

**DEVELOPMENT OF CERTAIN ASPECTS OF THE
A. V. LUIKOV HEAT- AND MASS-TRANSFER THEORY**

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It has been proposed that A. V. Luikov's system of heat- and mass-transfer equations be supplemented with balance differential equations of change in the temperature and degree of saturation of a medium with its motion in the material for an a priori unknown character of their change. The approach to determination of the relative coefficient of thermal diffusion, the criterion of phase transition, and the value of the Fo number for the beginning of the stage of a regular regime of a one- and two-dimensional plate and to evaluation of the notion of the "soft" and "hard" processes of drying has been refined. The method of allowance for the multidimensionality of a body has been developed. The practical absence of the influence of moisture exchange on heat exchange in drying has been proved.

In A. V. Luikov's works, quite an orderly heat- and mass-transfer theory which enables one to calculate different processes, including those of drying and heat treatment, has been created. However, one may introduce certain generalizations, corrections, and simplifications into it.

1. We have supplemented A. V. Luikov's system of equations with balance differential equations conjugate to it, which enables us to obtain information on the temperature-humidity state of a medium and a material in its volume and to solve different technological problems [1–4]:

$$\frac{\partial t_m}{\partial z} = \frac{\alpha (t_{x=R} - t_m)}{R_p \omega \rho_0 c_m}, \tag{1}$$

$$\frac{\partial \varphi}{\partial z} = \frac{\alpha' \rho_0 (u_{x=R} - u_{eq})}{R_p \omega P_{sat.v}} - \frac{\varphi}{R_v} \left(\frac{(t_m + 273) (\partial P_{sat.v} / \partial z) - P_{sat.v} [\partial (t_m + 273) / \partial z]}{(t_m + 273)^2} \right) \frac{1}{P_{sat.v}}. \tag{2}$$

In the general case, in the presence of a deepened boundary of phase transitions, the system may be represented in the following form [3]:

$$c_{1,2} \rho_{1,2} \frac{\partial t_{1,2}}{\partial \tau} = \mu(x) \frac{\partial}{\partial x} \left[\lambda_{1,2} \frac{\partial t_{1,2}}{\partial x} v(x) \right] + \varepsilon_{1,2} r_{ph} \rho_0 \frac{\partial u_{1,2}}{\partial \tau}, \tag{3}$$

$$\frac{\partial u_{1,2}}{\partial \tau} = \mu(x) \frac{\partial}{\partial x} \left[\left(a'_{1,2} \frac{\partial u_{1,2}}{\partial x} + a_{1,2} \delta_{1,2} \frac{\partial t_{1,2}}{\partial x} \right) v(x) \right], \tag{4}$$

$$t_2(x; \tau = 0) = f(x), \tag{5}$$

$$u_2(x; \tau = 0) = f(x), \tag{6}$$

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$$\alpha [t_m(\tau) - t_{x=R}] - \lambda (\partial t / \partial x)_{x=R} - r_{ph} (1 - \varepsilon) q'(\tau)_{x=R} = 0, \quad (7)$$

$$q'(\tau)_{x=R} - a' \rho_0 (\partial u / \partial x)_{x=R} - a' \rho_0 \delta (\partial t / \partial x)_{x=R} = 0. \quad (8)$$

The boundary conditions at the phase-transition boundary are

$$t_1(\chi, \tau) = t_2(\chi, \tau), \quad (9)$$

$$u_1(\chi, \tau) = u_2(\chi, \tau), \quad (10)$$

$$[a'_1 (\partial u_1 / \partial x) + a'_1 \delta_1 (\partial t_1 / \partial x)]_{x=\chi} = [a'_2 (\partial u_2 / \partial x) + a'_2 \delta_2 (\partial t_2 / \partial x)]_{x=\chi}, \quad (11)$$

$$r_{ph} [(1 - \varepsilon_1) q'_1(\tau) - (1 - \varepsilon_2) q'_2(\tau)]_{x=\chi} = \lambda_1 (\partial t_1 / \partial x)_{x=\chi} - \lambda_2 (\partial t_2 / \partial x)_{x=\chi}. \quad (12)$$

Equations (3) and (4) correspond to the external and internal zones. They are suitable for both a plate (when $\mu(x) = 1$ and $\nu(x) = 1$) and a cylinder (when $\mu(x) = 1/x$ and $\nu(x) = x$).

