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HEATING OF PRODUCTION WOOD CHIPS IN A SATURATED-STEAM MEDIUM

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A mathematical model of heat and mass transfer in wood chips subjected to hydrothermal treatment in a saturated-steam medium for constant parameters of the external medium is developed. Filling of capillaries with a liquid moving with a finite velocity is responsible for the presence of different zones in which condensate transfer is determined by the corresponding mechanisms.

A promising method of obtaining a disperse material is blast crushing [1, 2]. The essence of this method lies in short-duration heating of the material by saturated steam under excess pressure followed by "release" of the pressure to atmospheric.

Use of the blast method is especially efficient for size reduction of colloidal capillary-porous materials [1] that are easily saturated with moisture and undergo structural changes under its action [3]. Such a material is wood chips, which serve as the initial raw material for obtaining fiber in the manufacture of fiber boards.

Hydrothermal treatment of wood chips with saturated steam causes hydrolysis of bonds of ester type and weakening of the wood structure, including the middle membrane that connects the shells of wood cells and consists mainly of lignin. The membrane thickness is $0.5 \cdot 10^{-6}$–$1.5 \cdot 10^{-6}$ m. In splitting of the ester complexes free hydroxyls appear that increase the hydrophilicity of the fibers and the plasticity related to it [4].

According to reference data [5], the average tensile strength of wood in tension along the fibers for all kinds of species is 130 MPa, while in the case of transverse tension it is 6.5 MPa. Combined heating and moistening of wood chips in treatment with saturated steam allows a twofold or more decrease in the wood strength and in the power consumption associated with the strength in subsequent size reduction of the material [2].

Production wood chips are placed in a steel autoclave, to which, at the instant $\tau = \tau_1$, saturated steam with prescribed parameters is supplied. Since the initial temperature of the chips is lower than the temperature of the saturated steam, condensation of the latter on the surface of particles in the form of a thin liquid film [6] and release of the heat of the phase transition occur.

To describe mathematically the process of heating of wood chips, it is necessary to make some assumptions. We assume that all the wood particles are under the same conditions and have the same indices of state within the entire autoclave volume for each instant of time. From this it follows that to describe the processes of heating and moistening of the entire volume of wood chips it is sufficient to consider heat and mass transfer in a single particle. The saturated steam in the free volume of the autoclave has constant thermodynamic parameters and is in equilibrium with the liquid condensed on the surface of the wood chips.

In a first approximation, the thickness of the condensate film is assumed to be equal to the reduced thickness of the liquid formed on the surface [7]:

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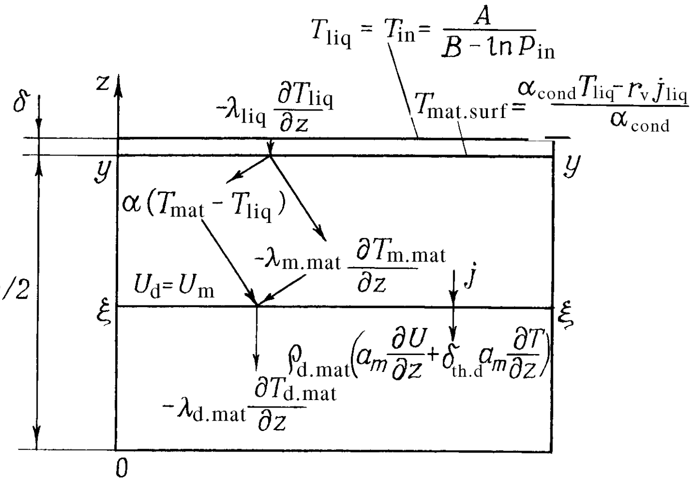

Fig. 1. Scheme of the boundary conditions for the system of saturated steam–moist material for $T(\tau_1, z > s/2 + \delta) = T_{in} = \text{const}$ and $P(\tau_1, z > s/2 + \delta) = P_{in} = \text{const}$.

$$\delta = \left(\frac{\mu_{liq}^2}{\rho_{liq}^2 g}\right)^{0.33}, \tag{1}$$

while the temperature of the material surface in condensation is determined from the equality of the heat fluxes in the phase transition and the convective heat transfer [8]:

$$r_v j_{liq} - \alpha_{cond}(T_{liq} - T_{mat.surf}) = 0 \tag{2}$$

or

$$T_{mat.surf} = \frac{\alpha_{cond} T_{liq} - r_v j_{liq}}{\alpha_{cond}}. \tag{3}$$

The heat-transfer coefficient α_{cond} in Eq. (3) can be determined from a formula [7] for the case of vaporization (steam generation) on a horizontal surface:

$$\alpha_{cond} = 0.725 \left(\frac{\lambda^3 \rho^2 g r_v}{b\,(T_{sat} - T_w)\,\mu}\right)^{1/4}. \tag{4}$$

In Eq. (4) the geometric dimension b is the governing one.

