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THE TRANSFER OF HEAT AND MASS IN CAPILLARY-POROUS MATERIALS IN THE HYGROSCOPIC STATE ON DRYING BY MEANS OF REDUCTION IN PRESSURE

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UDC 66.047.2

A mathematical model has been developed for the process of removing multicomponent moisture from disperse capillary-porous materials during the second drying period.

Selection of an optimum drying regime and development of efficient equipment designs to ensure required technological properties for materials to be dried are based on the solution of differential heat- and mass-transfer equations.

A description of the process for removing multicomponent moisture from capillary-porous materials by reduction of pressure in the second period of drying by a system of differential equations [1] involves certain difficulties resulting from the interaction of the components of the mixture in the course of their diffusion, the penetration to greater depths of the vaporization zone, and by such variable criteria of vaporization as the particle coordinate and time [2].

To derive analytical relationships describing the kinetic process, we made use of the Lykov solution [2] which corresponds to a simplified drying mechanism in the form of immersing the vaporization surface under the assumption that the i-th component of the mixture is transferred according to the principle of independent diffusion [3]. During the process of drying by means of pressure reduction, the inert gas is removed from the chamber at the very beginning of the process; consequently, we assume that the drying will subsequently occur in the vapor medium of the moisture that has been removed.

The distribution of the moisture content and temperature through the cross section of a particle which exhibits the shape of an infinite plate, according to the Lykov solution, is linear in nature in the vaporization zone:

$$\begin{gathered} U_{1i} = (U_{si} - U_{\xi i}) \frac{x-R}{\xi} + U_{si}, \\ T_{1m} = (T_{ms} - T_{m\xi}) \frac{x-R}{\xi} + T_{ms}, \end{gathered} \tag{1}$$

while in the moisture zone it is parabolic:

$$\begin{gathered} U_{2i} = U_{ci} - \left(\frac{x}{R-\xi}\right)^2 (U_{ci} - U_{\xi i}), \\ T_{2m} = T_{mc} - \left(\frac{x}{R-\xi}\right)^2 (T_{mc} - T_{m\xi}). \end{gathered} \tag{2}$$

The boundary conditions for the vaporization zone ξ can be formulated in the following manner:

$$T_{ms} = T, \tag{3}$$

Kirov Chemical Technological Institute, Kazan'. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 2, pp. 276-281, February, 1989. Original article submitted October 13, 1987.

$$a_{m1i}\rho_0\left(\frac{U_{\mathrm{s}i}-U_{\xi i}}{\xi}+\delta_{1i}\frac{T_{\mathrm{ms}}-T_{\mathrm{m}\xi}}{\xi}\right)+K_p\frac{p_i-p_{\xi i}}{\xi}-j_{\mathrm{s}i}(\tau)=0. \tag{4}$$

According to the boundary condition of the first kind (3), the temperature at the surface of the material particle throughout the entire drying process is equal to the temperature of the vapor medium, while the flow of moisture from the i-th component to the material surface is determined by the strength of the vapor removal system V_{vr}.

For expressions to link the equilibrium moisture content of the particle surface with the partial vapor pressure above that surface, we will use the Freundlich isotherm equation [4]:

$$U_{\mathrm{s}i}=a_{\mathrm{F}i}\left(\frac{p_i}{p_{\mathrm{sat}i}}\right)^{n_i^*}. \tag{5}$$

The boundary conditions for the moisture zone x = R − ξ are written in the form

$$\begin{gathered}\lambda_1\frac{T_{\mathrm{ms}}-T_{\mathrm{m}\xi}}{\xi}=-\lambda_2\left[\frac{2}{R-\xi}(T_{\mathrm{mc}}-T_{\mathrm{m}\xi})\right]-\sum_{i=1}^{n}r_ij_i(\tau),\\ a_{m1i}\left(\frac{U_{\mathrm{s}i}-U_{\xi i}}{\xi}+\delta_{1i}\frac{T_{\mathrm{ms}}-T_{\mathrm{m}\xi}}{\xi}\right)+\frac{K_p}{\rho_0}\frac{p_i-p_{\xi i}}{\xi}=\\ =2a_{m2i}\left(\frac{U_{\xi i}-U_{\mathrm{c}i}}{R-\xi}+\delta_{2i}\frac{T_{\mathrm{m}\xi}-T_{\mathrm{mc}}}{R-\xi}\right).\end{gathered} \tag{6}$$