It should be noted that the temperature at the phase-transition boundary in (9) is unknown in the general case before the solution of the problem. In actual practice, one occasionally takes this temperature at the evaporation boundary to be equal to the saturation temperature. In some cases, the parameters in Eqs. (9) and (10) are known in advance. As the experiments show, in melting, we have $t_{ph} = 0$, in high-temperature drying, t_{ph} is equal to the boiling temperature (100–101°C), and in low-temperature drying and for $u > u_{sat.v}$ the moisture content at the evaporation boundary is equal to $u_{sat.v}$ (analog of $u_{max.s}$).

In the case of moving boundaries, for example, in thawing, the field of moisture content in each of the zones is virtually stable, because of which we may represent Eq. (3) without a heat source; Eqs. (4), (6), (8), (10), and (11) drop out of the system. In Eq. (12), the criterion ε is the criterion of ice-to-water change in this case ($\varepsilon_2 = 0$ in the internal zone and $\varepsilon_1 = 1$ in the external zone). As a result, we obtain the Stefan relation

$$\lambda_2 (\partial t_2 / \partial x)_{x=\chi} - \lambda_1 (\partial t_1 / \partial x)_{x=\chi} = r_{ph} q'_2(\tau)_{x=\chi} = r_{ph} \rho_{ph} (\partial x / \partial \tau). \quad (13)$$

The third term of Eq. (13), which characterizes the flow rate of heat, may be written in physical meaning in the form $r_{ph} \rho_{ph} (\partial x / \partial \tau)$, where $\rho_{ph} = \rho_0(u - u_{non})$.

The system of equations (3)–(12) yields different particular cases not accompanied by the motion of the phase-transition boundary. For example, in heating of a body (if it is assumed that $\lambda_1 \neq \lambda_2$), we may obtain a system characteristic of boundary conditions of the fourth kind; the temperature at the boundary will change. If we have $\lambda_1 = \lambda_2$, the body becomes homogeneous and of the entire system (3)–(12) the known system for transfer of heat with boundary conditions of the first and third kind is left.

Analogous is the approach to obtaining the system of equations in the high-temperature process of drying, when $u \leq u_{sat.v}$ (the molar transfer of moisture is absent).

2. A drawback of A. V. Luikov's system of equations is the uncertainty of the variable value of the criterion of phase transition ε . This criterion in essence depends on the conditions of the process and the characteristic of the material; its description requires an additional equation. Since this quantity is not known, the system of equations is open, in fact, because of which we have to prescribe a discrete ε . Therefore, it is desirable to precalculate the system with different values of ε and to establish the influence of its changes on the basic parameters of the process. Of greatest interest is the possibility of taking $\varepsilon = 0$, when the system of equations "is untied" into individual equations of moisture and heat transfer.

The system of equations has been solved [5] for wood under different conditions and for $\varepsilon = 0, 0.25, 0.5, 0.75$, and 1.0 . A value of $\varepsilon = 0.25$ was taken into calculation based on the available data that the value of ε in wood

is close to it. The calculations have shown [5] that transition from $\varepsilon = 1$ to $\varepsilon = 0$ and particularly from $\varepsilon = 0.25$ to $\varepsilon = 0$ gives slight disagreements between similar quantities for most parameters. The sole exception is the temperature difference $\Delta t = t_{\text{surf}} - t_c$ (disagreements of 90% in transition from $\varepsilon = 0.25$ to $\varepsilon = 0$) and to a lesser extent W_c (0.44%), ΔW (0.63%), σ_{surf} (2.1%), and σ_c (1.98%). As the process becomes harder, these disagreements increase (they have been given above for the first stage of the regime at $\tau = 5$ h). At $\tau = 20$ h (harder regime), Δt , W_c , ΔW , σ_{surf} and σ_c amount to 90, 3.09, 3.98, 14.2, and 16.5% respectively. The general conclusion is that, except for determination of the difference Δt and, to a certain extent, of the internal stresses (σ_{surf} and σ_c), we may take $\varepsilon = 0$. We drop an analysis of the influence of the quantity ε for high-temperature drying.

