

Results of investigations of the thermophysical properties of layers of disperse material in various gaseous media are reported. The role played by individual components of heat-conduction in a disperse layer is considered.

A knowledge of the thermal properties of disperse materials is required for the solution of problems in assorted fields of science and technology.

As was noted in [1], the processes of molecular transfer of heat through granular systems has received fairly detailed theoretical and experimental study, both at normal and reduced pressure. As yet, only rough estimates can be made for contact heat exchange. Far less study has been given to the processes of radiant heat transfer in disperse material.

On the basis of experimental data [2-4], we shall consider the role of the individual components entering into the effective thermal conductivity of a layer of disperse material at high temperatures.

The process of heat transfer in layers of disperse material includes several different heat-propagation mechanisms, acting simultaneously but separate. They can be grouped as follows: heat conduction by solid particles, heat conduction by a gas, convection, and thermal radiation. It is difficult to make a quantitative evaluation of each component, so that the theoretical determination of the effective thermal conductivity is very difficult.

The effective thermal conductivity has been obtained in experimental studies of the thermal properties of spherical iron and slag pellets (in 0.5-1.0, 2.0-3.0, and 3.0-4.0 mm fractions) at $1 \cdot 10^{-4}$ mm Hg in the 373-1273°K range [2]; comparison of these data with the effective thermal-conductivity values obtained for the same materials at normal atmospheric pressure in air, carbon dioxide, and helium [3, 4] makes it possible to follow the change in structure of the total heat flux through the material over a wide temperature range.

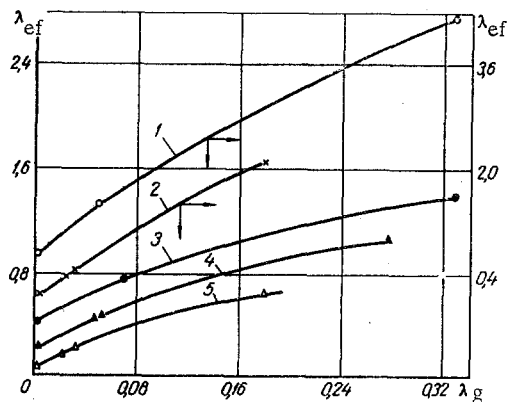


Fig. 1. Effective thermal conductivity of disperse material as a function of the thermal conductivity of the gas filler: 1, 2) 2.0-3.0 mm iron spheres at 873 and 373°K, respectively; 3-5) 2.0-3.0 mm slag spheres at 873, 673, and 373°K, respectively.

Figure 1 shows the effective thermal conductivity of the material as a function of the thermal conductivity of the gas filler. The initial points on the curves represent λ_{ef} in a high vacuum, when the molecular conduction of the gas is slight, and can be neglected, i.e., $\lambda_g \approx 0$. It is clear from Fig. 1 that the thermal conductivity of the material depends strongly on that of the gas. For material in gaseous media with low conductivity (air, carbon dioxide, etc.), heat transfer by the particle contact conductivity and by radiation is commensurate with the conductive transfer of heat by the gas (convection can be neglected for the materials investigated [5]).

Measurement of the effective conductivity of slag and iron spheres has shown that the thermal conductivity of the

Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from *Inzhenerno-Fizicheskii Zhurnal*, Vol. 17, No. 2, pp. 248-253, August, 1969. Original article submitted October 16, 1968.

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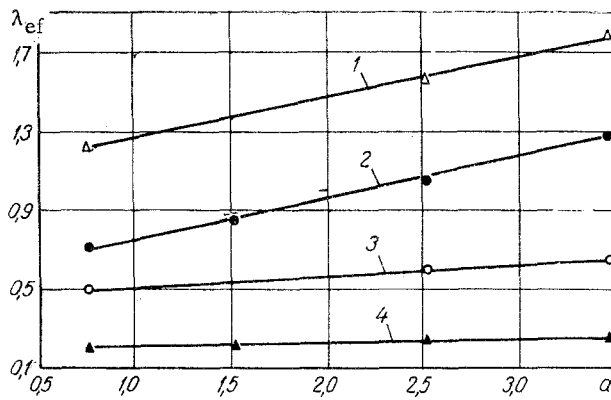


Fig. 2. Effective thermal conductivity of disperse layer as a function of particle diameter (mm) in air: 1, 3) iron shot at 873 and 573°K; 2, 4) slag spheres at 1073 and 373°K.

layer depends little on that of the material from which the particles are made. Thus at 373°K, the effective thermal conductivity of a layer of iron spheres differs from that of slag spheres by 30% in vacuum and by 50% in air at atmospheric pressure, while at the same temperature, iron and slag differ in thermal conductivity by more than a factor of 40. As the conductivity of the gas filler increases, this difference between the conductivities of the layers does also. Thus, at 373°K, the effective thermal conductivities of the same layers differ by more than a factor of 3 at atmospheric pressure in helium.

