SECTION 6. ENERGY

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6.1 Mass transfer during drying of capillary-porous colloidal materials in a fixed bed

During the drying of wet materials, two processes take place simultaneously: moisture evaporation (mass transfer) and heat transfer (heat exchange). Heat transfer, which takes place simultaneously with mass transfer, has specific features compared to pure heat transfer. The process of drying dispersed materials in a fixed bed through which the coolant passes is determined by the nature of mass transfer and the value of the mass transfer coefficient.

Recently, the high efficiency of the process of filtration drying and drying in a fixed bed [264 - 266] has been proven in comparison with the convective and fluidized bed. This is due to the fact that during the dehydration of dispersed materials by such methods, there is no release of the fine phase of the dried material into the environment, and energy costs for its implementation are significantly reduced. However, the efficiency of drying in a fixed bed in terms of mass transfer coefficients is not well understood.

Based on the study of the drying kinetics of capillary-porous colloidal materials [267] in a fixed bed, it is necessary to calculate the mass transfer coefficients. To obtain analytical dependencies in the form of criterion equations for predicting the coefficients in the studied range of changes in the operating parameters of the process.

Drying of the dispersed material was carried out in a fixed bed (convective method with simultaneous filtering of the coolant through the material layer). The study was performed in the range of temperature changes of 80 – 175 °C; fictitious coolant velocity of 0.4 –1.2 m/s and material layer height (20 – 60) · 10^{-3} m.

To study the drying kinetics in a fixed bed, lumpy polydisperse clay with an initial moisture content of ~18 % was used. The material particles had irregular geometric shapes of different fractional composition:

1. $0 < d < 0.005$ m – 1.7 % ;

2. 0.005 < d < 0.01 m – 11.7 % (nominal diameter d_{nom} = 7.3 mm);

3. 0.01 < d < 0.02 m – 84.5 % (nominal diameter d_{nom} = 14.3 mm);

4. d > 0.02 m – 2.1 % (nominal diameter d_{nom} = 17.7 mm).

The presence of particles of different sizes leads to an uneven diffusion resistance and, in general, increases the drying time and leads to energy consumption. However, drying pre-formed particles of the same size can significantly intensify the process. Therefore, another object of drying was clay formed in the form of cylindrical particles with a size of $d \times h = 6 \cdot 10^{-3} \times 10 \cdot 10^{-3}$ m with an initial moisture content of ~18 %.

To generalize the drying kinetics of lumpy polydisperse clay in a fixed bed in the first period, a system of differential equations of material balance in the bed and drying kinetics was used:

$$\begin{cases} \frac{\partial \varphi}{\partial H} = a \cdot (1 - \varphi); \\ \frac{\partial W}{\partial \tau} = n \cdot (1 - \varphi). \end{cases} \tag{1}$$

where, $\frac{\partial \varphi}{\partial H}$ – is the change in relative humidity in a layer of material with a height of H, 1/m; $\frac{\partial W}{\partial \tau}$ – is the change in material humidity over time, i.e., the drying rate, %/s; φ – is the relative humidity of the air; W – is the running humidity of the material, %; a is the kinetic coefficient, 1/m; n is the proportionality coefficient (1/s), which can be calculated: $n = S \cdot \beta \cdot P_S$; S is the total outer surface of the material parts, m^2.

The kinetic coefficient (a) does not depend on the process parameters, but depends on the structure of the material and is calculated by the formula:

$$a = \frac{\Pi \cdot m \cdot n}{0{,}622 \cdot P_S},$$

where, Π – is the barometric pressure, Pa; P_S – is the partial pressure of saturated vapor, Pa; m – is the proportionality coefficient (1/m) and can be determined:

$$m = \frac{\rho \cdot F}{100 \cdot M}$$

then

$$a = \frac{\Pi \cdot \rho \cdot F \cdot S \cdot \beta}{62{,}2 \cdot M}, \tag{2}$$

or $$\beta = \frac{a \cdot 62{,}2 \cdot M}{\Pi \cdot \rho \cdot F \cdot S}, \tag{3}$$

where, ρ – is the density of the coolant, kg/m^3; F – is the cross-sectional area of the container, m^2; M – is the mass velocity of the coolant, kg/s; β – is the mass transfer coefficient, %/(s·m^2·Pa).

