying objects. In the second part a physical model of a protective layer has been presented along with data regarding the geometrical dimensions of the tested tile and the grid of finite elements. The further part of this work is a discussion related to the mathematical model used for the calculations. It also lists the thermal properties of the used materials. There are also presented the simplifications used for the determination of the flow of the heat flux in the protective layer. The results of the simulation pertain to the insulation of the protective layer, both damaged and undamaged. The actual parameters for the comparison of the here presented results with the ones provided in literature is the temperature on the surface of the insulating material.

Key words: aerodynamic heating, transient thermal, heat protection

NOMENCLATURE

D	$[mm]$	diameter of damage
C	$[J/kg^oC]$	specific heat
T	$[^oC]$	temperature
k	$[W/m^oC]$	thermal conductivity
ρ	$[kg/m^3]$	density
q	$[W/m^2]$	heat flux
t	$[s]$	time

INTRODUCTION

When a spacecraft enters into the earth's atmosphere aerodynamic heating occurs, Figure 1. Its source is friction resulting from the viscosity of the fluid in the direction of the surface of the moving object, the consequence of which is conversion of kinetic energy into heat. The temperature of a spacecraft while entering the atmosphere grows rapidly due to a change of the object from a continuum to a non-continuum. The main transfer of heat to the surface of the spacecraft is realized through convection and, in higher temperatures, through radiation [Wikipedia, 11.2011].

A spacecraft entering the atmosphere maintains a velocity of Mach several dozen e.g. a space shuttle - Ma 25. Such a fast moving object initiates chemical reactions in the surrounding air. In order to prevent the object incineration a monitored thermal shield is necessary (monitoring of the thermal load distribution inside it) [Collective work, 2004].

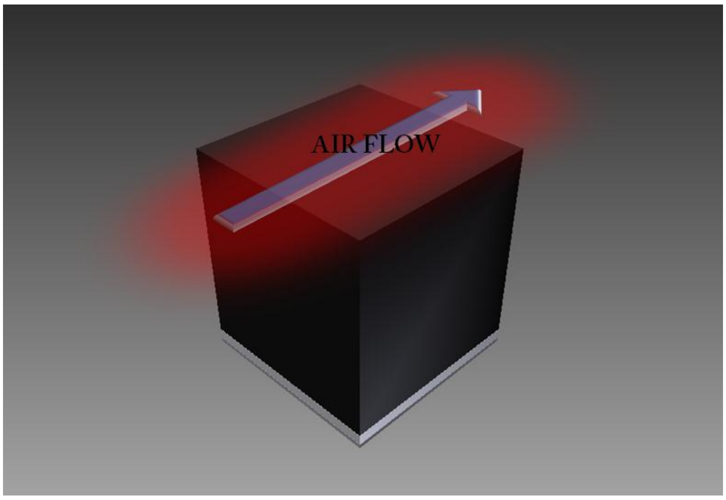

Figure 1. Aerodynamic heating phenomena

The aim of this paper is to verify the material data and compare the results of the calculations of the heat distribution the insulator with the data available in the literature. A very significant influence on the proper functioning of the insulator may have several types of damage occurring during the spacecraft missions. Such phenomena pose a risk of overheating and falling off of the elements of the insulator. Hence, the numerical simulations pertained to both damaged and undamaged model.

MODEL OF TILE

For simulation the insulation LI material was used. This material is manufactured in 99.9% from pure silica glass fibres and 94% of its whole volume is air. It can operate at temperatures reaching 1204^{o}C. It is a construction material for HRSI (black) and LRSI (white) insulation tiles applied in the American Space Shuttle [Wikipedia, 112.2011].

A simplified research model is composed of three layers. The first is the aluminum skin, the second is the polymer SIP (Strain Isolator Pad) and the third one is the silicon-based insulator. A real tile also contains layers of adhesive and RCG coating (Reaction Cured Glass). The dimensions of the model base are 76.2 x 76.2 mm. The thickness of the skin is 1.6 mm, the SIP 4.394 mm, and LI 78.486 mm. The undamaged tile has 4608 elements and 22319 nodes, Fig. 2. The model of the damaged tile was divided into several types according to the size of the damage, Table 1, Figure 2.

