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TRANSFER PROCESSES IN POROUS MEDIA

MATHEMATICAL SIMULATION OF THE DRYING OF SUSPENSIONS AND COLLOIDAL SOLUTIONS BY THEIR DEPRESSURIZATION

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The heat and mass transfer in the process of drying of high-humidity materials by their depressurization has been investigated. The results of experimental investigation and mathematical simulation of the indicated process are presented. They allow one to determine the regularities of this process and predict the quality of the finished product. A technological scheme and an engineering procedure for calculating the drying of the liquid base of a soap are presented.

One of the most promising methods used for removal of liquid from high-humidity materials, such as colloidal solutions and suspensions, is the drying of them by their depressurization [1–3]. The specificity of this method is that a solution found in a closed volume is overheated relative to the parameters of a drying chamber and then is injected into the chamber through injectors. As a result of the depressurization of the product, it disperses and the moisture within each of its particles comes to the boil. An overheating of the solution leads to a decrease in its surface tension and viscosity with the result that the dispersivity of particles increases, their dispersion becomes homogeneous, and the finite moisture content of the dried material substantially decreases [2]. At the same time, the temperature of the preliminary heating and the differential pressure influence the properties of chemical compounds and deteriorate them in certain cases. However, the technological properties of a finished product can be controlled by optimization of the conditions of drying of a solution with account for its percent composition. Thus, the choice of the drying conditions is an important problem that can be solved by mathematical simulation.

When a colloidal solution or a suspension is dispersed as a result of its depressurization, a liquid jet is broken down into drops and the moisture overheated relative to the parameters of a drying chamber comes to the boil. The sizes of the drops are determined on the basis of the balance relation between the internal pressure and the surface tension:

$$2\pi R^2 (P_{\text{sat}} - P_{\text{f}}) = 4\pi R\sigma \,. \tag{1}$$

The heat-balance equation for the moment the solution leaves an injector can be represented in the form of the dependence

$$(c_{\text{d}} + U_{\text{in}} c_{\text{liq}}) (T_{\text{sat}} - T_{\text{f}}) = r_{\text{v.f}} \Delta U \,. \tag{2}$$

Having determined the temperature from the Antoine equation [4]

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$$P_{sat} = \exp\left(A - \frac{B}{T_{sat}}\right), \tag{3}$$

from Eq. (2) we determine the amount of moisture removed at this stage of the drying process

$$(c_d + U_{in} c_{liq}) \left(\frac{B}{A - \ln P_{sat}} - \frac{B}{A - \ln P_f}\right) = r_{in} \Delta U , \tag{4}$$

and, from Eq. (1), we determine the radius of the dispersed-liquid drops

$$R = \frac{2\sigma}{\left[\exp\left(A - \frac{B}{T_{sat}}\right) - P_f\right]} . \tag{5}$$

The mechanism of subsequent removal of moisture from the suspension in the drying chamber is determined by the properties of its base. The transfer of heat and mass in the first period of drying of the suspension particles shaped as a sphere is described by the differential Fourier equation

$$c\rho_d \frac{\partial T_{mat}}{\partial \tau} = \lambda \left(\frac{\partial^2 T_{mat}}{\partial r^2} + \frac{2}{r} \frac{\partial T_{mat}}{\partial r}\right). \tag{6}$$

When the free moisture is removed, the intensity of evaporation is mainly determined by the external heat and mass transfer. The amount of the evaporated liquid can be determined by the heat supplied to the surface of the body:

$$j = \frac{\lambda}{r_{v.f}} \left|\frac{\partial T_{mat}}{\partial r}\right|_R , \tag{7}$$

which, according to [5], is equal to

$$j = \frac{dm_{liq}}{F d\tau} = \frac{m_d}{4\pi R^2} \frac{dU}{d\tau} . \tag{8}$$

On the basis of combined solution of (7) and (8), we obtain the equation for the kinetics of drying

$$\frac{dU}{d\tau} = \frac{4\pi R^2}{m_{mat}} \frac{\lambda}{r_{v.f}} \left|\frac{\partial T_{mat}}{\partial r}\right|_R . \tag{9}$$

Thus, Eqs. (6) and (9) describe, respectively, the temperature distribution over the cross section of a solid suspension particle and its mean-integral moisture content.

