DYNAMICS OF A VARIABLE MASS PARTICLE DURING DRYING OF DISPERSED MATERIALS IN A PNEUMATIC DRYER

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An equation is obtained for the motion of a variable mass particle in a pneumatic dryer during drying of dispersed materials in a period of decreasing drying rate.

Development of reliable techniques for calculating the operation of pneumatic dryers presents certain difficulties in relating the hydrodynamics of the gas suspension to the kinetics of the process.

The drying agent is a heat source, which simultaneously transports the particles of materials along the channel. Due to differences between the velocities of the drying agent and the solid particles, the temperature conditions for drying of the material change constantly, while thermal losses to heating and drying change the density and volume of the drying agent. Thus, a complex relationship develops between the hydrodynamics of the gaseous suspension and the kinetics of dispersed material drying. Calculation of the equipment hydrodynamics from averaged gas flow characteristics during drying of dispersed materials with simultaneous pneumotransport is a forced solution, since more-exact approaches meet with mathematical complications in describing the process.

A method has been developed for relating the equipment hydrodynamics to the drying process kinetics given the condition that drying occurs during the time of decreasing drying rate. The method will be presented for the example of a solitary particle moving in a straight horizontal tube. The essence of the approach would remain the same for any other type of pneumodryer. We make the following assumptions: 1) change in particle mass occurs only due to evaporation and removal of moisture through the surface; 2) the particle size is such that turbulent pulsations have no significant effect on the character of its motion.

The flow over the particle occurs within the Newtonian range, ξ = const. This assumption is not necessary in principle, since substitution of a variable $\xi = f(\mathrm{Re}, \psi)$ does not change the path of the method, although the final result will be more cumbersome.

Case I. D = const. The equation of motion of a spherical particle of variable mass in a horizontal tube in the stable pneumotransport regime has the form

$$m\frac{du}{d\tau} = \xi\,\frac{\pi D^2 \rho_g}{8}(v-u)^2 - \frac{dm}{d\tau}u. \tag{1}$$

The particle mass, expressed in terms of the mass of the absolutely dry material and the moisture content, is

$$m = m_0(1+w). \tag{2}$$

Then the change in particle mass during the drying process will be

$$\frac{dm}{d\tau} = m_0\frac{dw}{d\tau}. \tag{3}$$

Substituting Eqs. (2), (3) in Eq. (1), we obtain the equation of particle

$$m_0(1+w)\frac{du}{d\tau} = \xi\,\frac{\pi D^2 \rho g}{8}(v-u)^2 - m_0 u\frac{dw}{d\tau}, \tag{4}$$

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for the solution of which we must know the moisture content and rate of change of moisture content as functions of time. We write the mass transfer equation for the period of decreasing drying rate.

$$\frac{dw}{d\tau} = -\frac{F\beta_{II}}{G_p}(t - t_p). \tag{5}$$

In this equation the unknowns on the right side are the mass transfer coefficient and the temperatures of the drying agent and the material being dried.

The mass transfer coefficient for the second drying period can be found from the expression presented in [1]:

$$\beta_{II} = \beta_I \left(\frac{w}{w_{cr}}\right)^n, \tag{6}$$

where β_I is the mass transfer coefficient in the period of constant drying rate. It is calculated from known criterial dependences.

To determine the temperatures of drying agent and material in the period of falling drying rate, we write the thermal balance equation

$$-[G_g c_g + c_v(W_i^v + W)]\,dt = r\,dW + [G_p c_p + (W_i^p - W)c_w]\,dt_p. \tag{7}$$

Expressing the quantity of evaporating moisture in terms of the moisture content and dividing both sides of Eq. (7) by G_g, we obtain

$$-[c_g + c_v x_i + \mu_0 c_v(w_i - w)]\,dt = [\mu_0 c_p + c_w x_i^p - c_w \mu_0 (w_i - w)]\,dt_p - r\mu_0 dw, \tag{8}$$

where $x_i^p = \frac{W_i^p}{G_g}$ is the ratio of the initial moisture content in the solid particle to the flow rate of absolutely dry gas.

