NONISOTHERMAL MOISTURE TRANSFER IN CLOSED DISPERSE SYSTEMS

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This paper shows that the factors determining the magnitude of the reverse flow of moisture, which compensates the moisture transfer due to the temperature gradient, have a decisive influence on the final form of the moisture-content profile in horizontal, closed, disperse, nonisothermal systems.

The prediction of the effect of temperature distribution on the distribution of moisture content in a porous medium by means of the rapidly developing theory of interconnected heat and mass transfer [1, 2] is difficult owing to the inadequate development of methods of determining the functional relationships between D_l and D_T of the vapor and liquid phase, on one hand, and the factors affecting them, on the other. In current theories of transfer the hysteresis of the relationships $\Theta(U)$ and $D_l(\Theta)$ is ignored.

At the present state of the theory of nonisothermal moisture transfer in porous materials the collection and analysis of experimental data characterizing the most important features of moisture thermotransfer* in porous media will facilitate the establishment of relationships between the generally accepted characteristics of porous materials and their behavior in a temperature field, and will also assist the development of appropriate classifications.

As far as we know, no such classifications exist at present, since it is not quite clear what properties or characteristics of a porous material favor the redistribution of the moisture content due to a temperature gradient, and what factors oppose such a redistribution. The main reason for this situation is the diversity of mechanisms of moisture transfer in unsaturated porous media or, to be more precise, the existence of vapor and liquid isothermal and thermal transfer of moisture. Effective vapor and liquid transfer of moisture is promoted by various (often opposing) properties of the porous material and, hence, an inadequate knowledge of the phase composition of the moisture flux in nonisothermal moisture transfer prevents the assessment of a porous material as regards moisture thermotransfer a priori, on the basis of its properties.

We tried to classify various porous materials as regards moisture thermotransfer by investigating the phase composition of the moisture flux by direct methods and by comparing some characteristics of the porous material with the redistribution of moisture in it due to a temperature gradient.

EXPERIMENTAL

The investigated materials, which differed appreciably from one another in the properties which significantly affect vapor and liquid transfer of moisture, and some of their characteristics are listed in Table 1.

In the experiments, which were described in [3, 12], the same thermal regime with a linear, steady-state temperature distribution was created simultaneously in several (up to 12) columns containing the investigated material. From moisture-coordinate plots for experiments of different duration we were able to investigate the kinetics of the moisture distribution in the system, to determine the onset of a quasi-stationary moisture distribution, and to calculate q, ΔU_{cb}, and Π as functions of U_i, γ, α, and other experimental conditions.

EXPERIMENTAL RESULTS AND THEIR DISCUSSION

One method of investigating the mechanisms of moisture thermotransfer is to determine the rate (flux density) of this process and to compare it with the flux rates of known transfer mechanisms, such as the rate of vapor diffusion. The change in moisture distribution in porous material depends on the interaction of fluxes due to the moisture gradient and the temperature gradient [1]. In steady-state conditions in a horizontal closed system which initially had a uniform moisture content these fluxes are in opposition. Hence, the true rate of moisture thermotransfer

Characteristics of Investigated Porous Materials

Material	Size of particles or aggregates, mm	Moisture content, % by weight		Specific surface m^2/g	Cation exchange capacity, mg-equ/100 g
		maximum hygroscopic	with moisture potential 33 J/kg		
Quartz sand	0.25—0.50	0.1	2.0	1.5	0.1
Heavy loam	1	4.8	33.0	49.9	16.2
Chernozem, heavy loam	1	6.5	37.0	97.5	37.5
Crushed porous clay filler	1	0.3	9.2	2.1	0.7
Crushed fireclay (PKM)	1	0.2	4.6	2.0	0.5

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*For brevity this term will henceforth be used to mean moisture transfer due to a temperature gradient.

