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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, $\tau = L/l_f$. The case where $\tau >> 1$ 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 τ 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 λ_r within the framework of the electrodynamic and thermodynamic approaches have been obtained:

$$\lambda_r = \frac{16}{3}\frac{n^2}{\kappa}\sigma T^3 , \tag{1}$$

$$\lambda_r = \frac{16}{3}\sigma T^3 l_f . \tag{2}$$

Comparing relations (1) and (2) obtained by different methods, one must note, first of all, the cubic temperature dependence of the values of λ_r. In both approaches, to determine the radiation heat-conductivity coefficients, it is necessary to have the values of the attenuation coefficient κ 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.

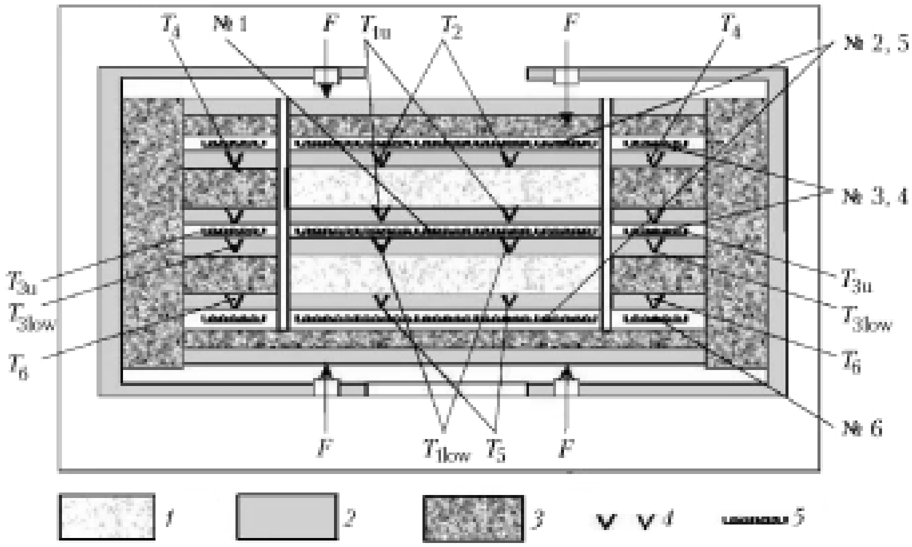


Fig. 1. Schematical representation of the experimental facility for investigating the heat transfer in porous semitransparent materials: 1) sample being investigated; 2) metal plate; 3) insulation; 4) thermocouples; 5) heaters.

The investigated samples, heater Nos. 1, 2, and 5, and the metal plates placed between them are of size $0.15 \times 0.15 \times h\ \mathrm{m}^3$. The side heater Nos. 3, 4, and 6 and the metal plates adjoining them, as well as the heat insulation between them, are made in the form of square frames with internal sizes of $0.152 \times 0.152\ \mathrm{m}^2$ and outer sizes of $0.27 \times 0.27\ \mathrm{m}^2$. The thickness of the side insulation is equal to the thickness of the investigated sample $h = 0.001$–0.06 m. Outside (on the side, lower, and upper surfaces), the system consisting of samples, heaters, metal plates, and heat insulation is additionally covered with a heat-insulating layer of thickness 0.04 m. If necessary, the sizes of the sample and other elements of the device can be changed.

The above elements — samples, heaters, metal plates, and heat insulation — are placed on a frame equipped with a spiral compressing device performing a double function. First, it stabilizes the contacts of metal plates with the sample and the heater. Second, in investigating deformable materials, e.g., cotton, it ensures the given density of the sample and its thickness in the above range of h.

The infrastructure of the facility includes the following systems:

(a) a system of evacuation and controlled puffing of gases (air, nitrogen, carbon dioxide, inert gases) into the chamber ensuring the given composition and pressure of the gaseous medium in the chamber in the 1–10^5-Pa range;

(b) an electric power-supply system that ensures autonomous regulated operation of the six heaters under automatic or manual control;

(c) an information-measuring system incorporating means for measuring the temperature (up to 50 thermocouples), the gas pressure in the chamber, and the power of the heaters, as well as a computer for experimental information processing and heater power control in the automatic regime.