3. Considering the thermal and moisture conductivity, A. V. Luikov gives [6] the data of V. P. Mironov obtained by the method of stationary current on wood [7]. The results sharply differ for different types of wood (for example, five times for pine wood and oak). Referring to the primary sources has shown that these data are incorrect. The stationarity of the temperature field was attained in the experiments, but no stationarity of the humidity field was ensured. In addition, a more thorough analysis has shown [8] that the coefficients δ referred to the potential of moisture transfer (for example, μ) must not depend on the density of the body (type of wood), which is consistent with our experiments and the results [9] found on another material. It follows that the transfer potential μ , which is a function of t and φ , may be equal for different densities only in the case of sorption (desorption) isotherms equal for them, which has precisely been confirmed experimentally [2, 3] and which leads to an independence of δ from the type of wood.

In different literature sources, the problem on the parameter characterizing the transfer of moisture under the influence of a nonuniform temperature field is presented ambiguously. There is inconsistency in terminology. Thus, the parameter δ having the dimensions of 1/deg and involved in the transfer equation was called by A. V. Luikov simultaneously the coefficient of thermal and moisture conductivity and the relative coefficient of thermal and moisture conductivity (in 1946), just the coefficient of thermal and moisture conductivity (in 1950), the thermogradient coefficient (in 1956), and the relative coefficient of thermal diffusion (in 1968). Also, there are contradictions as far as the definition of the quantity δ is concerned. Let us take the chemical potential μ as the potential of transfer and write the moisture-flux density in the form

$$q'_\mu = -\lambda'_\mu \nabla \mu - \lambda''_\mu \nabla (t + 273), \quad \mu = f[u, (t + 273)]. \quad (14)$$

Then the relative coefficient of thermal diffusion δ will be

$$\delta = c'_\mu \left\{ \left[\frac{\partial \mu}{\partial t} (t + 273) \right]_u + \left(\frac{\lambda''_\mu}{\lambda'_\mu} \right) \right\} = c'_\mu \left[\frac{\partial \mu}{\partial t} (t + 273) \right]_u + c'_\mu \left(\frac{\lambda''_\mu}{\lambda'_\mu} \right) = \delta_{\mu_1} + \delta_{\mu_2}. \quad (15)$$

If we write the law of transfer in the same form (14) but assume, as many authors consider, that $\mu = f(u)$ and the second term of Eq. (14) allows for the influence of t , we obtain

$$\delta = \delta_{\mu_2} = c'_\mu \left(\frac{\lambda''_\mu}{\lambda'_\mu} \right). \quad (16)$$

The moisture-flux density may be written in the form

$$q'_\mu = -\lambda'_\mu \nabla \mu, \quad \mu = f[u, (t + 273)], \quad (17)$$

$$\delta = \delta_{\mu_1} = c'_\mu \left[\frac{\partial \mu}{\partial t} (t + 273) \right]_u. \quad (18)$$

Thus, different approaches lead to different results. In the literature, these are contradictory indications on the relation between δ_{μ_1} and δ_{μ_2} . The experiments performed [3, 10] have shown that the parameter δ_{μ_1} , related to the temperature coefficient of chemical potential $\left[\frac{\partial \mu}{\partial t} (t + 273) \right]_u$, is substantially smaller than δ_{μ_2} related to the Soret effect $\left(\frac{\lambda''_\mu}{\lambda'_\mu} \right)$. The ratio $\delta_{\mu_1} / (\delta_{\mu_1} + \delta_{\mu_2})$ increases with increase in t and decrease in W . Thus, at $t = 40^\circ\text{C}$, it is equal to 0.1 virtually regardless of W ; this ratio is 0.35 at $t = 80^\circ\text{C}$ and $W = 6\%$ and only 0.17 at $W = 18\%$.

