Journal of Engineering Physics and Thermophysics, Vol. 77, No. 4, 2004

INFLUENCE OF MOISTURE TRANSFER ON HEAT TRANSFER UNDER THE ACTION OF AN INHOMOGENEOUS ELECTRIC FIELD IN CONICAL CAPILLARIES

N. V. Polishchuk, I. M. Panchenko, and M. S. Panchenko

UDC538.6:541.18:577.1:621.187.3:628.335:337:667.2

A numerical study of the influence of an inhomogeneous electric field (IEF) on the film moisture transfer in the presence of a temperature gradient along a water film in a quartz conical capillary has been made. It has been shown that in the case of oppositely directed temperature gradients and the electric field (EF) intensity in the film, there is a considerable increase in the heat flux in the capillary due to the intensification of the transfer of the heat content of water as a result of the appearance of additional electromoisture fluxes under the action of the ponderomotive forces of the inhomogeneous electric field.

The scientific-technological progress made in different fields of engineering and technology is inseparably linked with the use of electric fields of high intensity E. The increasing requirements for the maintenance of given thermal regimes under these conditions dictate more extensive and deeper investigations of the interrelated processes of heat and mass transfer in EFs [1].

The interaction of porous materials with moisture occurs mainly under the influence of static and alternating electric fields of natural and industrial origin. An inhomogeneous electric field can strongly influence the mass-exchange dynamics in capillary-porous bodies (CPB) due to the force action on both the dipole molecules of vapor and the macrovolumes of a liquid dielectric [2, 3]. A high-intensity EF causes in disperse systems a number of effects that are of practical and theoretical interest. In particular, a steady flow of liquid polar dielectrics in an EF of intensity 10^5–10^7 V/m is observed. This flow is due to the appearance of inhomogeneous polarization of the phases and a space charge in the near-electrode regions of the liquid, as well as to the presence of an interphase boundary, where a jump of the dielectric constant occurs, and a double electric sphere or a noncompensated charge. These phenomena should be taken into account in interpreting the electrophysical processes in moist disperse systems and systems modeling them.

In a moist CPB, together with the heat transfer in the solid phase, there occurs an internal energy transfer due to the moisture transfer, which is influenced to a considerable extent by the presence of an EF [4]. Therefore, the heat conductivity in moist CPBs placed in different EFs should be considered in close connection with the moisture transfer. Consequently, the problem of determining the heat flow at interrelated heat and mass transfer in moist CPBs under the action of external EFs is topical.

The aim of the present paper is to study the influence of electro-moisture processes on the heat transfer in a model of a porous space element in the form of a conical macrocapillary partially filled with moisture when the wetting liquid menisci have a different curvature and are separated by a vapor-air bubble.

The heat flow in a moist CPB obeys the heat-conduction law [5]

$$j_{\mathrm{s}} = -\lambda_{\mathrm{s}} \nabla T + \sum_i I_i j_i \,. \tag{1}$$

The heat-conductivity coefficient of a moist CPB obtained experimentally by the formula

---

Rovno State Humanities University, 31 Ostafov Str., Rovno, 266000, Ukraine; email: mail@rdgu.rv.ua. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 77, No. 4, pp. 121–127, July–August, 2004. Original article submitted August 7, 2003.

1062-0125/04/7704-0808 ©2004 Springer Science+Business Media, Inc.

$$\lambda_{\text{ef}} = \frac{j_{\text{s}}}{\nabla T}, \tag{2}$$

defines the effective heat-conductivity coefficient λ_{ef} rather than the true one. In the case of additivity,

$$\lambda_{\text{ef}} = \lambda_{\text{s}} + \lambda_{\text{r}} + \lambda_{\text{c}} + \lambda_{\text{a}} + \lambda_{\text{v}} + \lambda_{\text{liq}} . \tag{3}$$

As is known [4, 5], for a pore diameter not exceeding $5 \cdot 10^{-5}$ m, the convective and radiative heat exchange at a temperature difference between the pore walls of $\Delta T \approx 10$ K can be neglected. Thus, in a dry CPB (capillary radii of less than 10^{-5} m) at normal temperature differences the heat transfer by convection and radiation is negligibly small compared to the true heat conductivity.

