# EFFECTIVE THERMAL CONDUCTIVITY OF MOISTENED POROUS BODIES

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This article examines a method and results of measurement of the effective thermal conductivity of porous materials impregnated with a liquid and proposes an interpretation of the physical processes of heat and mass transfer.

It is known that heat transfer occurs in moistened porous bodies by conduction through the solid skeleton of the material or the liquid or gaseous medium, as well as by radiation from particle to particle and by convection of the moisture or gas [1]. The process is complicated by phase transformations. Two approaches can be taken to describing the temperature fields in such media: construction and solution of a system of equations describing the above transfer processes; the use of one heat conduction equation for a certain quasiuniform substance. In the last case, the heat-transfer characteristics are effective values dependent on temperature, moisture content, pressure, etc. [1-4].

This article presents results of experimental studies of the integral (averaged over the thickness of a layer) effective thermal conductivity $\lambda_{ef}$ of different porous solids (porous concrete, porous glass filters, beds of glass beads) in relation to moisture content $\omega$, temperature T, and heating time $\tau$.

The investigations were conducted by a stationary method using a measurement cell (Fig. 1) consisting of thermostatted blocks 5 and 6. The planar specimen 1 was placed between the blocks. The heat flux entering $q_1$ and leaving $q_2$ the specimen was determined from the temperature drop on the layers of a standard material 4 placed between copper disks 2 and 3 provided to equalize the temperature field. The temperature drops on the layers of the standard material 4 and the specimen 1 were measured with differential-connected Chromel–Copel thermocouples a–b, c–d, and b–c with an error of about 0.6% for a gradient of about 2°K. The standard material was certified with an error of 1.3% in regard to its thermal conductivity. Heat losses from the lateral surface were evaluated from the formula $2(q_1-q_2)/(q_1 + q_2)$ and did not exceed 1-2%. To reduce the contact thermal resistance between the specimen 1 and the disks 2, we used lead washers. The blocks 5 and 6 were pressed together with a force on the order of $3 \cdot 10^4$ N/m$^2$.

The lateral surface of the moistened materials was hermetized with a rubber film having a thickness of 0.1 mm and a thermal conductivity of about 0.16 W/(m·K). The bulk material was placed in a dish with copper bottoms and a wide wall of polymethylmethacrylate having a thickness of 0.2 mm and a thermal conductivity of about 0.20 W/(m·K). We ignored the heat flows through the hermetizing film and the wall of the dish, since we estimated them to be about 0.2 and 0.4% of the heat flux through the specimen. The total error of the thermal conductivity measurement was 4%.

Effect of Duration of Experiment on Effective Thermal Conductivity. The studies [2, 3] indicated the incorrectness of using stationary methods to determine the effective thermal conductivity of moist porous materials in connection with movement of the phases and the formation of a partially dried layer, which may offer significant resistance to heat transfer. However, experimental studies of the kinetics of formation of this layer in a specimen of porous concrete with $\rho$ = 525 kg/m$^3$ showed that the process of redistribution of the phases filling the pore space has an effect on the integral (averaged over the thickness of the layer) effective thermal conductivity only within a narrow range of moisture contents $0 < \omega < 0.3$, when the liquid is distributed discretely over the volume of the material. With an increase

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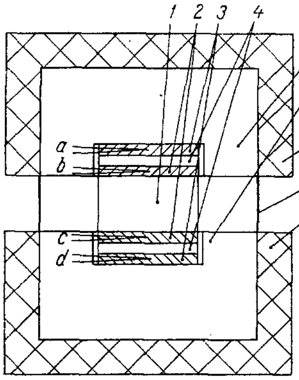

Fig. 1

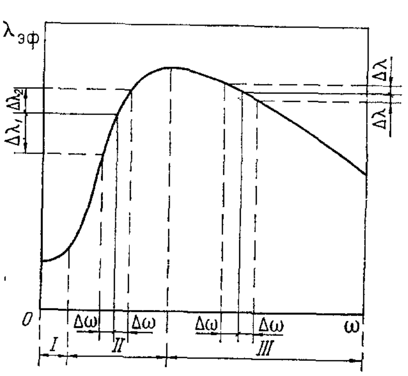

Fig. 2

Fig. 1. Measurement cell: 1) specimen; 2, 3) copper disks; 4) disks of a standard material; 5, 6) thermostatted blocks; 7, 9) thermal insulation; 8) shield insulation.