In view of the fact that the structure of the material impedes the outflow of the vapor mixture, the partial pressure of the i-th component at the vaporization front is different from the partial pressure of the component over the surface of the particle material. The pressure drop for the i-th component of the mixture can be presented by means of the empirical Ergan equation [5]

$$p_{\xi i}-p_i=\left[150\frac{(1-\varepsilon_{\mathrm{m}})^2}{\varepsilon_{\mathrm{m}}^3}\frac{\mu_{\mathrm{d}i}w}{d_{\mathrm{C}}^2}+1.75\frac{1-\varepsilon_{\mathrm{m}}}{\varepsilon_{\mathrm{m}}^3}\frac{\rho_iw^2}{d_{\mathrm{C}}}\right]\xi. \tag{7}$$

The bound moisture is removed from the capillary-porous material during the second drying period. Since the bound moisture in the capillary-porous material moves rather slowly, the temperature of the fluid is virtually equal to the temperature of the capillary walls [6] and is associated with the pressure in the capillary by a relationship which, with consideration of the Antoine equation [7], is written in the form

$$p_{\xi i}=\exp\left\{(A_i-B_i/T_{\mathrm{m}\xi})+\left[-\frac{2\sigma_i\rho_i}{\rho_{\mathrm{f}i}r_{\mathrm{C}}\exp(A_i-B_i/T_{\mathrm{m}\xi})}\right]\right\}. \tag{8}$$

The total pressure over the vaporization surface will be determined by the relationship [7]

$$P_\xi=\sum_{i=1}^{n}p_{\xi i}. \tag{9}$$

The rates of change in the partial pressure of the i-th component of the mixture above the material and its temperature are determined on the basis of the material [8] and heat balance equations and are of the form

$$\begin{gathered}\frac{dp_i}{d\tau}=\frac{FRT}{V_{\mathrm{fr}}\mu_i}j_i-p_i\left(\frac{V_{\mathrm{vr}}}{V_{\mathrm{fr}}}-\frac{1}{T}\frac{dT}{d\tau}\right),\\ \frac{dT}{d\tau}=\left[\frac{F\left[\sum\limits_{i=1}^{n}j_i\right]T_{\mathrm{m}\xi}R^*}{\left(\sum\limits_{i=1}^{n}\mu_ip_i\right)V_{\mathrm{fr}}}-\frac{V_{\mathrm{vr}}}{V_{\mathrm{fr}}}\right]T.\end{gathered} \tag{10}$$

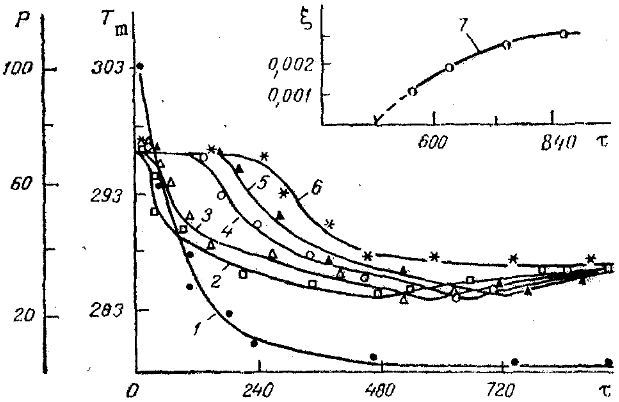

Fig. 1. Kinetic curves of the drying process: pressure (1); temperatures of particles of AR-3 activated carbon at various points: 2) x = 0; 3) 0.001; 4) 0.002; 5) 0.0025; 6) 0.003 m. Thicknesses of the vaporization zone (7).

