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THEORETICAL AND NUMERICAL CHARACTERIZATION OF THE THERMAL PHYSICAL PROPERTIES OF CARBON CERAMIC MATERIAL

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Abstract. The article presents models representative volume element of the porous carbon-ceramic material. Simulating of heat transfer process in a representative volume element is carried out and thermal characteristics of material are determined by a settlement way. Influence of characteristics of material structure – its porosity and type of reinforcement – on values of heat-physical characteristics is investigated. It is shown that in the field of high temperatures (more than 1500 T) the defining role in the course of heat transfer in high-porous (P> 40%) materials belongs to radiation heat exchange in a pores.

1 Introduction

Russia, the USA, EU and China are currently developing manned spacecraft, such as Orion, Dragon, PTKS for the Earth orbit, Moon and Mars missions. One of the most important and complex scientific and technological challenges is to create a reliable and weight efficient thermal protection system.

Thermal protection coating (TPC) used for the Vostok, Soyuz, Mercury and Apollo reentry modules was based on ablative materials. In this case, a significant part of the energy from high enthalpy gas flow to the front surface is absorbed due to disintegration and ablation of specialized polymer composite materials, while heat transfer to the frame is blocked with a thermal protection layer. Ablative TPC have proved highly reliable, however, they are characterized by significant linear density and non-reusability [1].

New generation spacecraft industry requires multi-use reentry vehicles and TPC. Such TPC can be manufactured on the basis of carbon ceramic composite materials (CCCM) with the operating temperature of 2000°C, density of 2000 kg/m^3 [2]. The load-bearing capacity of CCCM is achieved by means of high strength carbon fiber and SiC ceramic matrix serving as antioxidant. The possibility of creating TPC based on CCCM and an extra layer of thermal protection material [3, 4] is currently under consideration.

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TPC linear density can be reduced if porous CCCM are used, where carbon fibers are coated against oxidation with a thin (1-2 μm) layer of SiC. It can be assumed that the CCCM heat transfer coefficient can be significantly decreased by regulating the material porosity and selecting the rational layout of the reinforcement fibers.

Theoretical rationale of the possible characteristics of porous CCCM is presented in [5], however, only a limited set of material structure variants was analysed, excluding the radiative heat transfer in the porous CCCM volume. Thus it remains relevant to research the possible thermal physical properties of porous CCCM with 1000 to 2000 kg/m^3 density.

2 Analysing the effect of the CCCM layers layout

The model of the porous CCCM structure was based on microimages from an optical microscope (fig. 1). It was assumed that the porous CCCM comprised separate orthogonal layers of carbon fibers 6 mm in diameter with 1 μm SiC ceramic coating.

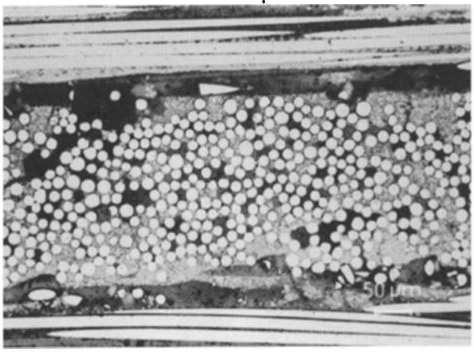

Fig. 1. Image of carbon ceramic material microstructure [2].

MSC.Digimat software package was used to create geometric models of the representative element for the 18% porous volume (fig. 2). The models comprised various combinations of the carbon layers thicknesses in orthogonal directions.

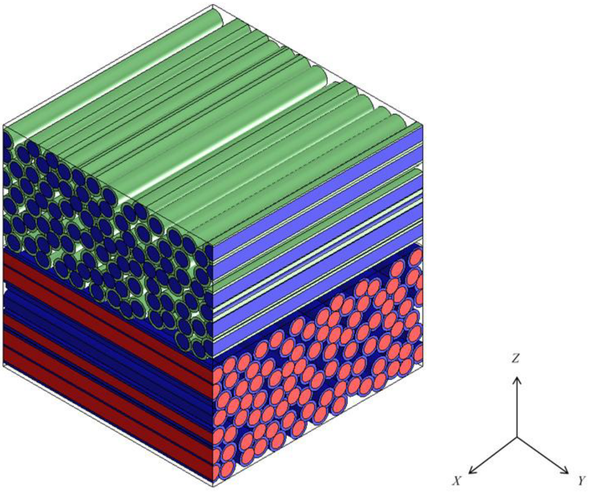

Fig. 2. Geometric model of a representative element of porous CCCM with orthogonal pattern reinforcement from SiC coated carbon fibres.

