THERMAL CONDUCTIVITY OF POROUS MATERIALS AS A FUNCTION OF MOISTURE CONTENT

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Results are presented of studies of the thermal conductivity of porous materials (including cermets, fireclay ceramics, and glass bead models) as a function of moisture content.

The thermophysical characteristics of moist porous materials, particularly their thermal conductivity, are strongly dependent on the moisture content and the kind of filler. The existing data on the thermal conductivity of moist porous systems are inadequate for the construction of a single $\lambda = f(u)$ relation for a broad class of porous materials. This is particularly true of materials having overly large or too small values of the moisture content. The thermal conductivity of moist materials varies in a complicated way with moisture content, and this makes it difficult to perform accurate calculations of the heat-transfer rate through such porous materials.

We have performed experiments to determine the thermal conductivity of porous materials as a function of the kind and amount of liquid contained in them. The experimental samples were flat elements of porous titanium cermet, fireclay ceramics, and bodies made of glass beads. Distilled water, alcohol, and glycerine were used as fillers.

The thermal conductivity of the moist porous elements was determined by a steady-state method. A schematic diagram of the experimental arrangement and the procedure for making the measurements are given in [1]. In order to eliminate the effect of mass transfer on the thermal conductivity of a moist porous material and consequently to employ the steady-state method without significant error, the temperature difference between the hot and cold sides of the plates was kept small at ~2°C. The average temperature of a sample was kept close to the ambient temperature.

The samples were filled with liquid under vacuum by using special equipment. After evacuating the air from the sample through its pores, liquid was fed in under pressure to produce saturation. Then part of the moisture was removed from the sample by evaporation to a definite moisture content and the porous element was weighed on an analytical balance and placed in the conductometer for the experiment. Thin rubber gaskets practically prevented the loss of mass by evaporation during the experiment and λ_e was measured at constant moisture content of the porous element.

Before adding another filler the sample was carefully washed in solvent and then placed in boiling distilled water for a certain time. After this the sample was dried in a desiccator at a temperature $T \geq 375°K$ and again placed in the vacuum chamber for filling with another liquid. The effective thermal conductivity λ_e (W/m · deg) is shown in Fig. 1 as a function of the moisture content u (%) for porous elements filled with various liquids. Curves a and b correspond to porous titanium filled with distilled water, and c and d to glycerine and ethyl alcohol, respectively. Curve e characterizes the relation $\lambda_e = f(u)$ for fireclay ceramics, and curves f and g for models made of glass beads of diameters 0.1, 0.2, 0.4, 1, and 3 mm. Since the effective thermal conductivity in the moisture range up to ~70% does not depend on the size of the particles, the graph shows only the points for bodies made of beads 0.1 and 3 mm in diameter. For particle diameters between 0.1 and 3 mm and u > 70% the values of λ_e lie between the segments of curves f and g and decrease with increasing bead diameter.

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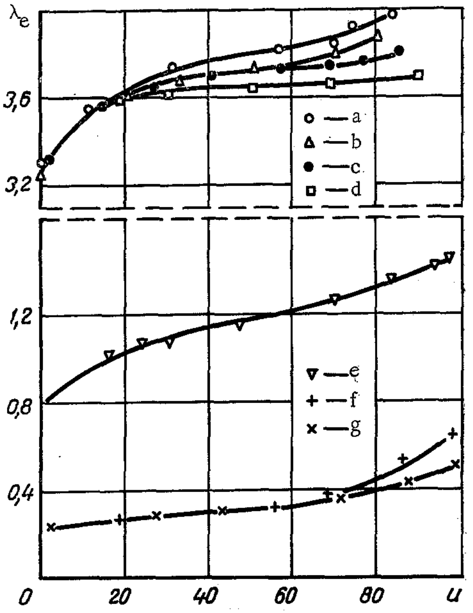

Fig. 1. λ_e for porous media as a function of moisture content u.

Models of fireclay ceramics and glass beads are chosen because for approximately identical values of the thermal conductivity of the skeleton material and the same porosity $\Pi = 30\%$ they differ in the nature of the interparticle bonds. In fireclay ceramics the particles are tightly joined to one another, while the contact between glass beads depends on the magnitude of the external pressure [3].

It is evident from Fig. 1 that the $\lambda_e = f(u)$ relation for the liquid fillers cited is similar for all bodies studied. When u decreases from its maximum value to ~20%, λ_e decreases approximately by the value of the thermal conductivity of the liquid filler. An element filled with glycerine is an exception; its effective thermal conductivity is higher than the sum of the thermal conductivities of the dry porous material and the liquid. The extra large value of λ_e for the cermet element filled with glycerine appears to be due to the fact that because of adsorption, when the sample is filled with glycerine some of the microgaps and microcracks partially absorbed water. When the sample was again filled with water after glycerine we did not obtain reproducible results although the sample was carefully washed and dried. For a moisture content <20% the effective thermal conductivity decreases more rapidly with decreasing u.

Let us analyze the relation $\lambda_e = f(u)$ at various stages of the moisture content of the material. When part of the moisture is removed from a porous element, for example by evaporation, the moisture is not uniformly distributed over the layers of the element. Close to the surface of the element moisture is liberated from the macropores while communicating pores in layers far from the surface remain completely filled with liquid. The liberation of liquid from macropores close to the surface of a porous element means that in layers far from the surface the liquid is in a capillary state, while in layers close to the surface it is in a contact state. Therefore a porous element consists of two layers having different thermal conductivities. As liquid is removed from a porous element the boundary between these layers is displaced into the element, and this leads to a decrease in the effective thermal conductivity.

