Journal of Engineering Physics and Thermophysics, Vol. 80, No. 4, 2007

MODELING OF THE PROCESS OF DRYING OF A DISPERSED MATERIAL BY A SUPERHEATED STEAM IN A PNEUMATIC-TRANSPORT SYSTEM

Yu. S. Teplitskii and V. I. Kovenskii

UDC 677.057.135.2

Mathematical modeling of the cyclic drying of a dispersed material moving in the ascending and descending flows of a superheated steam has been performed. The dependence of the moisture content of particles on the operating parameters of a pneumatic-transport system has been established.

By virtue of its well-known advantages (inert heat-transfer agent with a specific heat nearly twice as high as the specific heat of air, integration of two or more processes in one apparatus, elimination of thermal pretreatment of raw material in many cases, etc.), superheated-steam drying is a rational method of drying different materials [1]. Investigation of the pneumatic-transport technology and equipment for drying of moist dispersed materials in the flow of a superheated steam enables one, as evaluations show, to create rather compact and economical dryers. In this connection, the present work seeks to formulate a physical model of the process and to perform, on this basis, its mathematical modeling for establishing the influence of different physical, hydrodynamic, and thermophysical factors on the intensity of the process of drying.

Figure 1 diagrammatically shows the *i*th cycle of the process of drying of a moist dispersed material in the ascending (a) and descending (b) steam flows. A physical model of the process is based on the following assumptions:

(a) the process follows the regime of decreasing drying rate;

(b) when the temperature of particles is lower than the critical temperature of the steam, we allow for its condensation on the particle surface; subsequent removal of the condensed moisture occurs in the regime of constant drying rate;

(c) the temperature of the steam escaping from the particles is equal to the particle temperature;

(d) constant pressure is maintained in the system;

(e) conductive transfer of heat is disregarded;

(f) drying occurs under external-problem conditions;

(g) particle-momentum loss in passage from one riser to the other is disregarded (Fig. 1).

A mathematical model of drying involves the following equations describing the process in the *i*th cycle (for the sake of simplicity we have omitted the notation of the cycle in the equations.)

1. Continuity Equation for Solid Particles:

$$\frac{d\,(\rho_s\,(1-\varepsilon)\,u_s)}{dx} = \rho_s^0\,(1-\varepsilon)\,u_s\,\frac{d\hat{c}_s}{dx}\,. \tag{1}$$

With account for $\rho_s = \rho_s^0(1+\hat{c}_s)$, we obtain

$$\frac{d}{dx}\,(u_s\,(1-\varepsilon)) = 0\,. \tag{2}$$

Equation (2) demonstrates that the volumetric flow rate of particles is preserved in the system.

A. V. Luikov Heat and Mass Transfer Institute, National Academy of Sciences of Belarus, 15 P. Brovka Str., Minsk, 220072, Belarus; email: kvi@hmti.ac.by. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 80, No. 4, pp. 147–155, July–August, 2007. Original article submitted January 26, 2006.

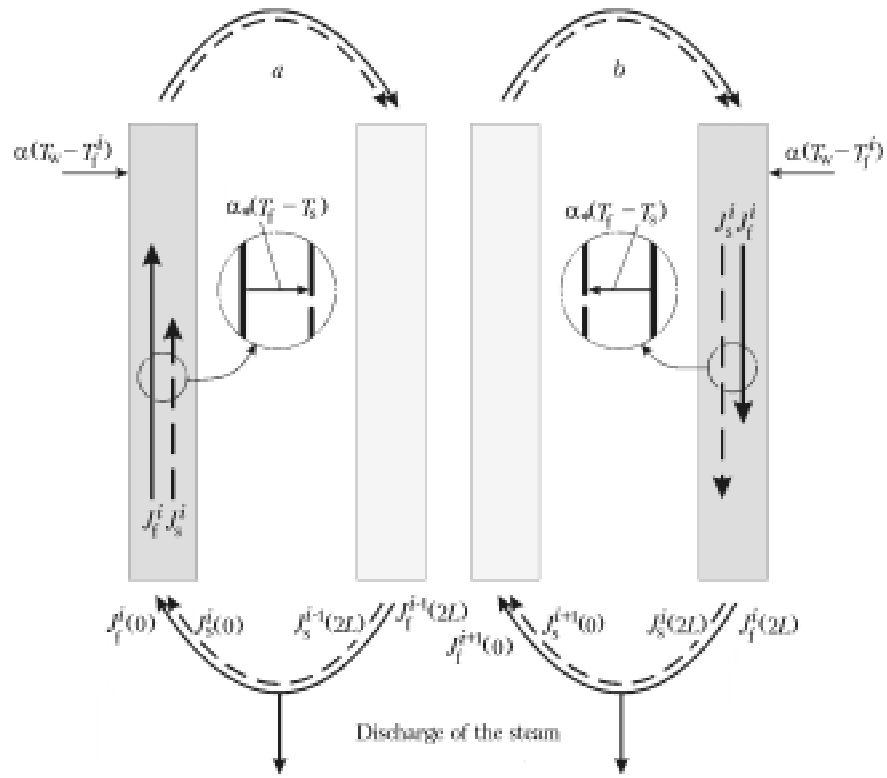

Fig. 1. Model of drying in the pneumatic-transport system: a and b) first and second halves of a cycle.

