Theoretical basis of continuous drying of dispersed materials

Natalia Sorokova [1], Julia Kolchyk[2], Rodion Sorokovoi[3]

1. National Technical University of Ukraine "KPI named after Igor Sikorsky", Kiev, 02000, Polytechnic Street, 6,
E-mail: n.sorokova@ukr.net

2. Kyiv National University of Construction and Architecture, Kiev, 03680, Povitroflotsky Avenue, 31,
E-mail: yuliia.kolchyk@gmail.com

3. Institute of Engineering Thermophysics of the National Academy of Sciences of Ukraine, Kiev, 03164,
Bulakhovsky street, 2, E-mail: emo4ka69@gmail.com

A mathematical model, a numerical method, and the calculations results of the heat and mass transfer dynamics and phase transformations in the processes of continuous drying dispersed materials are presented. The calculation of continuous drying a chopped wood was carried out. The calculation results testify to the adequacy of the mathematical model and the efficiency of the calculation method.

Key words – continuous drying, dispersed material, mathematical modelling, crushed willow.

Introduction

Drying processes are an integral part of most production technologies in the energy, chemical, food, construction, paper, pharmaceutical and other industries. The trend of modern production processes is the introduction of continuous automated technological cycles, in which it is advisable to use continuous dryers. When developing effective modes of continuous drying, it is important to have the results of the dynamics of heat and mass transfer in a porous material, taking into account changes in the parameters of the coolant along the length of the drying chamber. If a dispersed porous material is to be dried, then the dispersion characteristics of the wet layer should be taken into account. The method of mathematical modeling makes it possible to solve these problems. In [1], for the first time, a mathematical model was built and a numerical method was developed for calculating the dynamics of heat and mass transfer and phase transformations during the dehydration of consolidated capillary-porous materials in continuous convective dryers. In [2], shrinkage was taken into account during continuous drying of colloidal capillary-porous materials. In this paper, a mathematical model of the dynamics of continuous convective drying of dispersed capillary-porous materials is presented.

Results and discussion

The wet dispersed layer can be considered as a multicomponent heterogeneous system, including the skeleton, liquid, and gas-vapor mixture. When constructing a mathematical model of the dynamics of drying a dispersed layer, it was assumed that the liquid phase moves only in the particle capillaries, while vaporous moisture moves along the particle capillaries and in the space between them. The system of equations was built on the basis the differential equation of substance transfer W (energy, mass, momentum) [1]

$$\frac{\partial W}{dt} + \operatorname{div}(W\mathbf{w}) = -\operatorname{div} \mathbf{j}_W + I_W - \frac{W}{1+\varepsilon_V}\left[\frac{\partial \varepsilon_V}{\partial t} + \operatorname{div}(\varepsilon_V \mathbf{w})\right], \qquad (1)$$

where $\mathbf{w}$ – speed of substance movement, $\mathbf{w} = \mathbf{w}_L + \mathbf{w}_\psi$, where $\mathbf{w}_L$ – speed of conveyor belt, $\mathbf{w}_\psi$ – filtration speed of substance's components (liquid $\psi = fl$, vapor $\psi = v$, air $\psi = ai$) relative to its skeleton; $\mathbf{j}_W$ – substance fluence rate W; I_W – power of internal sources of the substance; ε_V – relative volumetric strain. Transfer of the substance W is carried out by diffusion and filtration: $\mathbf{j}_W = \mathbf{j}_W^d + \mathbf{j}_W^f$. In the steady state operation of the dryer: $\partial W/\partial t = 0$, $\partial \varepsilon_V /\partial t = 0$ and $\mathbf{w}_L = \text{const}$.