After the liquid in the whole porous element is in the contact state ($u \sim 20\%$) a further decrease in the moisture content leads to a decrease in the liquid bonds at the points of contact between particles, which play the role of thermal bridges in heat transfer. The effective thermal conductivity of the element is then rapidly reduced to the value it takes on in a medium of moist air.

Experiment shows that for a moisture content $u \leq 20\%$ the dependence of λ_e on u can be described by the equation

$$\lambda_e = \lambda_s + AU^n, \tag{1}$$

where n and A depend on the thermophysical properties of the porous medium and the method of binding the particles to one another. For ceramic bodies A is close to unity, for cermets A = 0.96, and for fireclay ceramics 1.09. For models of glass beads A = 0.3 and is independent of the size of the particles. The exponent for cermets is 0.5, and for fireclay ceramics it is 0.96; for models of glass beads n is independent of the bead size and is close to unity.

For moisture content u > 20% a porous element can be regarded as consisting of two layers with a thermal resistance equal to the sum of the resistances of these layers:

$$\frac{d}{\lambda_e} = \frac{d-h}{\lambda_{\max}} + \frac{h}{\lambda_c}. \tag{2}$$

For the densest hexagonal packing of spherical particles a contact bound liquid occupies 22.6%, and for cubic packing 18.3% of the total volumes of the porous space [2]. A body made of spherical particles had a porosity between porous cubic ($\Pi = 47.64\%$) and hexagonal ($\Pi = 25.95\%$) packing. Therefore it can be assumed that contact bound moisture in such bodies occupies approximately 20% of the volume of the porous space. In liberating liquid from a porous body the first to be removed is the least bound moisture, which comprises about 80% of the maximum amount of liquid filling the porous space. Then 0.8 M/d is the mass of the least bound liquid in a layer of unit thickness. If a mass of liquid Δm is removed from a flat porous element the boundary between the layers is lowered by h, which is related to Δm by the equation

$$\Delta m = \frac{0.8M}{d} h. \tag{3}$$

On the other hand Δm is related to u by

$$\frac{\Delta m}{M} = 1 - u. \tag{4}$$

Transforming (2) by using (3) and (4), we obtain finally for λ_e

$$\lambda_e = \frac{\lambda_{max}}{1 + \frac{1-u}{0.8} \cdot \frac{\Delta\lambda}{\lambda_c}}, \tag{5}$$

where $\Delta\lambda = \lambda_{max} - \lambda_c$ is the difference between the thermal conductivity of a porous medium completely filled with liquid and a medium with the liquid in the contact state. Experiment shows that $\Delta\lambda$ is close to λ_L for the liquid filler.

Substituting into (5), in place of $\Delta\lambda$, the thermal conductivity of the liquid filler and, in place of λ_{max}, taking account of (1), $\lambda_c + \lambda_L$, when $u > 20\%$, we have

$$\lambda_e = \frac{\lambda_s + \lambda_L + Au_0^n}{1 + \frac{1-u}{0.8} \cdot \frac{\lambda_L}{\lambda_s + Au_0^n}}, \tag{6}$$

where u_0 is the moisture content at 20%. The relation obtained is in good agreement with experiment for $u > 20\%$. For $u \leq 20\%$ the experimental results satisfy Eq. (1).

The experimentally observed difference between the effective thermal conductivity of a model made of glass beads 3 mm in diameter and λ_e of a similar body made of 0.1 mm diameter beads for complete wetting (curves f and g) can be explained in a similar way.

When such media are completely filled with liquid a dried layer develops close to the surface of the body as a result of the concavity of the miniscuses. The thickness of this layer containing liquid in the contact state depends on the cross section of the capillaries and consequently on the size of the particles r. If it is assumed that the radius of a capillary close to the surface of the body is equal to the radius of the sphere inscribed within four particles in cubic packing, 0.73 r, then for complete wetting the thickness of the dried layer can be considered approximately equal to the radius of a capillary ($h = 0.73\,r$). For small r the thickness h can be neglected and the thermal conductivity for maximum wetting of a porous medium is taken equal to λ_{max}. For thin flat elements ($d \leq 12$ mm) composed of large-sized particles $r \geq 1.5$ mm. the presence of a dried layer appreciably decreases the effective thermal conductivity. This experimentally observed (curves f and g) decrease in the thermal conductivity is in good agreement with Eq. (1) which assumes the presence of a dried layer. Actually after transforming (1) we have

$$\frac{\Delta\lambda}{\lambda_{max} - \lambda_c} \cdot \frac{\lambda_c}{\lambda_e} = \frac{2h}{d}. \tag{7}$$

The results show that for thin porous elements filled with liquid it is necessary to take account of dried layers at the phase boundaries. The layer thickness depends on the size of the particles.

NOTATION

λ_e	is the effective thermal conductivity of a porous element;
λ_s	is the thermal conductivity of the skeleton material;
λ_L	is the thermal conductivity of the liquid filler;
λ_{max}	is the thermal conductivity of a porous element which contains the maximum amount of liquid;
λ_c	is the thermal conductivity of a porous element when the liquid fills approximately 20% of the porous space (contact state of the liquid);
u	is the moisture content, the ratio of the mass of liquid in a porous element to the maximum amount of liquid that the element can contain;

d is the thickness of the porous element;
h is the depth of the boundary between the two layers of a porous element.

LITERATURE CITED

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