UDC 536.2. : [674.817-41 + 674.815-41]

STUDY OF HEAT AND MASS TRANSFER IN WOOD-BASED FIBREBOARD AND PARTICLEBOARD PANELS

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For optimal fulfilment of various tasks related to production and operation of wood-based panels (acclimatisation and conditioning, calculation of enclosing structures, development of accelerated test methods, etc.), it is necessary to perform calculations of the variation over time of temperature and moisture content fields under various external conditions.

The following notations are used in this article:

τ – time, s;
T – temperature, K;
u – moisture content, $kg \cdot kg^{-1}$;
p – pressure of gas-vapour mixture, Pa;
φ – relative air humidity;
ρ_0 – dry matter density, $kg \cdot m^{-3}$;
Θ – experimental mass transfer (moisture) potential, °M (mass transfer degree)
μ – chemical potential, $J \cdot mol^{-1}$;
M – molar mass, $kg \cdot mol^{-1}$;
j_m – mass flow density, $kg \cdot m^{-2} \cdot {}^\circ C^{-1}$;
λ – coefficient of thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$;
c – specific thermal capacity, $J \cdot kg^{-1} \cdot K^{-1}$;
r – specific heat of evaporation, $J \cdot kg^{-1}$;
ε – phase transformation criterion;
a_m – moisture diffusion coefficient, $m^2 \cdot s^{-1}$;
λ_m – mass conductivity (moisture permeability) coefficient normalised to the difference in experimental mass transfer potential, $kg \cdot m^{-1} \cdot s^{-1} \cdot M^{-1}$;
λ'_μ – mass conductivity coefficient normalised to the difference in chemical potential, $kg \cdot mol \cdot m^{-1} \cdot W^{-1}$;
λ''_μ – thermal mass conductivity coefficient, $kg \cdot m^{-1} \cdot s^{-1} \cdot K^{-1}$;
δ – thermogradient coefficient normalised to the difference in water content, K^{-1};
δ_Θ – thermogradient coefficient normalised to the difference in experimental mass transfer potential, $^\circ M \cdot K^{-1}$;
$\lambda''_\mu/\lambda'_\mu$ – thermogradient coefficient normalised to the difference in chemical potential, $J \cdot mol^{-1} \cdot K^{-1}$;
c_m – specific isothermal mass capacity (moisture content) normalised to the difference in experimental mass transfer potential, $kg \cdot kg^{-1} \cdot M^{-1}$;
c_μ – specific isothermal mass capacity normalised to the difference in chemical potential, $kg \cdot kg^{-1} \cdot J^{-1} \cdot mol^{-1}$;
Θ'_T – temperature coefficient of experimental mass transfer potential, $^\circ M \cdot K^{-1}$;
μ'_T – temperature coefficient of chemical potential, $J \cdot mol^{-1} \cdot K^{-1}$;
n – mole concentration of steam;
χ – thermal diffusion constant of the binary gas mixture;
R = 8,314 $J \cdot mol^{-1} \cdot K^{-1}$ – universal gas constant; number 1 corresponds to $0<\varphi\leq 0,5$; number 2 corresponds to $0,5<\varphi\leq 1$;
п – steam;

п.н – saturated steam;

There is a good reason to consider the processes of heat and mass transfer without filtration mass flow and clearly defined boundaries of phase transitions on the basis of the phenomenological theory developed by A.V. Lykov and his students. The systems of differential equations for this case are provided in [5]:

when used as temperature and moisture transfer potentials

$$c\rho_0 \frac{\partial T}{\partial \tau} = \nabla \left(\lambda \nabla T + \varepsilon r \rho_0 \frac{\partial u}{\partial \tau} \right); \tag{1}$$

$$\rho_0 \frac{\partial u}{\partial \tau} = \nabla \left(a_m \rho_0 \nabla u + a_m \rho_0 \delta \nabla T \right); \tag{2}$$

when used as temperature and experimental mass transfer potential

$$\rho_0 \left(c + \varepsilon r c_m \Theta'_T \right) \frac{\partial T}{\partial \tau} = \nabla \left(\lambda \nabla T \right) + \varepsilon r \rho_0 c_m \frac{\partial \Theta}{\partial \tau}; \tag{3}$$

$$c_m \rho_0 \frac{\partial \Theta}{\partial \tau} = \nabla \left(\lambda_m \nabla \Theta + \lambda_m \delta_\Theta \nabla T \right) + c_m \rho_0 \Theta'_T \frac{\partial T}{\partial \tau}; \tag{4}$$