In microcapillaries, the heat-conductivity coefficient of air is proportional to the gas pressure and the capillary radius; therefore, it is not a gas constant. The mechanism of heat transfer in such microcapillaries is determined by the molecular (Knudsen) flow. But the molecular concentration of air and water vapor in moistured microcapillaries is negligible compared to the amount of water molecules in a unit volume of the adsorption-bound moisture film. Their ratio is about 10^{-5} [4, 5]. Consequently, the heat transfer in the microcapillaries of moist CPBs occurs mainly via the molecular (atomic) heat conduction through the body skeleton and intraporously bound substances — liquid in the form of polymolecular films and columns of capillary-condensed moisture.

There are a number of works [4–7] devoted to the investigation of the dependence $\lambda_{\text{ef}}(W)$ at a certain porosity of the CPB. In all these works, it is noted that, in the main, the value of λ_{ef} considerably increases as the porosity coefficient of the above-mentioned bodies decreases and their W increases at a given porosity.

Under the joint action of an IEF and the gradient temperature field, moisture transfer occurs under the action of not only the diffusion (∇W) and thermodiffusion (∇T) forces, but also under the action of the motive thermodynamic force that is due to the IEF (∇E) and the electroosmotic forces ($\nabla \varphi$) [4]. In the general case, the moisture flow in a moisture-saturated body in the presence of a constant IEF, in accordance with the thermodynamics of irreversible processes, is defined by the relation

$$j = -\lambda_{\text{mc}} \nabla W - \lambda_{\text{tg}} \nabla T - \lambda_{\text{e}} \nabla E - \lambda_{\text{eos}} \nabla \varphi . \tag{4}$$

Consequently, the value of λ_{ef} of a moist CPB should be strongly influenced by the gradients W, T, E, and φ of the EF. Therefore, in the case of the action in a moist microporous body of the gradient fields given in (4), the heat-conductivity coefficients that are caused by heat transfer due to moisture conduction, moisture thermodiffusion, electro-moisture-diffusion heat conduction, and electroosmotic heat conduction should enter into (3) as additional terms.

In [8], the electroosmotic flow in thin α-films formed in quartz macrocapillaries of radii 5–10 μm and bounding an air bubble of length up to 300 μm was investigated. In the approximation of small potentials of the film surface, the dependence of the flow velocity of water in the film $V_{\text{eos}}(E)$ is of the form

$$V_{\text{eos}} = \varepsilon_0 \varepsilon \frac{\psi_1 h}{2\pi\eta r} \left[1 - \left(1 + \frac{\psi_2}{\psi_1} \right) \frac{\tanh (\chi h/2)}{\chi h} \right] E . \tag{5}$$

According to (5), V_{eos} varies in direct proportion to the constant EF intensity. Then the heat flow caused by the electroosmotic flow of the liquid in the film will have the value

$$j_{\text{s,eos}} = V_{\text{eos}} \rho I_1 = \varepsilon_0 \varepsilon \frac{\psi_1 h}{2\pi\eta r} \left[1 - \left(1 + \frac{\psi_2}{\psi_1} \right) \frac{\tanh (\chi h/2)}{\chi h} \right] \rho I_1 E . \tag{6}$$

Consequently, even a homogeneous but constant EF acting on the film moisture should have a stronger effect on the heat transfer, the more significant the value of the field intensity.