The following boundary conditions can be formulated for the first period of drying:

$$U(0) = U_{in} - \Delta U , \quad T(0, 0 \le r < R) = T_h , \quad T(\tau, R) = T_{sat} . \tag{10}$$

The removal of moisture from a solid suspension particle in the second period of the drying leads to an increase in the depth of the evaporation zone. The moisture-content and temperature fields in the moist zone [0; $R - \xi$] were determined by the differential heat-conduction (6) and mass-transfer [5] equations

$$\frac{\partial U}{\partial \tau} = a_m \left(\frac{\partial^2 U}{\partial r^2} + \frac{2}{r} \frac{\partial U}{\partial r}\right) + a_m \delta_t \left(\frac{\partial^2 T_{mat}}{\partial r^2} + \frac{2}{r} \frac{\partial T_{mat}}{\partial r}\right), \tag{11}$$

and the approximate Luikov solution [5], taking into account the linear law of change in the temperature and moisture content, was used for determining the indicated parameters in the evaporation zone $[R - \xi;\ R]$.

The velocity of the evaporation front was determined on the assumption that all heat supplied to the evaporation front as a result of the heat conduction is completely expended for the moisture evaporation. In this case, the equation for the evaporation-front velocity has the form [6]

$$\frac{d\xi}{d\tau} = \frac{\lambda R\,(T_{\text{mat}\xi} - T_{\text{mat,s}})}{\xi\rho_{\text{d}} r_{\text{v.f}} U_{\text{in}}\,(R - \xi)}\,. \tag{12}$$

The following boundary conditions are set for the moist zone $[0;\ R - \xi]$:

$$\lambda_1 \frac{T_{\text{mat}\xi} - T_{\text{mat,s}}}{\xi} = \lambda_2 \frac{T_{\text{mat,c}} - T_{\text{mat}\xi}}{R - \xi} + r_{\text{v.f}}\, j_2\,, \tag{13}$$

$$j_1(\tau) = j_2(\tau)\,, \tag{14}$$

and for the evaporation zone:

$$U_{\text{s}} = a\left(\frac{P}{P_{\text{sat}}}\right)^n, \tag{15}$$

$$a_{m1}\,\rho_{\text{d}} \frac{U_{\text{s}} - U_{\xi}}{\xi} + a_{m1}\,\rho_{\text{d}}\delta_{\text{t}} \frac{T_{\text{mat,s}} - T_{\text{mat}\xi}}{\xi} + K_p \frac{P - P_{\xi}}{\xi} - j_{\text{s}}(\tau) = 0\,. \tag{16}$$

In the second period of drying, the adsorptionally bound moisture and the moisture of macro- and microcapillaries is removed from the solid suspension particles. In this case, the temperature of the liquid is related to the pressure in a capillary by the relation [7]

$$P_{\xi} = \exp\left\{(A - B/T_{\text{liq}\xi}) + \left[-\frac{4\sigma\rho_{\text{v}}}{\rho_{\text{liq}} d_{\text{cap}} \exp(A - B/T_{\text{liq}\xi})}\right]\right\}. \tag{17}$$

Since the structure of a material exhibits a resistance to the transfer of vapor from its internal layers to the surface, the partial pressure of the vapor at the evaporation front will differ from that under the surface of a particle. The differential pressure can be estimated by the Ergun equation [8]

$$P_{\xi} - P = \left[150\,\frac{1 - \varepsilon}{\varepsilon^3}\frac{\mu w}{d_{\text{cap}}^2} + \frac{1 - \varepsilon}{\varepsilon^3}\frac{\rho_{\text{v}} w^2}{d_{\text{cap}}^2}\right]\xi\,. \tag{18}$$

The initial conditions for the second period of drying are as follows:

$$w(0, r) = 0\,, \quad U(0, r) = U_{\text{cr1}}\,. \tag{19}$$

In colloidal solutions, unlike suspensions, moisture is in the bound state and is evaporated only from the surface of the particles [5]. The heat and mass transfer in a particle of a colloidal substance can be defined, in the case where phase transformations are absent and the filtration flow is negligibly small, by the differential equations of heat conduction (6) and mass transfer (11).

The boundary condition for the heat transfer on the surface of a particle will be formulated in the following form:

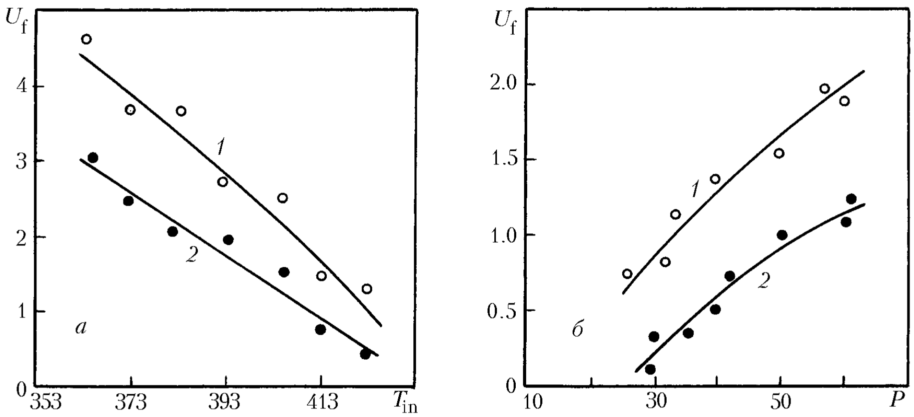


Fig. 1. Dependence of the finite moisture content in a fluoroplastic powder on the initial-material temperature (a) and the residual pressure in the drying chamber (b): U_{in} = 8 (1) and 5 kg/kg (2). U_f, kg/kg; T_{in}, K; P, kPa.

$$j_s r_{v.f} + \lambda \frac{\partial T_{mat}}{\partial r} = 0 , \tag{20}$$

where the first term of the left side of the equation characterizes the heat expended for the phase transformation and the second term characterizes the heat transferred from the internal layers of a particle to its surface as a result of the heat conduction.

The radius of a colloidal-solution particle decreases continuously in the process of its drying and tends to the radius determined in the first approximation by the density of the substance:

$$m_{m,mat} = V\rho_{m,mat} \frac{1}{1+U} , \tag{21}$$

where

$$V = \frac{4}{3} \pi R^3 ; \tag{22}$$

$$\rho_{m,mat} = \frac{\rho_{liq} U}{1+U} + \frac{\rho_d}{1+U} . \tag{23}$$

Let us express the current mass and volume of a particle in terms of its moisture content:

$$m_{m,mat} = m_d (1+U) , \tag{24}$$

$$V = \frac{m_d (1+U)^2}{\rho_{liq} U + \rho_{d,mat}} . \tag{25}$$

As a result of the rearrangements, we obtain an equation from which the current radius of a drop can be calculated depending on its moisture content:

$$R = \sqrt[3]{\frac{3V}{4\pi}} = \sqrt[3]{\frac{3}{4\pi} \frac{m_d (1+U)^2}{\rho_{liq} U + \rho_d}} . \tag{26}$$

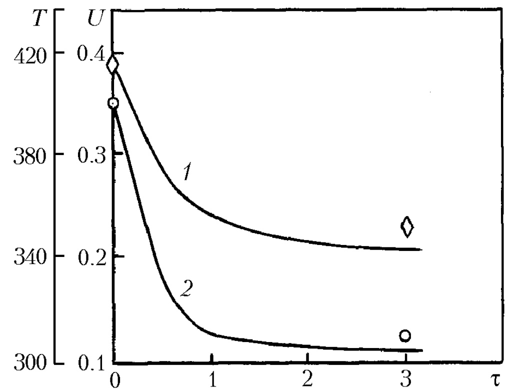


Fig. 2. Kinetic curves of the moisture content (1) and temperature (2) of the base of a dried soap. T, K; U, kg/kg; τ, sec.

Combined solution of the equations of heat and mass transfer (6) and (11) and the Luikov equations [5] for the evaporation zone with boundary conditions (13)–(16) allows one to determine the kinetics of heat removal from a particle of a colloidal solution.

The system of equations defining the interrelated processes of dispersion and drying of high-humidity materials by their depressurization was solved by a numerical method. To verify the adequacy of the mathematical model to the actual process, we have performed experiments, in the process of which a solution was placed in a hermetic reservoir and was heated to a definite initial temperature. The temperature and pressure in the reservoir were controlled by indications of devices. After heating, the solution was dispersed into a drying chamber, in which a necessary residual pressure was maintained. The product obtained was removed to a collector. The processing of the data obtained by methods of mathematical statistics [9] has shown that the difference between the theoretical and experimental data does not exceed 22%.

The mathematical model of drying of a suspension was experimentally verified by the example of dispersion of F-4SF fluoroplastic in freon 113. The experimental and calculation dependences, shown in Fig. 1, indicate that the drying of an F-4SF fluoroplastic suspension with an initial moisture content of 5 kg/kg and an initial temperature of 423 K at a residual pressure of 50 kPa in a drying chamber makes it possible to obtain a practically dry fluoroplastic powder. This is due to the practically instantaneous removal of the surface moisture contained in the finely dispersed particles of the suspension after the ebullience. Thus, one method for increasing the amount of moisture removed in the process of drying of a material by its depressurization is decreasing the residual pressure in the drying chamber. Analysis of the curves presented in Fig. 1b shows that a decrease in the residual pressure by two times decreases the moisture content in the finished product by more than 1 kg/kg.