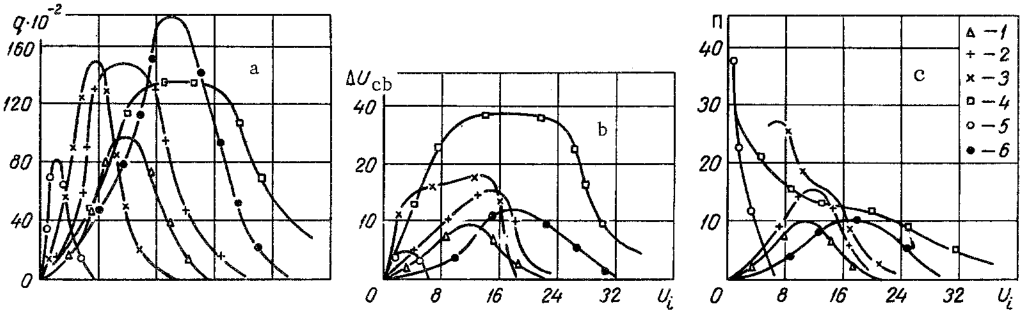

Fig. 1. Indices of effectiveness of moisture thermotransfer a) q; b) ΔU_{cb}; c) Π as functions of U_i; 1) Heavy loam, $\gamma = 1.22$ g·cm^{-3}; 2) the same, $\gamma = 1.05$ g·cm^{-3}; 3) crushed PKM fireclay; 4) porous clay filler; 5) quartz sand; 6) chernozem.

(specific flux density) can only be determined approximately in certain specific conditions.

We will discuss one of the methods of determining the rate of moisture thermotransfer by considering the case of the kinetics of the moisture distribution in several columns loaded with quartz sand with U_i much greater than the maximum hygroscopic moisture content. In the first 10–20 hr after the establishment of a constant temperature distribution (which takes 1.5–2.5 hr) the moisture gradient in the middle section of the column is negligibly small, and all the other factors are practically constant. During this period the reverse transfer of moisture due to the moisture gradient can be neglected, and the rate of moisture thermotransfer can be regarded as constant in a first approximation. This rate can be determined by calculating the flux through the considered section from the graphs in Fig. 1a. It is 3.33 g · cm^{-2} · sec^{-1} for U_i = 1% (by weight), dT/dx = 1 deg/cm, T_{av} = 22°C, and a = 0.42. The rate of moisture thermotransfer in this sand for U_i = 3% and a = 0.39 in the same temperature conditions is 4.81 · g · cm^{-2} · sec^{-1}. The same method is used to determine the rates of moisture thermotransfer in the other investigated materials with values of U_i corresponding to the region situated immediately on the left of the maxima of the curves shown in Fig. 1a.

We will mention another method which we have used to estimate the rate of moisture thermotransfer in porous materials with moderate initial moisture content. Three columns of material with the same U_i, appreciably greater than the maximum hygroscopic moisture content, are subjected to the action of a temperature gradient for a time which is small in comparison with that required for the establishment of the steady-state moisture distribution. We then determine the changes in U and the moisture transfer through the middle section of the first column A. Column B is removed from the apparatus at the same time as A and, after the temperatures have leveled out (in 1–2 hr), is subjected for the same time as before to the action of a temperature gradient of the same magnitude as before but acting in the opposite direction. The third column C is removed from the apparatus at the same time as A, is kept in isothermal conditions, and is analyzed for moisture content at the same time as B.

In column A the mean rate of thermotransfer $\bar{v}_A$ is less than the actual rate $\bar{v}_T$ owing to the effect of the reverse flux which is due to the moisture gradient and has a mean rate $\bar{v}_I$. In column B the mean rate of thermotransfer $\bar{v}_B$ is greater for the same reason than the actual rate $\bar{v}_T$ owing to the superimposed rate of flow due to the moisture gradient, the rate of which $\bar{v}_I$ is the same in the first approximation as in A. In column B during the period spent in the isothermal state the moisture content levels out at a mean rate $\bar{v}'_I$, which is also approximately equal to $\bar{v}_I$.

