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NONSTEADY HEAT AND MASS TRANSFER IN DRYING BY REDUCED PRESSURE

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The article examines nonsteady heat and mass transfer in the process of drying by reduced pressure, on the assumption that the moisture is situated on the surface of an infinite plate.

Drying by reduced pressure may be effected in various regimes: linear reduction of moisture content, linear reduction of temperatures, or constant rate of reducing pressure. The most favorable regime is linear reduction of moisture content which makes it possible to carry out the process of moisture removal at optimum speed. In this case the moisture content has to change according to the regularity

$$U = U_{\mathrm{i}} - N\tau. \tag{1}$$

The drying rate is determined on the basis of the technological requirements that the product has to fulfill. The drying rate depends on the heat flux supplied for evaporating the liquid [1]:

$$N = \frac{qf}{rm_{\mathrm{d.m.}}}. \tag{2}$$

If we neglect the change of evaporation heat, of the heat-exchange surface, and of the weight of dry substance in the drying process, then the constant value of the drying rate is determined by the constant value of the heat flux. In the process of realizing this regime of drying by reduced pressure, evaporation of moisture is effected by liberation of the internal energy of the moist material [2].

If there is considerable thermal resistance or if the particles are large, the evaporation process of the moisture will to a certain extent be affected by the inhomogeneity of the temperature field inside the particles. Finding the temperature field is connected with the solution of the differential equation of heat conduction. For an infinite plate, on condition that the moisture is only on the surface, the equation is as follows:

$$\frac{\partial T(x;\ \tau)}{\partial \tau} = a\,\frac{\partial^2 T(x;\ \tau)}{\partial x^2}. \tag{3}$$

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The solution of Eq. (3) with the boundary conditions

$$T(x;\ 0)=T_{\mathrm{i}}; \tag{4}$$

$$\pm\frac{\partial T(\pm b;\ \tau)}{\partial x}+\frac{q}{\lambda}=0; \tag{5}$$

$$\frac{\partial T(0;\ \tau)}{\partial x}=0 \tag{6}$$

has the form [3, 4]

$$T(x;\ \tau)=T_{\mathrm{i}}-\frac{q}{c\gamma b}\left[\tau-\frac{b^2-3x^2}{6a}-\frac{b^2}{a}\sum_{n=1}^{\infty}(-1)^{n+1}\frac{2}{n^2\pi^2}\cos\left(n\pi\frac{x}{b}\right)\exp\left(-n^2\pi^2\varphi\right)\right]. \tag{7}$$

With x = b, Eq. (7) yields the dependence of the surface temperature on time:

$$T(b;\ \tau)=T_{\mathrm{i}}-\frac{q}{c\gamma b}\left[\tau+\frac{b^2}{3a}-\frac{b^2}{a}\sum_{n=1}^{\infty}(-1)^{n+1}\frac{2}{n^2\pi^2}\cos(n\pi)\exp\left(-n^2\pi^2\varphi\right)\right]. \tag{8}$$

Assuming that the temperature of the moisture on the surface of the material is equal to the temperature of the surface of the plate, and using Antoine's equation [5], we obtain the dependence of the pressure of the medium above the surface of the plate on time that ensures a constant drying rate:

$$P=\exp\left[A-\frac{B}{T_{\mathrm{i}}-\dfrac{q}{c\gamma b}\left[\tau+\dfrac{b^2}{3a}-\dfrac{b^2}{a}\displaystyle\sum_{n=1}^{\infty}(-1)^{n+1}\frac{2}{n^2\pi^2}\cos(n\pi)\exp\left(-n^2\pi^2\varphi\right)\right]}\right]. \tag{9}$$

Experiments showed that the deviation from the linear regularity (1) due to increased evaporation heat in proportion to reduced temperature of the evaporating liquid does not exceed 5%. The process of decreasing pressure above the surface of the material continues up to some minimum value that depends on the characteristics of the vacuum pump [6].

We assume that henceforth, beginning at the instant τ_1 determined from Eq. (9), the pressure above the surface of the plate remains constant and equal to this minimum value. Then the temperature of the surface of the material does not decrease any more although the heat supply to the surface does not cease since the inner layers of the plate are warmer than the outer layers.