when used as temperature and chemical potential

$$\rho_0 \left(c + \varepsilon r c_\mu \mu'_T \right) \frac{\partial T}{\partial \tau} = \nabla \left(\lambda \nabla T \right) + \varepsilon r \rho_0 c_\mu \frac{\partial \mu}{\partial \tau}; \tag{5}$$

$$c_\mu \rho_0 \frac{\partial \mu}{\partial \tau} = \nabla \left(\lambda'_\mu \nabla \mu + \lambda''_\mu \nabla T \right) + c_\mu \rho_0 \mu'_T \frac{\partial T}{\partial \tau}. \tag{6}$$

The specific isothermal mass capacity normalised to the differences in corresponding mass transfer potentials and the temperature coefficients of mass transfer potentials are determined as follows:

$$c_m = \left(\frac{\partial u}{\partial \Theta} \right)_T; \tag{7}$$

$$\Theta'_T = \left(\frac{\partial \Theta}{\partial T} \right)_u; \tag{8}$$

$$c_\mu = \left(\frac{\partial u}{\partial \mu} \right)_T; \tag{9}$$

$$\mu'_T = \left(\frac{\partial \mu}{\partial T} \right)_u. \tag{10}$$

The mass conductivity coefficients are related to the diffusion coefficient and specific isothermal mass capacity by the following relations:

$$\lambda_m = a_m \rho_0 c_m; \tag{11}$$

$$\lambda'_\mu = a_m \rho_0 c_\mu. \tag{12}$$

The thermogradient coefficient normalised to the difference in moisture content is expressed through the following thermodynamic mass transfer parameters

$$\delta = c_m \Theta'_T + c_m \delta_\Theta; \tag{13}$$

$$\delta = c_\mu \mu'_T + c_\mu \frac{\lambda''_\mu}{\lambda'_\mu}. \tag{14}$$

Even so, at the present time, these equations are not used owing to a lack of data on thermodynamic parameters and mass transfer coefficients. Below are the results of theoretical and experimental determination of these values. Since production and operation of wood-based panels occur at a moisture content lower than the maximum sorption content, the studies are limited to the hygroscopic area (in the temperature range of 273–373 K and a density range of 200-1,000 kg/m^3).

The most important parameter characterising the statics and dynamics of moisturisation of wood-based panels is the moisture content. The following data was used in determining the dependence of moisture content of wood-based panels on relative air humidity and temperature.

1. The theory of hygroscopic similarity of capillary-porous materials, according to which (wood is considered as a hygroscopically similar material) the ratio between the moisture content of wood-based panels u and wood $u_д$ at the same temperature and air humidity is as follows [2]

$$u = \frac{u_c}{u_{д.c}} u_д, \tag{15}$$

where the index "c" is used to denote the maximum sorption moisture content.

2. The equation developed by I.V. Krechetov for approximating the dependence of $u_д$ (φ, T) [3]

$$u_{д1} = 0{,}0036 \left[13{,}9 - \left(\frac{T}{100}\right)^2\right] + 0{,}0072 \left[29{,}5 - \left(\frac{T}{100}\right)^2\right] \varphi_1; \tag{16}$$

$$u_{д2} = \frac{0{,}512}{121 - 100\varphi_2} \left[21{,}7 - \left(\frac{T}{100}\right)^2\right]. \tag{17}$$

3. The proposed and experimentally confirmed dependence of u_c (T)

$$u_c = A \left[21{,}7 - \left(\frac{T}{100}\right)^2\right]. \tag{18}$$

4. Experimental data of various researchers on sorption isotherms (at T = 298 K) for various types of particleboard and fibreboard panels, allowing the average value of A

$$A = 0{,}016. \tag{19}$$

to be established.

Application of equations (15) through (19) leads to the following dependencies of u (φ, T) for wood-based panels:

$$u_1 = 0{,}00236 \left[13{,}9 - \left(\frac{T}{100}\right)^2\right] + 0{,}00472\varphi_1 \left[29{,}5 - \left(\frac{T}{100}\right)^2\right]; \tag{20}$$

$$u_2 = \frac{0{,}336}{121 - 100\varphi_2} \left[21{,}7 - \left(\frac{T}{100}\right)^2\right]. \tag{21}$$

In accordance with definitions (7) through (10), using equations (20), (21) and the approximation of dependence of experimental mass transfer potential on air humidity (which is much more accurate than that proposed in the works of A.V. Lykov and B.A. Posnov [6]) proposed by us

$$\Theta_1 = 5{,}03 + 42{,}43\varphi_1; \tag{22}$$

$$\Theta_2 = \frac{17{,}8}{1{,}178 - \varphi_2}, \tag{23}$$

we obtained equations for calculating all thermodynamic parameters of mass transfer, with the exception of thermogradient coefficients.

