THERMOPHYSICAL PROPERTIES OF A TWO-PHASE DISPERSED SYSTEM SATURATED WITH DIFFERENT LIQUIDS

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The thermophysical properties of a dispersed system (small silicate spheres) saturated with different liquids were experimentally determined. Dul'nev's formula can be used to calculate λ_{eff} of such systems.

In general, heat and mass transfer between bodies and the surrounding medium is the only interconnected process of heat and mass transfer in the boundary region of a solid and in the boundary layers of media [1]. Hence, in the investigation of the nature of external heat and mass transfer we cannot avoid considering the thermophysical and structural characteristics of the dispersed materials used.

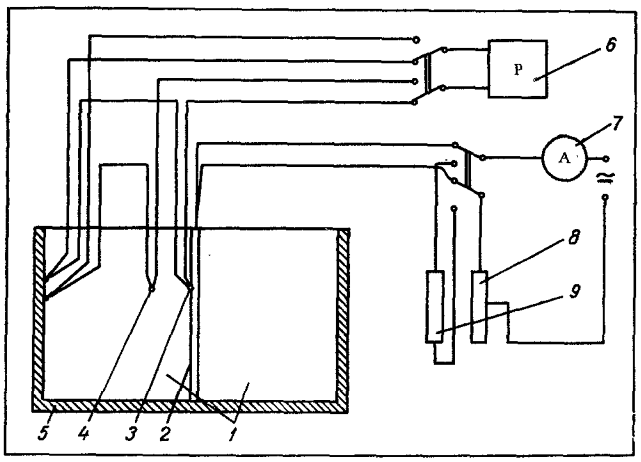

Fig. 1. Layout of apparatus for thermophysical tests: 1) Investigated layer; 2) heater; 3) heater thermocouple; 4) specimen thermocouple; 5) box; 6) recording potentiometer; 7) ammeter; 8) rheostat; 9) resistor for adjusting heater current.

Porous materials are widely used for the construction of filters and various devices which are subjected to the action of high temperatures, and, hence, require intense cooling. There have been many investigations of the interaction of porous bodies with a moving phase in the presence of a transverse supply of material [2].

The properties of porous media depend greatly on the structure and thermophysical characteristics of the skeleton and the movable substance. However, reference data and general formulas for their determination are often lacking, as in the case, for instance, of porous systems saturated with different liquids. Hence, such data have to be determined in each particular case.

We encountered this necessity in an investigation of convective heat and mass transfer during the nonadiabatic evaporation of highly volatile liquids (ethyl alcohol, benzene, and acetone) from the surface of a porous plate in an air flow. Owing to the low heats of phase transition of such liquids the amount of evaporated liquid depends very greatly on various nonconvective factors and on the internal structure of the porous material. Experiments on the evaporation of acetone from the surface of specimens of the porous metal Kh23N18 with almost equal porosity (40–43%) showed an appreciable spread in the temperature distribution at the surface and inside the specimen. Since the measurements were made in the same hydrodynamic and thermal conditions such a result must be attributed to the different structure of the specimens. Exclusion of the effect of structural inhomogeneities on the process, reduction of the heat loss to the surroundings, and minimization of the conduction equalization of the temperature along the plate necessitated the choice of a poorly conducting material of uniform chemical and granulometric composition. In addition, work with organic solvents requires a solid skeleton, which is chemically resistant. Our experiments with a fireclay–clay ceramic, made according to [3], showed that the pores in the plate soon became clogged if the liquids dissolved even a little of the material of the supply tubes, the case of the specimen, or other structural material of the flow system.

Layers of almost equal-sized spherical particles were found to be more suitable. They provide a uniform, reproducible structure, and clogging of the pores is easily removed by agitation, washing, or replacement of the material. We used a layer of silicate spheres, 0.3–0.5 mm in diameter, which had been thoroughly cleaned mechanically and chemically. The particles were put into a rectangular box with an open top, thus providing a model of a flat porous wall with a porosity of 39.6%.

For the experimental determination of the thermophysical characteristics we used the unsteady-state method with a plane heat source of constant power [4].

