EXPERIMENTAL STUDY OF THE HEAT TRANSFER IN POROUS SEMITRANSPARENT HEAT-SHIELD MATERIALS

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Studies of the stationary heat transfer and effective heat conductivity of two materials in the temperature range \( T = 573–1473 \) K and the air-pressure range \( p = 1–10^5 \) Pa have been made. A comparative analysis of the heat transfer in them and other porous materials is given.

Introduction. The specificity and difficulty of investigation of the heat transfer in porous materials is that in them all three kinds of heat transfer take place simultaneously: the contact-conductive heat transfer \( (q_c) \) through the solid phase forming the frame of the material and the radiation \( (q_r) \) and molecular \( (q_g) \) heat transfer through the gas phase in the gas–solid state system in pores. The contribution of each of the above kinds to the total heat transfer depends on their chemical composition, the physical structure of the material, the temperature levels and gradients in the material, and the pressure of the gaseous medium in which the material is used.

A large volume of various studies, both theoretical and experimental, devoted to the heat transfer in porous semitransparent materials and the determination of their effective heat conductivity and its separate components have already been made (see, e.g., 1–14]. Within the framework of calculation-theoretical studies one usually uses a generalized mathematical model representing a set of individual models describing each of the above kinds of combined heat transfer in the materials being considered. In so doing, a large part of the above works pertains to investigations of the radiation heat transfer, since at higher temperatures and in rarefied media its contribution to the total heat transfer is comparable to the conductive-molecular heat transfer is or even prevailing. Two approaches to the problem of mathematical modeling of the radiation heat transfer — an electrodynamic and a thermodynamic approach — are noteworthy [1–4]. The first of them is based on the investigation of the interaction of electromagnetic waves with ensembles of fibers (particles) of the substance with the use of the equations of classical electrodynamics [1–3]. The cooperative effects within the framework of this approach are described by the theory of multiple scattering of waves [13]. Within the framework of the second (thermodynamic) approach, the material being investigated is considered as a quasi-homogeneous macrosystem, and the radiation heat transfer is described by the equation of the radiation transfer in an absorbing, a radiating, and a scattering medium or by the equation of the photon diffusion in an attenuating medium [3, 4]. Each approach uses its characteristics to describe the optical properties of materials.

Because of the complex structure of porous partially transparent materials and the insufficient knowledge of the physical phenomena being investigated, the works in the field of mathematical modeling of the radiation heat transfer are approximate and are carried out with the use of many simplifying assumptions. At the same time, they make it possible to estimate the qualitative influence of the structure parameters, in particular, the diameter and orientation of fibers, on the radiation heat transfer and the growth of its role in the total heat transfer with increasing temperature in the investigated materials and determine the optimal diameters of fibers depending on the temperature and their orientation with respect to the direction of the heat flow in the material [5, 7, 10].

In analyzing the radiation heat transfer in absorbing and scattering media, it is customary to use the dimensionless parameter called the optical thickness of the layer, \( \tau = L/l_c \). The case where \( \tau \gg 1 \) corresponds to the model of an optically thick layer and the case where \( \tau \leq 1 \) — to that of an optically thin layer. The intermediate values of the parameter \( \tau \) correspond to the model of the sliding radiation.

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In applied studies of the radiation heat transfer and the effective heat conductivity of dispersive materials, the model of an optically thick layer is widely used. For this case, the following relations for the radiation heat-conductivity coefficient $\lambda_r$ within the framework of the electrodynamic and thermodynamic approaches have been obtained:

$$\lambda_r = \frac{16}{3} n^2 \kappa \sigma T^3,$$  \hspace{1cm} (1)

$$\lambda_r = \frac{16}{3} \sigma T^3 l_f.$$  \hspace{1cm} (2)

Comparing relations (1) and (2) obtained by different methods, one must note, first of all, the cubic temperature dependence of the values of $\lambda_r$. In both approaches, to determine the radiation heat-conductivity coefficients, it is necessary to have the values of the attenuation coefficient $\kappa$ and the refractive index $n$ or the mean free path of photons $l_f$.

The problems of investigating the contact-conductive and gaseous components of the heat transfer in the materials being considered and the corresponding components of their effective heat conductivity are just as difficult. At the present time, there are no adequate models that permit identifying the frames formed by fibers (particles) and the contact thermal resistances between the fibers, which makes it impossible to estimate theoretically both the contact-conductive and the gaseous components, and, consequently, the total heat transfer in the material and its effective heat-conductivity coefficient. In this connection, in investigating and determining $q_c$ and $q_g$ in real dispersive heat-shield materials, which, as is known, have an irregular structure of the solid phase, experimental studies and empirical approaches based on them are used.

In view of the foregoing, it can be stated that the basic method for investigating heat transfer in porous semi-transparent materials consists of thermophysical experiments, and the calculation data obtained on the basis of modern mathematical models require experimental verification and determination of the field of their application.

In contemporary practice in project and engineering thermal calculations, the heat transfer in the structural elements from such materials is estimated mainly by means of numerical calculations of the nonlinear heat-conduction equations with the use of the effective values of the heat conductivity coefficients of the materials, and, in so doing, all three components of the heat transfer are taken into account additively. The temperature and barometric dependences of the above coefficients are determined by experimental methods.

At the present time, to investigate the heat transfer and determine the effective heat-conductivity coefficients of the materials under consideration, the method of a heated plate with a compensation of thermal leakages from the main heater and the flat samples being investigated is widely used [6, 8, 12]. In accordance with this method, in the measuring device a one-dimensional heat flow is created in the samples being investigated between the heated and the cooled sides. The measuring device is placed in a thermal vacuum chamber with a controlled composition and pressure of the gaseous medium, which permits investigating its influence on the heat transfer in the material.

**Method and Facility for Investigating the Heat Transfer and Determining the Effective Heat-Conductivity Coefficients of Heat-Insulating Materials.** We propose a new version of the method for investigating the heat transfer and the effective heat conductivity of porous heat-insulating materials. The experimental facility is schematically represented in Fig. 1.

The main part of the facility is a vacuum chamber with a measuring device located in its working volume. It incorporates a system of regulated flat ohmic main heaters — the central heater No. 1, the upper heater No. 2, and the lower heater No. 5. These heaters provide the given mean temperature and temperature drops in identical investigated samples arranged one-dimensionally about heater No. 1 and the compensation side heater Nos. 3, 4, and 6 providing, jointly with the side heat insulation, elimination of thermal leakages from the samples and heater No. 1 and a simultaneous heat flow in the samples. Between the main heaters and the samples, as well as between the heaters and the insulation, metal plates prepared by thermocouples are placed. On each plate, from four to six thermocouples are installed. By the temperature measurement data of the plates the temperatures of the sample surfaces adjoining the plates are determined.