When the filtration transfer of the substance takes place, the components ψ move relative to the body's skeleton with the speed $\mathbf{w}_\psi$, and relative to the body of the apparatus with the speed $\mathbf{w}$. For this case, equation (1) can be written as

$$\mathbf{w}_L \cdot \nabla W + \operatorname{div}(W\mathbf{w}_\psi) = -\operatorname{div}\mathbf{j}_W + I_W - \frac{W}{1+\varepsilon_V}\left[\mathbf{w}_L \cdot \nabla\varepsilon_V + \operatorname{div}(\varepsilon_V\mathbf{w}_\psi)\right]. \tag{2}$$

At moderate temperature conditions of drying, heat and mass transfer in the dispersed layer is carried out by diffusion. Then $\mathbf{w}_\psi = 0$ and (1) takes the form

$$\mathbf{w}_L \cdot \nabla W = -\operatorname{div}\mathbf{j}_W + I_W - \frac{W}{1+\varepsilon_V}\left(\mathbf{w}_L \cdot \nabla\varepsilon_V\right). \tag{3}$$

Usually, the width and length of the tape is much greater than the height of the layer of material on it. In the Cartesian coordinate system, where the x-axis is perpendicular to the working surface of the belt, and the z-axis is parallel to the wL vector, Equations (2), (3) can be simplified. Then the mathematical model for the case of continuous diffusion drying of a layer of a dispersed colloidal capillary-porous body

$$c_{\text{ef}} w_L \frac{\partial T}{\partial z} = \frac{\partial}{\partial x}\left(\lambda_{\text{ef}} \frac{\partial T}{\partial x}\right) - LI_V, \tag{4}$$

$$w_L \frac{\partial U_{\text{fl}}}{\partial z} = \frac{\partial}{\partial x}\left(D_{\text{fl}} \frac{\partial U_{\text{fl}}}{\partial x}\right) - I_V - \frac{U_{\text{fl}}}{1+\varepsilon_V} w_L \frac{\partial\varepsilon_V}{\partial z}, \tag{5}$$

$$w_L \frac{\partial U_{\text{v}}}{\partial z} = \frac{\partial}{\partial x}\left(D_{\text{v}} \frac{\partial U_{\text{v}}}{\partial x}\right) + I_V - \frac{U_{\text{v}}}{1+\varepsilon_V} w_L \frac{\partial\varepsilon_V}{\partial z}, \tag{6}$$

where U_{fl}, U_{v} – volume concentrations of liquid and steam; $\lambda_{\text{ef}} = \lambda_{\text{b}}\Psi_{\text{b}} + \lambda_{\text{fl}}\Psi_{\text{fl}} + (\lambda_{\text{v}} + \lambda_{\text{ai}})\Psi_{\text{g}}$; $c_{\text{ef}} = c_{\text{b}}\rho_{\text{b}}(1-\Pi)(1-\varepsilon_{\text{la}}) + c_{\text{fl}}U_{\text{fl}} + c_{\text{v}}U_{\text{v}} + c_{\text{ai}}\rho_{\text{ai}}\Psi_{\text{g}}$ – effective thermal conductivity and heat capacity of the dispersed layer; where, the volume fractions of the body $\Psi_{\text{b}} = (1-\Pi)(1-\varepsilon_{\text{la}})$, liquid $\Psi_{\text{fl}} = U_{\text{fl}}/\rho_{\text{fl}}$ and gas $\Psi_{\text{g}} = 1-\Psi_{\text{b}}-\Psi_{\text{fl}}$ in the dispersed layer, Π – material porosity; ε_{la} – layer porosity; L – is the heat of vaporization; ehe relative volume deformation ε_V is based on the differential equation of the thermal-concentration deformation [1]. The diffusion coefficients of the liquid and gas phases is determined by the formulas: $D_{\text{fl}} = \gamma_D[\exp(A_D/RT)-1]^{-1}$ [3], $D_{\text{v}} = \gamma_{\text{v}}T^{3/2}/P_{\text{v}}$ [4], where R – universal gas constant, A_D – activation energy, P_{g} – gas phase pressure, $\gamma_{D\text{fl}}, \gamma_{D\text{v}} = \text{Const}$.