4. The processing time and potential of transfer in two- or three-dimensional bodies have been calculated in [11–13], where the existence of several variants of allowance for the multidimensionality and anisotropy of bodies in the processes of drying, heating, and diffusion is shown, namely: (1) obtaining formulas for a multidimensional body that are based on computation of one or several series terms of the solution, (2) construction of special criterial plots, (3) introduction of the equivalent dimension of the body or the shape factor, and (4) introduction of corrections for multidimensionality. All four variants have been developed by us [2, 11, 13]. We briefly dwell on the latter. A long two-dimensional plate (thickness S_1 and width S_2) is compared to a one-dimensional one having the same governing dimension S_1 . It is evident that, for example, in drying, the one-dimensional plate will have a higher \bar{u} than the multidimensional one, or it will take more time to attain the same \bar{u} by the one-dimensional plate. Such an approach enables us to establish a correction for the multidimensionality of the plate (two-dimensional in this particular case) of $G_\tau \leq 1.0$, which is used in the form

$$\tau_{\text{mult}} = C_\tau \tau_{\text{one}} \quad (19)$$

or in the criterial form

$$\text{Fo}_{\text{mult}} = C_\tau \text{Fo}_{\text{one}} \quad (20)$$

The values of τ_{mult} and Fo_{mult} were taken for the two-dimensional plate by numerical solution of the problem or from the criterial plots constructed on this basis. In these cases, the corrections C_τ are suitable from the very beginning of the process, since we used solutions for the sum of the series terms.

5. The processes of heat and mass transfer are accompanied by the stages of an irregular regime and then a regular regime. Determination of the first stage requires the sum of the series terms of the solution, whereas that of the second stage requires the first term. In the works of A. V. Luikov, there are data enabling one to establish the beginning of the stage of a regular regime (Fo_{reg}) for the axis of a cylinder and a plate with a prescribed degree of accuracy p [14] and for the plate potential averaged over the cross section [15] without indicating the accuracy; it is taken to be $\text{Fo}_{\text{reg}} = 0.1$. In this connection, we made an attempt [2, 3] at establishing Fo_{reg} for the average-over-the cross section potential with a prescribed accuracy, initially analytically with boundary conditions of the third kind. However, in the expression resulting in this case for the residual sum of the series terms Δ_k (representation of the expression is dropped), replacement (required for solution) of the integral in this expression by the exponential function leads to a certain overstatement of the value of Δ_k and finally to an increase in $\text{Fo} = \text{Fo}_{\text{reg}}$. In this connection, the problem of determination of Fo_{reg} for different Bi values was performed for one- and two-dimensional plates by the numerical method on a computer (for the first two terms of the series). The calculations have shown that A. V. Luikov's result, according to which we have $\text{Fo}_{\text{reg}} = 0.1$ for the one-dimensional plate, is obtained when $\text{Bi} = 10$ and the accuracy is $p = 1.9\%$. When $p = 0.5\%$ we have $\text{Fo}_{\text{reg}} = 0.18$ for $\text{Bi} = 10$ and $\text{Fo}_{\text{reg}} = 0.16$ for $\text{Bi} = 80$. For the two-dimensional plate the quantity Fo_{reg} decreases. For example, when $p = 0.5\%$ and $S_1/S_2 = 0.5$, we have $\text{Fo}_{\text{reg}} = 0.04$ for $\text{Bi} \geq 20$, and when $S_1/S_2 = 1.0$ we have $\text{Fo}_{\text{reg}} = 0.025$ for $\text{Bi} = 20$.

