the mean lifetime of a vapor bubble on the heat-liberating surface can be found. For the given experimental conditions these values proved equal to $\tau_s \approx 1$ msec and $\langle\tau\rangle \approx 1.57$ msec.

At high thermal fluxes the ratio $\varphi_{max}/\langle\varphi\rangle$ increases, reaching, in individual cases (at thermal fluxes close to critical) values close to four. This intensification of the effect at higher thermal fluxes can be obtained by studying a more complex model which considers coalescence of vapor bubbles on the surface. Coalescence leads to distortion of the bubble distribution over current and separation radii. Moreover, the vapor films which thus appear can accumulate the contribution to vapor content of the short-lived vapor bubbles, which also encourages intensification of the observed effect.

It can thus be assumed that the theoretical conclusions obtained on the basis of elementary statistical theory of collective phenomena in boiling do not contradict the experimental results. The divergence which appears in regimes close to critical should stimulate the development of a theory which can be applied in the region of regimes which have the greatest practical interest.

NOTATION

τ, time; τ_s, time required for attaining most probable separation radius; $\langle\tau\rangle$, mean lifetime of vapor bubbles on heater surface; φ, vapor content; φ_{max}, maximum vapor content achieved in transition process; $\langle\varphi\rangle$, mean vapor content in steady state; N, number of vapor formation centers acting on surface; R_0, resistance of experimental heater element; R_e, resistance of equivalent load.

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CALCULATION OF INSTALLATIONS FOR DRYING GAS SUSPENSIONS

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UDC 66.047

A method is given for calculating drying installations where an air suspension of finely dispersed particles is used as the drying agent.

In convective dryers the drying intensity is increased either through an increase in the coefficients of heat exchange between the material being dried and the drying agent or through an increase in the temperature of the latter. In the second case, even in the drying of fine particles, a significant temperature difference often develops between their surface and center, which leads to worsening of the quality of the finished product [1]. An increase in the coefficients of heat exchange requires considerable velocities of motion of the heat-transfer agent and corresponding expenditures of electrical energy. In the drying of finely dispersed particles in a fluidized bed the values of the coefficients of heat exchange play almost no role owing to their large specific surface area [2]. Here the amount of heat, proportional to the velocity and excess temperature of the gas, becomes the limiting factor. However, the

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gas velocity is limited by the carrying away of the particles, while a high temperature can lead to damage of the product or even to its combustion.

A third course, increasing the volumetric heat capacity of the agent, is almost unused in industry. In an air chamber located in front of the drying chamber we can mix the hot gas and finely dispersed dry particles which do not suffer from overheating. The time the particles spend in the air chamber is chosen as not less than the time of their thermal interaction with the gas. At the entrance to the thermal-treatment bed the drying agent will consist of a gas suspension with the gas and dust particles having equal temperatures. The volumetric heat capacity of such a drying agent and the amount of heat supplied to the fluidized bed of particles being dried increase almost in proportion to the mass flow-rate concentration of dust. It should be noted that the use of a dusty fluidizing agent leads to some decrease in the working velocities in the apparatus [3], but still considerably increases the total amount of heat supplied. The coefficients of heat exchange grow somewhat in the process [4], which also has a positive effect on the performance of the drying process. The powdered particles can either be removed from the bed separately from the particles being dried or unloaded together with time if particles of two kinds can enter into the compensation of the finished product. In the granulation of pulps and suspensions in a fluidized bed the hot dust particles supplied with the gas can serve as additional granulation centers and improve the granular composition of the finished product [5].

In the general case a drying installation for drying a gas suspension will consist of an air chamber, an air heater for heating the gas or gas suspension, and the dryer proper. A method of calculating such installations using an I—x diagram for the humid air is suggested in the present report.