Moisture transfer upon incomplete moisture saturation of a CPB in a constant, and especially in an alternating low-frequency EF is influenced mainly by the IEF. This influence extends to individual dipole molecules of water

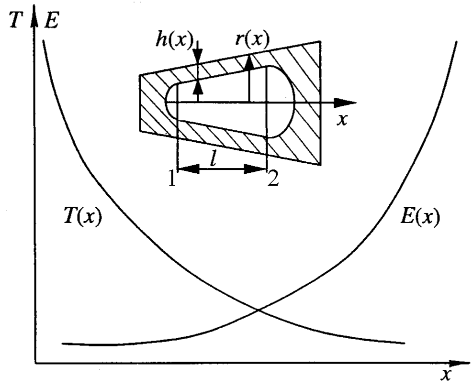

Fig. 1. Calculation scheme of the porous space element in inhomogeneous electric $E(x)$ and temperature $T(x)$ fields.

vapor and discrete films and water columns in micro- and macrocapillaries. In the first case, the velocity of travel of molecules is directly proportional to ΔE, and in the other cases — to VE^2 [2, 3].

Thus, the heat-transfer process in a fairly moist CPB should be influenced by constant homogeneous and inhomogeneous EFs. In a low-frequency alternating field, in particular, in the most common field of industrial frequency, such an influence can only be produced by an IEF [9]. It is extremely difficult to perform experimental studies on the influence of the IEF on the heat transfer in an individual microcapillary and even in micron macrocapillaries, since thermal instruments introduce considerable distortions into the course of thermal processes. Therefore, to elucidate the influence of the IEF on the heat transfer in an individual thin macrocapillary as an elementary CPB [10], in which the moisture transfer is strongly influenced by the applied IEF [11], we make use of the calculation procedure.

In the complex geometry of the porous space of real CPBs, conical capillaries prevail [12]. The phenomena of heat and mass transfer in the case where the pores are not completely filled with liquid deserve particular attention. These processes occur during moistening and drying of soils, in making and using building materials, structures, etc.

To analyze the mass transfer, consider a model of a porous space element in the form of a conical capillary partly filled with liquid (Fig. 1). The wetting liquid menisci have a different curvature and are separated by an air bubble of length l (distance of 1–2). The capillary surface in this part is coated with a wetting film whose thickness $h(x)$ depends on the x coordinate: $h_1 = h(0)$ and $h_2 = h(l)$. To calculate the two-phase mass flows under the action of the IEF intensity gradient $\nabla E = dE/dx$, as in [13, 14], where the thermogradient liquid and vapor flows were investigated, we use the condition of local equality of the chemical potentials of the vapor and liquid molecules in the film in each cross section of the capillary:

$$\Pi(h) + \frac{\sigma}{r} = \frac{RT}{\nu} \ln \frac{P_s}{P} . \qquad (7)$$

In the presence of an IEF, the total mass flow j, taking into account various kinds of moisture flow, is written in the form

$$j = -\frac{D\mu\,(r-h)^2}{r^2 RT} \nabla p + \frac{D p_e c}{kT} \nabla E - \frac{2\rho R T h^3}{3\eta\nu r} \frac{\nabla p}{p} + \frac{2\rho h^3 \varepsilon_0 (\varepsilon - 1)}{3\eta r} E \nabla E + \frac{h^2 \rho\gamma\Delta T}{r\eta l} - \frac{2h\rho\vartheta\Delta T}{rTl} . \qquad (8)$$

The function $h(x)$ was determined from Eq. (7) by the experimental isotherm $\Pi(h)$ [13]. The boundary conditions of Eq. (8) in view of [14] are of the form

$$p_1 = p(0) = p_s \exp(-2\sigma\nu / r_1 R T_1) , \quad p_2 = p(l) = p_s \exp(-2\sigma\nu / r_2 R T_2) . \qquad (9)$$