The solution to the system of differential equations (1) is the equation describing the drying kinetics in the first period until the critical moisture content is reached:

$$\frac{W}{W_0} = 1 - \alpha \cdot \tau \cdot e^{-a \cdot H}, \tag{4}$$

where, α – drying coefficient (1/s), which can be calculated using the formula:

$$\alpha = \frac{S \cdot \beta \cdot \mathrm{P}_S \cdot (1 - \varphi_0)}{W_0}, \tag{5}$$

W_0 – initial moisture content of the material, %; φ_0 – initial relative humidity.

Let's write equation (4) in the form: $\frac{1 - \frac{W}{W_0}}{\tau} = \alpha \cdot e^{-a \cdot H}$. Let's assume that $\frac{1 - \frac{W}{W_0}}{\tau} = y$

Then: $$y = \alpha \cdot e^{-a \cdot H} \tag{6}$$

Logarithmizing equation (6), we obtain:

$$\ln(y) = \ln(\alpha) - a \cdot H \cdot \ln(e)$$

or $$\ln(y) = \ln(\alpha) - a \cdot H \tag{7}$$

To determine the coefficients and a, using equation (7), the results of studies of the kinetics of the drying process in the first period are presented in the form of dependence: $\ln \frac{1 - \frac{W}{W_0}}{\tau} = f(H)$ (figs. 1-2).

From the graphical dependencies shown in Figs. 1 - 2, the drying coefficient $\ln(\alpha)$ is determined by the segment cut off by the line on the ordinate axis. The value of the kinetic coefficient a was found as the tangent of the angle of inclination of the line to the abscissa. The results of determining the kinetic coefficients a and α are presented in Table 1.

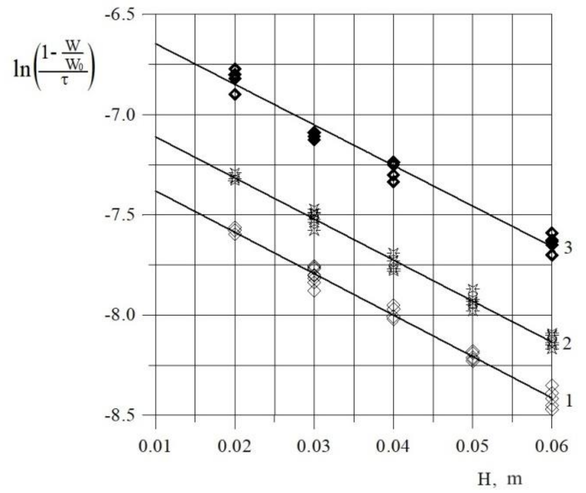

Figure 1. Determination of the kinetic coefficients α and *a* for lumpy polydisperse clay (ΔP_c =100 Pa): 1 – T = 80°C; 2 – T = 100°C; 3 – T = 150°C

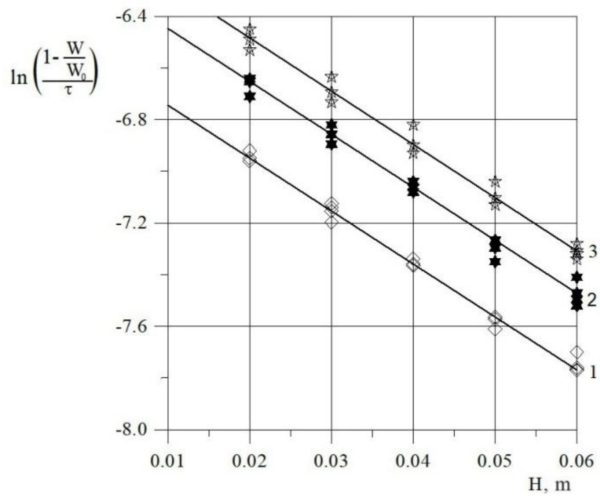

Figure 2. Determination of the kinetic coefficients α and *a* for lumpy polydisperse clay (T=175°C): 1 – ΔP_c = 100 Pa; 2 – ΔP_c= 200 Pa; 3 – ΔP_c= 400 Pa

