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Estimation of the thermophysical properties of heat-protective composite materials

Yu. P. Aleksandrova[1*]

[1]Moscow Aviation Institute (National Research University), 4, Volokolamskoe Shosse, Moscow, 125993, Russia

Abstract. The paper proposes a mathematical simulation method for identifying thermophysical properties using a developed software package based on a composite material model presented as a combination of plates of alternating heterogeneous components, fiber material and air, oriented parallel and perpendicular to the heat flux. The effect of the orientation angle of the fibers and their volume content on the effective thermal conductivity has been determined.

1 Introduction

Currently, the accuracy of mathematical models describing properties of composite materials is increasingly demanding. In the case of a tile thermal protection coating, the main structural part is a thermal protection element, which consists of fibrous insulating tiles, erosion-resistant and lacquer coatings, damping pads and glue, connecting the damping substrate with the tile and the entire thermal protection element with the aircraft body (Figure 1).

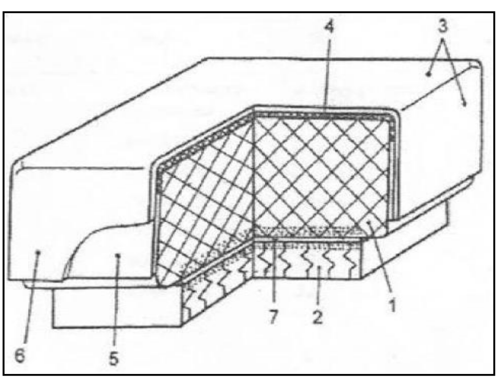

Fig. 1. The design of the thermal protection element: 1– a tile made of a fibrous thermal protection composite material; 2 – a damping gasket; 3,6 – a lacquer moisture-proof coating; 4,5 – an external and lateral vitreous erosion-resistant coating; 7 – an adhesive layer.

* Corresponding author: nbulychev@mail.ru

In this structure, each material fulfills its functional role, and in the absence of any of these materials, the thermal protection element as a whole, that is, the tile thermal protection of the aircraft will not work. The main role is assigned to the thermal protection tile. It is made of a fibrous thermal protection material and is a rigid spatial frame made of inorganic high-temperature fibers.

2 Materials and methods

It is important to note that the properties of thermal protection tiles (thermal conductivity, density, strength, and thermal expansion coefficient) are determined primarily by the fibers – their composition, structure, morphological features, etc. [1-10]. There is a sufficient number of works on obtaining and studying the thermophysical and mechanical properties of composite materials [11-19]. As a rule, two approaches are used when modeling composite materials: the theory of effective media [20-31] and the solution of inverse problems for the identification of thermophysical parameters of composite materials. A modern methodology for solving inverse coefficient problems is proposed in [32-37]. The works [38-49] also solve direct problems of determining temperature fields in composite materials characterizing by significant anisotropy of properties, using both analytical and numerical methods, as well as describe experiments to determine the properties of composite materials. In this paper, we consider a composite material in which the matrix is air, and inclusions are cylindrical fiber inclusions. Simulation of thermo-physical properties was carried out using a specially developed software package based on a composite material model presented as a combination of plates of alternating heterogeneous components, in this particular case consisting of air and fiber material, oriented parallel and perpendicular to the heat flux.

3 Results and discussion

3.1 Mathematical model

To evaluate the thermophysical properties of the materials under consideration, a model of the structure of a chaotic fibrous system was considered, which was represented as a combination of plates of alternating heterogeneous components, in this particular case, consisting of air and fiber material, oriented parallel and perpendicular to the heat flux. The thermal conductivity of such a model can be represented as a function of the thermal conductivity of two models – packages of flat plates, of which part is oriented parallel, and part perpendicular to the direction of heat flux.

3.2 Determination of thermal conductivity in the parallel and perpendicular direction to the plate plane depending on the orientation angle and the volume fraction of the fibers

Let's consider a composite material in which the matrix is air, and inclusions are cylindrical fibers.

Simulation of thermophysical properties was carried out employing a specially developed software package using two different methods for setting the orientation angle of the fibers. To choose the most suitable method, we will conduct a test study for mullite fibers, after which let's apply the results obtained to determine the thermal conductivity of a plate of thermal protection material.

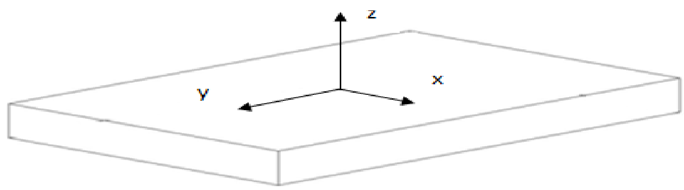

Fig. 2. Panel of thermal protection composite material.