If we bring the term $r\mu_0 dw$ out of brackets in Eq. (8), then the right side of the equation takes on the form

$$(\mathrm{Rb} - 1)\,r\mu_0 dw.$$

Equating this expression to the left side of Eq. (8), we find

$$-[c_g + c_v x_i + c_v \mu_0 (w_i - w)]\,dt = (\mathrm{Rb} - 1)\,r\mu_0 dw. \tag{9}$$

For dispersed materials in the case of convective drying the value of Rb may vary by the empirical rule presented in [2]:

$$\mathrm{Rb} = Bw^k, \tag{10}$$

where B and k are constants, independent of the drying regime, but defined by the physicomechanical properties of the material being dried.

Substituting Eq. (10) in Eq. (9), separating variables, and integrating, we find the drying agent temperature as a function of moisture content

$$t = t_{fI} + \int_{w_{cr}}^{w_e} \frac{r\mu_0 (Bw^k - 1)\,dw}{c_g + c_v x_i + c_v \mu_0 (w_i - w)}. \tag{11}$$

For a number of dispersed materials with equilibrium moisture content $w_e \geqslant$ 2-3%, we can assume with accuracy sufficient for engineering calculations that the Rebinder number is significantly less than unity, so that the temperature of the drying agent as a function of moisture content will have the form

$$t = t_{fI} - \frac{\bar{r}}{c_v} \ln \frac{c_g + c_v x_i + c_v \mu_0 (w_i - w_e)}{c_g + c_v x_i + c_v \mu_0 (w_i - w_{cr})}. \tag{12}$$

To determine the actual temperature of the material in the falling drying rate period, the right side of Eq. (8) may be transformed and one of the terms set equal to the value of Rb from Eq. (10):

$$\frac{[\mu_0 c_p - c_w x_i^p - c_w \mu_0 (w_i - w)]\, dt_p}{r\mu_0 dw} = Bw^k. \tag{13}$$

Separating variables and integrating Eq. (13), we obtain

$$t_p = \bar{t}_{wb} + B\bar{r}\mu_0 \int_{w_{cr}}^{w_e} \frac{w^k dw}{\mu_0 c_p + c_w x_i^p - c_w \mu_0 (w_i - w)}. \tag{14}$$

Now, combining Eqs. (5), (6), (11), (14) and keeping in mind that for a spherical particle $F/G_p = 6/(D\rho_p)$, we obtain an equation for the rate of change of particle moisture content:

$$\frac{dw}{d\tau} = -\frac{6\beta_I \left(\frac{w}{w_{cr}}\right)^n}{D\rho_p}\left[t_{fI} + \int_{w_{cr}}^{w_e} \frac{r\mu_0 (Bw^k - 1)\, dw}{c_g + c_v x_i + c_v \mu_0 (w_i - w)} - \bar{t}_{wb} - B\bar{r}\mu_0 \int_{w_{cr}}^{w_e} \frac{w^k dw}{\mu_0 c_p + c_w x_i - c_w \mu_0 (w_i - w)}\right]. \tag{15}$$

Integrating Eqs. (11), (14), we define w_{cr}:

$$w_{cr} \cong w_i/1.8 + w_e \tag{16}$$

and the current moisture content:

$$w = \frac{\exp(-1.8/w_i N\tau)}{0.56 w_i} + w_e, \tag{17}$$

where N is the drying rate in the constant rate period. Substituting the value of $dw/d\tau$ from Eq. (15) in Eq. (14), we obtain a differential equation for the motion of the variable mass particle:

$$D\rho_p (1 + w)\frac{du}{d\tau} = \frac{3}{4}\xi\rho_g (v - u)^2 + 6\beta_I \left(\frac{w}{w_{cr}}\right)^n \left[t_{fI} + \int_{w_{cr}}^{w_e} \frac{r\mu_0 (Bw^k - 1)\, dw}{c_g + c_v x_i + c_v \mu_0 (w_i - w)} - \bar{t}_{wb} - B\bar{r}\mu_0 \int_{w_{cr}}^{w_e} \frac{w^k dw}{\mu_0 c_p + c_w x_i^T - c_w \mu_0 (w_i - w)}\right] u. \tag{18}$$