2. Equation of Motion of a Solid Particle. The force acting on a particle on the source side of the gas flow is calculated from the well-known Ergun formula [2]. The equation of motion of a particle of variable mass (Meshcherskii equation) has the form [3]

$$\rho_s \frac{du_s}{dt} - u_r^s \frac{d\rho_s}{dt} = \mp \rho_s g + \text{sign}\,(\text{Re}_r)\,\frac{\mu_f^2}{\rho_f d^3}\left(150\,\frac{1-\varepsilon}{\varepsilon^3}\,|\text{Re}_r| + 1.75\,\frac{1}{\varepsilon^3}\,\text{Re}_r^{\,2}\right). \tag{3}$$

A minus sign before the first term on the right-hand side of (3) refers to the case of motion of the lift riser (Fig. 1a), and a plus sign refers to the motion in the drop riser (Fig. 1b). With account for $dt = dx/u_s$, $\rho_s = \rho_s^0(1+\hat{c}_s)$, and $u_f^s \approx 0$, from (3) we obtain

$$u_s\,(1+\hat{c}_s)\,\frac{du_s}{dx} = \mp\, g\,(1+\hat{c}_s) + \text{sign}\,(\text{Re}_f)\,\frac{\mu_f^2}{\rho_s^0 \rho_f d^3}\left(150\,\frac{1-\varepsilon}{(\varepsilon)^3}\,|\text{Re}_r| + 1.75\,\frac{1}{(\varepsilon)^3}\,(\text{Re}_r)^2\right). \tag{4}$$

3. Continuity Equation for the Steam:

$$\frac{d\,(\rho_f u_f)}{dx} = -\,\rho_s^0\,(1-\varepsilon)\,u_s\,\frac{d\hat{c}_s}{dx}\,. \tag{5}$$

Equation (5) is consistent with (1); here, we obtain

$$\frac{d\,(\rho_s\,(1-\varepsilon)\,u_s + \rho_f u_f)}{dx} = 0\,.$$

At constant pressure, we have $\rho_f = \rho_f(T_f)$ and can write Eq. (5) as

$$\rho_f \frac{du_f}{dx} = -\rho_s^0 (1-\varepsilon) u_s \frac{d\hat{c}_s}{dx} - u_f \frac{d\rho_f}{dT_f} \frac{dT_f}{dx} . \tag{6}$$

Assuming that steam is an ideal gas, we take the dependence $\rho_f(T_f)$ in the form

$$\rho_f = \rho_f^0 T_f^0 / T_f . \tag{7}$$

Hence for $d\rho_f/dT_f$ we have

$$d\rho_f/dT_f = -\rho_f^0 T_f^0 / T_f^2 . \tag{8}$$

4. Heat-Conduction Equation for the Steam. With account for assumption (c), it is written in the form

$$\frac{d}{dx}\left(\rho_f u_f I_f^f\right) = -\frac{2\alpha}{R}(T_f - T_w) + \frac{6(1-\varepsilon)}{d}\alpha_* (T_s - T_f) - \rho_s^0 (1-\varepsilon) u_s \left(I_f^s (1-U_T) + I_f^f U_T\right)\frac{d\hat{c}_s}{dx} . \tag{9}$$

Using (5) and the equality $I_f^f = q + c_f(T_f - T_{cr}) + c_{liq}(T_{cr} - 273)$, we obtain

$$\rho_f c_f u_f \frac{dT_f}{dx} = -\frac{2\alpha}{R}(T_f - T_w) + \frac{6(1-\varepsilon)}{d}\alpha_* (T_s - T_f) + \rho_s^0 (1-\varepsilon) u_s (1-U_T)\left(I_f^f - I_f^s\right)\frac{d\hat{c}_s}{dx} . \tag{10}$$

Finally the heat-conduction equation for the steam will have the form $(I_f^f - I_f^s = c_f(T_f - T_s))$

$$\rho_f c_f u_f \frac{dT_f}{dx} = -\frac{2\alpha}{R}(T_f - T_w) + \frac{6(1-\varepsilon)}{d}\alpha_* (T_s - T_f) + \rho_s^0 (1-\varepsilon) u_s (1-U_T) c_f (T_f - T_s)\frac{d\hat{c}_s}{dx} . \tag{11}$$

5. Heat-Conduction Equation for Particles (with the use of assumption (c)) is

$$\frac{d}{dx}\left(\left(\rho_s^0 c_s T_s + \rho_s^0 \hat{c}_s I_{liq}\right)(1-\varepsilon) u_s\right) = \frac{6(1-\varepsilon)\alpha_*}{d}(T_f - T_s) + \rho_s^0 (1-\varepsilon) u_s \left(I_f^s (1-U_T) + I_f^f U_T\right)\frac{d\hat{c}_s}{dx} . \tag{12}$$