The general arrangement for this method (Fig. 1) is as follows. A plane heater of constant power is placed between two semi-infinite rods of the material of which the thermophysical characteristics have to be determined. The temperature distribution in the rods is determined by solution of the general differential heat conduction equation

$$\frac{\partial t(x, \tau)}{\partial \tau} = a \frac{\partial^2 t(x, \tau)}{\partial x^2} \qquad (1)$$

in conjunction with the initial and boundary conditions

Thermophysical Characteristics of Mixtures

Liquid	Bulk density kg/m³	Specific heat, J/kg · deg	Thermal conductivity, W/m · deg	Thermal diffusivity, m²/sec	Specific heat from additive relationship	λ_{eff} from Dul'nev's formula
Air	1710	844	0.214	1.482	844	—
Benzene	2030	993	0.446	2.21	986	0.452
Ethyl alcohol	2063	1060	0.520	2.38	1092	0.485
Distilled water	2110	1390	0.730	2.49	1480	0.779
Acetone	2023	—	—	2.29	1036	0.481

$$t(x,\ 0) = t_{av} = \text{const},$$

$$\frac{\partial t(\infty,\ \tau)}{\partial x} = \frac{\partial t(\infty,\ \tau)}{\partial \tau} = 0,$$

$$-\lambda \frac{\partial t(0,\ \tau)}{\partial x} = \dot{q}'' \qquad (2)$$

and has the form

$$t(x,\ \tau) = \frac{2\dot{q}''\sqrt{a\tau}}{\lambda}\, i\text{erfc}\, \frac{x}{2\sqrt{a\tau}}. \qquad (3)$$

The determination of the thermophysical characteristics of the material necessitates measurement of the temperature of the heater and the temperature at some point a short distance from it. In this case the graph of $\Delta t_h = f(\tau)^{1/2}$ is a straight line passing through the origin. The linearity of this graph provides a check that the boundary conditions (2) of the problem are fulfilled.

The choice of this method for measuring the thermophysical characteristics of two-phase systems consisting of a granular layer and a liquid phase is no accident. Most experimental methods of determining thermophysical properties are based on a consideration of the differential heat-conduction equation for continuous media. In the case of dispersed systems their effective properties are determined.

The use of the one-dimensional heat-conduction equation for processes uncomplicated by mass transfer without the additional heat-source terms is justified in cases where mass transfer by diffusion and thermal diffusion is slight. This is the case when the temperature gradient is low and the heat flux acts for a short time.

Unsteady-state methods satisfy these requirements in most cases. The method which we chose also provides a check on fulfillment of the boundary conditions. This allows an objective assessment of the processes occurring in the dispersed material under the action of the heat flux. In the case of dry dispersed systems convection distorts the temperature distributions in several cases. We considered a system consisting of a solid skeleton and a liquid, where the effect of the indicated factors is even greater. Hence, in the determination of the effective thermal conductivity it is very important to select conditions of measurement and a heat flux which reduce the mass flux to a minimum. In this case the temperature distribution is determined by the thermal characteristics of the system.

The conducted experiments satisfied the required conditions. A clear plastic box with 60 × 60 × 155 mm dimensions and volume 560 cm³ was constructed. A flat electric heater (60 × 60 mm) made of 0.1-mm manganin wire and insulated with varnished cloth was fitted into the box. A thermocouple was cemented to the heater and another thermocouple was placed at a distance of 6.3 mm from it. The investigated material was put into the box and its bulk density was determined.

To determine the thermophysical characteristics of the mixture we poured liquid from a measuring vessel into the box containing the spheres. The measurements were carried out in the usual sequence. The experimental procedure was described in [5]. For each liquid we carried out several experiments. The table gives the mean results.

Besides the check from the shape of the graph of $\Delta t_h = f(\tau)^{1/2}$ we verified the results by comparing the experimental values of the specific heat with the theoretical values. We used the known property of additivity of the specific heats for systems which do not react chemically (see table). The values of the specific heats of the liquids were taken from [6]. The satisfactory agreement between the experimental and calculated values indicates the reliability of the obtained data. The differences between them do not exceed ±6.7%.