6. A. V. Luikov introduced the notions of "soft" and "hard" processes of drying [15]. By "soft" he meant the process occurring with a low intensity of evaporation and characterized by the presence of both the period of a constant drying rate and a constant temperature at the level $t = t_{c,\text{lim}}$. By "hard" he meant the process in which the surface temperature increases above $t = t_{c,\text{lim}}$ in the period of a constant drying rate. However, we should introduce corrections into such a classification. It is assumed [2, 3, 13] that the form of a temperature field over the cross section is determined by the level of temperature acquired by the body and not by the evaporation intensity, which establishes the value of moisture conductivity — at low temperatures, it is low, the evaporation zone bites deeper into the body, and the surface temperature continuously grows; such a situation has been proved experimentally. In drying of wood sheets ($S_1 = 2$ mm), at $t_m = 205^\circ\text{C}$ and $t_w = 80^\circ\text{C}$ (intense evaporation, $q' = 5.5$ kg/(m²·h), and $t_{\text{wood}} = 80^\circ\text{C}$), the process follows the "soft" scheme without a rise in the surface temperature, whereas at $t_m = 80^\circ\text{C}$ and $t_w = 33^\circ\text{C}$ (evaporation intensity $q' = 1.8$ kg/(m²·h) and $t_{\text{wood}} = 33^\circ\text{C}$), it follows the "hard" scheme. The noted trends are confirmed by the character of the dependence of the Luikov criterion $\text{Lu} = a'/a$ on temperature. The quantity Lu decreases with the latter (as t_m changes from 80 to 33°C, Lu is reduced three times — from 0.006 to 0.002), i.e., the progress of the moisture field will lag behind the progress of the temperature field still further.

7. Discussions on the influence of mass exchange on heat exchange were held in the thermophysical literature over a long period in the 1960–70s. Specialists in the field of a boundary layer stated [16] that any flow transverse to this layer increases its thickness and decreases the coefficient of heat exchange. They extended this principle to the processes of evaporation (drying), too. Specialists in the field of drying obtained data from which it followed that evaporation intensifies heat exchange [17–20]. The experiments on evaporation [21] from the plate surface (fine wood) carried out in the 1980s with the use of laser illumination in the boundary layer and filming unambiguously have shown that in the case of moderate evaporation from the surface we have removal of liquid particles to the boundary layer. (A. V. Luikov demonstrated earlier the case histories (obtained by the Swedes) of removal of liquid particles to the boundary layer in drying in a superheated vapor. No conclusions based on the removal of liquid particles on the influence of mass exchange on heat exchange were drawn.) Our experiments explain the true interrelation between evaporation and heat exchange. The coefficient of heat exchange is usually calculated from the formula

$$\alpha = q' r_{ph} / [(t_m - t_{wet}) F_{geom}] \quad (21)$$

In actual practice, not only does evaporation occur from the surface but it also occurs in the boundary layer, i.e., we have $q'_{tot} > q'_{geom}$. The reference of the total amount of the evaporated liquid to F_{geom} artificially overstates the coefficient of heat exchange. The transverse flux is relatively small in drying and cannot substantially reduce heat exchange. In [22], A. V. Luikov gave the solution of the problem of American authors for a laminar boundary layer which is precisely our case. The parameter of blowing in our experiments was $f_{\omega} = \frac{q'}{\rho\omega} \text{Re} = (0.0012/0.9722) \cdot 67.47 = 0.041$. As follows from the plot given in [22], the coefficient of heat exchange is reduced by 5% for such a value of the parameter of blowing. If we were to introduce, into Eq. (21), the quantity q' only from the surface, this reduction would be even smaller or, in all probability, it would be completely absent. The latter is confirmed by the interferometric investigation [2, 21] performed in the process of the experiments and showing a virtual coincidence of the thicknesses of the boundary layer in evaporation and in blowing without it.