With account for Eq. (2), it is transformed to

$$\rho_s^0 c_s u_s \left(1 + \hat{c}_s \frac{c_{liq}}{c_s}\right)\frac{dT_s}{dx} = \frac{6\alpha_*}{dx}(T_f - T_s) + \rho_s^0 u_s \left(I_f^s - I_{liq} + U_T\left(I_f^f - I_f^s\right)\right)\frac{d\hat{c}_s}{dx} . \tag{13}$$

Since we have $I_f^s - I_{liq} = q + (c_{liq} - c_f)(T_{cr} - T_s)$, the heat-conduction equation for particles will be determined as

$$\rho_s^0 c_s u_s \left(1 + \hat{c}_s \frac{c_{liq}}{c_s}\right)\frac{dT_s}{dx} = \frac{6\alpha_*}{dx}(T_f - T_s) + \rho_s^0 u_s \left(q + (c_{liq} - c_f)(T_{cr} - T_s) + U_T c_f (T_f - T_s)\right)\frac{d\hat{c}_s}{dx} . \tag{14}$$

A combination of (11) and (14) yields the equation

$$\rho_f c_f u_f \frac{dT_f}{dx} + \rho_s^0 (1-\varepsilon) c_s u_s \left(1 + \hat{c}_s \frac{c_{liq}}{c_s}\right)\frac{dT_s}{dx} =$$

$$= \frac{2\alpha}{R}(T_w - T_f) + \rho_s^0 (1-\varepsilon)\, u_s \left(q + (c_{liq} - c_f)(T_{cr} - T_s) + c_f (T_f - T_s)\right) \frac{d\hat{c}_s}{dx}\,, \tag{15}$$

which no longer contains the Heaviside function and consequently has the same form in the case of both condensation of the steam and evaporation of particles from it.

6. Kinetic Equation. With account for assumptions (a) and (b), the equation of drying kinetics can be represented in the following form:

$$\rho_s^0 (1-\varepsilon)\, u_s \frac{d\hat{c}_s}{dx} = \frac{6(1-\varepsilon)}{d} \beta \rho_s^0 (\hat{c} - \hat{c}_s)(1 - U_c) + \frac{6(1-\varepsilon)}{d} \tilde{\alpha} \frac{(T_{cr} - T_s)}{1 + c_{liq}(T_{cr} - 273)} U_T U_c +$$
$$+ \frac{6(1-\varepsilon)}{d} \alpha_* \frac{(T_s - T_f)}{(q + (c_{liq} - c_f)(T_{cr} - T_s))} U_c (1 - U_T)\,. \tag{16}$$

Setting the equilibrium moisture content $\hat{c} = 0$ [4], we obtain

$$\rho_s^0 (1-\varepsilon)\, u_s \frac{d\hat{c}_s}{dx} = -\frac{6(1-\varepsilon)}{d} \beta \rho_s^0 \hat{c}_s (1 - U_T)(1 - U_c) + \frac{6(1-\varepsilon)}{d} \tilde{\alpha} \times$$
$$\times \frac{(T_{cr} - T_s)}{q + c_{liq}(T_{cr} - 273)} U_T U_c + \frac{6(1-\varepsilon)}{d} \alpha_* \frac{(T_s - T_f)}{q + (c_{liq} - c_f)(T_{cr} - T_s)} U_c (1 - U_T)\,. \tag{17}$$

The kinetic equation under the conditions of condensation of moisture has been obtained from the balance relation

$$\rho_s^0 (1-\varepsilon)\, u_s \left(q + c_{liq}(T_{cr} - 273)\right) \frac{d\hat{c}_s}{dx} = \frac{6(1-\varepsilon)}{d} \tilde{\alpha} (T_{cr} - T_s)\,,$$

which represents the value of the heat flux entering the particles through a condensate film. Furthermore, the last term in (16) and (17) allows for the evaporation of moisture condensed on the particles in the regime of constant drying rate, when the entire heat to the particles is consumed by the evaporation of free moisture.

The obtained equations (2), (4), (6), (11), (14), and (17) enable us to calculate six unknown functions $u_f(x)$, $u_s(x)$, $T_f(x)$, $T_s(x)$, $\varepsilon(x)$, and $\hat{c}_s(x)$. Boundary conditions with allowance for cyclicity (i is the cycle No.) have the form (see Fig. 1)

$$T_f^1(0) = T_f^0\,, \quad T_f^i(0) = T_f^{i-1}(2L)\,,$$

$$T_s^1(0) = T_s^0\,, \quad T_s^i(0) = T_s^{i-1}(2L)\,,$$

$$\varepsilon^1(0) = \varepsilon^0\,, \quad \varepsilon^i(0) = \varepsilon^{i-1}(2L)\,,$$

$$\hat{c}_s^1(0) = \hat{c}_s^0\,, \quad \hat{c}_s^i(0) = \hat{c}_s^{i-1}(2L)\,, \tag{18}$$

$$u_s^1(0) = \frac{u_f^0}{\varepsilon_0} - \frac{(u_t^*)_0}{\varepsilon_0}\,, \quad u_s^i(0) = u_s^{i-1}(2L)\,,$$

$$u_f^1(0) = u_f^0\,, \quad u_f^i(0) = u_f^0 \frac{T_f^{i-1}(2L)}{T_f^0}\,, \quad i = 2, 3, \ldots\,.$$