The mathematical model developed for colloidal solutions was verified using the liquid base of a soap, representing a colloidal solution containing 64.4% fatty acids, 0.18% free caustic alkali, 0.5% sodium chloride, 0.2% free sodium carbonate, and 34.72% water [19]. Figure 2 presents experimental and calculated kinetic curves. Analysis of these curves has shown that the drying of a soap mass with an initial temperature of 418 K and a moisture content of 0.38 kg/kg, dispersed into a drying chamber with a residual pressure of 5.3 kPa, decreases the moisture content in it to 0.21 kg/kg.

The most important requirement imposed on the drying of a soap is provision of a definite moisture content in it, because this parameter determines the content of fatty acids in the finished product and, consequently, its quality. If the content of these acids in a soap exceeds the normal one, the dissolvability of the soap deteriorates, and, in contrast, a decrease in the content of fatty acids increases the dissolvability of the soap and leads to an uneconomical use of it.

For the purpose of practical application of the results of our theoretical and experimental investigations, we have developed an engineering method and an apparatus for realization of the process considered (Fig. 3). The apparatus includes a solution heater, a drying chamber, and a condenser [12]. According to the scheme of drying proposed, the mass of a soap is preliminarily heated in a heat exchanger 3. The hot mass is fed from the heat exchanger into a vacuum-drying chamber 5, where it is scattered through injectors. The soap particles obtained as a result of the drying

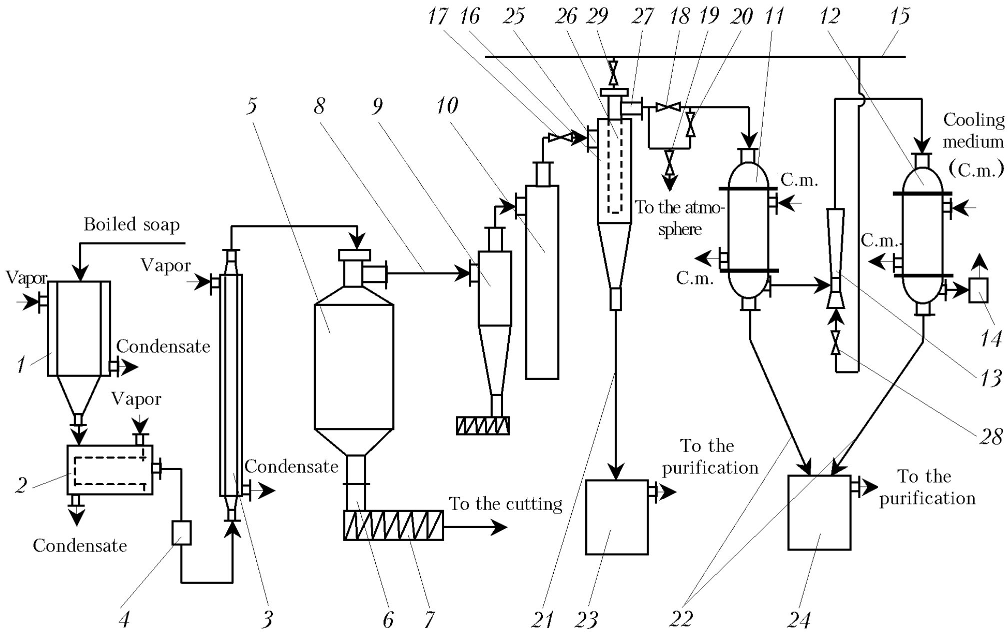
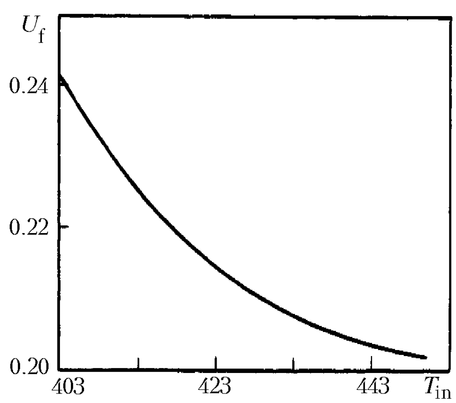


Fig. 3. Diagram of a vacuum-drying apparatus for soap production: 1) soap collector; 2) filter; 3) pipe heater; 4) pump; 5) vacuum-drying chamber; 6) double-hose bin; 7) auger machine; 8, 21, 22) pipelines; 9, 10) cyclones; 11, 12) heat exchangers-condensers; 13) steam-jet ejector; 14) vacuum pump; 15) steam line; 16) bag filter; 17, 18) stop valves; 19, 20, 28, 29) valves; 23, 24) condensate collectors; 25, 27) branch pipes; 26) perforated hose.