On the basis of this we have

$$\bar{v}_T = (\bar{v}_A + \bar{v}_B)/2, \tag{1}$$

$$\bar{v}_I = (\bar{v}_B - \bar{v}_A)/2. \tag{2}$$

In such an experiment for loam with U_i = 9.8% in the temperature conditions given above we obtained the following values for the densities of the different fluxes: $\bar{v}_A = 5.02 \times 10^{-7}$ g · cm^{-2} · sec^{-1}, $\bar{v}_B = 6.34 \times 10^{-7}$, $\bar{v}_T = 5.68 \times 10^{-7}$, $\bar{v}_I = 0.66 \times 10^{-7}$, $\bar{v}'_I = 0.70 \times 10^{-7}$.

The rate of vapor diffusion due to a temperature gradient was determined from the transfer of moisture through layers of the same materials made hydrophobic by treatment with silicone preparations [3]. In our experiments with a temperature gradient of 1.0 deg/cm and a mean temperature of 22° C v_{VT} was 0.9–1.4 · 10^{-7} g · cm^{-2} · sec^{-1}, which was 110–130% of the values calculated for the experimental conditions from the equation for vapor diffusion in porous media [4].

The measured rates of total moisture thermotransfer exceeded the experimentally determined vapor diffusion rates by a factor of 3–8.

Like several other investigators, who have suggested that the higher rate of moisture thermotransfer in comparison with vapor diffusion is due to thermotransfer of the liquid phase, we attempted to detect the latter. For this purpose we labeled the liquid phase with the nonabsorbable radioactive tracer $Na_2S^{35}O_4$ or a Co^{60} chelate. However, in the case of moisture thermotransfer in positive temperature conditions, the resultant transfer of the tracer was in a direction opposite to the resultant moisture transfer. In the case of thermotransfer with freezing we observed a transfer of the tracer in the freezing front, and this was greater, the higher the initial moisture content of the system. The transfer of the tracer to the "warm" end of the column, which was also observed in this case, confirmed the existence of two fluxes of the liquid phase in a freezing porous system: towards the freezing front and towards the warm boundary owing to the circulation of water in the melted region [12].

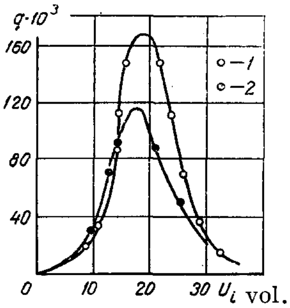

Fig. 2. Plot of mean specific moisture flux in chernozem against initial moisture content (% by volume) for aggregates of diameter 1 mm (1) and 0.5 mm (2).

We will deal more fully with the effect of the mechanical composition, structure, specific surface, bulk density, and total and free porosity on moisture thermotransfer in closed systems.

In closed systems composed of moist porous materials the creation of temperature gradients does not necessarily give rise to appreciable moisture gradients. If the system has sufficiently high capillary moisture conduction the moisture circulation [5], which is clearly revealed by tracer experiments, ensures the rapid and total return of the moisture transferred by the thermal flux to the cold boundary of the system. Such moisture thermotransfer without the appearance of appreciable moisture gradients has no significant effect on the main thermophysical and mechanical properties of the material, although it may alter some properties of the system, such as the distribution of soluble substances in it and the electrical conductivity.

The most interesting from the engineering viewpoint are systems and conditions in which moisture thermotransfer leads to a change in the moisture distribution. Such moisture thermotransfer can be called effective.

The effectiveness of moisture thermotransfer, which is distinguished by a change in the moisture distribution due to the temperature distribution, is usually assessed from the value of the thermogradient coefficient δ [1], which is numerically equal to the ratio of the moisture differential to the temperature differential in the system with a steady-state distribution of U and T. However, as experimental data show, a linear temperature distribution is generally associated with a nonlinear moisture distribution. Hence, δ in practice is an integral characteristic of the system which does not reveal all the features of the behavior of different capillary-porous materials in a temperature field.

In view of this, we introduce additional characteristics of moisture thermotransfer which in standard test conditions can serve as comparative quantitative indices of the effectiveness of moisture thermotransfer. Such characteristics are ΔU_i, q, ΔU_{cb}, and Π. The position of the maximum of plots of these indices against U_i is frequently used as a characteristic index (Fig. 1, a, b, c).