To determine the effect of the porosity ε_{la} on the desired functions and the intensity of evaporation I_W, the control volume ΔV, which includes one particle, is considered. If the number of particles in a unit volume of n_{p}, then the average value of the control volume $\Delta V = 1/n_{\text{p}}$, and the average volume of the particle $V_{\text{p}} = \Delta V(1-\varepsilon_{\text{la}})$. In this case, relations were found for the volume concentrations of the components of the dispersed layer: $U_{\text{fl}} = U_{\text{fl}}^{\text{par}}(1-\varepsilon_{\text{la}}), U_{\text{v}} = U_{\text{v}}^{\text{par}} - \rho_{\text{v}}\varepsilon_{\text{la}}$, $U_{\text{ai}} = \rho_{\text{ai}}\Psi_{\text{g}}$.

The average area of the outer surface of the particle is determined by its effective size. The intensity of the phase transition in a unit volume of the dispersed layer is represented by [5]

$$I_V = \gamma_{\text{c}}\left[\exp(A/RT)-1\right]^{-1}(\varphi_{\text{b}} - \varphi)[S_{\text{p}}n_{\text{p}} + (1-\varepsilon_{\text{la}})S], \qquad \gamma_{\text{c}} = \varepsilon\rho_{\text{fl}}\delta*/4 = \text{const} \tag{7}$$

where the contact surface area of the liquid and vapor phases consists of the outer S_{p} and the inner S [1] surfaces of the particle; φ_{b}, φ is the humidity of the body and steam in the pores of the layer; A – activation energy; ε is the radiation coefficient; ρ_{fl} is the density of the liquid; $\delta*$ –thickness of the condensate layer in which the evaporation process takes place; the value $\bar{\delta} = \delta/\delta*$ is found from the conditions: for $0 < \delta < \delta*$ and $\bar{\delta} = 1$ with $\delta > \delta*$, $\delta = \delta*(1-\sqrt{1-\varphi_{\text{e.m.}}})$ the thickness of

the condensate layer (formula Nikitenko N.I. [5]); A is the activation energy. This expression follows under the condition of local thermodynamic equilibrium of phases from the formula Nikitenko [1] for the intensity of liquid evaporation from the free surface of the condensed layer

$$I = \gamma_c \left\{ \bar{\delta}(2-\bar{\delta}) \left[\exp\left(A/RT\big|_{v=0}\right)-1 \right]^{-1} - \varphi_{e.m.} \left[\exp\left(A/RT_{e.m.}\right)-1 \right]^{-1} \right\}, \tag{8}$$

$\varphi_{e.m.}$ medium's relative humidity, $\varphi_{e.m.} = P_v / P_{eq}$, P_v vapor partial pressure, P_{eq} saturation pressure.

At the entrance to the drying chamber, all parameters of the coolant are known. To determine the average values of temperature $T_{e.m.}$, pressure $P_{e.m}$, volumetric concentrations of steam $U_{v,e.m}$ and air $U_{ai,,e.m}$ in the drying agent in section z along the length of the channel, the elementary volume $dV = S_{e.m}dz$ was considered, where the cross-sectional of a channel $S_{e.m} = XY$, in contact with the drying agent. The change pressure $dP_{e.m}$ in section z from the Bernoulli equation for the gas flow in the channel, without taking into account local resistances is determined:

$$\frac{dP_{e.m}}{dz} = -\lambda_{fr}\rho_{e.m}\frac{w^2}{2d_{eq}} + \rho_{e.m}\cos(g,z) \cdot \tag{9}$$

The average temperature $T_{e.m}$ over the z is determined from the energy balance equation for dV:

$$\frac{dq_{e.m}}{dz} = \left\{ \left[\alpha - \gamma_{v,e.m}\left(U_v\big|_{v=0} - \rho_{v,e.m}\Psi_g\right)c_v - \gamma_{ai,e.m}\left(U_{ai}\big|_{v=0} - \rho_{ai,e.m}\Psi_g\right)c_{ai} \right](T_{e.m} - T\big|_{v=0}) - LI \right\}Y. \tag{10}$$

where $q_{e.m}(z) = [G_{v,e.m}(z)c_v + G_{ai,e.m}(z)c_{ai}]T_{e.m}(z)$. The average speed $w_{a.m}(z)$ of the drying agent in accordance with the equations of state and continuity for steam and air

$$w_{e.m}(z) = \left[\frac{G_{v,e.m}(z)}{\mu_v} + \frac{G_{ai,e.m}(z)}{\mu_{ai}} \right]\frac{RT_{e.m}(z)}{P_{e.m}(z)S_{e.m}}. \tag{11}$$