The last condition requires explanation. Since a constant pressure is maintained in the system, the entire steam released from the particles must be removed from the dryer. Within the framework of this model, it is assumed that the excess steam generated in the cycle is removed at the end of it and thereby the constancy of the mass rate of flow of the steam is maintained:

$$J_{\rm f} = \rho_{\rm f}^0 u_{\rm f}^0 = \rho_{\rm f}^i (0)\, u_{\rm f}^i (0) \tag{19}$$

or

$$u_{\rm f}^i (0) = \rho_{\rm f}^0 \frac{u_{\rm f}^0}{\rho_{\rm f}^i (0)} . \tag{20}$$

With allowance for (7) and for the first boundary condition in (18), we obtain the boundary condition sought for the steam velocity:

$$u_{\rm f}^i (0) = u_{\rm f}^0 \frac{T_{\rm f}^{i-1} (2L)}{T_{\rm f}^0} . \tag{21}$$

We write the resulting system in dimensionless form:

$$\frac{d\,((1-\varepsilon)\, u'_{\rm s})}{dx'} = 0 , \tag{22}$$

$$u'_{\rm s} (1 + \hat{c}_{\rm s}) \frac{du'_{\rm s}}{dx'} = \mp \frac{1 + \hat{c}_{\rm s}}{\rm Fr_t} + \frac{\text{sign}\,({\rm Re_r})}{\rm Fr_t\, Ar} \left(150 \frac{1-\varepsilon}{\varepsilon^3} |{\rm Re_r}| + 1.75 \frac{1}{\varepsilon^3} {\rm Re_r}^2 \right), \tag{23}$$

$$\frac{\rho_{\rm f}}{\rho_{\rm f}^0} \frac{du'_{\rm f}}{dx'} = - \frac{\rho_{\rm s}^0}{\rho_{\rm f}^0} (1-\varepsilon)\, u'_{\rm s} \frac{d\hat{c}_{\rm s}}{dx'} - u'_{\rm f} \frac{T_{\rm f}^0 - T_{\rm s}^0}{\rho_{\rm f}^0} \frac{d\rho_{\rm f}}{dT_{\rm f}} \frac{d\theta_{\rm f}}{dx'} , \tag{24}$$

$$\frac{\rho_{\rm f}}{\rho_{\rm f}^0} u'_{\rm f} \frac{d\theta_{\rm f}}{dx'} = -2 \frac{L}{R} {\rm St}\, (\theta_{\rm f} - \theta_{\rm w}) + 6\,(1-\varepsilon) \frac{L}{d} {\rm St}_* (\theta_{\rm s} - \theta_{\rm f}) + \frac{\rho_{\rm s}^0}{\rho_{\rm f}^0} (1-\varepsilon)\, u'_{\rm s} (\theta_{\rm f} - \theta_{\rm s}) \frac{d\hat{c}_{\rm s}}{dx'} (1 - U_T) , \tag{25}$$

$$u'_{\rm s} \left(1 + \hat{c}_{\rm s} \frac{c_{\rm liq}}{c_{\rm s}} \right) \frac{d\theta_{\rm s}}{dx'} = 6 \frac{L}{d} {\rm St}_* \frac{c_{\rm f} \rho_{\rm f}^0}{c_{\rm s} \rho_{\rm s}^0} (\theta_{\rm f} - \theta_{\rm s}) + \left(\frac{1}{\rm Ja} + \frac{c_{\rm liq} - c_{\rm f}}{c_{\rm s}} (\theta_{\rm cr} - \theta_{\rm s}) + \frac{c_{\rm f}}{c_{\rm s}} (\theta_{\rm f} - \theta_{\rm s})\, U_T \right) u'_{\rm s} \frac{d\hat{c}_{\rm s}}{dx'} , \tag{26}$$

$$\frac{d\hat{c}_{\rm s}}{dx'} = -6 \frac{L}{du'_{\rm s}} \left(\hat{c}_{\rm s} \beta' (1 - U_T)(1 - U_c) - \frac{\tilde{\alpha}\, (T_{\rm f}^0 - T_{\rm s}^0)(\theta_{\rm cr} - \theta_{\rm s})}{\rho_{\rm s}^0 (u_{\rm f}^0 - (u_{\rm t}^*)^0)(q + c_{\rm liq} (T_{\rm cr} - 273))} U_T U_c - \right.$$
$$\left. - \frac{\alpha_* (T_{\rm f}^0 - T_{\rm s}^0)(\theta_{\rm s} - \theta_{\rm f})}{\rho_{\rm s}^0 (u_{\rm f}^0 - (u_{\rm t}^*)^0)(q + (c_{\rm liq} - c_{\rm f})(T_{\rm cr} - T_{\rm s}))} (1 - U_T)\, U_c \right). \tag{27}$$

