in the stream core, °K; λ, wavelength, μm; $C_1 = 1.19088 \cdot 10^{-16}$, constant in Planck's law, $(W \cdot m^2)/sr$; $C_2 = 1.4388 \cdot 10^{-2}$, constant in Planck's law, m·°K; L, thickness of gas stream, m; $\Delta T = T_c - T_0$, temperature drop in the boundary layer of gas, °K; I_{λ_1}, I_{λ_2}, I_{λ_3}, I_{λ_4}, I_{λ_5}, spectral emission intensities measured at wavelengths of 4.273, 4.525, 4.566, 4.608, and 4.651 μm, respectively, 10^{10} W/(m³·sr). Indices: STP, standard conditions (P_{CO_2} = 1 atm and T = 273°K); w, boundary surface (wall); ref, reflected radiation.

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DESIGN OF INSTALLATION FOR DRYING BY A GAS CONTAINING HYGROSCOPIC PARTICLES

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UDC 66.047

A method is given for designing drying installations where a suspension of finely dispersed hygroscopic particles in air is used as the drying agent.

One way to intensify convective drying is to increase the volumetric heat capacity of the gaseous agent by introducing finely dispersed solid particles into it. A method of designing such installations published in [1] contemplates the use of a drying agent containing nonhygroscopic particles and presumes that their moisture content equals zero at any stage of this process. In practice such a condition is satisfied either at high temperatures or when the particles are absolutely nonhygroscopic. Ignoring the influence of the moisture adsorbed by the particles of drying agent can result in appreciable errors in the calculation. There also exist a number of processes of complex drying when solid particles contained in the gas stream are dried simultaneously with the primary object (material). The use of capillary-porous colloidal bodies as the finely dispersed particles is also advantageous for the reason that their hygroscopicity increases as well as their mass capacity, i.e., the drying capacity of the agent.

We allow for the presence of hygroscopic moisture in the particles of the agent in designing a drying installation, which in general consists of an air chamber (mixer), an air heater for heating the gas suspension, and the dryer proper. We assume that heat losses are absent; the mass flow rate of absolutely dry air is constant; the hygroscopic particles have small sizes and the establishment of their equilibrium parameters and those of the air takes place rather rapidly; the heat capacities c_p, c_a, and c_w do not vary.

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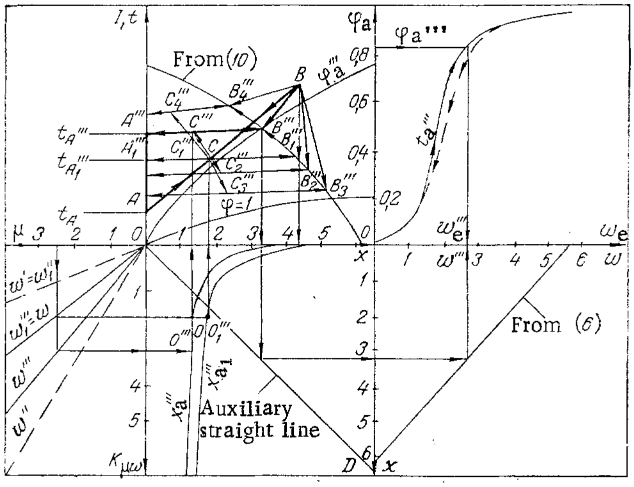

Fig. 1. Diagram for designing the air chamber.

Process in the Aeration Chamber

Let air with the parameters G_a, x_a, and t_a and particles of dispersed material with the parameters G_p, c_p, t_p, and w_p be supplied to the entrance of the thermally insulated chamber. We determine the final parameters of the components of the gas suspension, having conditionally divided the continuous process of heat and mass exchange into two successively occurring stages. In the first we assume that during the mixing of the hygroscopic particles with air only the process of heat exchange between them takes place until temperature equalization. Despite the change in φ_a, the moisture content of the particles does not vary and remains equal to w_p. The interaction of the latter with humid air is treated as the interaction of air in two states, where the influence of the hygroscopic particles, but now together with the moisture in them, is replaced by the equivalent thermal effect of absolutely dry air:

$$Q_{ap} = Q_p + Q_w \quad \text{or} \quad G_{ap} c_a t_p = G_p c_p t_p + G_p w_p c_w t_p. \tag{1}$$