Change in the flow rate of air and vapor of the agent through the z from the mass balance equations

$$dG_{ai,e.m}(z)/dz = \gamma_{ai,e.m}\left[\rho_{ai}(z,X) - \rho_{ai,e.m}(z)\Psi_r\right]Y, \quad dG_{v,e.m}(z)/dz = \gamma_{v,e.m}\left[\rho_v(z,X) - \rho_{v,e.m}(z)\Psi_g\right]Y,$$

where are the partial densities of vapor and air in the drying agent $\rho_{v,e.m} = U_{v,e.m}$, $\rho_{ai,e.m} = U_{ai,e.m}$. The total consumption of material G_{m0} at the channel inlet ($z=0$) in accordance with the continuity equation, assuming that $S_m = X_m Y$ is the cross-sectional area of the material layer, is equal to $G_{m0} = G_{b0} + G_{fl0} + G_{v0} + G_{ai0} = w_L S_m (U_{b0} + U_{fl0} + U_{v0} + U_{ai0})$, and the total consumption of material $G_m(z)$ through z: $G_m(z) = w_L S_m[\bar{U}_b(z) + \bar{U}_{fl}(z) + \bar{U}_v(z) + \bar{U}_{ai}(z)]$, where $\bar{U}_\psi(z)$ − average value of the volumetric concentration of the component ψ (ψ = b, fl, v, ai) wet material by section S_m. For a channel with impermeable walls: $G_m(z) + G_{e.m}(z) = G_{m0} + G_{e.m0} = const$. In this case, the consumption of steam of the drying agent through the section z of the channel according to the mass balance equation: $G_{v,e.m}(z) = w_{e.m}S_{e.m}\rho_{v,e.m}(z) = G_{m0} + G_{e.m0} - G_m(z) - G_{ai,e.m}(z)$. Densities $\rho_{v,e.m}$, $\rho_{ai,e.m}$ from the continuity equations: $\rho_{v,e.m}(z) = G_v(z)/\left[w_{e.m}(z)S_{e.m}\right]$, $\rho_{ai,e.m}(z) = G_{ai}(z)/\left[w_{e.m}(z)S_{e.m}\right]$, pressures $P_{пс}$, $P_{вс}$ from the state equations: $P_{v,e.m}(z) = R\rho_{v,e.m}(z)T_{e.m}(z)/\mu_v$, $P_{ai,e.m}(z) = R\rho_{ai,e.m}(z)T_{e.m}(z)/\mu_{ai}$.

The conditions of heat and mass transfer at the boundary $x = X_m$ of the contact between the layer of material being dried and the drying agent for system (4) – (6) are written as follows

$$D_{fl}\frac{\partial U_{fl}}{\partial v}\bigg|_{v=0} = -I, \quad (12) \qquad D_v\frac{\partial U_v}{\partial v}\bigg|_{v=0} = I - \gamma_{v,e.m.}\left(U_v\big|_{v=0} - \rho_{v,e.m.}\Psi_g\right), \qquad (13)$$

$$\lambda\frac{\partial T}{\partial v}\bigg|_{v=0} = \alpha(T_{e.m.} - T\big|_{v=0}) - LI - \left[\gamma_{v,e.m.}\left(U_v\big|_{v=0} - \rho_{v,e.m.}\Psi_g\right)c_v + \gamma_{ai,e.m}\left(U_{ai}\big|_{v=0} - \rho_{ai,e.m}\Psi_g\right)\right](T_{ai} - T\big|_{v=0}), \quad (14)$$

where $T\big|_{v=0}$ − temperature at the layer surface.