In the process of test preparation, the assembled measuring device is placed in the vacuum chamber, then it is connected to the power-supply system and the systems for measuring the temperatures of the metal plates and the heater No. 1 power. Then the chamber is sealed and the given composition and gas pressure are created in it.

During tests, the energy supply to the heaters upon heating and reaching the steady-state regime is regulated so as to maintain equality of temperatures of the metal plates and frames positioned in one plane, $T_{1u} = T_{3u}$, $T_{1low} = T_{3low}$, $T_2 = T_4$, $T_5 = T_6$, as well as the temperature difference in the samples $\Delta T_{u,c} = \Delta T_{1c} \le 100^{o}$C. In so doing, in the chamber the given pressure of the gaseous medium is set and maintained. The regime is considered to be stationary when the readings of all thermocouples are stabilized and the electric power N of the main heater No. 1 and the chamber pressure are held constant within the instrumental measurement errors. After that, the readings of all devices are registered and a transition to the next regime is made.

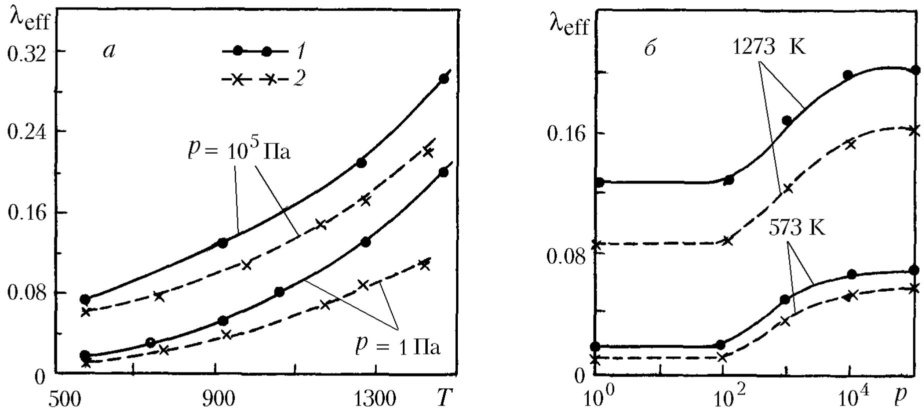


Fig. 2. Temperature (a) and barometric (b) dependences of the effective heat-conductivity coefficients: 1) material No. 1; 2) material No. 2.

Since in real designs complete elimination of thermal leakages is impossible, the design of the measuring device and the testing procedure and its information support make it possible to not only minimize and control thermal leakages from samples in heater No. 1, but, if necessary, estimate them. Two types of thermal leakages from the investigated samples in heater No. 1 are possible: though the side insulation q_{leak1} and over the commutation wires connecting the heater to the external power supply circuit q_{leak2}. These leakages are estimated in each experiment and taken into account in calculating the heat flows passing through the samples. Thus, the quantity $q_{\text{tot}} = N - q_{\text{leak1}} - q_{\text{leak2}}$. Analysis has shown that in view of the above estimates the contribution of thermal leakages to the total error of determining the thermal flow passing through the samples does not exceed 1.2%.

The heat-conductivity coefficient λ_{eff} of the samples being investigated in the stationary regime is determined from the relation

$$\lambda_{\text{eff}} = q_{\text{tot}} h / S \, (\Delta T_{\text{u,c}} + \Delta T_{\text{1c}}) \, .$$

Our facility can be used to investigate the heat transfer and heat conductivity of materials in the temperature range of T = 400–1000 K and in the range of pressures of an inert and an air gaseous medium of $p = 1\text{–}10^5$ Pa. In the air medium, investigations are carried out at temperatures up to T = 1500 K. The measurement errors for the effective heat-conductivity coefficients of the investigated samples are 5–7%.