The boundary conditions are as follows:

$$\theta_f^i(0) = 1\,, \quad \theta_f^i(0) = \theta_f^{i-1}(2)\,,$$

$$\theta_s^i(0) = 0\,, \quad \theta_s^i(0) = \theta_s^{i-1}(2)\,,$$

$$\varepsilon^1(0) = \varepsilon^0\,, \quad \varepsilon^i(0) = \varepsilon^{i-1}(2)\,,$$

$$\widehat{c}_s^{\,1}(0) = \widehat{c}_s^{\,0}\,, \quad \widehat{c}_s^{\,i}(0) = \widehat{c}_s^{\,i-1}(2)\,,$$

$$(u_s')^1(0) = \left(\frac{u_f^0}{\varepsilon_0} - \frac{(u_t^*)_0}{\varepsilon_0}\right) \Big/ \left(u_f^0 - (u_t^*)^0\right), \quad (u_s')^i(0) = (u_s')^{i-1}(2)\,,$$

$$(u_f')^1(0) = u_f^0 \Big/ \left(u_f^0 - (u_t^*)^0\right), \quad (u_f')^i(0) = \frac{u_f^0}{(u_f^0 - (u_t^*)^0)} \frac{T_f^{i-1}(2)}{T_f^0}\,, \quad i = 2, 3, \ldots \,. \tag{28}$$

Thus, the process of drying under pneumatic-transport conditions is determined by the following dimensionless parameters:

$$\mathrm{Ar},\ \mathrm{Fr}_t^*,\ \mathrm{Ja},\ \mathrm{Re}_r,\ \mathrm{St},\ \mathrm{St}_*,\ \beta'\,,\quad \frac{L}{d}\,,\ \frac{L}{R}\,,\ \frac{\rho_f^0}{\rho_s^0}\,,\ \frac{c_f}{c_s}\,,\ \frac{c_{liq}}{c_s}\,,\ \varepsilon^0\,. \tag{29}$$

The values of the heat-exchange coefficients α and α_* involved in the numbers St and St_* are determined from the following dependences [5, 6]:

$$\mathrm{Nu} = \frac{\alpha d}{\lambda_f} = 0.078\mathrm{Re}^{0.66}\mu^{0.45} + \frac{d}{\lambda_f}\sigma_0 \frac{(T_{fb}^2 + T_w^2)\,(T_{fb} + T_w)}{1/\varepsilon_w + 1/\varepsilon_{fb} - 1}\,, \tag{30}$$

$$\mathrm{Nu}_* = \frac{\alpha_* d}{\lambda_f} = 2 + 0.6\left(|\mathrm{Re}_r|/\varepsilon\right)^{1/2}\mathrm{Pr}^{1/3}\,, \quad \frac{|\mathrm{Re}_r|}{\varepsilon} < 200\,. \tag{31}$$

The heat-exchange coefficient in condensation of moisture is found as [7]

$$\tilde{\alpha} = \frac{\lambda_{liq}}{\delta}\,. \tag{32}$$

The thickness of the condensate film can be determined from the balance relation

$$\pi d^2 \rho_{liq}\delta = \frac{\pi d^3}{6}\rho_s^0\left(\widehat{c}_s - \widehat{c}_s^{\,0}\right), \tag{33}$$

whence we have the following dependence for calculation of $\tilde{\alpha}$:

$$\tilde{\alpha} = \frac{6\lambda_{liq}\rho_{liq}}{d\rho_s^0\,(\widehat{c}_s - \widehat{c}_s^{\,0})}\,. \tag{34}$$

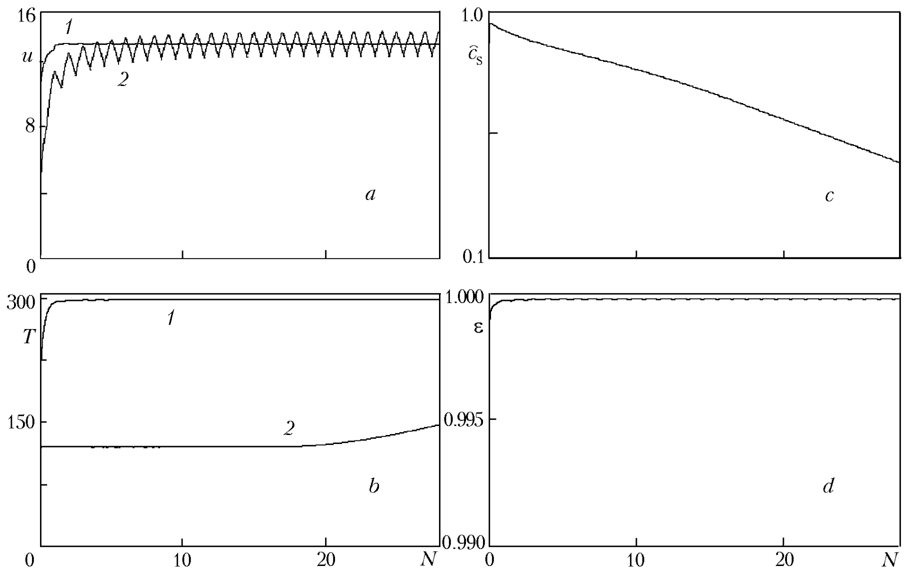

Fig. 2. Velocity (a), phase temperature (b), moisture content (c), and porosity (d) of the dispersed flow vs. number of cycles (basic variant): 1) steam; 2) particles. u, m/sec.