Simultaneously with heating, the wood chips are moistened with the liquid. Due to the total-pressure gradient moisture moves from the condensate film into the porous material [5]; the liquid front formed generates two zones: a moist zone, where the free space of the wood chips is totally filled with moisture, and a conventionally dry zone (Fig. 1).

In the majority of analytical works, for instance [9], devoted to investigation of a two-phase model of heating or cooling of porous bodies the authors adopt the assumption suggested by Schumann [10], in which consideration is given to the flow of an incompressible liquid through a porous body and terms describing heat transfer by conduction are neglected in the energy equations.

Within the limits of the moist zone the equations have the form

$$\frac{\partial T_{\text{liq}}}{\partial \tau} + w_z \frac{\partial T_{\text{liq}}}{\partial z} = \alpha\,(T_{\text{m.mat}} - T_{\text{liq}})\,\frac{f}{c_{\text{liq}}\,\rho_{\text{liq}}\varepsilon}\,, \tag{5}$$

$$\frac{\partial T_{\text{m.mat}}}{\partial \tau} = \alpha\,(T_{\text{liq}} - T_{\text{m.mat}})\,\frac{f}{c_{\text{mat}}\,\rho_{\text{mat}}(1-\varepsilon)}\,, \tag{6}$$

in which the specific surface of the material is calculated from the formula [11]

$$f = \frac{2}{s} + \frac{4}{d}\,. \tag{7}$$

For the one-dimensional problem under consideration the differential equation of momentum transfer without allowance for the influence of mass forces [12] has the form

$$w_z \frac{\partial w_z}{\partial z} + \frac{1}{\rho_{\text{liq}}}\frac{\partial P}{\partial z} - \frac{4}{3}\nu_{\text{liq}}\frac{\partial^2 w_z}{\partial z^2} - R_{\text{sp}} = 0\,, \tag{8}$$

where R_{sp} is the specific hydraulic resistance of the capillary system to the liquid flow [13]:

$$R_{\text{sp}} = \left(\frac{36.3}{\text{Re}_{\text{eq}}} + 0.45\right)\frac{f}{\varepsilon^3}\frac{w_z}{2}\rho_{\text{liq}}\,; \tag{9}$$

Re_{eq} is the equivalent Reynolds number [13]:

$$\text{Re}_{\text{eq}} = 4\,\frac{\rho_{\text{liq}} w_z}{f\mu}\,. \tag{10}$$

Since the actual capillary-porous material has a complex structure, to describe the process a simplified Kozeny–von Kármán model is employed in which all the capillaries are considered to be tubes of the same diameter. Then to calculate the hydraulic resistance of the straight portion of a capillary in the case of a laminar liquid flow, we can use the following formula:

$$\frac{\Delta P}{L} = k\mu\,\frac{d^2}{\varepsilon^3}\,w_z\,, \tag{11}$$

in which k is assumed to be equal to 4.5 [14].

Filtration motion of the liquid into a material particle occurs through a system of macrocapillaries whose average diameter is $3\cdot10^{-5}$ m [15]. The mass flow of the incompressible liquid in its laminar flow inside the material along capillaries of the above dimensions can also be determined from a known hydrodynamic equation [14]:

$$j = \frac{r^2}{8\nu}\,\frac{\Delta P}{L}\,. \tag{12}$$

On the basis of formulas (11) and (12) the liquid flow can be written in the following form:

$$j = \frac{r^2}{8\nu} k\mu \frac{d^2}{\varepsilon^3} w_z \,. \tag{13}$$

In the conventionally dry zone heat and mass transfer proceeds due to the moisture-content and temperature gradients. For the one-dimensional problem under consideration the differential equations describing the mass diffusion in the material and the temperature distribution with respect to the zone thickness have the form [16]

$$\frac{\partial U_{\text{d}}}{\partial \tau} = a_m \frac{\partial^2 U_{\text{d}}}{\partial z^2} + \delta_{\text{th.d}} a_m \frac{\partial^2 T_{\text{d.mat}}}{\partial z^2} \,, \tag{14}$$

$$\frac{\partial T_{\text{d.mat}}}{\partial \tau} = a \frac{\partial^2 T_{\text{d.mat}}}{\partial z^2} \,. \tag{15}$$