Differentiation of Eq. (8) with respect to the x coordinate permits finding its value in the form $p = p(x)$ by the iteration method. To this end, quasi-linearization of the obtained equation according to [15] was carried out, after which the boundary-value problem was solved on a computer by the sweep method. The iteration process of solving the formulated problem was continued until the required accuracy of the problem solution, which was controlled by the condition

$$\max \left| \frac{j_{n+1} - j_n}{j_n} \right| < \delta , \tag{10}$$

was attained. In a reduced form, Eq. (8) can be given as

$$j = j_1 + j_2 + j_3 + j_4 + j_5 + j_6 . \tag{11}$$

Because of the different curvature of the menisci ($r_1 < r_2$) bounding the vapor–air mixture bubble in the capillary, the vapor pressure gradient ∇p will be positive ($p_1 < p_2$). Therefore, the first and third terms of Eqs. (8) and (11) are negative: the first term defines the diffusion flow of vapor and the third one — the reverse flow in the film under the action of the pressure gradient that is due to the capillary conicity. At $\nabla E > 0$, the second term, representing the electrodiffusion flow of dipole vapor molecules, and the fourth term, characterizing the liquid flow in the film under the action of the IEF, will be positive. The fifth term, defining the liquid flow in the film along the solid body surface in the presence of the temperature gradient ∇T (thermocapillary flow on the capillary wall [16]) has a positive sign, since this flow is always directed to the cold side of the capillary, i.e., it coincides with the positive direction of the x axis. The sixth term, describing the thermoosmotic flow in the film is directed towards the temperature gradient and, therefore, is negative at the chosen direction. The thermogradient mass transfer due to the vapor movement in the bubble from its more heated surface to the relatively cold one at moderate values of ∇T can be neglected.

For the calculations we used the table values of the physical constants for water and its vapor, as well as molten quartz (substance of the capillary walls), which corresponds to the given mean temperature $T_{\text{mn}} = (T_1 + T_2)/2$ at a given gradient $\nabla T = (T_1 - T_2)/l$. In the l portion (Fig. 1), the dependences $E(x)$ and $T(x)$ were thought to be linear, i.e., ∇E = const and ∇T = const. Taking into account these conditions, we determined the corresponding distribution of $p(x)$ and $\nabla p(x)$. This enabled us to find both individual components of the flow and the total mass flow j.

The dependences of j and individual flow components on the capillary radius and conicity have been obtained for ∇E values from $3{\cdot}10^7$ to $3{\cdot}10^8$ V/m^2 at a mean value of $E = 10^6$ V/m and $\nabla T = 500$ K/m for a mean temperature of 293 K. The radius of the conical quartz capillary was determined as a function of the coordinate:

$$r = r_1 + \alpha x . \tag{12}$$

The ratio l/r was varied from 10 (for large r) to 1000 (for small r).

According to [4, 5, 12–16], in cylindrical capillaries with radii $r < 100\,\mu$m in their partial filling with water, the main mechanism of mass transfer is the liquid flow in the films covering the capillary walls. The liquid flow in the film can arise, in particular, under the action of the force-field gradient [2], and the flow in the form of vapor thereby is insignificant.

But in conical capillaries even in the absence of external fields the liquid flow j_3 in the films arises due to the difference of capillary pressures of menisci with different radii. The flow j_3 in the total mass flow increases with increasing conicity of capillaries α and becomes dominant at fairly large values of α [17–19]. In particular, in [18] it has been shown that in conical capillaries immersed in a liquid a diffusion vapor flow undoubtedly exists and promotes the filling of capillaries. Nevertheless, in considering other mechanisms of this phenomenon, it can be neglected because its contribution makes up less than one percent of the actually observed flow. In [19], a physical theory of the formation and growth of a liquid column in the dead end of a conical capillary immersed in the liquid is presented. As a result, it has been established that the mechanism of this phenomenon is based on the stabilized pressure-wedging film flow on the capillary walls as a result of the pressure difference of two liquid columns caused by the capillary forces. In so doing, the basic qualitative features of the process following from the theory, namely, the time constancy of the film flow of the liquid to the apex and the linear dependence of the reverse flow on the opening angle of the capillary, have been confirmed experimentally. The quantitative results with regard for the multitude of factors influencing the parameter spread in these experiments are in good agreement with the experiment.