Model number	D [mm]	Elements	Nodes
1	0	4608	22319
2	6.35	18891	29556
3	12.7	18889	29500
4	19.05	18946	29687
5	25.40	18719	29319
6	31.75	18743	29400
7	38.10	18866	29533
8	44.45	18634	29176
9	50.80	18440	28931
10	57.15	18437	28969
11	63.50	18124	28521
12	69.85	18035	28388
13	76.20	17693	27916

Table 1. Construction of the grid damaged models

The geometry of the damage is represented by an indentation in the form of a quarter of a sphere of the radius of 19.05 mm in one of the corners of the model. This spot is at the same time the center of the tile as the model represents a solid of the base that is four times smaller than the actual tile.

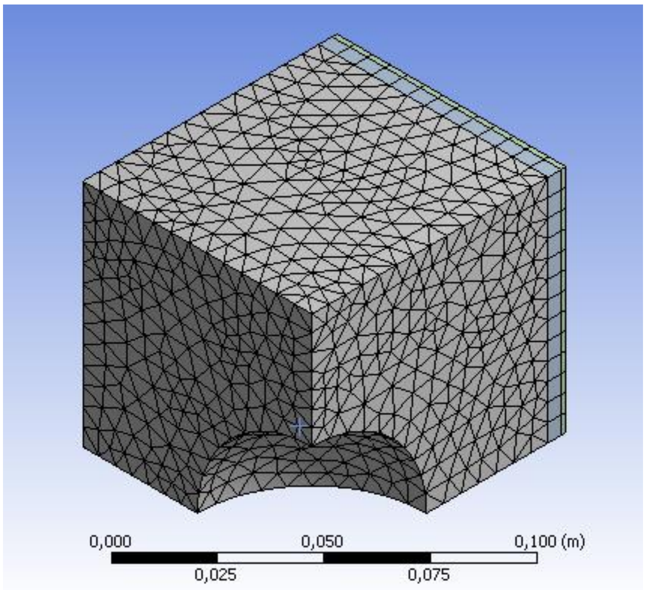

Figure 2. Construction of the grid damaged model 13

MATEMATICAL MODEL OF THE CALCULATIONS

For the simulation Ansys software was used. The calculations were carried out according to the Crank-Nicolson method, for transient thermal conditions (1) [Lewis, 2004].

1. $$\rho c \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k \frac{\partial T}{\partial x}\right)$$ (Collective work, 2004)

ASSUMPTIONS SIMPLIFIYING CALCULATIONS

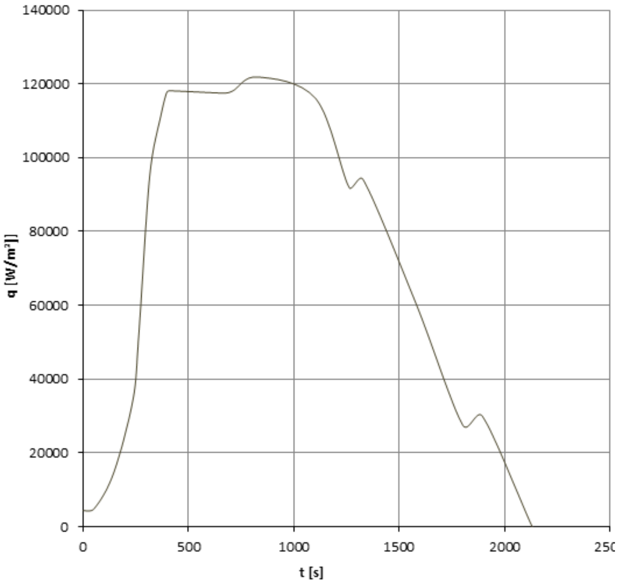

Figure 3. Profile of the heat flux in time

For the calculations the following were assumed:

a) The emissivity of the tile is constant for both the damaged and undamaged tiles and amounts to $\varepsilon=0.85$;
b) The heat transfer coefficient of materials changes as a function of temperature;
c) Each of the materials has isotropic properties;
d) All surfaces of the model are perfect insulated except the outer insulation;

The heat flux is the same for both analyzed cases as given in Fig. 3.