Fig. 2. Character of the dependence of effective thermal conductivity $\lambda_{ef}$, W/(m·K), of the porous solid on the moisture content $\omega$ (fractions of unity) in the high-temperature region.

in moisture content, isolated inclusions of liquid begin to merge – conditions arise for flow of the liquid. This explains the slower (by a factor of about four) change in the integral effective thermal conductivity of porous concrete over time at $\omega = 0.20$ compared to $\omega = 0.10$. With a moisture content greater than 0.30, the liquid covers all of the walls of the pore space and ensures stable dynamic equilibrium between the flows of the liquid and gas phases – the integral effective thermal conductivity of the material does not depend on time.

The character of the relation shown in Fig. 2 makes it possible to explain the fact that redistribution of the liquid due to the temperature gradient has no effect on the integral value of the effective thermal conductivity of the material in the region of high moisture contents $\omega > 0.3$ (the right branch of the curve). Redistribution of the liquid in part of the specimen reduces moisture content ($\Delta\omega$) and, thus, increases local effective thermal conductivity ($\Delta\lambda$). In another part of the specimen, due to inflow of liquid, moisture content increases – local effective thermal conductivity decreases. Since the function $\lambda_{ef} = f(\omega)$ can be considered linear with a small change in moisture content $\pm\Delta\omega$ at $\omega > 0.3$ as a first approximation, then local changes in effective thermal conductivity occurring with migration of the moisture will not have an effect on the integral value of thermal conductivity.

In the region of low moisture contents $\omega < 0.3$ (left branch of the curve), the changes in the local values of effective thermal conductivity resulting from liquid redistribution are not proportional, since the function $\lambda_{ef} = f(\omega)$ is nonlinear even with a small change in moisture content $\pm\Delta\omega$, i.e., $\Delta\lambda_1 \neq \Delta\lambda_2$. Due to this, the process of redistribution of the liquid will have an effect on the integral effective thermal conductivity of the moist porous material.

Effect of Moisture Content on Effective Thermal Conductivity. It was established that the dependence of the effective thermal conductivity of moist porous materials on moisture content has a distinct maximum at high temperatures [1]. This is evidently due to the simultaneous effect of two factors. One of these factors leads to an increase in thermal conductivity, while the other leads to its decrease.

As indicated above, heat transfer through the moist porous medium is accompanied by phase transformations, specifically: in the high-temperature region, some of the liquid is evaporated and under the influence of a gradient of the partial pressure of the vapor (resulting from the temperature gradient) is transported by diffusion into the low-temperature region, where it is condensed on the surface of the pores. In the case of low moisture contents (section I of Fig. 2), this process makes a small contribution to the effective thermal conductivity of the material because the number of moistened pores is small and these pores are distributed over the volume of the material. As moisture content $\omega$ increases (section II), the isolated layers of liquid merge into a single layer, cover all of the walls of the pores, and increase the conductive component of thermal conductivity. Optimum conditions are also created for diffusion transport of heat by vapor. At high temperatures, the contribution of

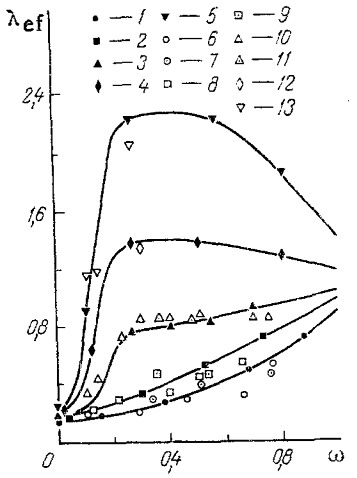

Fig. 3

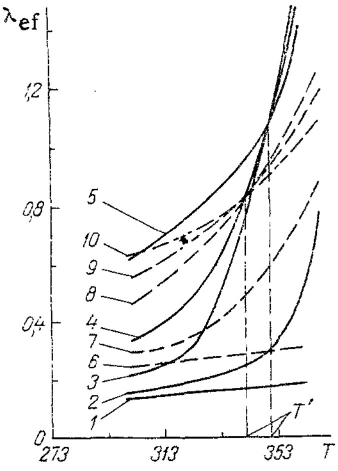

Fig. 4

Fig. 3. Dependence of the effective thermal conductivity $\lambda_{ef}$ of porous concrete, $\rho = 525$ kg/m$^3$, on moisture content $\omega$ at different temperatures T, K: 1, 6, 7) 299; 2, 8, 9) 323; 3, 10, 11) 340; 4, 12) 356; 5, 13) 367; 6, 8, 10) data from [4]; 7, 9) [3]; 11, 12, 13) [1]; 1-5) our data.