The thermogradient coefficient δ is usually determined either experimentally by the stationary method (usually taking several weeks for one experiment), or by calculation, based on equalities (13) and (14) and assuming that

$$\frac{\lambda''_\mu}{\lambda_\mu} \ll \mu'_T; \quad \ll \Theta'_T, \tag{24}$$

$$\delta_\Theta \ll \Theta'_T, \tag{25}$$

i.e., with the help of the following ratios

$$\delta = c_m \Theta'_T; \tag{26}$$

$$\delta = c_\mu \mu'_T. \tag{27}$$

We have proposed a method for calculating thermogradient coefficients without using assumptions (24) or (25) and without experiments. The idea of the method consists in considering a thermodynamic equilibrium of a capillary-porous body with a binary vapour-air mixture that obeys the law of thermal diffusion.

The following provisions were used to obtain the formula for calculating δ *(u, T)*.

1. Obvious ratios

$$du(\varphi, T) = \left(\frac{\partial u}{\partial \varphi}\right)_T d\varphi + \left(\frac{\partial u}{\partial T}\right)_\varphi dT; \tag{28}$$

$$d\varphi = d\left(\frac{\rho_{\text{п}}}{\rho_{\text{п.н}}}\right) = \varphi\left(\frac{d\rho_{\text{п}}}{\rho_{\text{п}}} - \frac{d\rho_{\text{п.н}}}{\rho_{\text{п.н}}}\right). \tag{29}$$

2. Approximation

$$\lg p_{\text{п.н}} = 9{,}1513 - \frac{2317{,}7}{T}. \tag{30}$$

3. The law of thermal diffusion for a binary gas mixture

$$dn = \varkappa n (1 - n) \frac{dT}{T}. \tag{31}$$

4. Water vapour in humid air obeys the equation of state for ideal gases.

$$\rho_{\text{п}} = \frac{M_{\text{п}} p_{\text{п}}}{RT}. \tag{32}$$

5. Determination of thermogradient coefficient

$$\delta = -\left(\frac{du}{dT}\right)_{j_m = 0}. \tag{33}$$

6. Estimation of values based on known literature data [4]

$$\varkappa (1 - n) \approx 0{,}02 \ll \frac{5330}{T}; \tag{34}$$

$$\frac{T}{\rho}\frac{dp}{dT} \approx 0{,}02 \ll \frac{5330}{T}. \tag{35}$$

The following follows from equations (28) through (35)

$$\delta_{\Theta_1} = \frac{5330}{T^2}\varphi\left(\frac{\partial u}{\partial \varphi}\right)_T - \left(\frac{\partial u}{\partial T}\right)_\varphi. \tag{36}$$

Similarly, the following expressions are obtained

$$\delta_{\Theta_1} = \frac{5330}{T^2}(\Theta_1 - 5{,}03); \tag{37}$$

$$\delta_{\Theta_2} = \frac{352{,}8}{T^2}\Theta_2(\Theta_2 - 15{,}1); \tag{38}$$

$$\frac{\lambda''_\mu}{\lambda'_\mu} = \frac{5330R - \mu}{T}. \qquad (39)$$

Taking into account formulae (20) and (21), equation (36) may be rewritten for wood-based panels as follows

$$\delta_1 = \frac{5330}{T^2}\left\{u_1 - 0{,}00236\left[13{,}9 - \left(\frac{T}{100}\right)^2\right]\right\} + \frac{0{,}00236\cdot 10^{-4}\,T\left[45{,}1 - \left(\frac{T}{100}\right)^2\right]}{29{,}5 - \left(\frac{T}{100}\right)^2}; \qquad (40)$$

$$\delta_2 = \frac{5330u_2\,(360u_2 + 2\cdot 10^{-4}T)}{T^2\left[21{,}7 - \left(\frac{T}{100}\right)^2\right]}. \qquad (41)$$

Expressions (36) through (39) are valid for any capillary-porous bodies. The reliability of these equations for particleboard and fibreboard panels has been confirmed by us experimentally.