Dividing both sides of (1) by $G_a c_a$, we obtain

$$K_{\mu w} = \frac{G_{ap}}{G_a} = \frac{G_p}{G_a}\left(\frac{c_p}{c_a} + w_p \frac{c_w}{c_a}\right) = \mu \left(\frac{c_p}{c_a} + w_p \frac{c_w}{c_a}\right). \tag{2}$$

We formulate the heat-balance equation for the air chamber.

$$Q_{gs} = Q_a + Q_{ap} \quad \text{or} \quad I_{gs} G_{gs} = I_{gs}(G_a + G_{ap}) = I_a G_в + I_{ap} G_{ap}, \tag{3}$$

from which, with allowance for (2),

$$\frac{I_{gs} - I_a}{I_{gs} - I_{ap}} = -K_{\mu w}. \tag{4}$$

We formulate the moisture-balance equation similarly, and after transformations we find

$$\frac{x_{gs} - x_a}{x_{gs} - x_{ap}} = -K_{\mu w}. \tag{5}$$

The equality from the left sides of (4) and (5) represents the equation of a straight line in the coordinates I and x passing through the points A ($x_A = x_{ap} = 0$; $I_A = I_{ap}$) and B ($x_B = x_a$; $I_B = I_a$) (Fig. 1). To seek the point C ($x_C = x_{gs}$; $I_C = I_{gs}$) characterizing the parameters of the gas suspension, we construct a $K_{\mu w}$–μ diagram in place of the K_μ–μ diagram [1]. For this we draw a series of auxiliary straight lines with angular coefficients of $\frac{c_p}{c_a} + w_p \frac{c_w}{c_a}$ in the indicated coordinates. From μ, c_p, c_w, and $w_p = w$ we determined $K_{\mu w}$ and find the point 0 of intersection of $K_{\mu w}$ = const with the x_B curve of the x–$K_{\mu w}$ diagram. The point C lies at the intersection of the straight lines AB and $x_C = x_{gs}$ = const passing through the point 0.

The parameters of the components of the gas suspension are determined at the points A_1''' and B_1''' lying on the isotherm t_C. The latter are nonequilibrium points, however, since the conditions outside the particles have changed, as well as the temperature of the particles themselves. In the second stage thermodynamic equilibrium is established between the components of the gas suspension as a result of heat and mass exchange up to the instant of their exit from the air chamber. In the process, the moisture content of the particles changes from w_1''' to w''', while the moisture content of the air changes from $x_{B_1'''}$ to $x_{B'''}$. It is easy to show that

$$x_{B'''} - x_{B_1'''} = \mu(w_1''' - w'''). \tag{6}$$

We determine the final temperatures $t_{A'''} = t_{B'''} = t_{C'''}$ of the components and the gas suspension at the exit from the mixer. Since equilibrium is established without heat exchange with the ambient medium, we have

$$Q_{gs_1}''' = Q_{gs}''' - \Delta Q^b_{AA'''}$$

or

$$I_{ap1}'''G_{ap1}''' + I_{B_1'''}G_a = I_{ap}'''G_{ap}''' + I_{B'''}G_B - \Delta Q^b_{AA'''}. \tag{7}$$

Here $\Delta Q^b_{AA'''} = G_p(w'''-w)\bar{q}^b_{AA'''}$ is the change in "bound" heat [2], equal to the additional energy expenditures above r on the evaporation of the adsorbed moisture in the process AA'''. The average specific heat $\bar{q}^b_{AA'''}$ can be determined from the data of [3] with allowance for the recommendations of [2] when the initial and final parameters of the process are known.