Now we will determine the moisture content of surface layers of the material at the instant $\tau \geq \tau_1$ from the condition of filling of the capillaries with the liquid in a singled-out volume element:

$$U = \frac{m_{\text{liq}}}{m_{\text{d.mat}}} = \frac{\rho_{\text{liq}}}{\rho_{\text{d.mat}}} \frac{\varepsilon}{(1 - \varepsilon)} \,. \tag{16}$$

Calculation of the system of equations (1)–(16) was carried out by the method of finite differences [17] with the following boundary conditions:

for the instant $\tau = 0$ the initial conditions are

$$T_{\text{m.mat}}(0, z) = T_{\text{d.mat}}(0, z) = T_{\text{mat.in}} \,, \quad P(0, z) = P_{\text{atm}} \,,$$

$$U_{\text{m.mat}}(0, z) = U_{\text{d.mat}}(0, z) = U_{\text{in}} \,, \quad w_z(0, z) = 0 \,; \tag{17}$$

for the instant $\tau = \tau_1$ the initial conditions are

$$T(\tau_1, z) = T_{\text{in}} \,;$$

$$P = P_{\text{sat}} = \exp\left(A - \frac{B}{T_{\text{in}}}\right); \tag{18}$$

for the steam–liquid system $z \geq y + \delta$ the boundary condition is

$$T_{\text{liq}} = T_{\text{in}} \,; \tag{19}$$

for the system of liquid–material surface $z = s/2$ in the cross section y–y the boundary conditions are

$$w_z = 0 \,, \quad j = 0 \,, \quad -\lambda_{\text{liq}} \frac{\partial T_{\text{liq}}}{\partial z} = -\lambda_{\text{m.mat}} \frac{\partial T_{\text{m.mat}}}{\partial z} + \alpha (T_{\text{mat}} - T_{\text{liq}}) \,. \tag{20}$$

The influence of the molecular component of the left-hand side of the equality on the heat-transfer process becomes the prevailing one over the diffusion component only upon saturation of the capillaries of the wood chips with moisture.

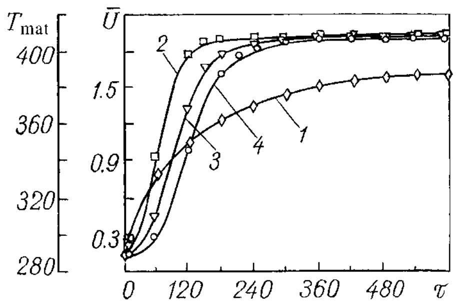

Fig. 2. Experimental kinetic curves for the process of hydrothermal treatment of wood chips: of the integral moisture content (1); of the temperature of the wood chips for z = 0 (2), 0.00125 (3), 0.0025 m (4). $\bar{U}$, kg/kg; T_{mat}, K; τ, sec.

At the interface of moist zone–conventionally dry zone in the cross section ξ–ξ the boundary conditions acquire the form

$$-\lambda_{\mathrm{m.mat}}\frac{\partial T_{\mathrm{m.mat}}}{\partial z}+\alpha\,(T_{\mathrm{mat}}-T_{\mathrm{liq}})=-\lambda_{\mathrm{d.mat}}\frac{\partial T_{\mathrm{d.mat}}}{\partial z}\,,$$
$$j-\rho_{\mathrm{d.mat}}\left(a_m\frac{\partial U}{\partial z}+\delta_{\mathrm{th.d}}a_m\frac{\partial T_{\mathrm{d.mat}}}{\partial z}\right)=0\,,\quad U_{\mathrm{d}}=U_{\mathrm{m}}=\mathrm{const}\,,\tag{21}$$

while the symmetry conditions are

$$\left.\frac{\partial U_{\mathrm{d}}}{\partial z}\right|_{z=0}=0\,,\quad \left.\frac{\partial T_{\mathrm{d.mat}}}{\partial z}\right|_{z=0}=0\,,\quad \left.\frac{\partial T_{\mathrm{m.mat}}}{\partial z}\right|_{z=0}=0\,.\tag{22}$$

To verify the adequacy of the mathematical model for a real process, we carried out experimental studies on an installation representing an airtight autoclave with metallic gauze in it, on which the investigated wood chips were placed. The temperature of the wood chips was controlled by a Chromel–Copel thermocouple and was recorded by a KSP-4 potentiometer. The change in the moisture content of the wood chips was determined using a laboratory analytical balance.