NOTATION

a , coefficient of thermal diffusivity, m^2/sec ; a' , coefficient of moisture conductivity, m^2/sec ; Bi, Biot criterion; C_{τ} , correction for multidimensionality; C , specific heat, $\text{J}/(\text{kg}\cdot^{\circ}\text{C})$; c' , specific isothermal moisture capacity, $1/(\text{J}/\text{kmole})$; Fo, Fourier number; Fo_{reg} , Fo number at the beginning of the stage of a regular regime; F , surface area, m^2 ; f_{ω} , parameter of blowing into the boundary layer; Lu, Luikov criterion; P , vapor pressure, Pa; p , accuracy; q' , moisture flux, $\text{kg}/(\text{m}^2\cdot\text{sec})$; R , characteristic dimension, m; R_p , half the thickness of the gap for passage of air, m; R_v , gas constant of the vapor, $\text{J}/(\text{kg}\cdot^{\circ}\text{C})$; r_{ph} , heat of phase transition, J/kg ; Re, Reynolds criterion; S_1 and S_2 , thickness and width of the plate, m; t_m , temperature of the medium, $^{\circ}\text{C}$; $t_{c.lim}$, t_w , t_{ph} , t_{wood} , and Δt , cooling-limit temperature, wet-bulb temperature, phase-transition temperature, wood temperature, and temperature difference across the plate thickness, $^{\circ}\text{C}$; $u_{s.lim}$, moisture content of the saturation limit of the cellular wall; $u = W/100$ and \bar{u} , moisture content and its average value; u_{eq} , equilibrium moisture content; W , humidity, %; ΔW , humidity difference across the plate thickness, %; x , y , χ , coordinates in the body, in the direction of motion of the air, and at the phase-transition boundary, m; α and α' , coefficients of heat exchange and moisture exchange, $\text{W}/(\text{m}^2\cdot^{\circ}\text{C})$ and m/sec ; δ , thermogradient coefficient, relative coefficient of thermal diffusion, and thermal and moisture conductivity, $1/^{\circ}\text{C}$; δ_{μ_1} and δ_{μ_2} , components of the relative coefficient of thermal diffusion, $1/^{\circ}\text{C}$; Δk , residual sum of the series terms; ε , criterion of phase transition; λ , thermal conductivity, $\text{W}/(\text{m}\cdot^{\circ}\text{C})$; λ' , coefficient of mass transfer, $\text{kg}\cdot\text{kmole}/(\text{m}\cdot\text{sec}\cdot\text{J})$; λ'' , coefficient of thermal mass transfer, $\text{kg}/(\text{m}\cdot\text{sec}\cdot^{\circ}\text{C})$; $\mu(x)$ and $\nu(x)$, shape parameters of the body; μ , chemical potential; J/kmole ; ρ , density, kg/m^3 ; ρ_0 , density of a perfectly dry body, kg/m^3 ; ρ_{ph} , amount of the substance that has undergone phase transition, kg/m^3 ; σ , internal stress, Pa; τ , time, sec; ϕ , relative humidity of air; ω , velocity of air, m/sec ; Subscripts: geom, geometric; wood, wood; w, wet; mult, multidimensional body, tot, total; one, one-dimensional body, max.s, maximum sorption moisture content; surf, surface; v, vapor; c.lim, cooling limit; sat.v, saturated vapor; p, passage; eq, equivalent; reg, regular; m, medium; c, center; ph, phase transition; 0, initial value, dry body; 1, and 2, external and internal zones; non, nonfreezing moisture.