The value of the kinetic coefficient *a* is constant and is *a* = 20.5 (1/m), and the coefficient α varies depending on the temperature and pressure drop (increases with increasing coolant temperature and pressure drop) (Table 1). Given a known value of the kinetic coefficient (*a*), the calculated dependence (3) is presented in the form:

$$\frac{W}{W_0} = 1 - \alpha \cdot \tau \cdot e^{-20,5 \cdot H} \quad (8)$$

The drying rate N for lumpy polydisperse clay in the first period, as follows from the analysis of kinetic coefficients, increases with increasing temperature and speed of the coolant movement through the layer of wet material and with decreasing its height (Table 1).

Table 1

Determination of kinetic drying coefficients depending on the parameters of the process of dehydration of lumpy polydisperse clay in a fixed bed

Process parameters			The first drying period			
T, °C	H, m	ΔP_c, Pa	*a, 1/m*	$\ln(\alpha)$	α*, 1/s*	N, %/s
175	0.03	100	20.5	-6.34	0.0018	0.0149
	0.03	200	20.5	-6.24	0.0019	0.0187
	0.03	400	20.5	-6.07	0.0023	0.0209
150	0.06	100	20.5	-6.44	0.0016	0.0068
	0.04	100	20.5	-6.44	0.0016	0.0083
	0.02	100	20.5	-6.44	0.0016	0.0197
	0.03	100	20.5	-6.44	0.0016	0.0128
80	0.03	100	20.5	-7.17	0.0008	0.0071
100	0.03	100	20.5	-6.91	0.0010	0.0099

In engineering calculations, criterion dependencies are often used to determine mass transfer coefficients, followed by modified equations that allow for the calculation of the material's running moisture content. To develop the mass transfer criterion equation, it is necessary to calculate the mass transfer coefficients and, accordingly, the Nusselt mass transfer criteria Nu' for different mass velocities of the coolant. Equation (3) was used to determine the experimental values of the mass transfer coefficients β. And from this value, the diffusion Nusselt similarity criterion Nu' was calculated for the first period of drying lumpy polydisperse clay in a fixed bed according to dependence:

$$\mathrm{Nu}' = \frac{\beta \cdot d_e'}{D}, \tag{9}$$

where Nu´ - Nusselt's diffusion similarity number; β - is the mass transfer coefficient, m/s; *D* – is the diffusion coefficient, m^2/s; d'_e - is the equivalent diameter of voids in the material layer, m.

Using the general form of the criterion equation, we obtained:

$$\mathrm{Nu}' = A \cdot Re^{m} \cdot Pr'^{n} \cdot \left(\frac{H}{d_e}\right)^{k}, \qquad (10)$$

where Re is the Reynolds similarity number; Pr' is the Prandtl diffusion similarity number; A is the proportionality coefficient; *m, n, k* – are the degree indices of the similarity number; (H/d_e) – is the ratio of the height of a material layer to the equivalent diameter of a particle;

or

$$\frac{\beta \cdot d_e'}{D} = A \cdot \left(\frac{\omega \cdot d_e' \cdot \rho}{\mu}\right)^{m} \cdot \left(\frac{\mu}{D \cdot \rho}\right)^{n} \cdot \left(\frac{H}{d_e}\right)^{k}, \qquad (11)$$

where ω – is the actual coolant velocity, m/s; ρ is the coolant density, kg/m^3; μ is the dynamic viscosity coefficient of the coolant, Pa·s.