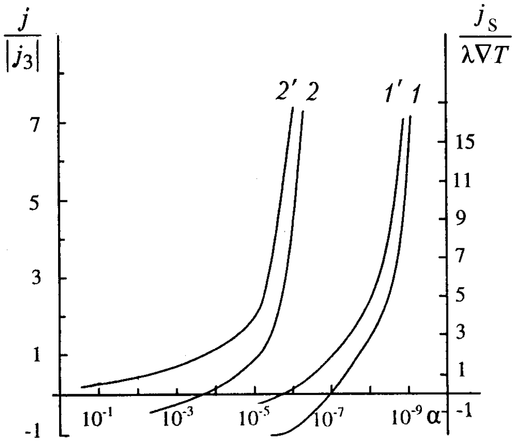

Fig. 2. Dependences of $j/|j_3|$ (1, 2) and $j_s/(\lambda \nabla T)$ (1′, 2′) on the conicity of capillaries α for water: 1) r_1 = 1 μm and l = 0.5 mm; 2) 40 and 1. E, 10^6 V/m, $\nabla E = 10^8$ V/m^2.

Thus, if j_3 is taken as the main flow, the influence of the IEF on the mass exchange in capillaries with a different conicity can be estimated by the relation $j/|j_3|$. The flow j_3 is always directed to the narrow part of the capillary, i.e., for the chosen configuration of the external field $j_3 < 0$. With increasing conicity α the value of j_3 increases in modulus [17]. At $j/|j_3| = -1$ the main mechanism of mass transfer is the flow in the films under the action of the capillary forces. For example, for water at r_1 = 1 μm and $\alpha \geq 10^{-5}$, it may be considered that $j \approx j_3$. With decreasing conicity the j_3 modulus tends to zero, with $j|j_3| \to \infty$. Under these conditions, the flows j_4 and j_5 in the film under the action of the IEF and ∇T become decisive. These flows considerably exceed the flow j_3 caused by the action of the capillary forces. Even the thermoosmotic flow j_6, which for such a small value of the capillary radius markedly exceeds the thermogradient flow j_5 [16], cannot change the situation.

As is seen from Fig. 2, with decreasing capillary radius the conicity acquires a significant value. While at r_1 = 40 μm for water the influence of the conicity shows up at $\alpha \geq 10^{-3}$, at r_1 = 1 μm it is already manifested at $\alpha \geq 10^{-6}$. This can be explained by the increase in the contribution of the flow in the film j_3 to the total flow j with decreasing mean radius of the capillary. The values of the total flow j in the capillaries at a sufficiently small conicity ($\alpha < 10^{-8}$) calculated by Eq. (8) agree with the experimental data [2, 14] obtained for the flow under the action of the IEF and ∇T in thin water films in cylindrical capillaries with radii of 1–100 μm.

The calculations have shown that for some value of conicity $\alpha = \alpha^*$ the total flow $j = 0$. Consequently, the vapor flow j_1, the electrodiffusion flow j_2, the electromigration flow j_4, and the thermogradient flow j_5 neutralize the reverse flows in the film j_3 and j_6. Such circulation flows exist in porous media upon their incomplete saturation with liquid [13]. The local value of the capillary conicity α^* complying with the condition $j = 0$ largely depends on the force-field intensity gradient and the capillary radius. In real porous bodies, capillaries have a variable radius. Therefore, the air bubble moving in the direction opposite to the intensity gradient can be retained in the pore expansion if the values of r, α, $E\Delta E$, and ∇T are such that the condition $j = 0$ is fulfilled. This means that the amount of moist air and, consequently, the moisture content of the porous body can remain unaltered despite the presence of the force-field gradient.