The functional dependence of the effective drying rate is evaluated from the assumption of the similarity of the processes of interphase heat and mass exchange under external-problem conditions (hypothesis (f)), when the main resistance to the transfer of the steam is set up by its diffusion from the particle surface into the volume:

$$\mathrm{Sh} \cong A \cdot \mathrm{Nu}_* \frac{\rho_f^0}{\rho_s^0}\,, \tag{35}$$

where $\mathrm{Sh} = \beta d / D_f$. From (35), for β' we have

$$\beta' = A \frac{\mathrm{Nu}_*}{\mathrm{Re}^0 \mathrm{Sc}} \frac{\rho_f^0}{\rho_s^0}\,. \tag{36}$$

The dimensionless parameter A thereby plays the role of a single "fitting" parameter of the model. Its value is determined according to the regular procedure by comparing experimental and calculated $\hat{c}_s(x)$ values.

The results of numerical modeling of the process of drying are presented in Figs. 2 and 3. We note that $\Delta x' = 2$ corresponds to one cycle ($\Delta N = 1$). To calculate the basic variant of the drying we used the following initial data:

the riser: $L = 2$ m, $R = 0.015$ m, $T_w = 573$ K, and $\varepsilon_w = 0.8$;

particles: $d = 0.002$ m, $c_s = 2700$ J/(kg·K), $\hat{c}_s^0 = 0.75$, $\rho_s^0 = 420$ kg/m^3, and $T_s^0 = 323$ K;

the two-phase flow: $\varepsilon^0 = 0.4$, $\varepsilon_{fb} = 0.9$, $J_f^0 = 10$ kg/(m^2·sec), and $J_s^0 = 3$ kg/(m^2·sec);

the steam ($p = 2$ atm and $T_f^{cr} = 393$ K): $\lambda_f = 0.0337$ W/(m·K), $\rho_f^0 = 0.926$ kg/m^3, $\nu_f = 1.71 \cdot 10^{-5}$ m^2/sec, $c_f = 2046$ J/(kg·K), $D_f = 2.31 \cdot 10^{-5}$ m^2/sec, Pr = 0.967, Sc = 0.74, $T_f^0 = 473$ K, $u_f^0 = 10.8$ m/sec, and $A = 0.5$;

water: $\lambda_{liq} = 0.55$ W/(m·K), $\rho_{liq} = 1000$ kg/m^3, and $c_{liq} = 4215$ J/(kg·K).

To determine the lower bound of existence of pneumatic transport (bridging velocity u_b) we used the formula [8]

$$\frac{u_b - u_t}{u_t} = 0.02 J_s^*\,, \tag{37}$$

based on which we obtained the expression for the minimum mass rate of flow of the steam

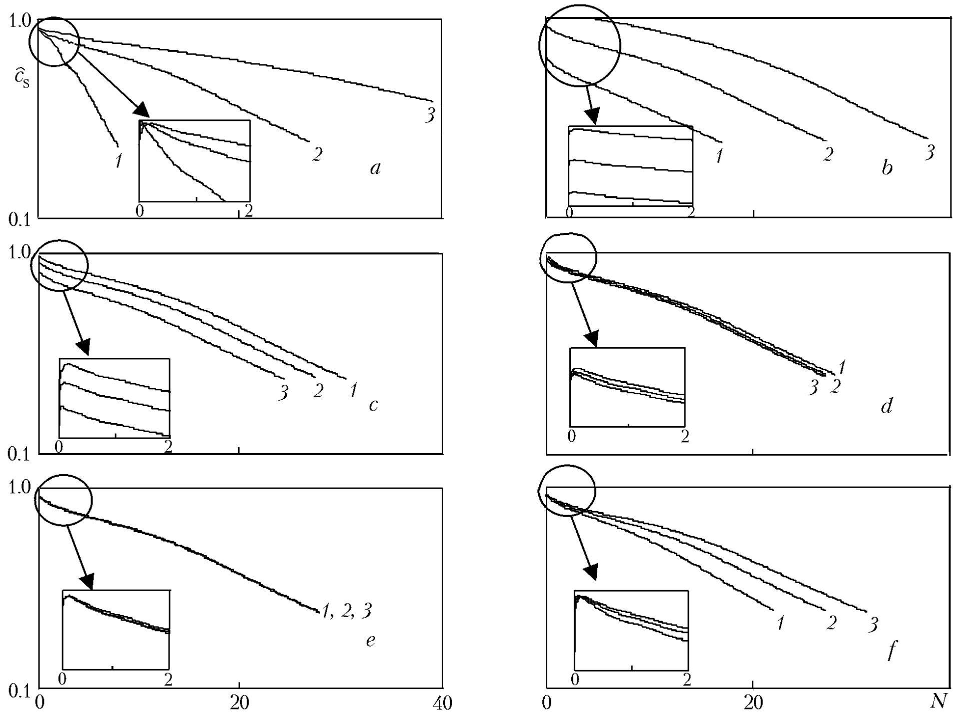

Fig. 3. Moisture-content of a dispersed material vs. number of cycles for different values of the particle diameter (a) [(1) d = 1, 2) 2, and 3) 3 mm], initial moisture content (b) [(1) $\hat{c}_s^0$ = 0.5, 2) 0.75, and 3) 1], initial particle temperature (c) [(1) T_s^0 = 293. 2) 323, and 3) 363 K], initial steam temperature (d) [(1) T_f^0 = 373, 2) 423, and 3) 473 K], mass particle flux (e) [(1) J_s^0 = 1, 2) 3, and 3) 5 kg/(m^2·sec)], and mass steam flux (f) [(1) J_f = 8, 2) 10, and 3) 12 kg/(m^2·sec)].