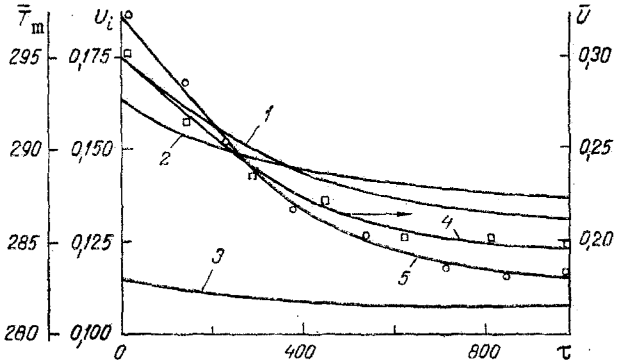

Fig. 2. Kinetic curves for the drying of AR-3 activated carbon: 1) ether moisture content; 2) alcohol moisture content; 3) water moisture content; 4) integral moisture content; 5) integral temperature.

Reduction of pressure in the drying chamber is accomplished by removal of the vapor mixture by means of a vacuum pump and through condensation of the vapors at the cooling surfaces. Consequently, the volumetric productivity of the vapor-removal system V_{vr} represents a combination of the volume productivities of the vacuum pump and the condenser: $V_{vr} = V_{vp} + V_{con}$. The total pressure of the vapor mixture above the material will be determined by an expression similar to Eq. (9).

We will formulate the initial conditions from the assumption as to a state of equilibrium for the system made up of the vapor and the moist material at the initial instant of time:

$$\rho_i(0)=\rho_{ei},\ T(x>R,\ 0)=T_m(x,\ 0)=T_I,\ U_i(x,\ 0)=U_{Ii},\ w(x,\ 0)=0. \tag{11}$$

For a solution of system of equations (1)-(11), describing the transfer of heat and mass in the capillary-porous material during the second period of drying, we use a numerical grid method.

To analyze the agreement between the model and the real process in an installation made up of a vacuum chamber with built-in scales, a vacuum pump, a condenser, a chromatograph, and instruments to record the temperatures of the material and the absolute pressure of the chamber, we conducted experimental studies of the process involved in the drying of AR-3 activated carbon with a three-component mixture made up of ethyl alcohol, diethyl ether, and water. Verification of the adequacy of the mathematical model showed that the divergence between the calculated values and the experimental data does not exceed 19%.

In modeling the drying process by means of system of equations (1)-(11), it became necessary to determine the relationship characterizing the velocity of vaporization-zone penetration. For the special case such a relationship was obtained through analysis of the temperature field [2] of the activated carbon particle (Fig. 1).

Analysis of the curves in the figure shows that removal of the moisture by reduction in pressure is accompanied by a decline in the temperature in the vaporization zone. Consequently, the position of the vaporization zone in the material with the passage of time can be determined on the basis of the change in temperature at specific control points of the material, separated at various distances from the surface. On cessation of moisture vaporization at a fixed segment of the material, the surface layers of the particle receiving heat from the warmer inner layers are heated. Beginning from that instant of time, a break is found to occur on the temperature curve. Processing of the obtained data by means of a computer yields an approximation curve of the function $\xi(\tau)$ in the form of a third-degree polynomial:

$$\xi(\tau) = -5.5162971 + 1.0104533\tau - 0.0196441\tau^2 - 0.0006297\tau^3.$$

The point at which the curve $\xi(\tau)$ intersects with the axis of abscissas corresponds to the onset of vaporization-zone penetration (τ_0 = 480 sec) and depends on the initial parameters of state for the moist material (temperature, moisture content).

As the ethyl alcohol, diethyl ether, and water mixture is removed from the AR-3 activated carbon by reduction of pressure there is a reduction in the integral vapor content and in the integral temperature of the material (Fig. 2). The integral moisture content on reduction of the integral temperature by 12-14 K changed from 30 to 20%. We can see on this curve that the rate of moisture evaporation diminishes markedly during the process. This is explained by a change in the energy binding the moisture to the material and by a reduction in the heat content.

Mathematical simulation reveals the nature of the change in the moisture-content curves with respect to the mixture components (Fig. 2). The moisture content of the diethyl ether which exhibits a low heat of vaporization and a weaker bond with the capillary-porous structure of the carbon undergoes a marked change during the drying process [9].