The calculations made ignore the capillary hysteresis — the difference between the advancing and receding wetting angles of the menisci. The resulting mass flow has been found additively, taking into account the diffusion and electrodiffusion flows and the film transfers under the action of the vapor pressure gradients in the bubble and the capillary pressure, as well as the intensity gradients of the force and temperature fields. Taking into account the mutual influence of these flows and the capillary antipressure caused by the hysteresis, one can refine the results obtained.

Thus, inhomogeneous electric and temperature fields can strongly influence the mass transfer in a porous medium upon its incomplete saturation with liquid. The results obtained can be used in developing methods and conditions for moistening, drying, capillary displacement of a liquid and solutions from a porous material, extracting substances from solutions of a porous material and capillary-porous polydisperse systems, and in other cases.

As mentioned in the beginning of this paper, using an IEF, one can effectively control the heat transfer in a moist CPB. Indeed, using Eq. (11), we represent expression (1) in the form

$$j_s = -\lambda_s \nabla T + (j_1 + j_2) I_1 + (j_3 + j_4 + j_5 + j_6) I_2 . \qquad (13)$$

The values of I_1 and I_2 were taken from the reference literature for the chosen mean temperature, as was the heat-conductivity coefficient. Calculations were made for the ratio $j_s / \lambda_s \nabla T$ in order to compare the thermal flow caused by the true heat conduction in a solid body from molten quartz and the heat transfer due to the various kinds of moisture transfer in conical capillaries under the action of the IEF.

From Fig. 2 it is seen that at a large conicity of capillaries the thermal flow almost disappears from a capillary with a large radius and becomes negative in a capillary with a radius 40 times smaller. This means that in the first case the counter heat flows caused by various thermodynamic moving forces in both the solid phase and the liquid and vapor-air phases are neutralized, i.e., a peculiar steady state appears in a heterogeneous system with various flows in nonstationary phases. In a capillary of radius 1 μm, the heat flow $j_6 I_2$ caused by the thermoosmotic flow j_6, which appreciably exceeds the thermocapillary flow j_5, is added to the capillary flow of a cooler liquid (thermal flow $j_3 I_2$) in the direction of ∇T. With decreasing conicity both these flows practically disappear and electromigration flows j_2 and j_4 and, together with them, the electroconvective heat transfer in the form of heat flows $j_2 I_1$ and $j_4 I_2$ begin to dominate. The values of the heat flows in the vapor-air medium of the bubble can be neglected as compared to all the other heat flows.

As is seen from the calculated curves presented in Fig. 2, the thermal flow in quartz capillaries with $\alpha < \alpha^*$, in the presence in them of various moisture- and vapor-gas flows, rapidly increases in a constant IEF, exceeding the heat flow in the solid phase of the capillaries by an order of magnitude or more. It is clear that predischarge IEFs cannot produce a strong effect on the heat conduction of the stationary solid phase. The latter statement is not so evident in the case of discharge IEFs.

The considerable influence of the film mass transfer on the heat transfer in gradient fields has been qualitatively confirmed by experimental results [9, 20] on the determination of λ_{ef} in micro- and macroporous CPBs (samples of silica gel and silica sand) in an IEF.

Thus, comparison of the calculated results on individual conical macrocapillaries and the experimental data with the use of real moist CPBs confirms the basic qualitative features of the strong influence of moisture transfer on heat transfer under the action of an IEF in conical capillaries.

It has been shown that, despite the relatively powerful film flow on the walls of conical capillaries towards the apex, as a result of the capillary pressure difference in two liquid columns separated by a vapor-air bubble, the thermoosmotic flow, the electrohydrodynamic flows caused by the IEP, and the thermogradient flow prevailing in relatively wide capillaries, also directed towards the apex, considerably exceed the negative moisture flows (flows 1, 3, and 6 in Eq. (8)). As a result, the effective heat conductivity of moist CPBs in an IEF can increase by an order of magnitude or more. A change in the directions and gradient values of the electric and temperature fields will lead to a change in the direction of the flows and the relation between them. This makes it possible to control the mass and heat transfer in real disperse systems, in particular, in the process of their moistening and drying.