$$(J_f^0)_{\min} = J_s^0 \frac{1 + 0.02 J_s^*}{J_s^*} . \tag{38}$$

The discontinuous character of the functions $u_f(N)$ is attributed to the removal of the excess steam at the end of each cycle (see condition (21)). Figure 2 corresponds to the basic varriant. The basic regularities of drying that have been obtained in the present work are given in Fig. 3. As is seen, the strongest influence on the drying intensity is exerted by the diameter of particles and their initial humidity (Figs. 3a and b). The influence of the initial particle temperature is more pronounced on the initial portion; next this influence becomes weaker (Fig. 3c). The value of the mass particle flux in the investigated range of variation in the parameters exerts no influence, in practice, on the dependence $\hat{c}_s(N)$ (Fig. 3e). An interesting and rather unexpected conclusion (important for practical implementation of the process) on the small influence of the initial steam temperature follows from an analysis of Fig. 3d. Such a dependence $\hat{c}_s(T_f^0, N)$ is attributable to the opposite influence of T_f^0 on the factors determining drying. Indeed, the steam viscosity increases with T_f^0. This leads to a drop in the relative phase velocity determining the values of the coefficients of heat and mass exchange of a moist particle with the steam flow. At the same time, growth in the steam temperature causes the transfer potential $T_f^0 - T_s^0$ to increase.

The results of numerical experiments were generalized in the form of the formula for the dimensionless effective drying rate $(\hat{c}_s^0 - \hat{c}_s^N)/N$. The use of the system of dimensionless quantities (29) seemed inefficient because of their large number. Therefore, the generalization was based on the apparatus (developed in [9]) of similarity theory of transfer processes in disperse systems. The quantity sought was represented in the form of the following functional dependence:

$$\frac{N}{(\hat{c}_s^0 - \hat{c}_s^N)} = f\left(\bar{J}_s, \text{Ja}, \text{Fr}, \text{Ar}, \text{Re}^0, \frac{T_f^0 - T_s^0}{T_f^0}\right). \quad (39)$$

Processing of the experimental data obtained by the least-squares method allowed the formula

$$\frac{N}{\hat{c}_s^0 - \hat{c}_s^N} = 0.15\, \bar{J}_s^{-0.15}\, \text{Ja}^{-0.35}\, \text{Fr}^{0.35} \left(\frac{T_f^0 - T_s^0}{T_f^0}\right)^{0.6} \text{Ar}^{0.8}\, (\text{Re}^0)^{-0.54} . \quad (40)$$

The standard error of calculation from (40) amounted to 24%. The range of variation in the system's parameters was as follows: L_0 = 1.5–2.5 m, d = 0.001–0.002 m, $\hat{c}_s^0$ = 0.5–1, T_s^0 = 293–363 K, T_f^0 = 423–523 K, J_s^0 = 1–3 kg/(m^2·sec), and J_f^0 = (1–3)$(J_f^0)_{min}$.

Thus, in this work, we have formulated the physical model of the process of drying of a dispersed material by a superheated steam in a pneumatic-transport system. A numerical analysis of the mathematical model has enabled us to establish the influence of different parameters of the system on the character of the process of drying. The simplicity of the model and allowance for the main factors influencing the process of convective drying make it possible to efficiently apply it to practical calculations.