We note that $G_{ap_1}''' = G_aK_{\mu w_1}'''$ while $G_{ap}''' = G_aK_{\mu w}'''$, from which

$$K_{\mu w_1}''' - K_{\mu w}''' = \mu(w_1''' - w''')c_w/c_a. \tag{8}$$

By convention, $w_1''' = w$, and hence $K_{\mu w_1}''' = K_{\mu w}$ and $x_{B_1}''' = x_B$. Then, with allowance for (6), (8) is rewritten as

$$K_{\mu w}''' = K_{\mu w} - (x_{B'''} - x_B)c_w/c_a. \tag{9}$$

By definition, $I_{ap_1}''' = c_at_{A_1}''' = c_at_C$, $I_{B_1'''} = c_at_{B_1'''} + x_{B_1'''}(r + c_vt_{B_1'''}) = c_at_C + x_B(r + c_vt_C)$, $I_{ap}''' = c_at_{A'''} = c_at_{B'''}$, and $I_{B'''} = c_at_{B'''} + x_{B'''}(r + c_vt_{B'''})$. Substituting the latter expressions into (9) and (7), after transformations we obtain

$$t_{B'''} = \frac{c_Bt_C(K_{\mu w}+1) + (r + c_\pi t_C)x_B - rx_{B'''} - \bar{q}^b_{AA'''}(x_{B'''} - x_B)}{c_a(K_{\mu w}+1) + c_wx_B - (c_w - c_v)x_{B'''}}. \tag{10}$$

For a concrete process all the parameters in (10) except for $x_{B'''}$ and $\bar{q}^b_{AA'''}$ are constant. In the coordinates t–x the dependence of $t_{B'''}$ on $x_{B'''}$ is represented by a curve, and if $t_{B'''} = t_C = t_{B_1'''}$, then $x_{B'''} = x_B = x_{B_1}'''$, which is possible in the mixing of humid air and particles with the same equilibrium parameters. The latter means that the curve (10) on the I–x diagram should pass through the point B_1'''. In Fig. 1 we show the directions of the process CC''' for a gas suspension which are possible in practice along the lines CC_1''', CC_2''', CC_3''', and CC_4''' and the directions of the process BB''' for humid air along the lines BB_1''', BB_2''', BB_3''', and BB_4''' as the equilibrium moisture content of the particles changes from w to w_1''', w_2''', w_3''', and w_4''', respectively. The direction of the process toward the sorption to or desorption of moisture from the particles is determined by the initial parameters of the air and the initial parameters of the hygroscopic dispersed material. Sorption, like desorption, can proceed both during the mixing of hot air with cold particles and during the mixing of cold air with hot particles. In this case the temperature $t_{C'''}$ of the gas suspension which forms can be higher than the highest temperature of the components owing to the release of heat of adsorption during the corresponding change in the equilibrium moisture content of the particles and it can be lower than the lowest temperature for the desorption of part of the moisture from the particles and the consumption of a corresponding amount of heat.

For the practical determination of the point B''' on the I–x diagram from an infinite set of pairs of numbers $t_{B'''}$ and $x_{B'''}$ satisfying (10), one must choose only that which simultaneously satisfies the moisture-balance equation (6) and the equations connecting the equilibrium moisture content of the particles with the equilibrium parameters of the humid air. The first of these equations is a sorption or desorption equation of the type

$$\varphi_{B'''} = \varphi_{B'''}(w''', t_{B'''}, \text{const}_1, \text{const}_2, \ldots, \text{const}_n), \tag{11}$$

which is usually interpreted graphically [4] because of the complexity and awkwardness of the analytical approximation. The constants in (11) are determined by the properties of the specific material. The others are the equations connecting $\varphi_{B'''}$, $x_{B'''}$, and $t_{B'''}$ and the pressure p'''_{sat} of saturated water vapor,

$$\varphi_{B'''} = \varphi_{B'''}(x_{B'''}, p'''_{sat}), \tag{12}$$

$$p'''_{sat} = p'''_{sat}(t_{B'''}), \tag{13}$$

used to construct the I–x diagram. Thus, the system of (6), (10), and (11)-(13) includes five unknowns $t_{B'''}$, $x_{B'''}$, w''', $\varphi_{B'''}$, and p'''_{sat} subject to determination.