The following initial data were set: the specific heat capacity of the air equal to 1000 J/(kg · K), the thermal conductivity of the air at 20^{0}C is equal to 0.025 W/(m · K), the density does not have a significant effect on the thermal conductivity coefficient. Fiber properties were as follows: the specific heat capacity of mullite equal to 1000 J/(kg · K), the thermal conductivity of mullite at 20^{0}c is equal to 0.35W/(m · K). The ratio of the longitudinal and transverse dimensions of the fiber was equal to 100. This parameter is used to specify an elongated ellipsoidal shape. When this parameter is equal to unity, the fiber acquires a spherical shape.

The fibers orientation angle can be set using two methods:

1. fixed model – with a fixed orientation angle of the fibers;
2. tensor model – using a fiber orientation tensor that determines the probability of fiber orientation in different directions

The components of the main diagonal of the fiber orientation tensor were set in accordance with the solution of the system of equations:

$$\begin{cases} A \cdot \tan\alpha = B\sqrt{2} \\ A + 2B = 1 \end{cases} \tag{1}$$

The solution of this system has the form, in which the values of the main diagonal components of the orientation tensor are put in accordance with the specific average angle of the fibers orientation:

When constructing a solution for isotropic cases with different volumetric fiber content, a model was used that corresponds to an isotropic material, while the fibers were arranged in a chaotic manner and oriented in all directions equally probable.

Figures 3-4 below show a comparative analysis of the results obtained using different fiber orientation models. Here λ is the coefficient of thermal conductivity, [W/(m·K)], and φ is the angle of fibers orientation.

Table 1. Solution to the equations system (1) determining the value of the diagonal components of the tensor of the fiber orientation angle.

Angle α	A	B
0	1	0
10	0.800407242	0.099796379
20	0.660182948	0.169908526
30	0.550510257	0.224744871
40	0.457317196	0.271341402
50	0.372384821	0.313807589
60	0.289897949	0.355051026
70	0.204686509	0.397656745
80	0.110859784	0.444570108
90	0	0.5

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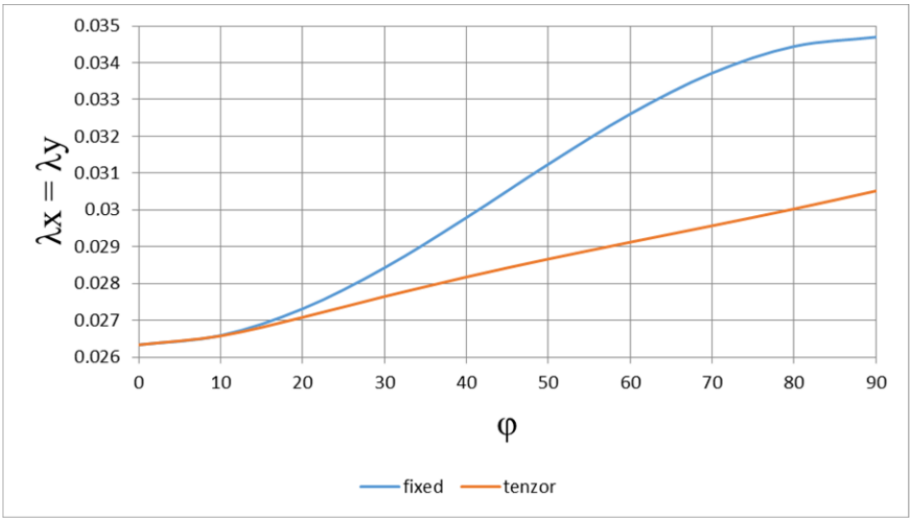

Fig. 3. Thermal conductivity in the direction of the X and Y axes (volume fraction of mullite m1 = 0.03%).

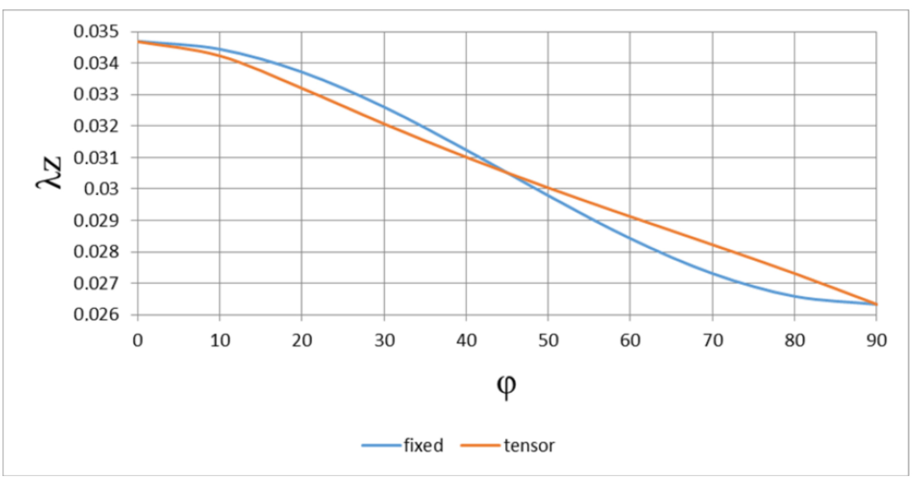

Fig. 4. Thermal conductivity in the direction of the Z axis (volume fraction of mullite m1= 0.03%).