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The models in STEP format were exported into Ansys Workbench 16 software package [6], where a finite element model of the representative element was created. The next stage was the simulation of heat transfer in the volume representative element. It was assumed that the temperatures in the two faces normal to one of the axes are different but constant over the surface. The remaining faces of the volume representative element were assumed to be thermally insulated. The simulation results were used to estimate the density of the heat flow in the direction of the selected axis, which enabled determing the coefficient of molecular heat transfer based on Fourier law. The initial data on the properties of the porous CCCM components were taken from [5].

The results in fig. 3 demonstrate that the combination of the carbon layer thicknesses in the orthogonal directions does not affect the heat transfer coefficient in the direction of the Z axis. However, the heat transfer is considerably affected by this ratio due to the high heat transfer along the fiber axis. Moreover, to enable XY-plane isotropy the carbon layer thickness ratios should be uniform in the orthogonal directions.

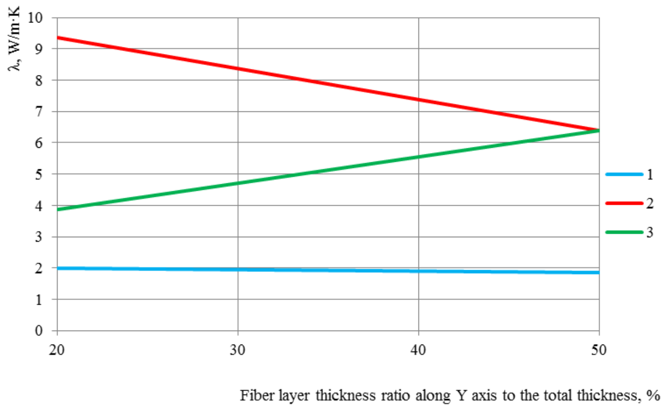

Fig. 3. Molecular heat transfer coefficient of CCCM with 18% density and orthogonal reinforcement pattern as a function of layer thickness ratio at 1700°C. 1 – molecular heat transfer coefficient along Z-axis; 2 – along X-axis; 3 – along Y-axis.

3 Analysis of the CCCM porosity effect

Two groups of models were used to estimate the porosity effect on the CCCM thermal physical properties. The first group included the models of the representative element with the orthogonal layers pattern and the equal layer thickness ratio in the orthogonal directions (fig. 4a). The second group employed the model of the representative element with the random fiber layout (fig. 4b). The both group models were based on homogeneous fibers 7 μm in diameter. These homogeneous fibers are assumed to possess thermal physical properties equivalent to those of SiC coated carbon fiber. The heat transfer process in a single SiC coated carbon fibre was simulated in order to determine the thermal physical properties of the homogeneous fibers, and the heat flux through the fiber section was determined. The condition of the thermal flux equality for the coated fiber and the homogeneous fiber was used to determine the equivalent heat transfer coefficient for the homogeneous fiber shown in fig. 5.

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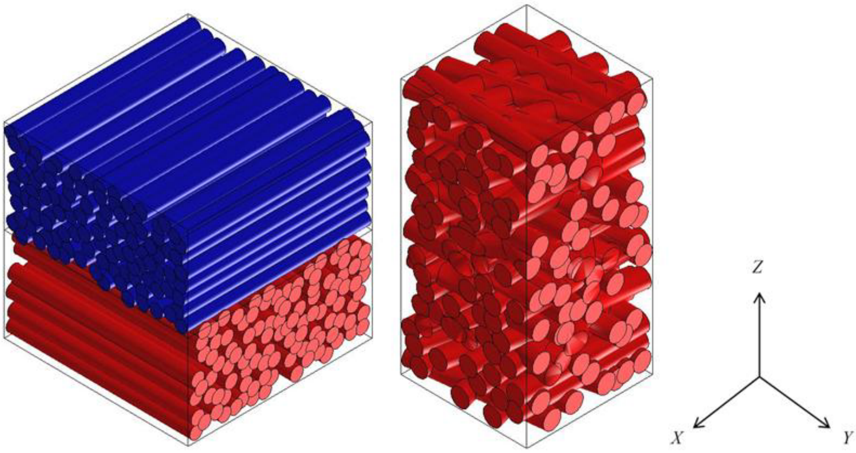

Fig. 4. Geometrical model of the representative element:a) with the orthogonal reinforcement pattern; b) with the random reinforcement pattern.