Based on the known values of mass velocities, the actual speed of the coolant movement through the material layer and the values of the numbers of the Reynolds Re and Prandtl number Pr' were calculated. In other words, a system of four equations with four unknowns at certain values of the calculated criteria Nu', Re, and Pr' was compiled and the unknowns of the proportionality coefficient A and the indicators of the degrees of similarity criteria *m, n, k* included in equation (10) were determined under different conditions of the drying process. The ratio of the height of the material layer to the equivalent diameter of the parts H/d_e of lumpy polydisperse clay was used as a geometric simplex. As a result of the calculation, the coefficients A = 2.6; *m* = 0.92; *n* = 0.9; *k* = -0.1 were determined. The criterion dependence is as follow

$$\mathrm{Nu}' = 2.6 \cdot \mathrm{Re}^{0.92} \cdot \mathrm{Pr}'^{\,0.9} \cdot \left(\frac{H}{d_e}\right)^{-0,1} \qquad (12)$$

That is, equation (12) shows that as the Reynolds and Prandtl numbers increase, the mass transfer coefficient increases, and an increase in the H/d_e ratio leads to its decrease.

The comparison of the calculated values determined by dependence (12) and the mass transfer coefficients of lumpy polydisperse clay in a stationary layer obtained by equation (3) is shown in Fig. 3. The calculated values β_{calc} have an acceptable agreement with the experimental values β_{exp}, and the error does not exceed 7 % (Fig. 3).

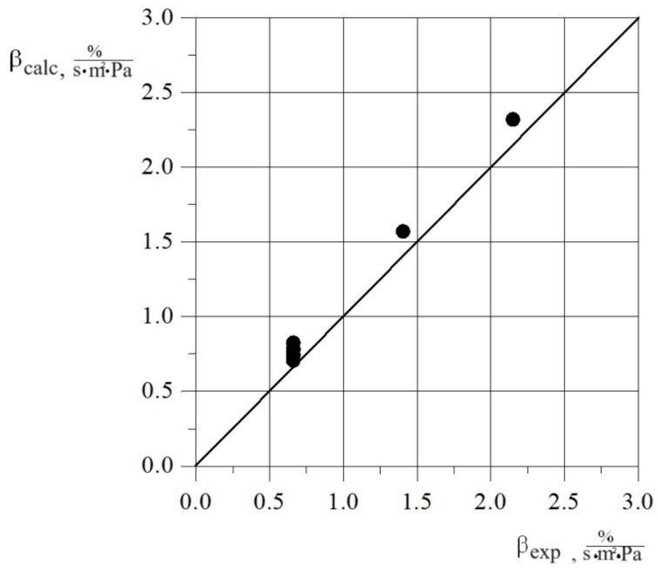

Figure 3. Comparison of the calculated values obtained by equation (12) and the experimental ones determined by dependence (3) of the mass transfer coefficients of drying lumpy polydisperse clay in a fixed bed

Similarly, the results of the drying kinetics of clay formed in the form of cylindrical particles with particle sizes (h x d = 0.006 x 0.01 mm) in a stationary layer were analyzed and summarized in the form of the following dependence: $\ln \frac{1-\frac{W}{W_0}}{\tau} = f(H)$ (Figs. 4, 5).

The graphical dependencies are linear (Figs. 4, 5). Based on the results of determining the kinetic coefficients, Table 2 was compiled, which contains the values found for the corresponding process parameters.

That is, increasing the height of the material layer does not affect the coefficient α, while the drying rate *N* decreases. An increase in the temperature of the coolant and the pressure drop leads to an increase in the coefficient α and the drying rate *N*. The value of the kinetic coefficient *a* does not change with the change in the conditions of the drying process in a fixed bed and is *a* = 23.45 (1/m) for clay particles formed in the form of cylinders.