If we approximate expression (7) for $\tau = \tau_1$ by a parabolic dependence and determine the surface temperature from (8) for $\tau = \tau_1$, we obtain new boundary conditions of the differential equation (3):

$$T(x;\ \tau_1)=\frac{T_0(b^2-x^2)}{b^2}; \tag{10}$$

$$T_{\mathrm{s}}(\tau)=T_{\mathrm{i}}-\frac{q}{c\gamma b}\left[\tau_1+\frac{b^2}{3a}-\frac{b^2}{a}\sum_{n=1}^{\infty}(-1)^{n+1}\frac{2}{n^2\pi^2}\cos(n\pi)\exp\left(-n^2\pi^2\frac{a\tau_1}{b^2}\right)\right], \tag{11}$$

with which its solution has the form

$$T(x;\ \tau)=T_{\mathrm{s}}+\frac{32(T_0-T_{\mathrm{s}})}{\pi^3}\sum_{n=0}^{\infty}\frac{(-1)^n}{(2n+1)^3}\exp\left[-\frac{a(2n+1)^2(n+1)^2(\tau-\tau_1)}{4b^2}\right]\cos\frac{(2n+1)\pi x}{2b}. \tag{12}$$

Figure 1 shows the results of mathematical modeling of the temperature profile over the section of the material for different instants. The object of investigation was a polystyrene plate 0.3 × 0.4 × 0.04 m in size from whose surface isopropyl alcohol evaporated.

If we determine the temperature gradient on the surface of the plate from Eq. (12) and substitute it into the Fourier equation

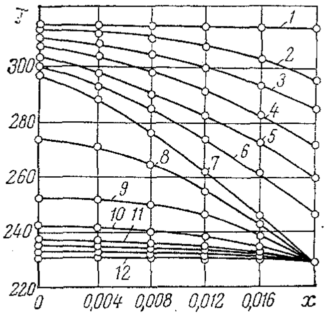

Fig. 1

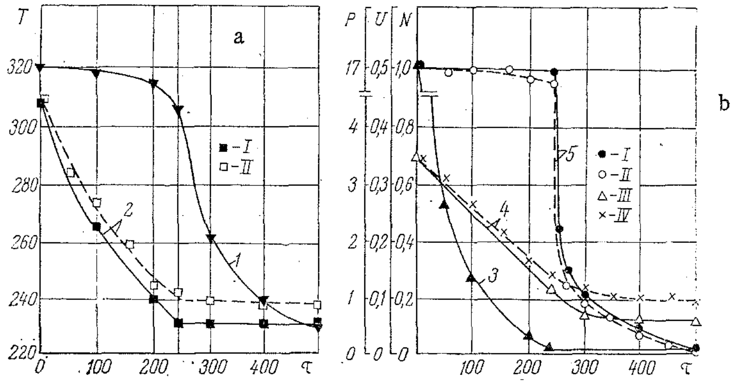

Fig. 2

Fig. 1. Temperature field (T, °K) in drying by reduced pressure for the instants (τ, sec): 1) τ = 0; 2) 40; 3) 80; 4) 120; 5) 160; 6) 200; 7) 240; 8) 280; 9) 320; 10) 360; 11) 400; 12) 500.

Fig. 2. Change of the principal parameters characterizing drying in time: a) 1) theoretical change of temperature at the center of the plate (T_0, °K); 2) surface temperature (T_s, °K): I) theoretical; II) experimentally obtained; b) 3) change of pressure (P, kPa); 4) moisture content (U, kg mst/kg dry mat.): III) theoretical; IV) experimentally obtained; 5) drying rate (N, liters/sec): I) theoretical; II) experimentally obtained.

$$dQ = -\lambda\left(\frac{\partial T(x;\ \tau)}{\partial x}\right)\Bigg|_{x=b} f d\tau, \tag{13}$$

we find what amount of heat is supplied from the inner layers to the surface of the plate. Under adiabatic conditions this heat is expended on evaporating the moisture:

$$dQ = [r_0 - (c_V - c_l)(T - 273)]\, m_{\text{d.m.}} dU. \tag{14}$$

The joint solution of Eqs. (12)-(14) describes the kinetics of drying at finite residual pressure above the surface of the material:

$$N = \frac{\lambda \dfrac{32(T_0 - T_s)}{\pi^3} \displaystyle\sum_{n=0}^{\infty} \frac{(-1)^n}{(2n+1)^3} (-1)^{n-1} \exp\left[-\frac{a(2n+1)^2(n+1)^2(\tau - \tau_1)}{4b^2}\right]}{[r_0 - (c_V - c_l)(T - 273)]} \; \frac{\dfrac{(2n+1)\pi}{2b} f}{m_{\text{d.m.}}}. \tag{15}$$

Figure 2 presents the principal theoretical and experimental dependences characterizing the process of removing isopropyl alcohol from the surface of a polystyrene plate.