The material used was a two-component system (liquid phase and solid inclusions) with communicating pores. For dry systems consisting of a solid skeleton and solid or gaseous inclusions Dul'nev [7] proposed a hypothetical model of heat transfer from which he obtained the following theoretical relationship for the effective thermal conductivity of the system:

$$\frac{\lambda_{eff}}{\lambda_1} = \left(\frac{h}{L}\right)^2 + \nu\left(1 - \frac{h}{L}\right)^2 + 2\nu\frac{h}{L}\left(1 - \frac{h}{L}\right)\left[1 - \frac{h}{L}(1-\nu)\right]^{-1}. \qquad (4)$$

The relationship $h/L = \varphi(n)$ is illustrated in [7]. It is convenient to determine λ_{eff} from formula (4), since the thermal conductivities of most of the substances forming the systems are given in the reference literature.

We attempted to extend the field of application of the proposed model and, hence, of formula (4) to a two-phase system consisting of a solid skeleton and a liquid.

The results of calculation of λ_{eff}, given in the last column of the table, are in good agreement with the experimental values; the differences do not exceed ±6.5%. The values of λ_1 and λ_2 are given in [6, 8]. Thus,

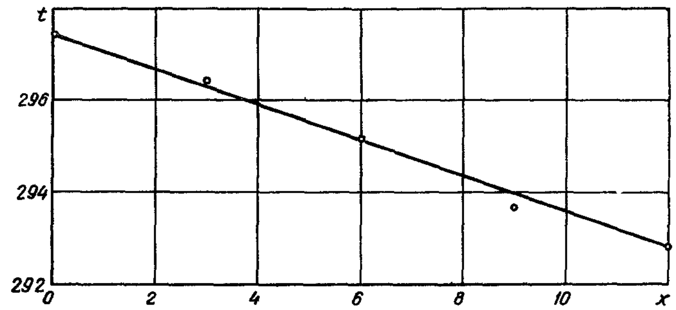

Fig. 2. Temperature of solid t, °K in relation to thickness x, mm of plate in case of evaporation of alcohol ($Re_\infty = 3.54 \cdot 10^5$; $T_\infty = 338°$ K).

we can recommend formula (4) for a reasonably accurate calculation of λ_{eff} of a porous system saturated with a liquid. From this formula we determined λ_{eff} for a layer of spheres saturated with acetone. The experimental determination of the thermophysical characteristics of this system is extremely difficult and unreliable, since acetone dissolves the plastic from which the box for the thermophysical tests is made. The bulk density and specific heat of the system were calculated by the additivity rule and the thermal diffusivity from the relationship $a = \lambda / c\gamma$.

An examination of the table shows that the selected material for simulation of a porous lid has a low λ_{eff} for all the liquids used. The maximum value of λ_{eff} was less than λ_{eff} of the dry fireclay ceramic (λ_{eff} = 1 W/m · deg) which is widely used for physical investigations of heat and mass transfer.

The experimentally determined and calculated thermophysical characteristics refer to a static system with no convective heat transfer and with a continuous supply of liquid to the surface of the experimental solid. However, our special experiments showed that the temperature distribution over the thickness of the plate was linear in all the experimental conditions. As an example, Fig. 2 shows a graph for the case of evaporation of alcohol. The temperature distribution was similar for the other liquids.

Thus, the results obtained in static conditions can be used for the investigated systems. From the known thermophysical characteristics of the material and the temperature distribution in a cross section of the plate the heat flux can be determined.

NOTATION

τ is time; x is the variable coordinate; λ is the thermal conductivity; a is the thermal diffusivity; c is the specific heat; γ is the bulk density; q" is the specific heat flux; n is the volume of the component; h/L is the relative characteristic dimension depending only on volume of component in system; Re is the Reynolds number; $v = \lambda_2/\lambda_1$; $\Delta t_h = t_h - t_{av}$. Subscripts: 1 refers to solid; 2 to liquid; eff is the effective value.

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