Figure 2 presents experimental data on the changes in the temperature and the moisture content in the wood sample at excess pressure P = 275 kPa. In the course of heat treatment the temperature of the wood-chip layers changed from 293 to 403 K in 300 sec. Since the moisture in the wood chips was transferred with the finite velocity $w_{\mathrm{av}} = 8.33\cdot10^{-6}$ m/sec, the attaining of a maximum temperature in the internal layers of wood chips was limited by the resistance of the capillary-porous system determined from Eq. (9). The integral moisture content of the wood chips in 300 sec for the limiting filling of the capillaries increased from 0.1 to 1.42 kg/kg. With further filling of microcapillaries, pores, and membrane holes in cell walls with moisture and owing to saturation of the intercellular substance with moisture in the next 300 sec, the moisture content increased by 0.255 kg/kg.

The integral moisture content was calculated from the formula [11]

$$\bar{U}=\frac{\bar{U}_{\mathrm{m}}V_{\mathrm{m}}+\bar{U}_{\mathrm{d}}V_{\mathrm{d}}}{V}\,,\tag{23}$$

where

$$\overline{U}_{\mathrm{m}} = U_{\mathrm{m}}\,,\quad \overline{U}_{\mathrm{d}} = \frac{1}{V_{\mathrm{d}}}\int\limits_0^{V_{\mathrm{d}}} U_{\mathrm{d}}\,(z)\;dV\,. \tag{24}$$

The suggested mathematical model of the process of heating of wood chips with saturated steam was used to calculate the parameters of the solid phase before the stage of pressure "release," at which the chips were crushed into fibers.

Prior to the stage of pressure "release" the wood chips were heated to a temperature of 403 K and saturated with the liquid up to a moisture content $\overline{U} = 1.68$ kg/kg. The steam pressure in the autoclave was 375 kPa. At the moment of pressure "release" ($\tau = \tau_2$), vigorous boiling-up of the moisture within the entire particle volume was observed, which led to the appearance of powerful filtration transfer of moisture from the internal layers of the wood chips to their surface. The transformation of the liquid phase into the vapor phase was accompanied by a substantial increase in the moisture volume. The excess pressure that developed in this case could not relax instantaneously through the porous structure of the wood. The pressure drop that formed in the wood chips as a consequence of the difference in the rates of decrease of the external pressure and the pressure in the wood-chip pores caused blast crushing of the wood [1].

The condition of crushing can be represented by the equation

$$2\pi r\,(P_{\mathrm{sat}} - P_{\mathrm{atm}})\,s \ge \sigma_{\mathrm{crush}} S_{\mathrm{membr}}\,, \tag{25}$$

which establishes the equality between the rupture force due to the excess pressure in the pores and the rupture strength of the material.

NOTATION

A and B, empirical coefficients in the Antoine equation; k, Kozeny–von Kármán constant; δ, thickness of the condensate film, m; μ, dynamic viscosity, Pa·sec; ρ, density, kg/m^3; q, specific heat flux, J/kg; r_{v}, latent heat of vaporization, J/kg; r, capillary radius, m; j_{liq}, flow of the liquid condensed on the surface of the wood chips, kg/(m^2·sec); j, flow of the liquid in a particle, kg/(m^2·sec); λ, thermal conductivity, W/(m·K); α, heat-transfer coefficient, W/(m^2·K); b, width of a particle of the material, m; s, thickness of a particle of the material, m; T, running temperature, K; P, pressure, Pa; ΔP, pressure differential over the particle thickness, Pa; $\delta_{\mathrm{th.d}}$, relative coefficient of thermal diffusion $1/K$; a_m, mass conductivity, m^2/sec; d, capillary diameter, m; ε, material porosity; w_2, velocity of the liquid phase, m/sec; ν, kinematic viscosity, m^2/sec; L, capillary length, m; f, specific surface of the material, m^2/m^3; g, free-fall acceleration, m/sec^2; a, thermal diffusivity, m^2/sec; U and $\overline{U}$, local and integral moisture content of the material, respectively, kg/kg; $\overline{U}_{\mathrm{av}}$ and $\overline{U}_{\mathrm{d}}$, average moisture content of the moist and conventionally dry zones, respectively, kg/kg; c, specific heat, J/(kg·K); m, mass, kg; V, volume, m^3; σ, rupture strength, Pa; S, area, m^2; τ, running time, sec; τ_1, time corresponding to the instant of steam supply to the autoclave, sec; τ_2, time corresponding to the instant of pressure release, sec. Subscripts: liq, liquid; in, initial; surf, surface; mat, material; cond, condensation; conv, convection; sat, saturated; w, wall; sp, specific; eq, equivalent; atm, atmospheric; d, dry; m, moist; z, coordinate; y, cross section of the material at the of boundary condensate–material surface; ξ, cross section of the material at the boundary of moist zone–dry zone; av, average; rup, rupture; membr, membrane; v, vaporization; th.d, thermal diffusion; 1, stage of heating and moistening of the material; 2, stage of blast crushing of the material.

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