The second tensor-based model corresponds more to a structure with a chaotic arrangement of fibers. This model implies that the fibers have a fixed average inclination angle to the normal to the plate surface, while they can be oriented arbitrarily in the plate plane (that is, they can "rotate" around the normal, at that each location will be equally probable). That is why the model based on the fiber orientation tensor setting demonstrates lower values of the thermal conductivity coefficient - there is no dedicated direction in the fiber plane, which is fixed when choosing a method for setting the fibers orientation with a fixed angle.

Based on the selected model, we will evaluate the thermal conductivity of a thermal protection element with a different angle of fibers orientation. In Figures 5-6, dots on the graphs indicate the values of thermal conductivity in isotropic cases.

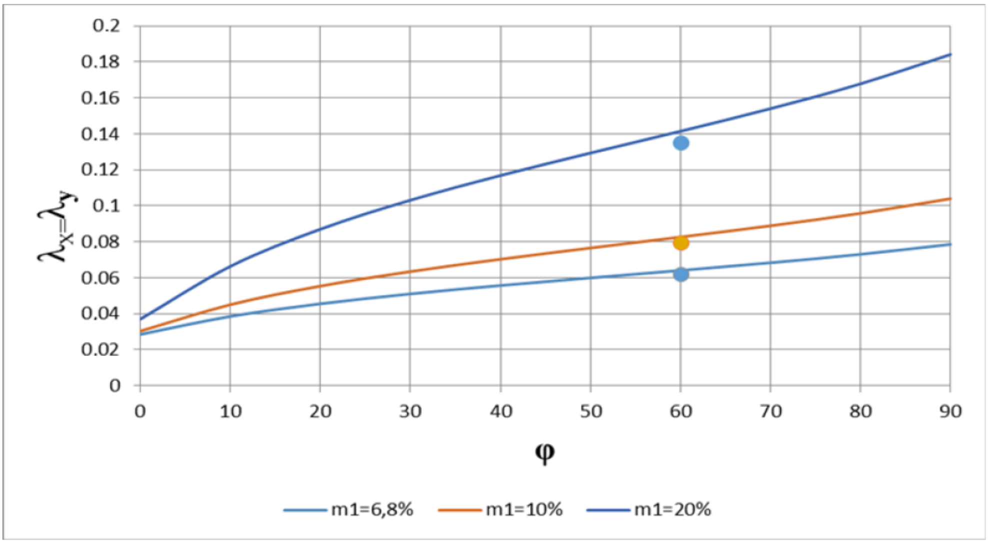

Fig. 5. Thermal conductivity in the plate plane of the thermal protection composite material depending on the orientation angle of the fibers and their volume fraction.

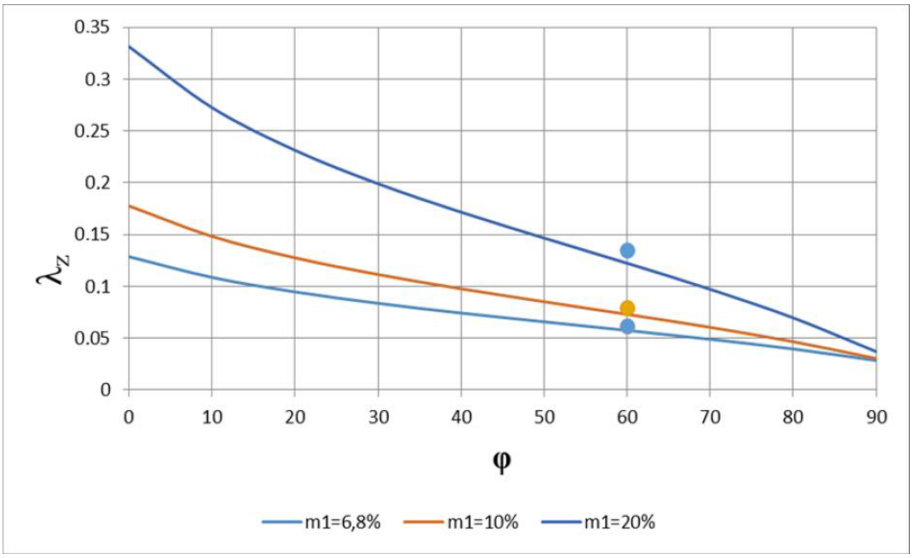

Fig. 6. Thermal conductivity in the selected direction of the plate of the thermal protection composite material depending on the orientation angle of the fibers and their volume fraction.

4 Conclusion

The microstructure of a plate of a thermal protection composite material was investigated in the work. The simulation of thermophysical properties was carried out using the developed software package based on a composite material model presented as a combination of plates of alternating heterogeneous components, in this case – of air and fiber material

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oriented parallel and perpendicular to the heat flux. The effect of the orientation angle of the fibers and their volume fraction on the effective thermal conductivity has been determined.

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