The results of our study were used in developing vacuum insulations which contained both a drying chamber and a condenser within a single hermetically sealed housing [10].

The mathematical model of the process for the removal of moisture by reduction of pressure is found in system of equations (1)-(11), which assumes identical conditions for any point within the drying chamber. Such conditions during the design stage are satisfied through uniform positioning of the distributive elements of the vacuum system within the confines of the equipment. The volume of the material in this case is divided into a number of layers of limited thickness, which ensure the uniformity of the product insofar as moisture content is concerned.

The operational regime of this insulation involves a sequence of creating a vacuum with uniform heating of the entire volume of the material, which provides for the intensity of the moisture-removal process from the capillary-porous bodies and the attainment of the required technological properties for the product being dried.

NOTATION

U, moisture content, kg/kg; x, an instantaneous coordinate, m; R, particle radius, m; T, T_m, temperatures of the vapor mixture and the material, K; ξ, thickness of the vaporization zone, m; a_m, coefficient of mass conductivity, m^2/sec; ρ, ρ_f, ρ_0, densities of the vapor, the fluid, and the material, respectively, kg/m^3; δ, relative coefficient of thermal diffusion, 1/K; K_p, coefficient of molar vapor transfer, kg/(m·Pa·sec); P, p, total pressure of the mixture and the partial pressure of the component, kPa; j, mass flow, $kg/(m^2\cdot sec)$; τ, time, sec; V_{vr}, V_{vp}, V_{con}, volumetric productivities of the vapor-removal system, the vacuum pump, and the condenser, respectively, m^3/sec; a_F, n^*, coefficients in the Freundlich isotherm equation; λ, coefficient of thermal conductivity for the material, W/(kg·K); r, latent heat of vaporization, J/kg; ε_m, porosity of the material; μ_d, coefficient of dynamic viscosity, Pa·sec; w, rate of vapor flow, m/sec; $\overline{r}_c$ and d_c, mean radius and diameter of the capillary, m; A, B, coefficients in the Antoine equation; σ, coefficient of surface tension, N/m; V_{free}, free volume of the equipment, m^2; μ, molecular weight of the component, kg/kmole; F, heat and mass exchange surface, m^2; n, number of components in the mixture; R^*, universal gas constant, J/(kmole·K). Subscripts: 1) vaporization zone; 2) moisture zone; i) component of the vapor or the fluid; s) particle surface; ξ) vaporization surface; m) material; c) particle center; sat) saturation; vr) system of vapor removal; fr) free; C) capillary; f) fluid; I) initial; con) condenser; vp) vacuum pump; e) equilibrium.

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THERMAL CONDUCTIVITY OF MOIST POROUS MATERIALS

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UDC 536.246

We propose both a model and a method of calculating the effective thermal conductivity of moist porous materials made of a three-component structure with interpenetrating components.

In studying the thermal conductivity of moist porous materials, extensive use is made of the methods of modeling, which make allowance both for the structure of the material and for the heat and mass transfer processes occurring within. In the model proposed by Krisher, considerable attention is given to the significant feature of a moist porous material, and namely, the presence of both dry and moist sections within the pores of the solid skeleton, and consideration is also given here to the effect of vapor diffusion on the transfer of heat [1]. However, the Krisher model is quite removed from the geometric structure of a real porous material and contains unknown empirical parameters *a* and b which describe the fraction (*a*) of the segments oriented perpendicular to the flow as well as the fraction (b) of the skeleton wetted by the moisture. The authors of [2] have modeled the moistened material of a structure with interpenetrating components, thus making it possible to do away with the empirical parameter *a*; however, the fraction of moistened sectors, as before, was taken into consideration by means of the parameter b.

It has been demonstrated experimentally in [3] that the thermal conductivity of a moistened material must significantly depend on the nature of the distribution of moisture through the volume. A characteristic of surface wetting is generally found in the contact wetting

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Leningrad Institute of Precision Mechanics and Optics. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 56, No. 2, pp. 281-291, February, 1989. Original article submitted October 5, 1987.