NOTATION

c, vapor concentration, kg/m^3; D, diffusion coefficient of vapor, m^2/sec; E, electric field intensity, V/m; h, water film thickness, m; $h(x)$, water-film thickness depending on the x coordinate, m; I_i, specific heat content of the corresponding flow inside the body, J/kg; j, moisture flow, kg$_m$/(m^2·sec); j_s, heat flow density, W/m^2; $j_{s,eos}$, heat flow due to the electroosmotic liquid flow in the film, J/(m^2·sec); j_i, flow in the form of vapor, liquid, kg/(m^2·sec); k, Boltzmann constant, J/K; l, bubble length, m; n, iteration number; p_e, dipole moment of the molecule, C·m; P_s and $p = p(x)$, saturated and unsaturated vapor pressure, Pa; r, capillary radius, m; $r = r(x)$, capillary radius depending on the x-coordinate, m; R, universal gas constant, J/(mole·K); T, temperature, K; V_{eos}, linear velocity of the electroosmotic moisture transfer, m/sec; W, moisture content of the sample, kg$_m$/kg$_{d.b}$; ∇E, gradient of the numerical value of the electric field intensity, V/m^2; $\nabla p = dp/dx$, pressure gradient, Pa/m; ∇T, temperature gradient, K/m; ∇W, moisture-content gradient, kg$_m$/(kg$_{d.b}$); $\alpha = (r_2 - r_1)/l$, capillary conicity; γ, surface-tension temperature coefficient, N/(m·K); $\delta =$

0.01, relative error of calculations; ε, dielectric constant of water in the film; ε_0, electric constant, Φ/m; η, water viscosity, N·sec/m^2; λ_a, λ_v, and λ_{liq}, heat-conductivity coefficient through the intraporous air, vapor, and moisture in the form of liquid (adsorption, wetting films, moisture of capillary condensation in micropores, and moisture of the capillary states in the CPB macropores), W/(m·K); λ_e, electro-moisture-diffusion mass conductivity coefficient, kg$_m$/(V·sec); λ_c, convective heat-conductivity coefficient of the gas medium in pores, W/(m·K); λ_r, radiation heat-conductivity coefficient between the pore walls, W/(m·K); λ_{mc}, mass conductivity coefficient; kg$_m$/(m·sec·kg$_m$/kg$_{d.b}$); λ_s, true heat-conductivity coefficient of the solid skeleton of the porous body, W/(m·K); λ_{tg}, thermogradient mass-conductivity coefficient, kg$_m$/(m·sec·K); λ_{eos}, electroosmotic moisture conductivity coefficient, kg$_m$/(m·sec·V); λ_{ef}, effective heat-conductivity coefficient, W/(m·K); μ, molar mass, kg/mole; ν, molar volume of the liquid, m^3/mole; $\Pi(h)$, wedging pressure of the liquid film, N/m^2; ρ, liquid density, kg/m^3; σ, surface tension, N/m; φ, potential, V; ϑ, thermoosmosis coefficient, m^2/sec; χ, inverse Debye radius, m^{-1}; ψ_1, capillary surface potential, V; ψ_2, potential of the air-contacting film surface, V; $\nabla\varphi$, potential gradient, V/m. Subscripts: a, air; m, moisture; e, electric; liq, liquid; *i*, kind of flow; c, convective; r, radiant; v, vapor; mn, mean; d.b, dry body; s, solid; tg, thermogradient; eos; electroosmotic; ef, effective; sat, saturated; mc, mass conductivity.