MATERIAL PROPERTIES

The properties of the applied materials have been presented in tables 2-4.

T (°C)	C ($\frac{J}{kg°C}$)	k ($\frac{W}{m°C}$)	P (kg/m³)
-73.2	787.0	163.0	2770
26.9	875.0	177.0	
126.9	925.0	186.0	
326.9	1042.0	-	

Table 2. Thermal properties of the skin

T (°C)	C ($\frac{J}{kg°C}$)	k ($\frac{W}{m°C}$)	P (kg/m³)
-17.6	1306.3	0.03271	194
93.5	1339.8	-	
204.6	1402.6	0.04636	
615.7	1444.5	0.06604	

Table 3. Thermal properties of SIP

T (°C)	C ($\frac{J}{kg°C}$)	k ($\frac{W}{m°C}$)	P (kg/m³)
-17.6	628.0	0.03165	144
121.3	879.2	0.03894	
260.2	1055.1	0.04779	
399.1	1151.4	0.05626	
538.0	1205.8	0.06791	
676.9	1239.3	0.08536	
815.7	1256.0	0.10650	
926.9	1264.4	-	
954.6	1268.6	0.13270	
1093.5	-	0.16320	
1260.2	-	0.20060	

Table 4. Thermal properties of LI900 tile

Material properties and dimensions of the model taken from literature [Ng, 2007].

CONCLUSIONS

In the simulation 13 models were used. The thermal resistance of the aluminum skin amounts to 150°C. Model 1 i.e. the undamaged model assumes the stream of heat that does not exceed the maximum thermal loads. Each consecutive damaged model results in an approximation to that thermal boundary. Figure 10 was drawn going on the assumption that the thermal conductivity from the temperature of 127°C and higher does not change. The distribution of temperature on the surface of the insulating material in the simulation of the undamaged tile is equivalent to the actual measurement performed during the flight. More prominent divergences can be observed from the 3500 seconds onwards. As for the temperature distribution on the surface of the sheet, there obtained results equivalent to another simulation realized in the Abaqus software [William, 1986, Ng, 2007]. The distribution of temperature in the materials was shown in the figures 4-6 and figures 7-9 (the temperatures on the surfaces).

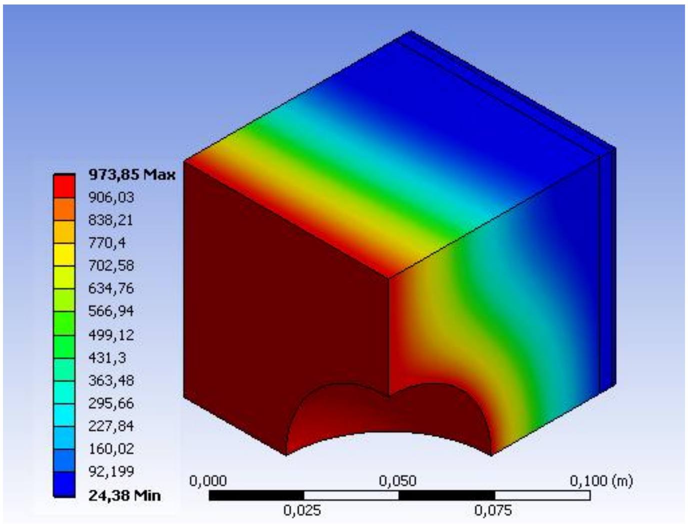

Figure 4. Temperature distribution T [^{o}C] in the damage model 13 (1100 s)