From an analysis of experimental plots with due regard to the characteristics of the investigated materials we can draw some conclusions regarding the factors responsible for the effectiveness of moisture thermotransfer in closed disperse systems similar to those investigated (porous silicate materials).

In spite of the opinion expressed in the literature [6], neither the effectiveness nor the rate of moisture thermotransfer depends directly on the cation exchange capacity or the cation composition. The maximum rates of effective moisture thermotransfer in closed systems—of the order of 10^{-6} g · cm^{-2} · sec^{-1} for a gradient of 1.0 deg/cm—have been observed in a porous ceramic with a low exchange capacity and in chernozem with a high content of exchangeable cations.

The specific surface in itself generally does not determine the effectiveness of moisture thermotransfer (Fig. 1). An increase in the specific surface of polydisperse systems lacking a macrostructure leads to a shift of the initial moisture content corresponding to the maximum effectiveness of moisture thermotransfer into the region of larger values of U_i. An explanation of this effect will be given below.

Figure 1 (curves 1 and 2) shows the effect of γ on the effectiveness of moisture thermotransfer in heavy loam. A reduction in γ leads to an increase in the effectiveness of moisture thermotransfer—to an increase in q, ΔU_{cb}, and Π in the former range of U_i, and this increase is greater, the higher U_i. In addition, there is an extension of the range of effective moisture thermotransfer towards higher U_i.

The effect of structure on the effectiveness of moisture thermotransfer in chernozem aggregates of diameter 0.5 and 1.0 cm is clearly revealed by Fig. 2 and by a comparison of the data on moisture thermotransfer in porous clay filler and a porous ceramic (PKM) (curves 3, 4, Fig. 1).

An increase in the diameter of the chernozem aggregates, which leads to a reduction in the effective specific surface, increases the effectiveness of moisture thermotransfer (Fig. 2). These two coarsely disperse ceramic systems, which have similar properties and in the experiments had similar values of γ and total porosity, differ in the structure of the individual particles, which are of the same size. In porous PKM ceramic the granules have holes right through them, whereas in porous clay filler the granules have blind pores on the surface. The data of Fig. 1 show that the presence in porous clay filler of numerous blind pores, which can retain moisture, but do not permit a through flux of liquid, ensures a higher effectiveness of moisture thermotransfer.

Systems which have a macrostructure—porous clay filler and PKM, despite their small specific surface, which is close to that of quartz sand, are much superior to the latter as regards effectiveness of moisture thermotransfer. The predominance of through pores in PKM, which increase the penetrability for the liquid flux, leads to a pronounced reduction of the range of U_i where moisture transfer is effective.

In view of the effect of γ and structure on the effectiveness of moisture transfer it was of interest to find out if these factors have a decisive effect on the magnitude of the direct thermal flux of moisture $D_T\nabla T$ or on the reverse flux $D_l\nabla U$ due to the ∇U produced in the closed system. For this purpose we investigated the relationship between $\bar{v}_T$ and a (or γ) for heavy loam with the same initial moisture content by weight and in different temperature conditions. The obtained relationship in the range $a = 0.28-0.50$ ($\gamma = 0.95-1.30$ g $\cdot$ cm^3) was approximated satisfactorily by the equation $v_T = 1.57 \cdot 10^{-5} a^4$ g $\cdot$ cm^{-2} $\cdot$ sec^{-1}.

It is known that the moisture conduction of an unsaturated porous medium for the liquid phase decreases appreciably with reduction of γ [8]. The conductivity for the liquid thermocapillary flux is proportional to h and the perimeter of the water films per unit area of section perpendicular to the flux [7]. The first of these quantities in different columns of the experiment was constant, while the second decreased with reduction of γ. Hence, the increase in v_T with reduction of γ cannot be attributed to the increase in the thermocapillary flux or thermal diffusion of liquid. Thus, the increase in the effectiveness of moisture thermotransfer with reduction in γ cannot be attributed to increased transfer of the liquid phase. According to theory [4] and experiments [14] D_{VT} increases linearly with a.