Process in the Aeration Chamber

At the entrance to the chamber let there be humid air with the parameters G_a, x_a, and t_a and dust with the parameters G_s, c_s, and t_s. The interaction of the dry dust with the humid air can be treated as the interaction of air of two states if the influence of the finely dispersed dust is replaced by the equivalent thermal action of absolutely dry air (it is assumed that the heat capacities c_s and c_a do not vary), i.e.,

$$Q_s = Q_{as} \quad \text{or} \quad G_s c_s t_s = G_{as} c_a t_s. \tag{1}$$

The heat-balance equation for the air chamber will be

$$Q_a + Q_s = Q_{ga} \tag{2}$$

Here $Q_{ga} = I_{ga}G_{ga}$ and $G_{ga} = G_a + G_s c_s/c_a$. With allowance for this and (1), Eq. (2) takes the form

$$I_a G_a + G_s \frac{c_s}{c_a} c_a t_s = I_{ga}\left(G_a + G_s \frac{c_s}{c_a}\right). \tag{3}$$

In the latter equation

$$I_a = \frac{Q_a}{G_a}; \; I_{as} = Q_s \Big/ \left(G_s \frac{c_s}{c_a}\right); \; I_{ga} = Q_{ga} \Big/ \left(G_a + G_s \frac{c_s}{c_a}\right).$$

Keeping in mind the $(G_s/G_a)(c_s/c_a) = \mu(c_s/c_a)$, and designating the latter expression as K_μ, from (3) we obtain

$$\frac{I_{ga} - I_a}{I_{ga} - I_{as}} = -K_\mu. \tag{4}$$

Let us construct the moisture balance equation for the air chamber:

$$G_s x_s + G_a x_a = G_{ga} x_{ga}, \tag{5}$$

where $G_s x_s = G_{as} x_{as}$.

Using (1), from (5) we obtain

$$x_a + \frac{G_s}{G_a}\frac{c_s}{c_a} x_{as} = \left(1 + \frac{G_s}{G_a}\frac{c_s}{c_a}\right) x_{ga}. \tag{6}$$

Here

$$x_a = \frac{W_a}{G_a}; \; x_{as} = W_s \Big/ \left(G_s \frac{c_s}{c_a}\right); \; x_{ga} = W_{ga} \Big/ \left(G_a + G_s \frac{c_s}{c_a}\right);$$

$$W_{ga} = W_a + W_s.$$

Then from (6) we have

$$\frac{x_{ga} - x_a}{x_{ga} - x_{as}} = -K_\mu. \tag{7}$$

Thus, with an equivalent substitution of dry air with the parameters $G_{as} = G_s c_s / c_a$, t_s, and $x_{as} = 0$ for dust with the parameters G_s, t_s, and $x_s = 0$ in a gas suspension the enthalpy of the mixture can be determined from (4) as

$$I_{ga} = \frac{I_a + I_{as} K_\mu}{1 + K_\mu}, \tag{8}$$

while the moisture content from (7) can be determined as

$$x_{ga} = \frac{x_a}{1 + K_\mu}. \tag{9}$$

The right sides of (4) and (7) are the same, so

$$\frac{I_{ga} - I_a}{I_{ga} - I_{as}} = \frac{x_{ga} - x_a}{x_{ga} - x_{as}}. \tag{10}$$

In the coordinates x, I the expression (10) is the equation of a straight line passing through the points $A(x_{as}, I_{as})$ and $B(x_a, I_a)$. It is proposed to determine the point $C(x_{ga}, I_{ga})$ on the straight line AB in the following way. We preliminarily construct additional diagrams (Fig. 1) in accordance with the expression $K_\mu = \mu c_s / c_a$ to determine K_μ and in accordance with (9) for x_{ga}. We plot the points $A(0, t_s)$ and $B(x_a, I_a)$ on the I–x diagram and connect them with a straight line. Having determined c_s/c_a we find K_μ from a K_μ–μ diagram and we find x_{ga} from an x_{ga}–K_μ diagram. It is clear that the point C of intersection of the straight lines x_{ga} = const and AB will be the sought point characterizing the state of the mixture at the exit from the air chamber. We determine the parameters of the mixture at the point C by the usual procedure, except for the relative humidity φ_{ga}, which does not have meaning for the actual mixture. Let us conditionally separate the mixture into components at the exit from the air chamber and determine their parameters. On the I–x diagram this process is depicted by a straight line passing through the point C and coinciding with the isotherm t_C. The points A''' and B''' characterizing the state of the components must lie on the lines $x_{as} = 0$ and x_a.