In the process of tests on the facility, replication in the samples of both stationary and dynamic regimes providing variation of the space and time gradients (temperature drops in samples from 0 to 1500 K, heating rates from 0 to 10 K/sec) is possible. This makes it possible to determine:

(a) the influence of the structural parameters, the thermophysical and radiative characteristics of the experimental samples, and the internal space and time gradients in them on the total heat transfer and its components, as well as the effective heat conductivity of the materials of the samples;

(b) the contribution of the gaseous component to the total heat transfer in materials depending on the temperature, composition, and pressure in the gaseous medium;

(c) the possibilities of using the temperature dependences of the effective heat-conductivity coefficients obtained by the stationary method for specific materials in the calculations of their nonstationary thermal regimes, and, if necessary, making corrections of the values of the effective heat-conductivity coefficients as applied to concrete dynamic regimes;

(d) the degree of confidence of the results of the determination of the effective heat-conductivity coefficients or individual components of these coefficients obtained with the use of new theoretical or empirical approaches for particular materials.

Test Data. As examples, Fig. 2 shows the results of testing two fibrous flexible heat-insulating materials. The samples had the same thickness h = 0.02 m and density ρ = 120 kg/m^3 and were made on the basis of fibers from aluminum oxide with the addition of an insignificant amount of silicon oxide (material No. 1) and from pure silicon

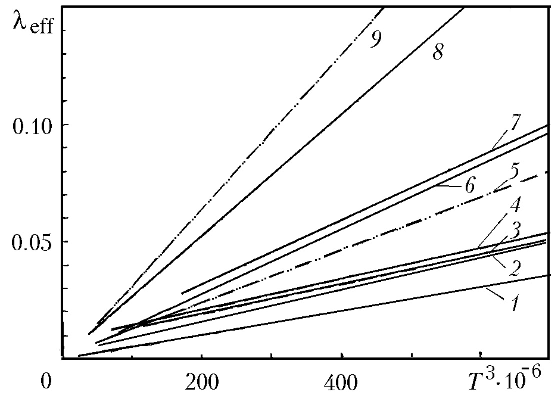


Fig. 3. Temperature dependences of the effective heat-conductivity coefficients of fibrous materials to the third power.

oxide (material No. 2). Tests were carried out in vacuum and in an air medium at atmospheric and intermediate pressures.

Figure 2 gives the temperature dependences of the effective heat-conductivity coefficients $\lambda_{eff} = f(T)$ in vacuum and in an air medium at atmospheric pressure and the barometric dependences $\lambda_{eff} = f(P)$ for the investigated materials.

From the data presented, it follows that the value of λ_{eff} for both materials increases monotonically (as nonlinear functions) with increasing temperature and air pressure in the chamber. In so doing, in the temperature range T = 573–1473 K the values of λ_{eff} of material No. 1 are higher than those of material No. 2 by a factor of 1.25–1.45 in vacuum and by a factor of 1.2–1.25 at atmospheric pressure.

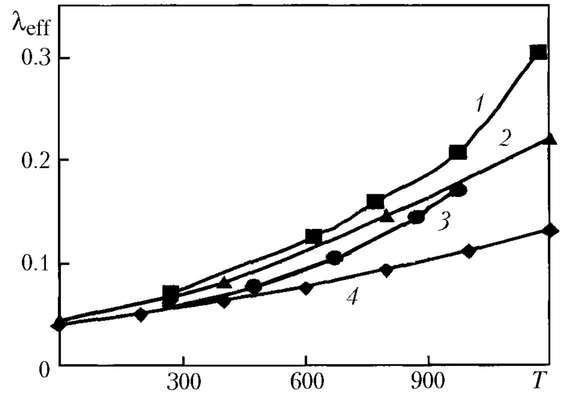
The increase in λ_{eff} with increasing temperature is explained mainly by the intensification of the radiation heat transfer and its gaseous component with increasing air pressure. In particular, in vacuum, in the investigated temperature ranges, the λ_{eff} value for material No. 1 increases 11 times and for material No. 2 — 6.5 times, whereas at atmospheric pressure it increases 4 and 3 times, respectively.