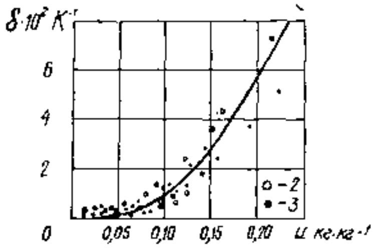


Figure 1. Dependence of thermogradient coefficient δ on moisture content *u*.
1 – calculated data;
2 – experimental data for particleboard panels (ρ_0 = 710 kg/m^3);
3 – experimental data for fibreboard panels (ρ_0 = 900 kg/m^{-3}).

кг·кг$^{-1}$	kg·kg^{-1}

Figure 1 shows a comparison of experimental and calculated values of thermogradient coefficient δ (within the range of 273-373 K, the coefficient is not temperature-dependent). The calculation based on formulae (26) and (27) for wood-based panels gives values that are approximately 50 times lower than the actual values. Known reference data on thermogradient coefficient δ [6] obtained using formula (27) may be adjusted. To do so, it is necessary to calculate the values of δ with the use of equation (14) taking into account the expression (39).

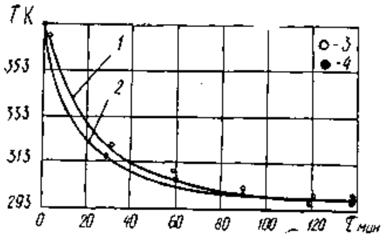
The moisture diffusion coefficient was determined using the transient method based on the laws of mass transfer in the system of two moisture-proof homogeneous materials with different initial moisture content.

According to the results of our research, the moisture diffusion coefficient within the studied range does not depend on the moisture content and the type of wood-based panels but only on temperature and density. The experimental data obtained were summarised using the following empirical formula

$$a_m = 1{,}93\cdot 10^{-10}\left(\frac{T}{273}\right)^{12{,}1}\left(\frac{\rho_0}{580}\right)^{-3{,}1}. \qquad (42)$$

In accordance with expressions (7), (11), (20), (21) and (42) and formulae (9), (12), (20), (21) and (42), formulae were also obtained for calculating mass conductivity coefficients λ_m and λ_{μ}.

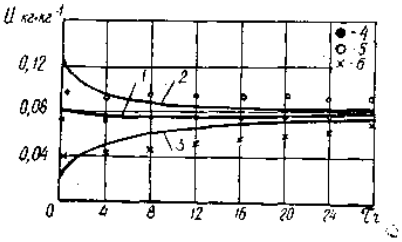
We have compiled an algorithm and a programme for a computational solution to the system of differential equations for heat and mass transfer (1) and (2) under boundary conditions of the third kind. The developed programme requires little time to calculate one variant owing to use of an automatic timestep selection calculation scheme [1]. Calculations of variation over time of temperature and moisture content fields during acclimatisation of a single particleboard panel were performed using a developed program on the BESM-6 computer with use of experimentally determined thermodynamic parameters and mass transfer coefficients. Since moisture transfer occurs virtually only in the form of steam under non-isothermal conditions, the criterion for phase transformation ε is taken as equal to unity.



мин	min

Figure 2. Temperature *T* change in the process of acclimatisation of a particleboard panel.

1, 2 – calculated data for centre and surface, respectively; *3, 4* – experimental data for centre and surface, respectively.



ч	h
кг·кг$^{-1}$	kg·kg^{-1}

Figure 3. Moisture content *u* change in the process of acclimatisation of a particleboard panel.

1, 2, 3 – calculated data for the average value, centre and surface, respectively; *4, 5, 6*– experimental data for the average value, centre and surface, respectively.

Certain calculation results in comparison with experimental data of other researchers [7, 8] are presented in Fig. 2 and 3, from which it can be seen that, taking into account the low accuracy in the measurement of local moisture content, as well as the inaccuracies in the setting of input parameters, the agreement between the experimental and calculated data is quite satisfactory. It takes several years for such experimental studies and approximately 1–2 minutes for one variant to be calculated.

As a result of the research, it became possible to resolve various practical problems associated with production and operation of wood-based panels. The indicators obtained may be used to calculate the processes of heat and mass transfer in other capillary-porous materials.

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Received 11 December 1979