Process of Air Heater

In the heating of a mixture to a temperature t_C' in a recuperative heat exchanger the lines of the processes of variation of its parameters and components on the I–x diagram coincide with x_{ga} = const, x_{as} = const, and x_a = const. The points A', B', and C' will characterize the components and the mixture at the exit from the air heater.

Process in an Ideal Drying Chamber

The process of heat and mass exchange between the gas suspension and the product takes place along $I_{C'}$ = const, since all the heat for moisture evaporation is drawn from gas suspension. The drying of the gas suspension will proceed until φ_a in the gas suspension becomes equal to 100%. First of all, therefore, we must know the process of variation of the air parameters for calculations of the drying process. To construct it we mark on the diagram the points A', B', and C' characterizing the parameters of the components and the mixture at the entrance to the drying chamber. Let the moisture content of the mixture change by Δx_C from x_C to x_D during the drying. The new parameters of the mixture are determined by the point D. It is seen from the construction that a change of x_C by Δx_C leads to a change in $x_{B'}$ by Δx_B to x_N. Then the moisture content at the points D, B', and N is determined as

$$x_D = x_{C'} + \Delta x_{C'}; \tag{11}$$

$$x_{B'} = x_{C'}(1 + K_\mu); \tag{12}$$

$$x_N = x_D(1 + K_\mu). \tag{13}$$

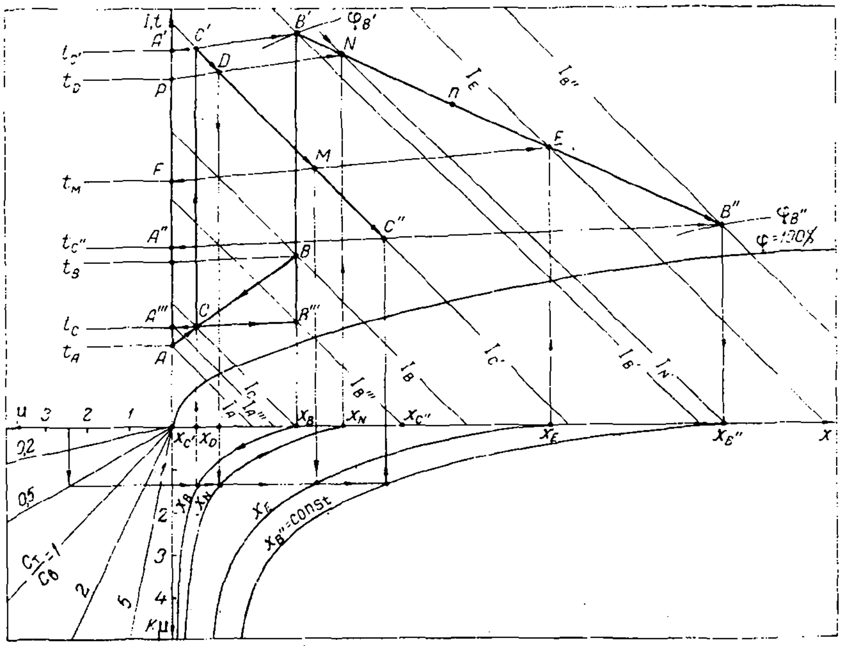

Fig. 1. Diagram for calculating an installation for drying a gas suspension.

In this process the enthalpy of the air changes by ΔI_B from I_B' to I_N. Let us determine the shape of the curve connecting the points B' and N. We find the enthalpy of the air at the points N and B':

$$I_N = c_a t_D + x_N (r + c_v t_D); \tag{14}$$

$$I_{B'} = c_a t_{C'} + x_{B'} (r + c_v t_{C'}). \tag{15}$$

We substitute the values of $x_{B'}$ and x_N from (12) and (13) into the latter equation and determine ΔI_B with allowance for (11):

$$\Delta I_a = c_a (t_D - t_{C'}) + (1 + K_\mu)[c_v x_{C'} (t_D - t_{C'}) + \Delta x_C (r + c_v t_D)]. \tag{16}$$