In considering the data presented in Fig. 2b, it is seen that the effective heat-conductivity coefficients of the materials in the gaseous medium increase mainly in the pressure range $p = 10^2$–10^5 Pa, where the value of λ_{eff} increases 4.1 and 1.5 times for material No. 1 and 4.4 and 1.9 times for material No. 2 at temperatures T = 573 and 1273 K, respectively. Consequently, the relative contribution of the gaseous component of the heat transfer in the investigated material decreases with increasing temperature. Thus, as compared to vacuum, this part equals 0.75 and 0.35 for material No. 1 and 0.77 and 0.48 for material No. 2 at temperatures T = 573 and 1273 K, respectively.

It should also be noted that if we take the value of λ_{eff} at atmospheric pressure as 1, then at pressures $p = 10^3$ and 10^4 Pa it will be equal to 0.7 and 0.9 within the measurement errors at a temperature of T = 573 K, and at T = 1273 K it will be equal to 0.45 and 0.88, respectively.

Results and Discussion. Along with the determination of concrete values of the effective heat conductivity, it is interesting to estimate the degree of correspondence of the data obtained for the investigated samples to the model of the optically thick layer, as well to compare them with the analogous data obtained by other authors. Figure 3 shows the experimental dependences $\lambda_{eff} = f(T^3)$ obtained for a series of heat-insulating materials in vacuum. This series includes the above materials No. 1 and No. 2 (plots 2 and 1, respectively), as well as the Saffil material based on aluminum oxide (Al_2O_3) fibers with different densities ρ = 96, 48, and 24 kg/m^3 (plots 3, 6, 8, respectively), the Q-fiber felt material made from fibers based on silicon oxide (SiO_2) with densities ρ = 96 and 48 kg/m^3 (plots 4, 7, respectively), and the Cerachrome material made from a mixture of aluminum oxide and silicon oxide fibers with densities ρ = 192.96 kg/m^3 (plots 5, 9) [8]. In considering the results presented, it can be noted that the dependences $\lambda_{eff} = f(T^3)$ for all the samples presented are close to linear ones and, consequently, the radiation heat transfer in them corresponds to the optically thick layer model.

The role of the contact-conductive heat transfer is more appreciable in the region of moderate and low temperatures ($T > 600$ K) and depends on the material density.



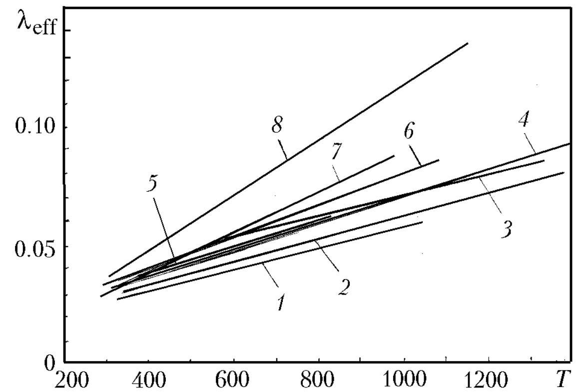


Fig. 4. Temperature dependences of the effective heat-conductivity coefficient of fibrous materials obtained for the regimes of stationary (1, 3) and nonstationary (2, 4) heat exchange.

Fig. 5. Gaseous component of the effective heat-conductivity coefficient of fibrous materials in the air medium at atmospheric pressure.

It should be noted that for the regime of the optically thick layer to reach a steady state, it is necessary that not only the relation $\tau >> 1$ be observed, but also the smallness of the temperature gradient in the sample at which the hypothesis on local thermodynamic equilibrium is fulfilled be ensured. The use of expressions (1) and (2) in the case of high rates of heating or large temperature gradients is improper. Thus, Fig. 4 gives a comparison of the temperature dependences of the heat-conductivity coefficient of material Nos. 1 and 2 obtained on the above-considered facility (curves 1 and 3) and the data determined from the solution of the two-dimensional inverse heat-conduction problem in processing the results of the experimental studies conducted on the "Uran-1" radiation heating device at the Heat and Mass Transfer Institute of the NAS of Belarus (curves 2 and 4) (see, e.g., [14]). On this device the nonstationary regime of heating a sample with a high rate (40–50 K/sec) is realized. At such rates of heating, the thickness of the material heated to a high temperature is comparatively small and the radiation field in the sample is essentially inhomogeneous; therefore, the regime of the optically thick layer does not reach the steady state. The results of mathematical modeling of the process of radiation-conductive heat exchange for nonstationary processes point to a decrease in the contribution of the radiation component to the total heat transfer compared to the stationary regime of heat exchange. Precisely this fact explains the wide difference between the data on the effective heat-conductivity coefficient (especially in the region of high temperatures) obtained on different facilities. These results definitively point to the necessity of determining the effective heat-conductivity coefficient under conditions made maximally realistic in terms of service conditions, in the first place, as to the temperature level, the rate of heating, and the characteristic dimensions of the sample.