The solution of differential equations (4) - (6) under conditions (7) - (14) was performed by a numerical method based on a three-layer explicit difference scheme Nikitenko N.I. [1] and algorithm splitting procedures for physical factors. As an example, a thin layer of X_m=5,6 mm, Π = 0,585, ε_{la} = 0,65 of crushed energy willow was considered, which was blown with a drying agent with initial parameters $T_{e.m0}$ = 200 °C, $P_{e.m0}$ = 103 kPa, $P_{ve.m0}$ = 1,6 kPa, $w_{e.m0}$ = 4,5 m/s, $G_{e.m0}$ = 8 kg/s. The calculation results are presented in Fig.1.
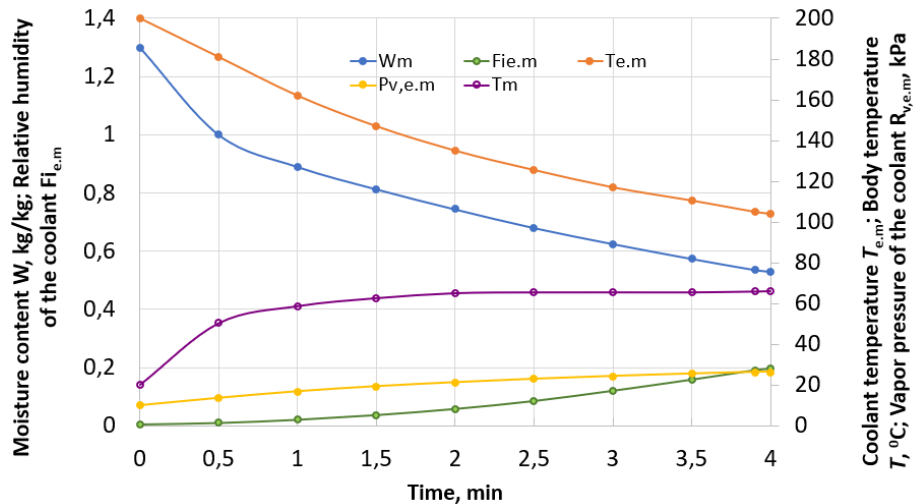

Fig. 1 Change in time of average moisture content W and temperature T of the layer of energy willow particles, as well as coolant temperature T_c, partial vapor pressure P_{vc} and relative humidity F_{ic} during drying in a belt dryer. Drying time $t=z/w_L$, where the tape speed w_L = 0,005 m/s.

Conclusion

The values of the parameters of the coolant in each section z along the length of the channel are related to each other as in the diagram of the state of moist air. This testifies to the adequacy of the proposed approach to the calculation of the continuous drying process. As can be seen from the figure, the drying agent cools and moistens rather quickly, which significantly slows down the process of the material reaching equilibrium moisture content. In some cases, it is not possible to dry the material to a low moisture content in a continuous convective drying unit without additional heating and drying of the drying agent.

References

1. Nikitenko N.I., Snezhkin Yu.F., Sorokovaya N.N., Kolchik Yu.N. (2014) Molecular radiation theory and methods for calculating heat and mass transfer. Kiev: Naukova Dumka, 744 p. http://ittf.kiev.ua/wp-content/uploads/2016/12/nikitenko.pdf (Book).
2. Sorokovaya N.N., Snezhkin, Yu.F, Shapar' R.A, Sorokovoi R.Ya. (1019) Mathematical Simulation and Optimization of the Continuous Drying of Thermolabile Materials. Journal of Engineering Physics and Thermophysics, V.92, № 5, pp 1180–1190. DOI 10.1007/s10891-019-02032-3
3. Nikitenko, N.I. (2000) Problems of the radiation theory of heat and mass transfer in solid and liquid media. Journal of Engineering Physics and Thermophysics V. 73, № 4, P.840-848. https://doi.org/10.1007/s10891-000-0102-9.
4. Rudobashta, S.P. (1980) Mass transfer in systems with a solid phase. Moscow: Chemistry, 248 p. https://www.libex.ru/detail/book796756.html
5. Nikitenko N.I. (2002) Investigation of the Dynamics of Evaporation of Condensed Bodies on the Basis of the Law of Spectral-Radiation Intensity of Particles, Journal of Engineering Physics and Thermophysics. vol.75, no 3, May, pp684–692, 2002.