For engineering problems it is more expedient to solve this system by graphic construction, since (6) is the equation of a straight line, (10) is an equation with one variable, (11) is given by a standard diagram, and the curves (12) and (13) are on the I–x diagram. For the solution one also needs a w–x diagram to connect the moisture of the air and particles through (6) and an auxiliary straight line OD on the x–$K_{\mu w}$ diagram. The latter is intended for transferring values of the moisture content to the vertical x axis. For convenience of use we arrange the diagram of sorption and desorption for particles so that its axis of equilibrium moisture contents coincides with the w axis of the w–x diagram.

In searching for the equilibrium parameters of the gas suspension we adhere to the following order. Using isotherms of the I–x diagram and preliminarily determining a series of values of $\bar{q}^{b}_{AA'''}$, we draw the curve $t_{B'''} = t_{B'''}(x_{B'''})$ through the known point B'''_i in accordance with (10) and the straight line $w''' = w'''(x_{B'''})$ in the coordinates w–x in accordance with (6). We choose a point B''' not far from the point B'''_i on the curve $t_{B'''} = t_{B'''}(x_{B'''})$ and determine $\varphi_{B'''}$. Using the straight line OD we transfer $x_{B'''}$ to the x axis of the w–x diagram and find the corresponding value of w'''. Depending on whether the point B''' was chosen above or below the point B'''_i, we determine the equilibrium moisture content w'''_e of the particles from the sorption or desorption isotherms for the $\varphi_{B'''}$ and $t_{B'''}$ found. If $w'''_e \neq w'''$ from the construction, we assign a new point B'''. As shown above, the equality $w''' = w'''_e$ will correspond to the establishment of equilibrium parameters between the components of the gas suspension. The isotherm $t_{B'''}$ intersects the I axis at the point A'''. To seek the point C''' from μ and w''' we find $K'''_{\mu w}$, the point O''', and $x_{C'''}$. The lines AA''', BB''', and CC''' reflect the variation of the parameters of the components and the gas suspension in the air chamber.

Process in the Air Heater

Let the temperature of the gas suspension at the exit from the regenerative heat exchanger be assigned and equal to $t_{C'}$ (Fig. 2). In accordance with the assumptions, the heating process passes through an infinite series of equilibrium states of particles and air. We are interested only in the final parameters of the gas suspension and its components, and therefore we also conditionally replace the continuous process of heat and mass exchange by another process consisting of two stages, but with identical parameters at the end.

In the first stage we assume that the moisture content of the particles does not vary and the heating in the regenerator takes place up to a certain temperature $t_{C'_i}$, different from $t_{C'}$ in the general case. Then the variations of the parameters of the components and the gas suspension on the I–x diagram are shown by straight lines coinciding with lines of x = const.

In the second stage, which proceeds without delivery of heat from outside, because of the change in external conditions relative to the particles the moisture content of the latter varies through heat and mass exchange with the air. In this case the process must be organized through the choice of $t_{C'_i}$ so that the final parameters at the points A', B', and C' lie on the isotherm $t_{C'}$. The temperature $t_{C'_i}$ must be higher than $t_{C'}$ from physical considerations, since with an increase in the temperature of the gas suspension the equilibrium moisture content of the particles decreases from w''' to w'. The latter causes an increase in the moisture content of the air from $x_{B'''}$ to $x_{B'}$, and a decrease in the temperature of the gas suspension owing to the heat expended on desorption of moisture from the particles.

Let us establish the dependence between $t_{C'}$ and $t_{C'_i}$. We note that

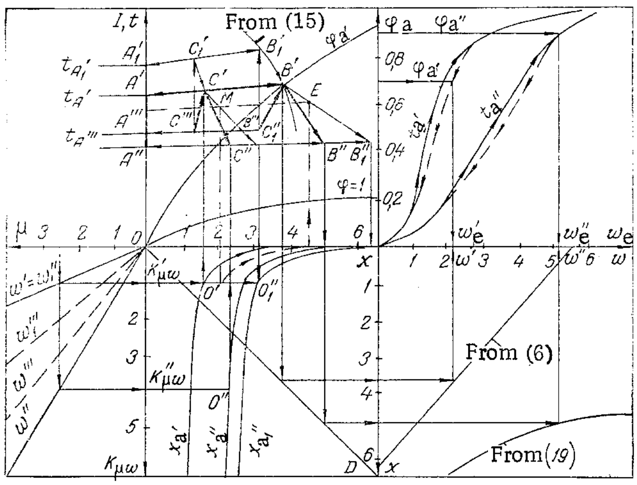

Fig. 2. Diagram for designing the air heater and drying chamber.