We express t_D through known parameters. For this we write the equations for determining the enthalpy of the mixture at points C' and D:

$$I_{C'} = c_a t_{C'} + x_{C'} (r + c_v t_{C'}) + K_\mu c_a t_{C'}; \tag{17}$$

$$I_D = c_a t_D + x_D (r + c_v t_D) + K_\mu c_a t_D. \tag{18}$$

But by convention the enthalpy of the mixture remains constant during the drying, i.e., $I_{C'} = I_D$. Solving (11), (17), and (18) jointly, we find that

$$t_D = \frac{c_a t_{C'} (1 + K_\mu) + c_v x_{C'} t_{C'} - r \Delta x_C}{c_a (1 + K_\mu) + c_v (x_{C'} + \Delta x_C)}. \tag{19}$$

We substitute t_D from (13) into (16), and after transformations we have

$$[c_a (1 + K_\mu) + c_v (x_{C'} + \Delta x_C)] \Delta I_B = c_a K_\mu (r + c_v t_{C'}) (2 + K_\mu) \Delta x_C. \tag{20}$$

From Eqs. (11)-(13) we get

$$\Delta x_C = \frac{\Delta x_B}{1 + K_\mu}. \tag{21}$$

Then by substituting $t_{B'}$ for $t_{C'}$ we can rewrite (20) in the form

$$c_a (1 + K_\mu)^2 \frac{\Delta I_B}{\Delta x_B} + c_v x_{B'} \frac{\Delta I_B}{\Delta x_B} + c_v \Delta I_B = c_a K_\mu (2 + K_\mu)(r + c_v t_{B'}). \tag{22}$$

Let us find the limits of the right and left sides of the equation as $\Delta x_B \to 0$. Since

$$\lim_{\Delta x_B \to 0} \frac{\Delta I_B}{\Delta x_B} = \frac{dI_B}{dx_B} \text{ and} \lim_{\Delta x_B \to 0} \Delta I_B = 0,$$

we have

$$\frac{dI_B}{dx_B} = \frac{c_a K_\mu (2+K_\mu)(r+c_v t_{B'})}{c_a(1+K_\mu)^2 + c_v x_{B'}} . \tag{23}$$

All the quantities on the right side of (23) are constant and do not vary in the given process. We integrate the latter equation in the limits from $I_{B'}$ and $x_{B'}$ to the variable upper limits I_n and x_n. Then

$$\frac{I_n - I_{B'}}{x_n - x_{B'}} = \frac{c_a K_\mu (2+K_\mu)(r+c_v t_{B'})}{c_a(1+K_\mu)^2 + c_v x_{B'}} . \tag{24}$$

The latter equation is easily reduced to the canonical form of the equation for a straight line passing through the point B':

$$I_n = a x_n + b. \tag{25}$$

Here the constants are

$$a = \frac{c_a K_\mu (2+K_\mu)(r+c_v t_{B'})}{c_a(1+K_\mu)^2 + c_v x_{B'}}$$

and

$$b = I_{B'} - x_{B'} \frac{c_a K_\mu (2+K_\mu)(r+c_v t_{B'})}{c_a(1+K_\mu)^2 + c_v x_{B'}} .$$

Thus, the process of variation of the state of the humid air in a drying chamber using a gas suspension as the drying agent proceeds along the straight line described by (25). The position of this straight line on the I–x diagram is determined by the coefficients a and b, constant for a given drying regime, which depend on μ and c_s of the dust and the state $x_{B'}$, $t_{B'}$ of the humid air at the entrance to the drying chamber.

To construct lines of the process of variation of the air parameters it is sufficient to know the initial point B' and any other point E characterizing the humid air in the chamber. The latter point is found as follows. On the line $I_{C'}$ = const we arbitrarily choose a point M (the farther from C' we choose M within allowable limits, the more accurate the construction). We go down along x_M = const to the intersection with K_μ = const and seek x_E on an auxiliary line of the x–K_μ diagram. We go up along x_E = const to the intersection with the isotherm t_M. Through the point E thus found and the point B' we draw a straight line which, as shown above, characterizes the process of variation of the parameters of the humid air in the chamber. The final point B" is determined for the state of the air at the exit from the dryer from the conditions of the concrete problem. To determine the parameters of the mixture (the point C") and of the second component (A") it is sufficient to find the intersection of the I axis and the line $I_{C'}$ = const with the isotherm $t_{B''}$.

