EFFECTIVE THERMAL CONDUCTIVITY OF A GRANULAR BED AT ELEVATED TEMPERATURES

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Inzhenerno-Fizicheskii Zhurnal, Vol. 14, No. 5, pp. 877–881, 1968

UDC 536.21

The effective thermal conductivity of beds of granular material has been investigated experimentally in the temperature range from 373 to 1200° K at a vacuum of $1 \cdot 10^{-4}$ mm Hg and at atmospheric pressure.

In most cases, granular materials are used in apparatus operating at elevated temperatures. Only a limited amount of experimental data has been published on the effective thermal conductivity of the bed under these conditions. Moreover, these data can be used only under conditions similar to those under which they were obtained. To have at least an approximate quantitative idea of the thermal conductivity of the bed at elevated temperatures, it is necessary to have data on the possible contribution of the radiative component to the total effective thermal conductivity as a function of the principal properties of the bed.

We have attempted to isolate the radiative component of the thermal conductivity of such a bed of granular material. The experiments were conducted in a deep vacuum, when the molecular thermal conductivity of the gas is low and can be neglected, and at atmospheric pressure under comparable conditions.

The test material was introduced into the annular gap, outside diameter 100 mm, inside diameter 40 mm, between an external asbestos-cement tube and a coaxial internal corundum tube. A cover, fastened to the corundum tube, was fitted on top. In the cover, there were four slots through which the annular gap was filled with the granular material. The temperature drop in the bed was measured with nine fixed chromel-alumel thermocouples. An electric heater, consisting of a rigid frame uniformly wound with nichrome wire was inserted into the corundum tube. To reduce axial heat losses, the ends of the tube assembly were thermally insulated.

The heat flux can be judged from the electrical power delivered by the heater. The thermal conductivity of the dispersed material was calculated from the formula

$$\lambda = \frac{\ln \dfrac{R_1}{R_2}}{2\pi l} \, \frac{IU}{T_2 - T_1} \, . \qquad (1)$$

The specific dissipated power was calculated from the voltage drop for both the heater as a whole and its central part. For this purpose nichrome potentiometric leads were connected to the central part of the heater through symmetrical openings 100 mm apart.

As the dispersed material, we used the following narrow fractions of slag pellets and iron shot: 0.5–1; 1.0–2.0; 2.0–3.0; 3.0–4.0 mm.

To investigate the thermal conductivity in a vacuum, we placed the cylinder assembly in a vacuum chamber and connected the power supply and measuring leads through vacuum seals.

On the average, each experiment lasted 24–36 hr.

The results of the effective thermal conductivity measurements at atmospheric pressure and $1 \cdot 10^{-4}$ mm Hg (Fig. 1) show that it increases with temperature, although the thermal conductivity of cast iron is known to decrease with increase in temperature. This

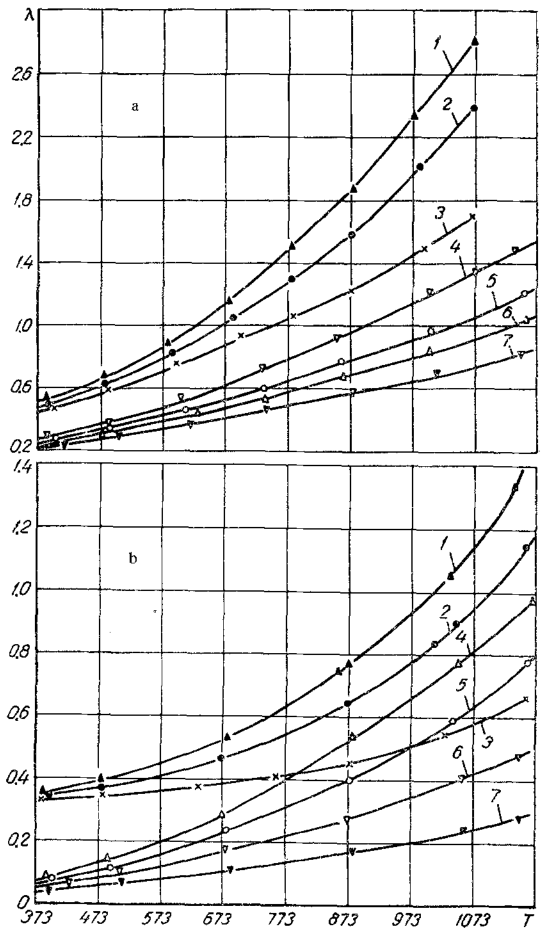

Fig. 1. Effective thermal conductivity of granular material as a function of temperature at atmospheric pressure (a) and at a vacuum of $1 \cdot 10^{-4}$ mm Hg (b): 1–3) iron shot: ϕ 3.5–4.0 mm, 2.0–3.0 and 0.5–1.0 mm, respectively; 4–7) slag pellets ϕ 3.0–4.0 mm; 2.0–3.0; 1.0–2.0 and 0.5–1.0 mm, respectively.