REFERENCES

1. M. K. Bologa, G. F. Smirnov, A. B. Didkovskii, and S. M. Klimov, *Heat Transfer in Boiling and Condensation in an Electric Field* [in Russian], Shtiintsa, Kishinev (1987).
2. I. N. Karpovich, N. V. Churaev, and M. S. Panchenko, Flow of wetting films of polar liquids in an inhomogeneous electric field, *Kolloid. Zh.*, **46**, No. 1, 114–117 (1984).
3. A. L. Panasyuk, M. S. Panchenko, V. M. Starov, and N. V. Churaev, Influence of inhomogeneous electric and magnetic fields on internal mass transfer in capillary-porous bodies, *Inzh.-Fiz. Zh.*, **35**, No. 1, 93–100 (1978).
4. A. V. Luikov, *The Theory of Drying* [in Russian], Énergiya, Moscow (1968).
5. A. V. Luikov, *Transport Phenomena in Capillary-Porous Bodies* [in Russian], Gos. Izd. Tekh.-Teor. Lit., Moscow (1954).
6. A. F. Chudnovskii, *Thermophysical Characteristics of Disperse Materials* [in Russian], Gos. Izd. Fiz.-Mat. Lit., Moscow (1962).
7. V. N. Kobranova, *Physical Properties of Rocks* [in Russian], Gos. Nauch. Izd. Neft. Gorno-Topliv. Lit., Moscow (1962).
8. G. L. Kuz'mina, V. D. Sobolev, and N. V. Churaev, Experimental studies of electroosmosis of wetting films of aqueous solutions, *Kolloid. Zh.*, **53**, No. 3, 493–496 (1990).
9. I. M. Panchenko and M. S. Panchenko, Influence of electric fields on the process of heat transfer in a wet macroporous body, *Élektron. Obrab. Mater.*, No. 3, 26–32 (2001).
10. A. V. Luikov, *Heat and Mass Transfer: Handbook* [in Russian], Énergiya, Moscow (1971).
11. N. V. Polishchuk, I. M. Panchenko, M. S. Panchenko, and I. M. Karpovich, Effects and aftereffects of electric fields on water ascent in macrocapillaries, *Élektron. Obrab. Mater.*, No. 4, 54–67 (2002).
12. G. A. Aksel'rud and M. A. Al'tshuler, *Introduction to Capillary Chemical Technology* [in Russian], Khimiya, Moscow (1983).
13. A. M. Globus, Influence of the volume weight, structure, and nature of the solid-phase surface on the moisture redistribution in closed dispersed systems under the effect of the temperature gradient, *Dokl. Akad. Nauk SSSR*, **160**, Issue 1, 81–84 (1965).
14. O. A. Kiseleva, V. M. Starov, and N. V. Churaev, Calculations of the film flow under the action of the temperature gradient in conical capillaries, *Kolloid. Zh.*, **39**, No. 6, 1164–1167 (1977).
15. R. E. Bellman and R. E. Kalaba, *Quasi-Linearization and Nonlinear Boundary-Value Problems* [Russian translation], Mir, Moscow (1968).
16. B. V. Deryagin and N. V. Churaev, *Wetting Films* [in Russian], Mir, Moscow (1984).
17. I. M. Karpovich, O. S. Mosievich, M. S. Panchenko, and A. A. Samsonyuk, Calculation of moisture transfer under the effect of the force field in conical capillaries, in: *Hydromelioration and Hydroengineering* [in Russian], Republ. Interbranch Sci.-Eng. Coll. of Papers, Issue 20, Svit, L'vov (1993), pp. 45–49.

18. N. P. Migun, A. I. Shnip, and L. E. Reut, Role of the diffusion mechanism of mass transfer processes in conical capillaries submerged in liquid, *Inzh.-Fiz. Zh.*, **75**, No. 6, 137–144 (2002).
19. N. P. Migun and A. I. Shnip, Model of the film flow in a dead-end conical capillary, *Inzh.-Fiz. Zh.*, **75**, No. 6, 145–150 (2002).
20. I. M. Panchenko, M. S. Panchenko, and N. V. Polishchuk, Influence of electric fields on the process of heat transfer in a wet microporous body, *Élektron. Obrab. Mater.*, No. 1, 46–51 (2002).