SOLUTION OF THE HEAT TRANSFER PROBLEM IN HYPERSONIC FLOW

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Abstract The paper presents the issue of aerodynamic heating and its effect on flying objects. In the first 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. There are also presented the simplifications used for the determination of the flow of the heat flux in the insulation tile. The results of the simulation pertain to the insulation of the protective layer, both damaged and undamaged. The aim of the article was to verify the results of calculations performed in ANSYS program. Numeric code was created in freefem++ environment. Thus was obtained the curves of maximum surface temperatures of the insulation, the underlying structure and the intermediate layer. Fluid flow around the vehicle is laminar and turbulent. Large angle of attack of the wings determines the strong turbulent flow, particularly in the later stage of the flight. In order to simplify the calculation the phenomenon of the flow the heat flux generated by friction of the object and the fluid was adopted. Heat flux curve derived from the literature. It was the result of a study or the real flight.

INTRODUCTION

A spacecraft entering the atmosphere maintains a velocity of Mach several dozen e. g. a Space Shuttle – 25 Ma. 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) [2].

The aim of this paper is to compare the results of the calculations of the heat distribution the insulator with the data received in commercial program, ANSYS [1]. A very significant influence on the proper functioning of the insulator may have several types of hazards occurring during the spacecraft missions. One of the most important are meteoroids. Phenomena associated with the collision of these objects pose a risk of overheating and off insulator elements. Hence, the numerical simulations pertained to both damaged and undamaged model.

GEOMETRIC MODEL

To the numerical simulation was used two-dimensional geometric model consisting of three layers. The first one was the skin of aluminum, the second one strain isolator pad of polymer, and the third one insulating material LI900. Layers RCG and RTV were omitted. For the model was assumed the insulation thickness equal to 78.5 mm. Axisymmetric model was created based on real dimensions of the insulating tile. Two-dimensional geometry helped reduce the computation time. Model of damage was made for the case, where the defect in insulation is formed by an impact with small object moving at a hypersonic speed [3]. Its shape and simplification is given as in literature [4].

FORMULATION OF THE HEAT TRANSFER PROBLEM

Calculations were made in two programs: ANSYS ver. 13 and FreeFem++ ver. 3.2. In both programs they were made using the same methods – the finite element method. She has an universal application. It is suitable both for solving of elliptic, parabolic, and hyperbolic type. In carrying out the analysis of the heat flow in non-stationary conditions for axisymmetric heat conduction model there was used the first law of thermodynamics and Fourier's law. Therefore, for the cylindrical coordinate system the following formula was used:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{1}{R}\frac{\partial}{\partial R} k_R R \frac{\partial T}{\partial R} + \frac{\partial}{\partial y} k_y \frac{\partial T}{\partial y} + \frac{1}{R^2}\frac{\partial}{\partial \theta} k_\theta \frac{\partial T}{\partial \theta} \tag{1}$$

The heat exchange takes place on the outside using radiation. Convection is negligibly small. In ANSYS for surface radiation was used an extended Stefan – Boltzmann law. This is a dependency Siegel and Howell, which relates to energy losses and surface temperature:

$$\sum_{i=1}^{N} \frac{\delta_{ji}}{\varepsilon_i} - F_{ji}\frac{1-\varepsilon_i}{\varepsilon_i} \frac{1}{A_i} Q_i = \sum_{i=1}^{N} \delta_{ji} - F_{ji} \sigma T_i^4 \tag{2}$$

In FreeFem++ to solve radiation was used method of spherical harmonics. The great advantage of the method of spherical harmonics is the conversion of the governing equation to relatively simple partial differential equations. In

ANSYS the grid was made from quadrilateral elements with eight nodes. In FreeFem++ was used triangles with six nodes.

In the calculations are consisted the following simplifications (as shown by the figure 3):

- heat flux density q for the walls of S1 and S2 are the same, and was taken from literature [4]
- heat flux density q=0 of the walls S3, S4 and S5
- thermal emissivity ε=0.85 for the walls of S1 and S2

All materials properties were taken from literature [4].

RESULTS

The formation of damage in the insulation and growth of the diameter results in an increase of temperature across the tile. Exceeding the temperature of 1370ºC causes flowing the material, and its structure does not return to the original shape already. Calculations showed that the damage, which has a diameter of 1 cm, is the cause of the initiation of this process. In figure 1 are presented the maximum temperature change in time of the damaged and undamaged models. The difference in temperature on the surface of the skin and connecting the skin with SIP is negligible and it is not considered in the analysis. The reason of that is chosen skin and SIP thickness.

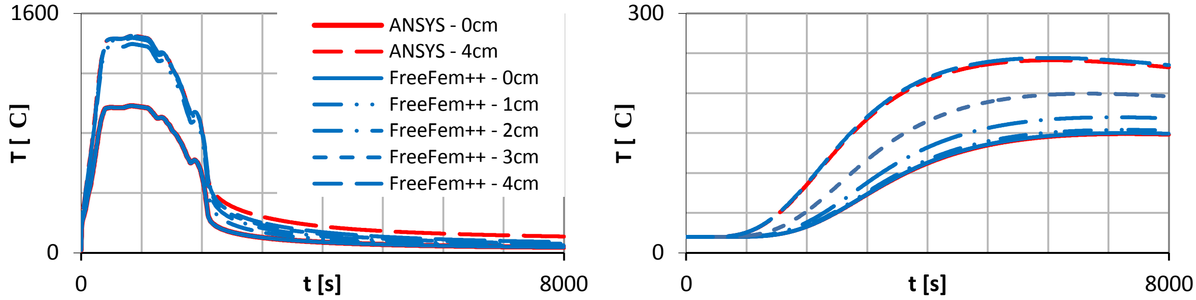

Figure 1. Maximum temperature in function of time, on the left side: the insulation surface, on the right side: the skin surface

The results show, that the maximum temperatures obtained at the surfaces of the insulation and skin slightly differ from those obtained in the ANSYS program. For the model of undamaged tile in temperatures on the skin surface is 1ºC. For a model with the largest diameter of damage differences are 3ºC, which gives 1.25%. For insulation, for the model of undamaged tile and the most damaged tile differences in maximum temperatures also does not exceed 1ºC. After 2100 seconds, there are differences in the results for the damaged model. For maximum diameter these differences reach their maximum at the time of 8000 s. and are 27ºC.

CONCLUSIONS

To sum performed calculations it can be concluded, that:

- the maximum temperatures obtained at the surface of both the insulation and skin are comparable,
- used a different model solution for the problem of radiation caused different results only during the cooling phase on the surface of the insulation after landing spacecraft.

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