Hence, we can conclude that the pronounced increase in the effectiveness of moisture thermotransfer with reduction of γ, particularly at high U_i, is due only in small part to the increase in vapor thermotransfer and is due mainly to the retardation of the reverse flux of the liquid phase resulting from the gradient of U in the system. The behavior of the reverse moisture flux is also responsible for the above-mentioned shift of the value of U_i for most effective moisture thermotransfer towards higher values with increase in the specific surface of microstructured polydisperse materials (Fig. 1). The greater the specific surface of the material the higher the weight moisture content U, which ensures a value of h such that the conductivity of the system for the reverse liquid flux is sufficient to compensate the moisture flux due to the temperature gradient.

In conclusion we make some deductions regarding the relationships between particular characteristics of porous materials and effective moisture thermotransfer in them.

Measurements of the rate of moisture thermotransfer in closed systems and an analysis of the flux rates in circulating systems without a moisture gradient [9–11] show that the true rate of moisture thermotransfer in different porous materials varies in a comparatively narrow range—from about $1 \cdot 10^{-7}$ to $1 \cdot 10^{-6}$ g $\cdot$ cm^{-2} $\cdot$ sec^{-1}—and depends mainly on their moisture content.

Differences in the structure of porous materials and in the properties of the solid phase when temperature gradients act mainly affect the effectiveness of moisture thermotransfer, i.e., the results of interaction of the direct (due to the temperature gradient) and reverse moisture fluxes. Alteration of the bulk density and structure of a porous material without altering its specific surface is a good method of regulating the effectiveness of moisture thermotransfer.

The range of U_i in which effective moisture thermotransfer occurs is narrowest in structureless monodisperse systems. In microstructured and polydisperse porous materials the width of this range and the moisture content of the most effective moisture transfer become greater with increase in the specific surface.

The highest value of ΔU_i is attained in macrostructured systems where ΔU_i is affected most by the size and structure of the aggregates or granules. With increase in the number of blind pores or specific surface of the aggregate the effectiveness of moisture thermotransfer becomes greater.

A reduction of γ of a particular porous material with a fixed moisture content by weight leads to an increase in all the indices of effectiveness of moisture thermotransfer.

The value of Π is greatest in weakly hygroscopic monodisperse and structured materials where it reaches 50% in the region of small U_i. It is in this region of moisture contents that the change in moisture content of a porous material most affects its thermophysical characteristics.

The effectiveness of thermotransfer increases with increase in temperature gradient and mean temperature (in the region of positive temperatures).

These statements apply to horizontal closed systems. For moisture transfer in vertical disperse systems in the region of positive temperatures the following cases should be distinguished:

1. In the range moisture content where vapor diffusion and the combined vapor-liquid mechanism of moisture thermotransfer [2] predominate, the relative direction of the thermal flux and the force of gravity does not significantly affect the effectiveness of moisture thermotransfer, particularly in macrostructured systems.
2. In moister systems where the direction of the thermal flux is opposite that of the force of gravity the region of effective moisture thermotransfer is similar to that for horizontal systems.
3. When the directions of the force of gravity and the thermal flux are the same the region of effective moisture thermotransfer is extended in the direction of greater U_i.

As distinct from moisture thermotransfer at positive temperatures, the effectiveness of moisture transfer in a freezing material is increased by all factors which increase the penetrability of the system for the liquid phase [13, 14].

NOTATION

U is the moisture content of material, % by weight; ΔU_{cb} is the difference of moisture content at boundaries of nonisothermal system, % by weight; ΔU_i is the range of initial moisture contents within which moisture thermotransfer is effective; U_i is the initial moisture content, % by weight; D_V, D_L are the coefficients of diffusion of vapor and capillary diffusion of liquid, respectively; T is the temperature; x is the coordinate; q is the mean specific moisture flux, $g \cdot cm^{-2} \cdot sec^{-1}$; Π is the moisture transferred as a percentage of total moisture content of system; γ is the bulk density, $g \cdot cm^{-3}$; a is the porosity free from water as fraction of total volume; h is the thickness of water films; ω is the potential of moisture transfer in isothermal conditions. The subscripts I and T denote isothermal and thermal, respectively.

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