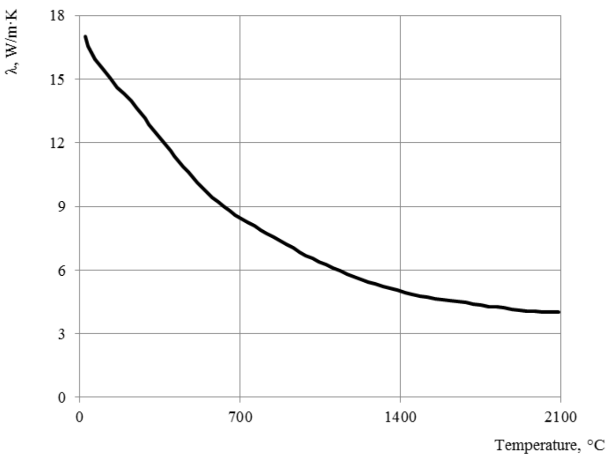

Fig. 5. Heat transfer coefficient for the homogeneous fiber.

CCCM porosity for the both models was in the range from 10 to 50%. The thermal conductivity coefficient of the porous CCCM was determined with the same method as presented above. The results (fig. 6) demonstrate a strong correlation between the heat transfer coefficient and the material porosity. The porous CCCM with the orthogonal layers has lower heat transfer than the random layers material. It is evident that increasing the CCCM porosity up to 50% reduces the heat transfer coefficient approximately 10 times, which makes porous CCCM desirable for thermal insulation purposes. The 50 % constraint with regard to the maximum porosity is due to the fact that the mechanical properties become unsatisfactory at greater porosity.

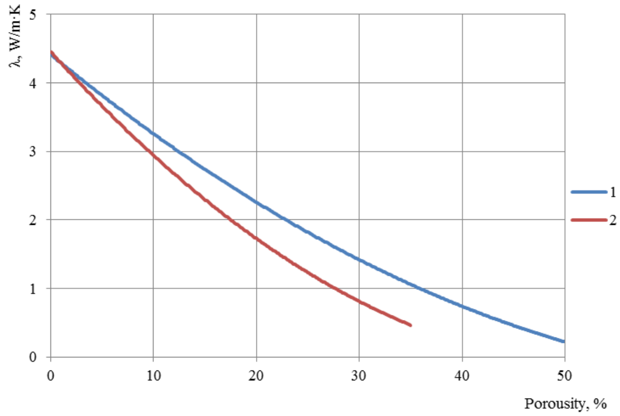

Fig. 6. Molecular heat transfer coefficient for CCCM with different reinforcement patterns as a function of residual porousity:
1 – model with the random reinforcement pattern; 2 – model with the orthogonal reinforcement pattern.

4 Effective heat transfer coefficient of the porous CCCM

The specific characteristic of the porous CCCM is that there are two simultaneous and interrelated heat transfer processes occurring within the material volume, i.e. conductive heat transfer along the frame and radiative heat transfer in the pore volume. The ratio of the conductive and radiative heat depends on the material porosity and temperature. The total heat exchange for porous media can be characterized by the effective heat transfer coefficient, which is a ratio of the total heat transfer through the porous medium to the local temperature gradient. Molecular heat transfer coefficient, unlike effective heat transfer coefficient, only accounts for the conductive heat transfer along the fibers, excluding the radiative process in the pore volume.

In order to estimate the effective heat transfer coefficient for the porous CCCM, a finite-element model of a volume representative element (fig. 7) was built using Siemens NX software package [7]. This model comprised the porous material zone (2, fig. 7) and two contacting plates (1 and 3, fig. 7).

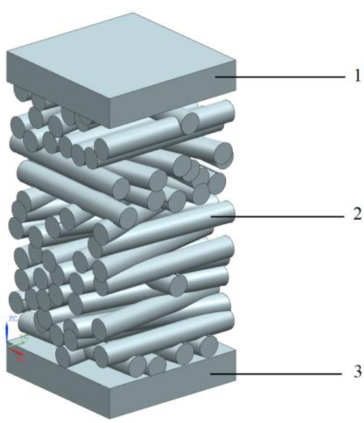

Fig. 7. Finite-element model of a representative element. CCCM with random reinforcement pattern.