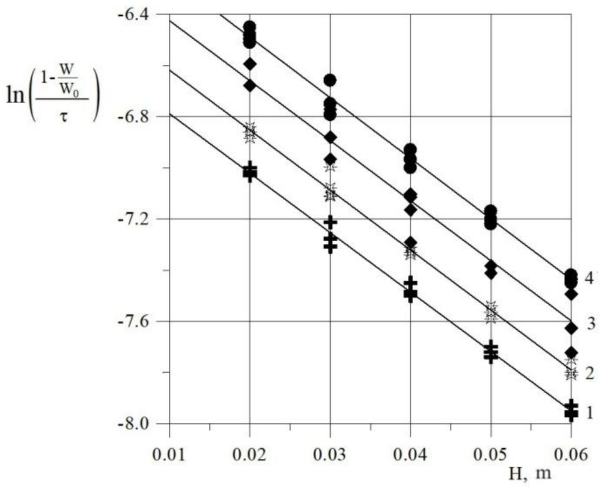

Figure 4. Determination of the kinetic coefficients α and *a* for clay formed in the form of cylindrical particles at different coolant temperatures (ΔP_c = 100 Pa): 1 – T = 80°C; 2 – T = 100°C; 3 – T = 150°C; 4 – T = 175°C

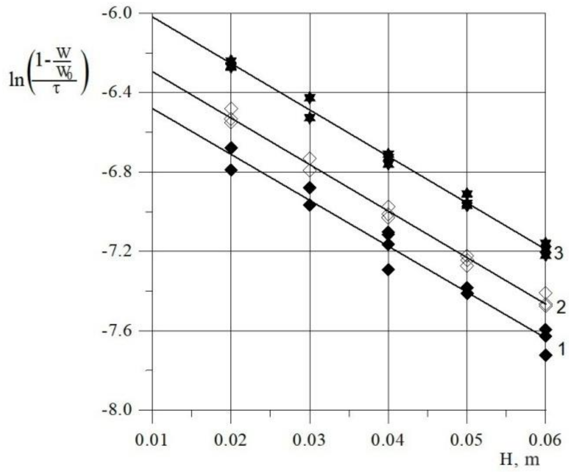

Figure 5. Determination of the kinetic coefficients α and *a* for clay formed as cylindrical particles at different pressure drops (T=150°C): 1 – ΔP_c = 100 Pa; 2 – ΔP_c = 200 Pa; 3 – ΔP_c = 400 Pa

Table 2.

Determination of kinetic drying coefficients depending on the parameters of the clay dehydration process, formed in the form of cylindrical particles in a fixed bed

Process parameters			The first drying period			
T, °C	H, m	ΔP_c, Pa	*a, 1/m*	$\ln(\alpha)$	α*, 1/s*	N, %/s
150	0.02	100	23.45	-6.19	0.0021	0.0258
150	0.03	100	23.45	-6.19	0.0021	0.0195
150	0.04	100	23.45	-6.19	0.0021	0.0158
150	0.05	100	23.45	-6.19	0.00217	0.0126
150	0.06	100	23.45	-6.19	0.0021	0.0108
150	0.03	200	23.45	-6.06	0.0023	0.0206
150	0.03	400	23.45	-5.78	0.0030	0.0265
80	0.03	100	23.45	-6.56	0.0014	0.0119
100	0.03	100	23.45	-6.38	0.0017	0.0146
175	0.03	100	23.45	-6.02	0.0024	0.0242

Based on the obtained value of the kinetic coefficient *a*, the values of the mass transfer coefficients β were calculated according to Equation (3), and then the value of the Nusselt diffusion number was found. As a result of solving the system of four equations with four unknowns, the coefficients A = 1.86; *m* = 0.99; *n* = 1.0; *k* = 0. The criterion dependence is as follows:

$$Nu' = 1.86 \cdot Re^{0.99} \cdot Pr'^{1.0} \cdot \left(\frac{H}{d_e}\right)^{0} \quad (13)$$

In the studied interval of changes in the height of the layer H, the component H/d_e can be neglected, then dependence (13) will have the form:

$$Nu' = 1.86 \cdot Re^{0.99} \cdot Pr'^{1.0} \quad (14)$$

Equation (14) shows that the mass transfer coefficients β increase with an increase in the Reynolds and Prandtl numbers. Based on the calculated values of the mass transfer coefficients according to dependence (14) and those obtained by equation (3) for clay formed in the form of cylindrical particles during its drying in a fixed bed, a correlation dependence was constructed (Fig. 6), which shows an acceptable consistency of these values.