REFERENCES

1. G. S. Shubin, The system of heat- and mass-transfer equations for the processes of drying under variable conditions of the medium, in: *Ext. Abstr. of Papers presented at the IInd Minsk Int. Forum on Heat and Mass Transfer* [in Russian], Kiev (1992), pp. 347–349.
2. G. S. Shubin, *Drying and Heat Treatment of Wood* [in Russian], Lesnaya Promyshlennost', Moscow (1990).
3. G. S. Shubin, Drying of Wood: Questions of Theory, Methods of Calculation, Advancement of Technology, *International Science Publisher*, No. 4, 147–186, USA, Canada, India (1992).
4. G. S. Shubin, Development of the theory of drying of wood, in: *Proc. Int. Wood Drying Conf.–3RD IUFRO*, August 1992, Vienna, Austria, pp. 165–174.
5. G. S. Shubin, The phase conversion as a parameter of the drying process, in: *Proc. IIIrd Minsk Int. Forum "Heat and Mass Transfer–MIF-96"* [in Russian], Vol. 8, 20–24 May 1996, Minsk (1996), pp. 202–205.
6. A. V. Luikov, *Transfer Phenomena in Capillary-Porous Bodies* [in Russian], GITTL, Moscow (1954).
7. V. P. Mironov, Study of laws governing the movement of moisture in wood as a function of temperature and humidity, in: *Proc. of Sci.-Res. Institute on Mechanical Processing of Wood* [in Russian], Arkhangel'sk (1952), pp. 15–16.
8. G. S. Shubin, Thermal moisture conductivity of colloidal capillary-porous bodies, in: *Proc. VI All-Union Conf. on Heat and Mass Transfer* [in Russian], Vol. 7, Minsk (1980), pp. 18–25.
9. Kh. B. Tsimermanis, *Thermodynamic and Transfer Properties of Capillary-Porous Bodies* [in Russian], Yuzhno-Ural'skoe Knizhnoe Izd., Chelyabinsk (1971).
10. G. S. Shubin, Thermal moisture conductivity of colloidal capillary-porous bodies, *Heat Transfer — Soviet Research*, **14**, No. 1, 65–72, ASME, New York (1982).
11. G. S. Shubin, Calculation of heat- and mass-transfer processes with due regard for multidimensionality, anisotropy, and dependence of the coefficients of transfer on potentials, in: *Proc. Int. Conf. "Heat and Mass Transfer-VII"* [in Russian], Vol. 6, Minsk (1984), pp. 154–158.
12. G. S. Shubin, *Designing Equipment for Hydrothermal Treatment of Wood. Manual for Higher Institutions* [in Russian], Lesnaya Promyshlennost', Moscow (1983).
13. G. S. Shubin, *Physical Principles and Calculation of the Processes of Wood Drying* [in Russian], Lesnaya Promyshlennost', Moscow (1973).
14. A. V. Luikov, *Heat-Conduction Theory* [in Russian], Vysshaya Shkola, Moscow (1967).
15. A. V. Luikov, *Heat and Mass Transfer in the Processes of Drying* [in Russian], Gosénergoizdat, Moscow–Leningrad (1956).
16. S. S. Kutateladze and A. I. Leont'ev, *Heat Transfer and Friction in a Turbulent Boundary Layer* [in Russian], Énergiya, Moscow (1972).
17. P. D. Lebedev, *Drying by Infrared Beams* [in Russian], GÉI, Moscow (1953).
18. A. V. Nesterenko, Experimental study of heat and mass transfer in evaporation of a liquid from the free surface of water, *Zh. Tekh. Fiz.*, **24**, Issue 4, 729–741 (1954).
19. F. M. Polonskaya, Heat and mass transfer at a constant rate of drying, *Zh. Tekh. Fiz.*, **23**, Issue 5, 802–805 (1953).
20. G. S. Shubin, Experimental study of heat and mass transfer in high-temperature convective drying of flat wood materials, in: *Heat and Mass Transfer* [in Russian], Vol. 4, Gosénergoizdat, Moscow–Leningrad (1963), pp. 186–196.
21. G. S. Shubin and A. V. Chemodanov, Removal of liquid particles to a boundary layer in drying, in: *Proc. Minsk Int. Forum "Heat and Mass Transfer–MIF"* [in Russian], Selected Papers of Secs. 6 and 7, Minsk (1989), pp. 139–146.
22. A. V. Luikov, *Heat and Mass Exchange: Handbook* [in Russian], 2nd ed., Énergiya, Moscow (1978).