Consumption of Heat, Air, and Dust in Drying

The heat per kilogram of dry air expended on heating the humid air is

$$q_a = I_{B'} - I_{B'''}.$$

The heat per kilogram of dry air expended on heating the finely dispersed particles of the gas suspension is

$$q_s = K_\mu (I_{A'} - I_{A'''}).$$

The heat per kilogram of dry air expended on heating the gas suspension is

$$q_{ga} = (1+K_\mu)(I_{C'} - I_C)$$

or

$$q_{ga} = K_\mu (I_{A'} - I_{A'''}) + (I_{B'} - I_{B'''}).$$

The fresh air expanded on the evaporation of 1 kg of moisture is

$$l_a = \frac{1}{x_{B''} - x_{B'}} .$$

The dust expended on the evaporation of 1 kg of moisture is

$$l_s = \mu \frac{1}{x_{B''} - x_{B'}} .$$

The heat expended on the evaporation of 1 kg of the moisture is

$$q = \frac{K_\mu (I_{A'} - I_{A'''}) + (I_{B'} - I_{B'''})}{x_{B''} - x_{B'}}$$

or

$$q = \frac{1 + K_\mu}{x_{B''} - x_{B'}} (I_{C'} - I_C).$$

Thus, the given procedure can be used in the calculation of installations for drying gas suspensions and the determination of the consumption of heat, air, and dust in drying.

NOTATION

c, mass specific heat, kJ/kg·°C; G, mass flow rate, kg/sec; I, enthalpy of a unit mass, kJ/kg; Q, heat, kW; t, temperature, °C; W, mass flow rate of moisture, kg/sec; x, moisture content per unit mass of dry material, kg/kg; μ, specific, mass, flow-rate concentration of dust, kg/kg dry air; φ, relative humidity, %; r, heat of vaporization of water, kJ/kg. Indices: v, vapor; a, air; s, dust; as, air substituting for dust; no prime, at entrance to air chamber; '", at exit from air chamber; ', at entrance to drying chamber; ", at exit from drying chamber.

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OPTIMUM CONTROL OF MULTIZONE CONVECTIVE DRYERS

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The problem of the optimum control of multizone convective dryers is solved. A dryer used for dying pipes is considered as an example.

Multizone convective dryers are widely used for drying materials in different branches of industry: chemical, construction materials, etc. In these dryers the drying agent is supplied by zones, and to each zone one can supply "fresh" drying agent, that "exhausted" for all the other zones, and "cold" air. Transfer of the material is accomplished with transporting devices.

As the optimality criterion characterizing the energy expenditure on drying we take a criterion allowing for the consumption of "fresh" drying agent and the consumption connected with the flows of drying agent from one zone over to another:

$$I = \sum_{j=1}^{n} \Big[c_{1j} G_{gj} + \sum_{\substack{i=1 \\ i \neq j}}^{n} (c_{2ji} G_{gji} + c_{3ji} R_{ji}) \Big], \tag{1}$$

where $R_{ji} = 0$ at $G_{gji} = 0$ and $R_{ji} = 1$ at $G_{gji} > 0$. The first term $c_{1j}G_{gj}$ in Eq. (1) characterizes the expenditure of "fresh" drying agent, with the coefficient c_{1j} depending on the potentialities of the heated gas as a drying agent; in particular, the value of c_{1j} increases with an increase in the gas temperature. The other two terms in Eq. (1), $c_{2ji}G_{gji}$ and $c_{3ji}R_{ji}$, characterize the expenditures connected with the flows of drying agent from the i-th to the j-th zone, with the value of the coefficient c_{3ji} being determined by the capital expenditures on the installation of the corresponding blower and the expenditures on the idle

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