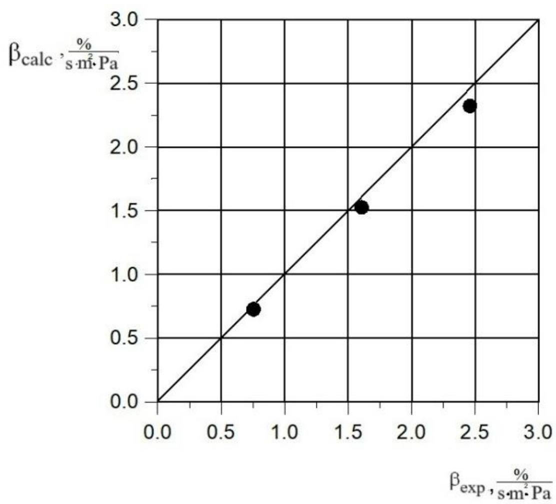

Figure 6. Comparison of the calculated values obtained by equation (14) and the experimental ones determined by dependence (3) of the mass transfer coefficients during the drying of clay in the form of cylindrical particles in a fixed bed

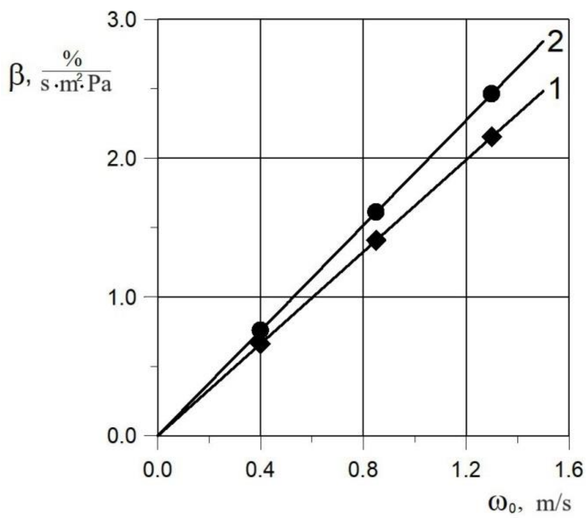

Figure 7. Dependence of the mass transfer coefficient on the fictitious coolant velocity: 1 - lumpy polydisperse clay; 2 - clay formed in the form of cylindrical particles

The value of mass transfer coefficients in the studied range of changes in process parameters varies within 0.66 – 2.15 %/(s·m^2·Pa) for lumpy polydisperse clay particles and 0.76 – 2.46 %/(s·m^2·Pa) for clay formed in the form of cylindrical particles and depends on the physical characteristics of the coolant, in particular, on the fictitious speed of its movement through the layer of dispersed material (Fig. 7).

Conclusions. The experimental studies on the kinetics of drying lumpy polydisperse clay in a fixed bed made it possible to determine the mass transfer coefficients and obtain criterion dependencies for their prediction. It was found that the mass transfer coefficients for clay in the form of cylindrical particles have higher values compared to lumpy polydisperse clay. For example, under drying conditions (T = 150°C; H = 0.03 m; ΔP = 100 Pa), the mass transfer coefficient β for cylindrical particles is 0.7239; for polydisperse clay, it is 0.6632 (1.1 times higher). This is due to the fact that the layer of polydisperse clay contains particles of different sizes and the largest of them limit the diffusion of moisture from the material and, accordingly, the mass transfer coefficient in this case will be lower.