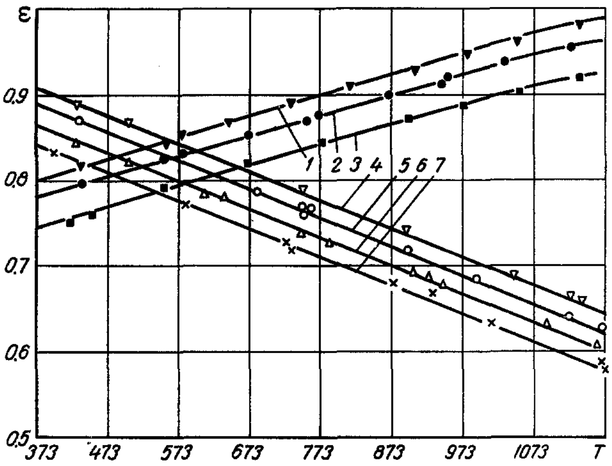

Fig. 2. Effective emissivity of bed of iron shot and slag pellets as a function of temperature (1–7, see Fig. 1).

qualitatively confirms the insignificant part played by contact heat conduction. In fact, in the vacuum experiments (Fig. 2) the low values of the effective thermal conductivity at reduced temperatures can be attributed to the action of two processes relatively ineffective from the standpoint of heat transfer—heat transfer through the contacts between grains, and the thermal conductivity of the rarefied air in the cavities. As the temperature increases, the particle diameter, which determines the "screen number," has an ever greater influence.

The effective emissivity of the bed of iron shot or slag pellets was determined approximately by a method [1] based on the determination of the amount of heat absorbed by a blackbody in one case from a black emitter and in the other from the surface of the granular material. The results are presented in Fig. 2.

Our results for the effective thermal conductivity of slag pellets and iron shot in a vacuum are described correct to ±5% by the formula

$$\lambda^0_{eff} = \lambda_c + 11\varepsilon^2\sigma T^3 d^{0.7}, \quad (2)$$

where λ_c is the contact thermal conductivity, 0.06 W/m·deg for iron shot and 0.015 W/m·deg for slag pellets.

The corresponding data at atmospheric pressure can be described correct to ±8% by the formula

$$\lambda_{eff.t} = \lambda_a\left[1 + 40k^2(1-m)\lambda_a^{0.45}\lambda_m^{0.2}\right] + \lambda^0_{eff}. \quad (3)$$

It is clear from relation (3) that the effective thermal conductivity can be expressed in terms of its components, if it is assumed that their effect is additive. This means that the total thermal resistance can be represented as the sum of the thermal resistances of the components connected in parallel in the path of the heat flux.

If this assumption is correct, the problem of studying the effective thermal conductivity at elevated temperatures at atmospheric pressure can be divided into two parts: the study of the effective thermal conductivity at reduced temperatures ($\lambda_{eff.c}$); and the investigation of the radiative component (λ^0_{eff}). The first problem has been solved by numerous authors [2–5] and relations are already available for calculating $\lambda_{eff.c}$ with acceptable accuracy.

We calculated the effective thermal conductivity of slag pellets and iron shot from the relations proposed by various authors [2–5] (disregarding the radiative component).

The sums of these calculated values of $\lambda_{eff.c}$ (in calculating $\lambda_{eff.c}$ we took the values of λ_m and λ_a at the corresponding temperature) and the λ^0_{eff} calculated from (2), less the λ_c which already enter into $\lambda_{eff.c}$, proved to be very close to the experimental values of the effective thermal conductivity at atmospheric pressure and elevated temperatures.

Correct to ±10%

$$\lambda_{eff.t} = \lambda_{eff.c} + \lambda^0_{eff} - \lambda_c. \quad (4)$$

Thus, in studying the thermal conductivity of the bed at elevated temperatures, it is possible to make effective use of previously accumulated data and substantially simplify the problem of creating a generalized relation describing the effective thermal conductivity of the bed over a broad temperature range.

The subsequent direct determination of the radiative component of the effective thermal conductivity of the bed in a vacuum can be replaced by the simpler procedure of finding the contribution of radiative transfer from the difference between the total effective thermal conductivity ($\lambda_{eff.t}$) and the calculated value of $\lambda_{eff.c}$ obtained from one of the known formulas, in which a sufficiently correct allowance is made for the effect of the thermal conductivity of the gas.

NOTATION

d is the particle diameter, m; R_1 and R_2 are, respectively, the radii of the inside and outside cylindrical surfaces of the bed of granular material, m; IU is the heat released by the heater over the length l, W; l is the length of the heater between the potentiometric leads, m; m is the porosity; $k = 1 - \lambda_a/\lambda_m$; λ_a is the thermal conductivity of air, W/m·deg; λ_m is the thermal conductivity of the granular material, W/m·deg; T is the absolute temperature, °K; λ^0_{eff} is the effective thermal conductivity of the granular material in vacuum, W/m·deg; λ_c is the effective contact thermal conductivity, W/m·deg; $\lambda_{eff.t}$ is the effective thermal conductivity of the granular material at high temperatures and atmospheric pressure, W/m·deg; $\lambda_{eff.c}$ is the effective thermal conductivity of the granular material at low temperatures, W/m·deg; σ is the Stefan-Boltzmann constant, $W/m^2 \cdot °K^4$; ε is the effective emissivity of the bed of granular material.

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5 November 1967

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