Deviations of the drying rate, of the moisture content, and of the surface temperature of the plate from the theoretical values established in the course of the experimental verification of the mathematical model did not exceed 8%.

NOTATION

U, running moisture content; U_i, initial moisture content; N, drying rate; T, T_i, T_0, T_s, temperature of the material: running, initial, at the center of the plate, on the surface, respectively; P, pressure above the surface of the material; q, heat flux on the surface of the material; r, specific evaporation heat; γ, specific weight of the material; a, thermal diffusivity; c, c_V, c_l, specific heat of the material, of vapor, and of the liquid, respectively; $m_{\text{d.m.}}$, weight of dry substance; A, B, constants in Antoine's equation; f, heat-exchange surface; x, running coordinate; τ, running time; $\varphi = a\tau/b^2$, dimensionless time; b, half-thickness of the plate; n, eigenvalues.

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EXPERIMENTAL INVESTIGATION OF THE THERMAL CONDUCTIVITY OF VAPOR—GAS MIXTURES WITH LOW VAPOR CONCENTRATION

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We give the results of an experimental investigation of the thermal conductivity of vapor—gas mixtures with low vapor concentration.

Determining the thermal conductivity of vapor—gas mixtures with low vapor concentration is of interest in studying, with the aid of a diffusion chamber, the early stages of the formation of aerosol particles when condensation processes take place [1].

An absolute heated-filament method (stationary variant) [2, 3] was used to investigate the thermal conductivity of mixtures of Ar (N_2) with vapors of C_2H_5OH, C_3H_7OH, C_3H_8O, C_6H_{14}, C_7H_{16}, and CCl_4 with an error not exceeding 1.5% in the 330-370°K temperature range. The vapor concentration in the mixture did not exceed 0.01-0.05 mole fraction.

The characteristics of the pure components were the following: Ar — brand A, with a 0.987 Ar content; N_2 — 0.99 N_2; the alcohols were brand KhCh. The vapor—gas mixtures were prepared at room temperature according to partial pressure with the aid of an MBP manometer in 10-liter tanks. The pressure of the mixture in the tank differed according to the vapor concentration and the temperature at which the investigation was carried out (see the saturation curves for the vapors, Figs. 1-2); however, the pressure was sufficient to repeat the experiment two or three times if necessary. With increasing vapor concentration in the mixture, there was a decrease in the total pressure of the vapor—gas mixture in the measuring cell (Table 1).

Determination of the thermal conductivities of Ar and N_2 at pressures of $(0.25\text{-}1.01)\cdot 10^5$ Pa showed (Table 2) that the differences in the thermal-conductivity values at the indicated pressures are within the error limits of the experiment.

Figures 1 and 2 show the variation of the thermal conductivity of mixtures of Ar (N_2) with vapors of C_2H_5OH, C_3H_7OH, C_3H_8O, C_6H_{14}, C_7H_{16}, and CCl_4 as a function of temperature in the 250-370°K range; the data for the 250-330°K range were obtained in experiments we conducted earlier [17]. It should be noted that the values of the thermal conductivity of the mixtures shown in Figs. 1-2 and the values for the pure components (Table 3) do not take account of the thermal-accommodation effect. An estimate of the temperature-jump correction to the measured thermal conductivity showed that for the mixture pressures shown in Table 1, the influence of the temperature jump does not exceed 0.27% for argon and 0.35% for nitrogen. The estimate was made according to the formula [6, 7].

$$\delta = \frac{100\lambda' \sqrt{T}}{r_1 \ln \frac{r_2}{r_1}} \frac{1}{P} \frac{2-a}{a} \sqrt{\frac{\pi M}{2R}} \left(\frac{c_v}{R} + \frac{1}{2} \right)^{-1}.$$

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