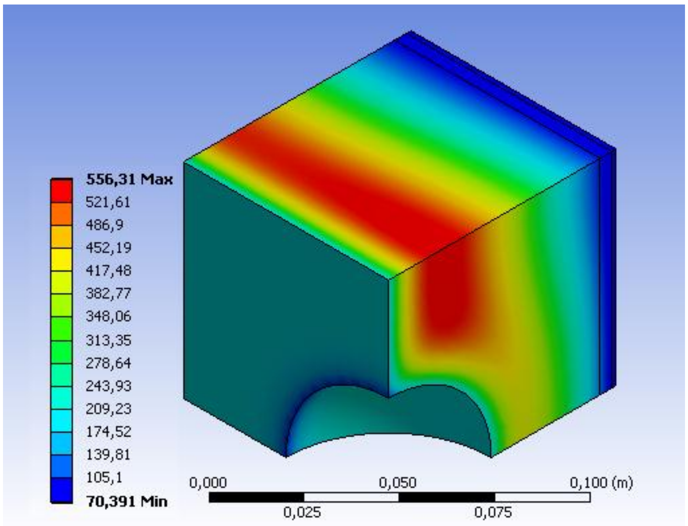

Figure 5. Temperature distribution T [^{o}C] in the damage model 13 (2200 s)

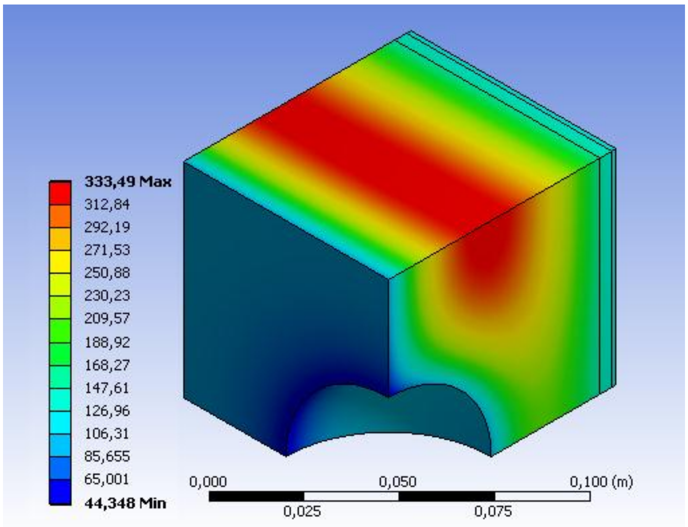

Figure 6. Temperature distribution T [^{o}C] in the damage model 13 (3300 s)