NOTATION

$\text{Ar} = \frac{gd^3\rho_s^0}{\nu_f^2\rho_f}$, Archimedes number; c_f, c_{liq}, and c_s, specific heats of the steam, water, and solid particles, J/(kg·K); $\hat{c}_s$, moisture content of particles; $\hat{c}_s^N$, moisture content of particles at the end of the Nth cycle; d, particle diameter, m; D_f, diffusion coefficient, m^2/sec; $\text{Fr}_t = (u_f^0 - u_t)^2/gL$, Froude number; g, free-fall acceleration, m/sec^2; I_f and I_{liq}, enthalpies of the steam and water, J/kg; $J_f = \rho_f u_f$ and $J_s = \rho_s(1-\varepsilon)u_s$, mass rates of flow of the steam and particles, kg/(m^2·sec); $J_s^* = J_s^0/\rho_f u_t$; $\bar{J}_s = J_s^0/\rho_s(u_f^0 - u_t)$; $\text{Ja} = c_s(T_f^0 - T_s^0)/q$, Jacob number; L, riser height, m; Nu and Nu$_*$, Nusselt numbers; N, number of cycles; Pr, Prandtl number; p, pressure, atm; q, specific heat of vaporization, J/kg; R, tube radius, m; $\text{Re} = \frac{u_f d}{\varepsilon\nu_f}$, $\text{Re}_r = \frac{u_r d}{\nu_f}$, $\text{Re}_f^0 = \frac{u_f d}{\nu_f^0}$, and $\text{Re}^0 = \frac{(u_f^0 - u_t)d}{\nu_f}$, Reynolds numbers; Sh, Sherwood number; $\text{St} = \frac{\alpha}{c_f\rho_f^0(u_f^0 - (u_t^*)^0)}$ and $\text{St}_* = \frac{\alpha_*}{c_f\rho_f^0(u_f^0 - u_t^*)}$, Stanton numbers; $\text{Sc} = \frac{\nu_f}{D_f}$, Schmidt number; t, time; T_f and T_s, temperatures of the steam and particles, K; T_w, temperature of the riser wall, K; U_T and U_c, Heaviside functions; $U_T = 1$ ($T_s \le T_{cr}$), $U_T = 0$ ($T_s > T_{cr}$), $U_c = 1$ ($\hat{c}_s \ge \hat{c}_s^0$), and $U_c = 0$ ($\hat{c}_s < \hat{c}_s^0$); u_f and u_s, velocities of the steam and particles, m/sec; $u_r = u_f - u_s\varepsilon$, slip velocity of phases, m/sec; u_r^s, relative velocity of the steam escaping from a particle, m/sec; u_t, free-fall velocity of a single particle, m/sec; $u_f' = u_f(u_f^0 - u_t)$ and $u_s' = u_s(u_f^0 - u_t)$, dimensionless velocity of the steam and particles; u_b, bridging velocity, m/sec; x, longitudinal coordinate; $x' = x/L$, dimensionless coordinate; α and α_*, heat-exchange coefficient, W/(m^2·K); $\tilde{\alpha}$, effective coefficient of interphase heat exchange under condensation conditions, W/(m^2·K); β, effective drying rate, m/sec; $\beta' = \beta/(u_f^0 - (u_t^*)^0)$, dimensionless drying rate; δ, thickness of the condensate film, m; ε, porosity; ε_{fb} and ε_w, emissivity factor; $\theta_s = \frac{T_s - T_s^0}{T_f^0 - T_s^0}$, $\theta_f = \frac{T_f - T_s^0}{T_f^0 - T_s^0}$, $\theta_w = \frac{T_w - T_s^0}{T_f^0 - T_s^0}$, and $\theta_{cr} = \frac{T_{cr} - T_s^0}{T_f^0 - T_s^0}$, dimensionless temperatures; λ_f and λ_{liq}, thermal conductivities of the steam and water, W/(m·K); μ_f and μ_{liq}, dynamic viscosities of the steam and water, kg/(m·sec); μ =

$(1-\varepsilon)\frac{\rho_s^0(1+\hat{c}_s^0)}{\rho_f}\frac{u_s}{u_f}$; ν_f, kinematic viscosity of the steam, m^2/sec; ρ_f and $\rho_s = \rho_s^0(1+\hat{c}_s)$, densities of the steam and particles, kg/m^3; ρ_s^0 and ρ_{liq}, densities of dry particles and water, kg/m^3; σ_0, Stefan–Boltzmann constant, $W/(m^2 \cdot K^4)$. Superscripts: f, steam to the particle (condensation); *i*, cycle No.; s, steam from the particle (drying); 0, initial state. Subscripts: b, bridging; cr, critical; f, steam; fb, two-phase flow; liq, liquid; r, relative; s, particle; t, conditions of free-fall acceleration of a single particle; w, riser wall.

REFERENCES

1. A. V. Luikov, *Drying in the Chemical Industry* [in Russian], Khimiya, Moscow (1970).
2. M. É. Aérov, O. M. Todes, and D. A. Narinskii, *Stationary Granular-Bed Apparatuses* [in Russian], Khimiya, Leningrad (1979).
3. A. P. Markeev, *Theoretical Mechanics* [in Russian], CheRo, Moscow (1999).
4. Yu. A. Mikhailov, *Drying by a Superheated Vapor* [in Russian], Khimiya, Moscow (1967).
5. Z. P. Gorbis, *Heat Transfer and Hydrodynamics of Disperse Straight-Through Flows* [in Russian], Énergoizdat, Moscow (1970).
6. O. M. Todes and O. B. Tsitovich, *Fluidized-Granular-Bed Apparatuses* [in Russian], Khimiya, Leningrad (1981).
7. V. P. Isachenko, V. A. Osipova, and A. S. Sukomel, *Heat Conduction* [in Russian], Énergoizdat, Moscow (1981).
8. Yu. S. Teplitskii and V. I. Kovenskii, *Some aspects of the stability of vertical pneumotransport of solid particles*, *Inzh.-Fiz. Zh.*, **72**, No. 1, 13–19 (1999).
9. Yu. S. Teplitskii, Similarity of transfer processes in disperse systems with suspended particles, *Inzh.-Fiz. Zh.*, **72**, No. 4, 757–763 (1999).