Fig. 4. Dependence of the effective thermal conductivity $\lambda_{ef}$ of the materials on temperature T at different moisture contents $\omega$: 1-5) porous concrete, $\rho = 525$ kg/m$^3$; 6-10) bed of 0.5-mm-diameter spheres of fused quartz; 1, 6) $\omega = 0$; 2, 7) 0.1; 3, 8) 0.3; 4, 9) 0.5; 5, 10) 0.8.

the diffusion component significantly exceeds the contributions of the other transport mechanisms. This ensures a sharp increase in the effective thermal conductivity of the porous material. With further moistening (section III), the liquid begins to completely fill the individual pores and thereby prevent diffusion heat transfer – thermal conductivity decreases.

Figure 3 shows the dependence of the effective thermal conductivity of porous concrete (total porosity 0.80, open porosity 0.65, closed porosity 0.15, thermal conductivity of the skeleton 2.3 W/(m·K)) on moisture content at different temperatures.

As shown by the experimental studies, the effective thermal conductivity of porous concrete ($\rho = 525$ kg/m$^3$), a bed of spheres of fused quartz (diameter 0.5 mm, porosity 0.40), and glass filters (total porosity 0.40, thermal conductivity of the skeleton 0.8 W/(m·K)) reaches maximum values at a moisture content $\omega = 0.20$-$0.25$ rather than at $\omega = 0.50$, as stated in [1]. This is due mainly to the fact that the merging of isolated films of liquid and the creation of optimum conditions for diffusion heat transfer by vapor in these materials occurs at $\omega \sim 0.20$. This conclusion is consistent with calculated values $\omega = 0.226$ for a bed of spheres with the densest packing [2].

Effect of Temperature on Thermal Conductivity. The process of diffusion heat transfer by vapor is characterized by the effective thermal conductivity $\lambda_d$ of the vapor–gas mixture in the pore space of the porous solid [1]:

$$\lambda_d = \frac{\delta M_v P}{RT(P - P_v)} \frac{dP_v}{dT} r. \tag{1}$$

It can be seen from (1) that the effective thermal conductivity of the vapor–gas mixture is proportional to the temperature coefficient of the partial pressure of the vapor $dP_v/dT$, which increases sharply with an increase in temperature. This explains the increase in the effective thermal conductivity of moistened porous materials $\lambda_{ef}$ in relation to temperature T. As can be seen from Fig. 4, the functions $\lambda_{ef} = f(T)$ intersect at different moisture contents at the temperature T'. At this temperature, the effective thermal conductivity of the porous solid does not depend on the moisture content $\omega$. Thus, the thermal conductivities of the liquid $\lambda_q$ and gas $\lambda_d$ phases are equal. It was shown in [1] that for water the thermal conductivities $\lambda_q$ and $\lambda_d$ from (1) have the same values at the temperature T' = 59°C. The temperatures we obtained experimentally for different materials turned out to be higher. This is due to the fact that Eq. (1) does not contain the diffusion resistance coefficient $\mu$, which shows by what factor the coefficient of diffusion of vapor in the porous medium $\delta_V$ is lower than the coefficient of diffusion of vapor in free space $\delta$ [2]: $\mu = \delta/\delta_V$.

Considering that the vapor encounters resistance during diffusion in the pores, we can express Eq. (1) in the form

$$\lambda_d = \frac{\delta M_V P}{\mu RT (P - P_V)} \frac{dP_V}{dT} r. \tag{2}$$

Having determined the temperature T' from experiments and knowing that $\lambda_q(T') = \lambda_d(T')$ ($\lambda_d$ is from Eq. (2)), we can suggest a method of determining the diffusion resistance coefficient $\mu$, having represented (2) in the form:

$$\mu = \frac{\delta M_V P}{\lambda_q(T') RT' (P - P_V)} \left. \frac{dP_V}{dT} \right|_{T'} r.$$

The coefficients $\mu$ calculated by this method take into account the actual occurrence of heat transfer in moistened porous solids, specifically: phase transformations during heat transfer, the presence of nonisothermal conditions for vapor diffusion, etc. The coefficient values make it possible to find the effective thermal conductivity of the vapor–gas mixture. At high temperatures, this thermal conductivity makes a significant contribution to the effective thermal conductivity of the material. We note that the use of literature values of the coefficients $\mu$ for these purposes will definitely lead to errors, since the measurements in [1, 2, 4-6] were made under isothermal conditions.