It is the considerable thermal contact resistances between the particles that account for the weak influence of the conductivity of the actual material on the effective layer conductivity. When heat propagates by contact conduction of particles, it does so along a crooked path, owing to the random positioning of the thermal-contact surfaces. Contact heat exchange depends on the physical and mechanical properties of the material, and on the specific load.

In our experiments [2], we took λ_c to be 0.06 W/m · deg for a layer of iron spheres and 0.015 W/m · deg for a layer of slag spheres.

A value of 0.07 W/m · deg is given in [6] for the λ_c of iron shot. As we see, these values do not disagree very much.

Figure 2 shows the effective layer thermal conductivity as a function of particle diameter. As we see, at low temperatures, λ_{ef} is nearly independent of particle diameter. This is so since at low temperatures (up to 373°K) the basic heat flux results from molecular motion of the gas, with radiation and convection playing no substantial role.

As the temperature increases, radiative conduction begins to play an important part in heat transfer, so that the layer conductivity is greatly affected by the particle diameter, whose value determines the "screen number."

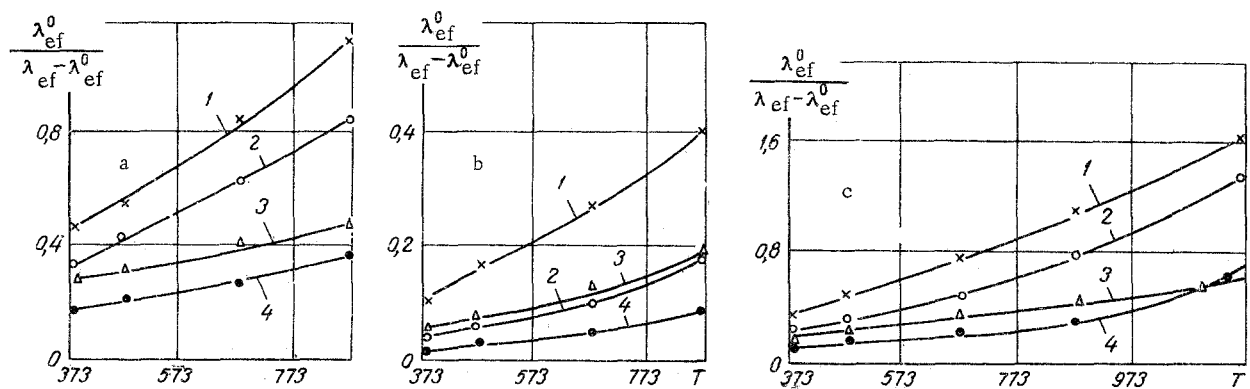


Fig. 3. Relationship between various types of heat transfer in a layer of disperse material in carbon dioxide (a), helium (b), and air (c): 1, 3) slag spheres, 2.0-3.0 and 0.5-1.0 mm in diameter, respectively; 2, 4) iron spheres, 2.0-3.0 and 0.5-1.0 mm in diameter, respectively.

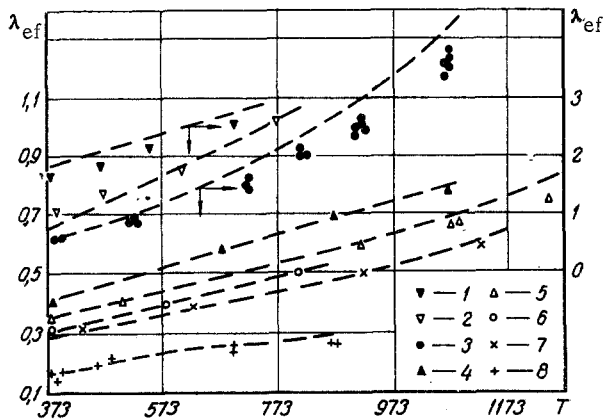


Fig. 4. Effective thermal conductivity of disperse material as a function of temperature: 1) MgO ($m = 0.42$, $d = 0.205$ mm), helium [10]; 2) iron filings ($m = 0.5$, $d = 0.177$ mm), neon [10]; 3) iron spheres ($m = 0.4$, $d = 11$ mm), air [11]; 4) MgO ($m = 0.42$, $d = 0.268$ mm), air [12]; 5) MgO ($m = 0.525$, $d = 0.45$ mm), air [13]; 6) iron filings ($m = 0.5$, $d = 0.177$ mm), argon [10]; 7) ZrO ($m = 0.42$, $d = 0.282$ mm), air [12]; 8) quartz sand ($m = 0.5$, $d = 0.12$ mm), air [14]; dashed curves, computed from (1).

$$\lambda_{ef} = \lambda_g \left[1 + 3.91 \lambda_g^{0.1} (1-m) \ln \frac{\lambda_m}{\lambda_g} \right] + \frac{3.46 \sigma T^3 d [3m\epsilon_p + (1-m)\epsilon_m]}{1 + (1-m)(1-\epsilon_m)} \quad (1)$$

It is interesting to compare the published experimental data on the thermal conductivity of such layers in various gases over a wide temperature range with data calculated from (1).