To solve this equation by numerical methods, the value of w is substituted from Eq. (17) or, in a stricter approach, is obtained by integration of Eq. (15). The values of ρ_g and v in Eq. (18)

$$\rho_g = \rho_g^{fI} T_{fI}\left[273 + t_{fI} + \bar{r}\mu_0 B \int_{w_{cr}}^{w_e} \frac{w^k dw}{c_g + c_v x_i + c_v \mu_0 (w_i - w)}\right]^{-1}, \tag{19}$$

$$v = \frac{v_{fI}}{T_{fI}}\left[273 + t_{fI} + \bar{r}\mu_0 B \int_{w_{cr}}^{w_e} \frac{w^k dw}{c_g + c_v x_i + c_v \mu_0 (w_i - w)}\right]. \tag{20}$$

When Rb is much less than unity, the expression in brackets in Eqs. (19), (20) simplifies significantly, in accordance with Eq. (12).

Case II. $D \neq$ const. It is assumed that in drying of the dispersed material the particle size changes only as a result of change in moisture content, not considering changes in size due to abrasive mass loss, mechanical fractionation, or agglomeration. The effect of each of these factors on particle size represents an independent question for each type of pneumodryer and material.

To consider the effect of change in particle size on the velocity of particle motion, we use the expression proposed by A. V. Lykov [2]:

$$D = D_0 (1 + \beta_l w)^q. \tag{21}$$

For a number of dispersed materials the exponent in this expression is equal to unity. Substituting in Eq. (18) the value of the particle diameter from Eq. (21), we obtain the equation of motion of a particle of variable mass and variable diameter. The sequence of steps in calculating the particle velocity will be similar to those presented above.

Thus, to calculate the velocity of a particle of varying mass and size, changing because of moisture content, we must have the following experimental data: the exponents of Eqs. (6), (10), (21), n, k, q, the constant coefficient B, and the shrinkage coefficient β_l. It should be kept in mind that B, k, β_l, and q may be determined under conditions different from the drying conditions in the real equipment. In a simplified calculation one must take a drying curve under conditions similar to those of the actual (projected) equipment. This is needed to determine the drying rate in the constant rate period.

NOTATION

c_g, c_v, c_p, specific heat of gas, vapor, and particle, kJ/kg; D, D_0, current diameter and diameter of absolutely dry particle, m; F, particle surface, m^2; G_g, G_p, flow rates of dry gas and particles, kg/sec; m, m_0, mass of wet and absolutely dry particle, kg; T, T_{fI}, t, t_{fI}, temperatures at current time and end of constant drying rate period, °K and °C; t_p, $\bar{t}_{wb}$, particle and mean wet bulb thermometer temperature, °C; u, v, particle and drying agent velocities, m/sec; W_i^v, W_i^p, initial moisture flow rates in drying agent and material, kg/sec; W, moisture evaporation rate, kg/sec; w_i, w, w_{cr}, initial, current, and critical material moisture content, kg/kg; x_i, initial moisture content of drying agent, kg/kg; β_I, β_{II}, mass transfer coefficients in constant and decreasing drying rate periods, kg/m²·sec·deg K; β_l, linear shrinkage coefficient; ρ_p, ρ_g, densities of absolutely dry particle and gas, kg/m³; μ_0, mass flow concentration referenced to absolutely dry material, kg/kg; ψ, geometric form coefficient; τ, time, sec.

LITERATURE CITED

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2. A. V. Lykov, Theory of Drying [in Russian], Énergiya, Moscow (1968).