In fact, comparison of the experimentally obtained values of the coefficients $\mu$ and the literature data [5, 6] (see Table 1) showed a significant discrepancy between them. As noted above, this difference is connected with features of the diffusion transport of vapor in the porous medium. With evaporation, vapor (thanks to the partial-pressure gradient) begins to diffuse in the direction of heat flow. Reaching the middle of the pores – which has a lower temperature – the vapor partially condenses and gives up energy to the frame of the porous solid. It is probable the vapor is able to diffuse only several pore spacings from the moment of evaporation to the moment of condensation. Accordingly, the vapor experiences less resistance than if it were to diffuse through the entire layer of porous material, the thickness of which is much greater than the dimensions of the pores. Such through-layer diffusion occurs in units used to determine $\mu$ [1, 4].

The proposed mechanism of vapor transport in the porous medium under nonisothermal conditions is similar to the mechanism proposed in [7] for the diffusion-filtration transport of vapor during the drying of porous solids. However, the motive forces are different in these mechanisms: it is the gradient of partial pressure with a constant total pressure in the first case; the motive forces in the second case are the gradients of total and partial pressure. Thus, diffusion transport of vapor takes place in the porous solids examined here, while in the porous solids examined in [7] this process is accompanied by vapor filtration (bulk motion) under the influence of a total-pressure gradient. The mechanism of vapor transport we propose is operative in moist porous solids isolated from the environment (mass entrainment is absent). The vapor transport mechanism in [7] is valid for nonisolated solids such as in drying processes. We also note that the model in [7], in contrast to our model, does not allow for the effect of recondensation on the diffusion resistance coefficient $\mu$.

TABLE 1. Diffusion Resistance Coefficients $\mu$

| Material | Data from [5, 6] | Experimental data |
|---|---|---|
| Porous concrete, $\rho$ = 525 kg/m$^3$ | 5,1—6,5 | 2,5 |
| Porous glass filter | | |
| pore size ~ 130 μm | — | 4,0 |
| pore size ~ 13 μm | — | 4,7 |
| Bed of quartz spheres $\phi$ 0.5 mm | 3,8 | 1,5 |

The following conclusions can be made on the basis of the experimental investigations completed here:

during the transfer of heat in moist porous materials, migration of the liquid has a significant effect on the integral (averaged over the thickness of the layer) effective thermal conductivity only in the case of low moisture contents, when the liquid is distributed discretely over the volume of the material;

in the high-temperature region, the maximum of the dependence of the effective thermal conductivity of porous solids on the moisture content $\omega$ is shifted to a region of low moisture contents ($\omega = 0.20$-$0.25$), which contrasts with the value $\omega = 0.50$ proposed in [1]; the determining contribution to the effective thermal conductivity of the porous material under these conditions is diffusion of the vapor—gas mixture;

in examining heat and mass transfer in a porous moist medium with phase transformations, it is necessary to use a diffusion resistance coefficient which accounts for the presence of nonisothermal conditions. Use of the diffusion resistance coefficient introduced in [1] is incorrect.

## NOTATION

$\lambda_{ef}$, effective thermal conductivity of moistened porous solids; $\lambda_d$, effective thermal conductivity of the vapor—gas mixture; $\lambda_q$, thermal conductivity of the liquid, W/(m·K); $\omega$, volumetric moisture content, ratio of the volume of liquid in the porous solid to the volume of the pores, fractions of unity; T, absolute temperature, K; $\delta$, coefficient of diffusion of the vapor in air, $m^2/sec$; $M_v$, molecular weight, kg/mole; P, $P_v$, total pressure of mixture and partial pressure of vapor, $N/m^2$; R, universal gas constant, J/(kmole·K); $dP_v/dT$, temperature coefficient of partial pressure of vapor, $N/(m^2 \cdot K)$; r, unit heat of vaporization, J/kg; $\delta_v$, coefficient of diffusion of the vapor in the porous medium, $m^2/sec$; $\mu$, diffusion resistance coefficient.

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