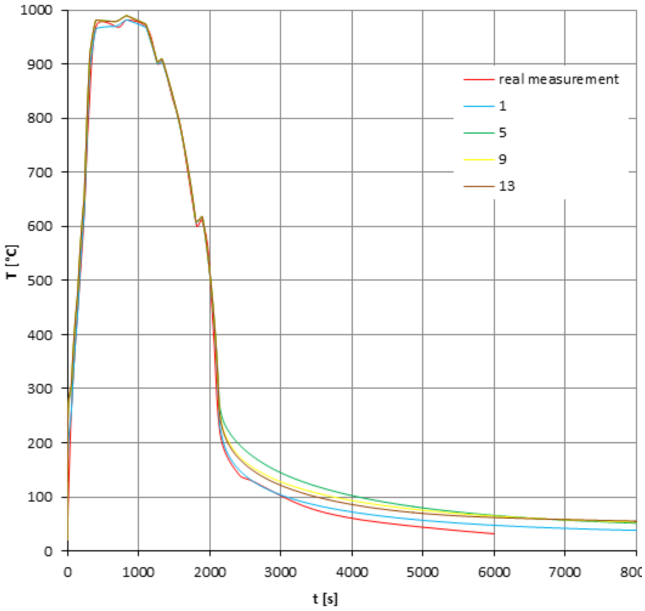

Figure 7. Temperature distribution on the surface of the insulation

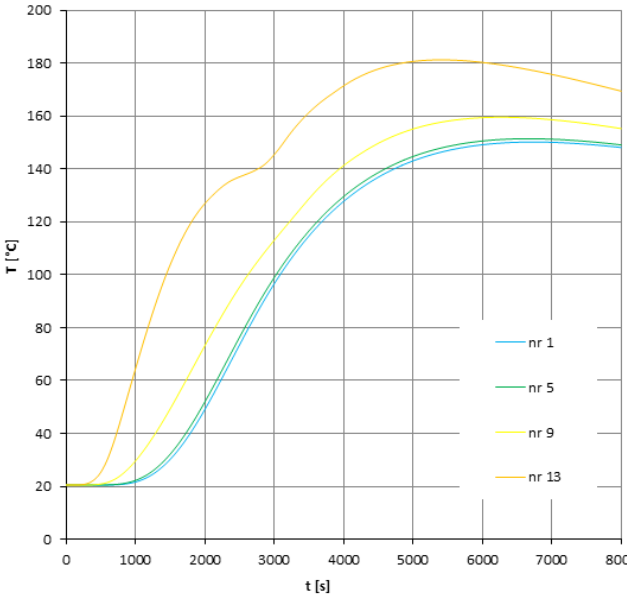

Figure 8. Temperature distribution at the boundary of the insulation and the SIP

For first seven damaged models on the surface of skin temperature not exceeded approximately 10°C above maximum work temperature. On the basis of calculations confirmed that the temperature on the surface of aluminum increases significantly and reaches its maximum after landing vehicle.

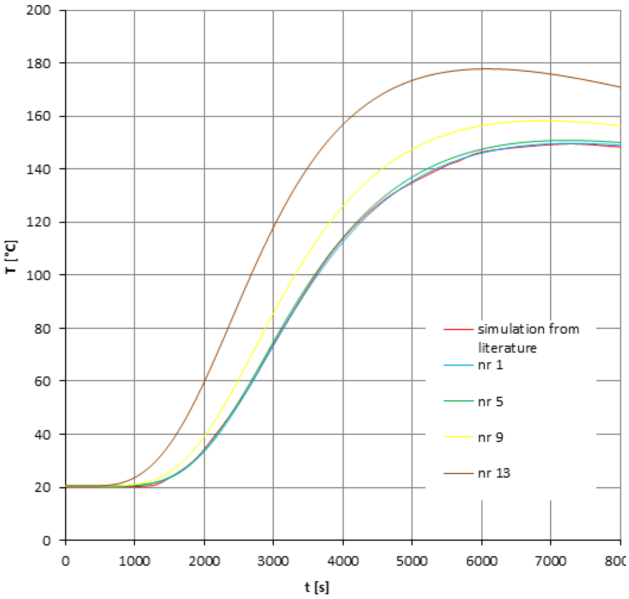

Figure 9. Temperature distribution on the surface of the skin

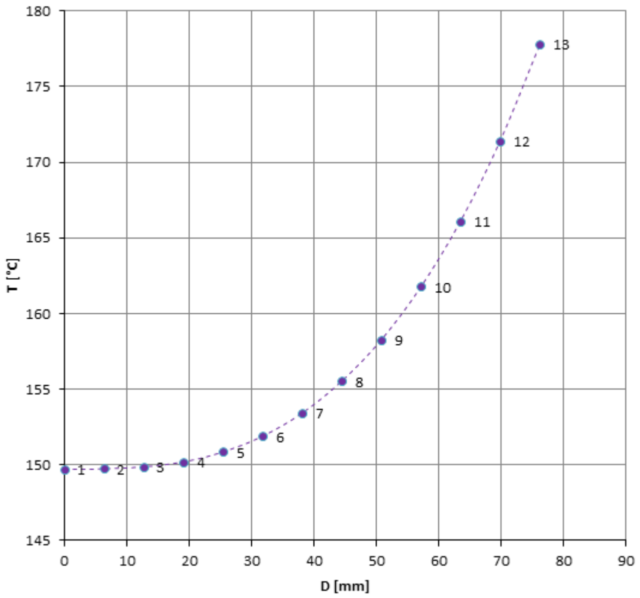

Figure 10. Growth of the maximum temperature as the diameter of the damage increases

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