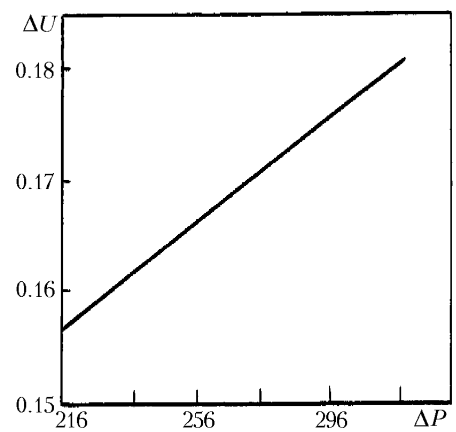


Fig. 4. Dependence of the finite moisture content of the base of a soap on the heating temperature. U_f, kg/kg; T_{in}, K.

Fig. 5. Dependence of the amount of moisture removed from a dried soap on its depressurization. ΔU, kg/kg; ΔP, kPa.

are deposited on the inner surface of the chamber, from which they are removed by scrapers. The dried mass is fed into an auger machine 7 for compaction. The water vapor together with the soap dust enters cyclones 9 and 10, connected in series with each other, where material flows are separated in the field of centrifugal forces. The vapor outflowing from the cyclones-separators enters the condensation unit comprising heat exchangers-condensers 11 and 12. For the purpose of preventing the penetration of soap dust into them, a separation unit, including bag filters 16 working in parallel, and a number of additional means are installed in the region of the pipeline between the cyclones and the heat exchangers-condensers.

The above-described computational procedure based on the mathematical model developed and known formulas allows one to determine the main design characteristics of equipment for drying, in particular the area of the heat-exchange surface of a heater and a condenser, the volume of a drying chamber, and the technological parameters of the drying of a soap by its depressurization; among these parameters are the temperature of heating of a solution and the amount of heat removed. The initial data necessary for calculating the process considered are the initial and finite moisture content, the output of the dried product, and the thermophysical parameters of this product.

The heating temperature of a soap solution influences the dispersivity of the particles obtained in the process of drying and their moisture content. Figure 4 presents the dependence of the moisture content of a finished soap on the temperature of its liquid base before the dispersion at a constant standard residual pressure of 5.33 kPa in a drying chamber. By this dependence one can select an optimum heating temperature of a soap mass, providing the obtaining of a finished product with the required moisture content. The results of investigations of the influence of the depressurization of the liquid base of a soap on the removal of heat from it are presented in Fig. 5. The dependence obtained is linear in character. An increase in the pressure difference in the drying chamber in the process of dispersion of the soap base as a result of an increase in its temperature decreases the moisture content in it. To an optimum amount of heat removed, equal to 0.16 kg/kg according to the production requirements, corresponds the differential pressure 246 kPa in the drying chamber. In this case, the temperature of the soap base should be equal to 418 K.

The dependences obtained (Figs. 4 and 5) allow one to determine the heating temperature of a definite soap compound and the differential pressure in a drying chamber, providing the obtaining of a dried product with the necessary dispersion composition and a definite moisture content.

NOTATION

A, B, empirical coefficients in the Antoine equation; n, coefficients in the Freundlich equation; a_m, mass-transfer coefficient, m^2/sec; c, specific heat capacity, J/(kg·K); d, diameter, m; F, area of a surface, m^2; j, mass flow, kg/(m^2·sec); K_p, coefficient of molar vapor transfer, kg/(m·Pa·sec); m, mass, kg; P, pressure, kPa; R and r, total and current radii of particles, m; $r_{\text{v.f}}$, latent heat of vapor formation, J/kg; T, temperature, K; U, moisture content of a material, kg/kg; ΔU, amount of heat removed, kg/kg; V, volume, m^3; w, velocity of vapor flow, m/sec; δ_t, relative coefficient of thermal diffusion, 1/K; ε, porosity, m^3/m^3; λ, heat-conductivity coefficient, W/(m·K); μ, coefficient of dynamic viscosity, Pa·sec; ρ, density, kg/m^3; σ, surface-tension coefficient, N/m; τ, time, sec; ξ, extent of the evaporation zone, m. Subscripts: m, moist; liq, liquid; f, finite; cap, capillary; cr1, first critical point; mat, material; in, initial; h, heating; sat, saturated; v.f, vapor formation; s, surface; v, vapor; d, dry; t, thermal diffusion; c, center; ξ, evaporation surface; 1, evaporation zone; 2, moist zone; p, pressure.

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