Figure 5 shows the temperature dependences of the gaseous component (λ_g) for material Nos. 1 and 2 (plots 3 and 6, respectively), the Saffil material with densities ρ = 24, 48, and 96 kg/m^3 (plots 7, 2, and 1, respectively), the Q-fiber felt material with a density ρ = 48 kg/m^3 (plot 5), the Cerachrome material with a density ρ = 96 kg/m^3 (plot 8), and the heat-conductivity coefficient of air (plot 4) at atmospheric pressure. The value of λ_g is equal to the difference of the λ_{eff} values obtained for the corresponding material at atmospheric pressure of the gaseous medium and in vacuum at equal temperatures. It is known [5, 7] that the value of λ_g depends on the heat conductivity of the gas, the accommodation coefficient of the gas molecules with respect to the solid phase of the porous material, and the Knudsen parameter, equal to the ratio of the mean free path of the gas molecules to the characteristic size of the pores in the material. At the above densities of the materials the gas molecular flow can be considered as a continuous medium. If the accommodation coefficient is taken to be equal to 1, then the value of λ_g becomes close to the heat conductivity of the gas. In considering the data presented in Fig. 5, it can be seen that for most of the materials, in particular, material Nos. 1 and 2, investigated in the present work, such an assumption is fulfilled.

The deviations of the values of λ_g from the heat-conductivity coefficients of air at equal temperatures are within the measurement errors of the effective heat-conductivity coefficients of the materials. The maximum deviations pertain to the Cerachrome and Saffil materials at a density of $\rho = 24$ kg/m^3. They can be explained by the relatively high values of λ_{eff} of these materials and, accordingly, by the absolute values of the measurement errors.

Thus, we have presented a method and an experimental facility for investigating the heat transfer and the effective heat conductivity of porous semitransparent materials in the range of temperatures $T = 400$–2000 K and the range of gaseous medium pressures $p = 1$–10^5 Pa. The facility is suitable for reproducing in the samples both stationary and dynamic regimes providing variation of the space and time temperature gradients (temperature drops in the samples from 0 to 1500 K, rates of heating from 0 to 10 K/sec).

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NOTATION

F, force created by the spiral compressor, N; h, sample thickness, m; L, characteristic size of the material layer, m; l_f, mean free path of a photon, m; N, electric power of heater No. 1, W; n, refractive index of a porous material; p, gaseous medium pressure, Pa; q, heat-flow density, W/m^2; q_{tot}, total density of the heat flow passed through the upper and lower investigated samples, W/m^2; S, cross-section area of the sample, m^2; T, temperature, K; ΔT, temperature difference between the hot and the cold side of the sample, K; κ, radiation attenuation coefficient, m^{-1}; λ, heat-conductivity coefficient of the material, W/(m·K); ρ, material density, kg/m^3; $\sigma = 5.67 \cdot 10^{-8}$ W/(m^2·K^4), Stefan–Boltzmann constant; τ = optical thickness of the material layer. Subscripts: eff, effective; r, radiation; c, conductive; g, gas; tot, total; 1u, hot surface of the upper sample adjoining heater No. 1; 1low, hot surface of the lower sample adjoining heater No. 1; 2, cold surface of the upper sample adjoining heater No. 2; 5, cold surface of the lower sample adjoining heater No. 5; leak1, heat leakage through the side insulation; leak2, heat leakage over commutation wires; f, photon.

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