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The temperature for the outer surfaces was set as uniform across the surface but different in value. The plates side surfaces were assumed to be thermally insulated. The thermal contact between the plates and the porous material fibers were assumed to be ideal. Additional reflecting surfaces with a zero thickness and the refractive index of 1 were located on the side surfaces of the porous material. This ensured one-dimensional radiative heat transfer in the porous CCCM. The plates and fibers surfaces were assumed to be grey, diffusely reflecting, with the emissivity factor of 0.8. It was assumed that the combined radiative-conductive heat transfer is taking place in the porous CCCM volume.

Simulating the heat transfer process in such volume representative element enabled determining the magnitude of the total heat flux through the porous material and estimating its effective heat transfer coefficient. The calculation results demonstrate that in the middle and low temperature range (below 1600°C) the CCCM with 50% porosity possess the minimal effective thermal conductivity. However, as the temperature increases and, consequently, the radiative heat transfer intensifies in the inter-fiber space, their effective heat transfer coefficient grows rapidly. On the contrary, the effective heat transfer coefficient of low porosity (20-30%) CCCM in the low and middle temperature range is sufficiently higher than that of the high porosity materials, however its temperature-driven increase is much smaller due to a lesser role of radiative heat transfer. As a result, the effective heat transfer coefficient of the low porosity CCCM is smaller than that of the high-porosity CCCM in the high temperature range. Thus, a conclusion can be drawn that thermal protection systems require varied porosity CCCM layers: low porosity in the “hot” zone, with high porosity in the area adjacent to the load-bearing structure. The exact porosity distribution can be determined by solving a thermal design problem.

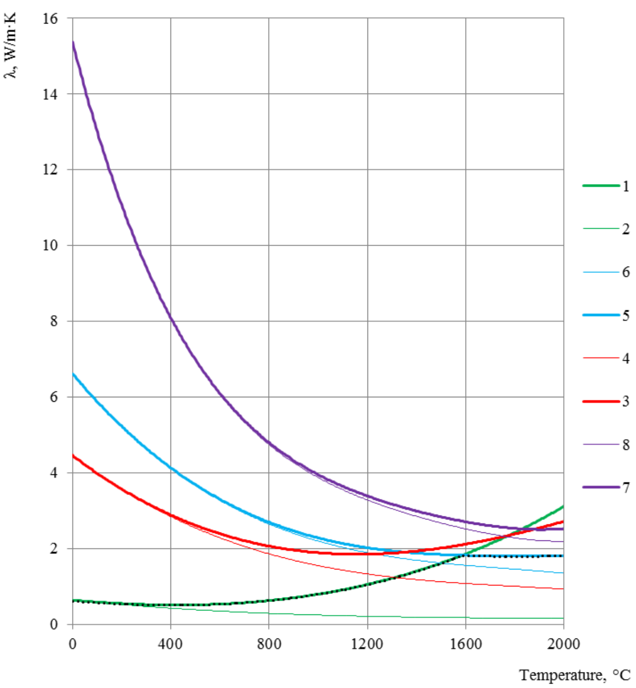

Fig. 8. Effective and molecular heat transfer coefficient of porous CCCM. 1,3,5,7 – effective heat transfer coefficient for 50, 40, 30, 20% porosity correspondingly; 2,4,6,8 – molecular heat transfer coefficient, 50, 40, 30, 20% porosity correspondingly.

5 Conclusion

The structure models were created for the porous carbon ceramic material with orthogonal and random carbon fibre reinforcement patterns. The thermal physical characteristics of the porous CCCM were determined based on the analysis of the heat transfer process in the representative volume element. It was demonstrated that increasing the CCCM porosity up to 50% would reduce the heat transfer coefficient approximately 10 times, making the porous CCCM a feasible choice as a thermal protection coating. The combined radiative-conductive heat transfer in the porous CCCM was simulated. It was demonstrated that for the high-porosity (over 40%) materials in the high temperature range (over 1400°C) the radiative heat transfer plays the key role in the heat transfer process. The conclusion was made that thermal protection systems require CCCM with variable porosity through the thickness.

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