Figure 4 illustrates the results of such a comparison. For the purposes of determining λ_{ef} , the values of ϵ_p and ϵ_m were taken from [7-9]. There is a 5-25% difference between the calculated and experimental values of λ_{ef} for a wide class of granular materials.

The good agreement between the calculated and experimental values indicates that our proposed formula (1) can be recommended for determining the effective thermal conductivity of monodisperse materials over a wide range of temperatures.

In studying heat conduction in disperse material at elevated temperatures, we can effectively replace the first term in (1) as was shown in [3, 4] by analytic relationships [16, 17, etc.] for determining the component of the effective thermal conductivity of a disperse layer that is produced by the conductivities of the gas and the material of the particles; this will substantially simplify the problem of devising a generalizing relationship to describe the effective thermal conductivity of such layers over a wide temperature range.

NOTATION

d	is the particle diameter, m;
m	is the porosity;
T	is the absolute temperature, °C;
ϵ_p, ϵ_m	are the emissivities of the pores and the particle material;
λ_m, λ_g	are the thermal conductivities of the particle material and the gas, W/m·deg;
λ_{ef}	is the coefficient of effective thermal conductivity for the disperse layer, W/m·deg;
λ_c	is the coefficient of contact conductivity for the disperse layer, W/m·deg;
σ	is the Stefan-Boltzmann constant, W/m ² ·°K ⁴ ;
λ_{ef}^0	is the coefficient of effective thermal conductivity of the layer at $1 \cdot 10^{-4}$ mm Hg, W/m·deg.

Measurement of the effective thermal conductivity of disperse layers at $1 \cdot 10^{-4}$ mm Hg and at atmospheric pressure in various gases made it possible to evaluate the role of radiation in the overall heat flux for disperse materials (Fig. 3).

The relative importance of radiation in the overall heat flow through a layer of disperse material increases rapidly with the temperature, since radiative heat transfer is proportional to the cube of the mean absolute temperature of the material.

As we see from Fig. 3, at low temperatures, radiation has little influence on the overall process of heat exchange, except for materials with particles of less than 1 mm in diameter. For 2.0-3.0 mm particles, the radiative component contributes relatively little to the heat conduction of the disperse layer only for helium; in carbon dioxide and air it becomes perceptible even at 473-573°K, while above 1073°K, radiative transfer is more important than conductive transfer by the gas.

The measurements of effective thermal conductivity for slag- and iron-sphere layers in various gases can be described with an accuracy of $\pm 12\%$ by the following formula [15]:

LITERATURE CITED

1. G. N. Dul'nev and Z. V. Sigalov, *Inzh. Fiz. Zh.*, 13, No. 5 (1967).
2. V. S. Nikitin, S. S. Zabrodskii, and N. V. Antonishin, *Vestsi AN BSSR, Ser. Fiz.-Énerg.*, No. 1 (1968).
3. S. S. Zabrodskii, N. V. Antonishin, and V. S. Nikitin, *Inzh. Fiz. Zh.*, 14, No. 5 (1968).
4. V. S. Nikitin, S. S. Zabrodskii, and N. V. Antonishin, *Vestsi AN BSSR, Ser. Fiz.-Énerg.*, No. 2 (1968).
5. A. F. Chudnovskii, *Thermal Characteristics of Disperse Materials* [in Russian], Fizmatgiz (1962).
6. Yu. P. Shlykov and V. S. Udalov, *Teploénergetika*, No. 4 (1961).
7. A. G. Blokh, *Fundamentals of Radiative Heat Exchange* [in Russian], Gosenergoizdat (1962).
8. V. E. Listovnichii, *Inzh. Fiz. Zh.*, 7, No. 11 (1964).
9. E. M. Sparrow and E. R. Eckert, *J. Heat Transfer*, 84C, No. 1 (1962).
10. R. G. Deissler and J. S. Boegli, *Trans. ASME*, 80, No. 7 (1958).
11. Sakae Yagi and Daizo Kunii, *AIChE J.*, 3, 373 (1957).
12. Herschel W. Gogbee and Waldemar T. Ziegler, *J. Appl. Phys.*, 37, No. 1 (1966).
13. M. J. Laubitz, *Canad. J. Phys.*, 37, No. 7 (1959).
14. G. L. Serebryanyi, L. B. Zarudnyi, and S. N. Shorin, *Heat and Mass Transfer* [in Russian], Vol. 5, Nauka i Tekhnika (1968).
15. V. S. Nikitin, S. S. Zabrodskii, and N. V. Antonishin, *Inzh. Fiz. Zh.*, 15, No. 4 (1968).
16. G. N. Dul'nev and Z. V. Sigalov, *Inzh. Fiz. Zh.*, 7, No. 10 (1964).
17. M. G. Kaganer, *Heat Insulation in Low Temperature Engineering* [in Russian], Mashinostroenie (1966).