$$Q'_{as_1} = Q'_{as} - \Delta Q^{b}_{A'''A'}$$

or

$$I'_{ap_1} G'_{ap_1} + I_{B'_1} G_a = I'_{ap} G'_{ap} + I_{B'} G_a - \Delta Q^{b}_{A'''A'}, \tag{14}$$

from which, after the appropriate transformations and change of parameters for the conditions under consideration, we obtain

$$t_{B'} = \frac{c_a t_{C'_1} (K'''_{\mu w} + 1) + (r + c_v t_{C'_1}) x_{B'''} - r x_{B'} - \bar{q}^{b}_{A'''A'} (x_{B'} - x_{B'''})}{c_a (K'''_{\mu w} + 1) + c_w x_{B'''} - (c_w - c_v) x_{B'}}. \tag{15}$$

From (15) it is easy to see that the problem of seeking the parameters of the components and the gas suspension with $t_{C'_1}$ is the inverse of the analogous problem of seeking the equilibrium parameters for $t_{C'''}$.

In practice, the search for equilibrium parameters based on diagrams is carried out as follows. We choose a point B' to the right of the point B''' on the given isotherm $t_{C'}$ of the I–x diagram, we determine $\varphi_{B'}$ and $x_{B'}$, and we find w' from the w–x diagram. We establish w'_e from the desorption isotherm for $\varphi_{B'}$ and $t_{B'}$. If $w'_e \neq w'$ from the construction, we assign a new point B'. We draw a curve $t_{B'} = t_{B'}(x_{B'})$ through the point B' in accordance with (15). The point B'_1 lies at the intersection of this curve with $x_{B'_1} = x_{B'''}$. A'_1 and C'_1 are the points of intersection of the isotherm $t_{B'_1}$ with the I axis and $x_{C'''}$ = const. To seek the point C' from μ and w' we find $K'_{\mu w}$, the point 0', and $x_{C'}$. The lines A'''A', B'''B', and C'''C' reflect the variation of the parameters of the components and the gas suspension in the air heater. The process for the air heater can be constructed more precisely by choosing several temperatures intermediate between $t_{C'''}$ and $T_{C'}$. Taking each intermediate temperature as the final temperature, we determine the intermediate points by the method given above and connect them with smooth curves.

Process in an Ideal Drying Chamber

Since the heat for the evaporation of moisture from the material is drawn only from the gas suspension, the latter starts to cool. In the process there is an increase in the relative humidity of the air and the equilibrium moisture content of the particles owing to adsorption, the heat of which goes in turn to the evaporation of additional moisture from the material being dried. We determine the parameters of the gas suspension and its components at the exit from the dryer if the temperatures $t_{A''} = t_{B''} = t_{C''}$ are assigned here. For this we assume that the moisture content of the particles does not change in the first stage during the cooling of the gas suspension to $t_{C''}$. The process of heat and mass exchange between the gas suspension and the material being dried travels along the isenthalpic line $I_{C'}$ between the points C' and C''_1. To construct the line $B'B''_1$ of the process of variation of the air parameters it is sufficient, according to [1], to know the initial point B' and any other point E characterizing the air humidity in the chamber. We find the latter point as follows. We arbitrarily choose a point M on the line $I_{C'}$ = const. We travel down along x_M = const to the intersection with $K'_{\mu w}$ = const and we seek x_E on the auxiliary line of the x—$K_{\mu w}$ diagram. We travel upward along x_E = const to the intersection with the isotherm t_M. We draw a straight line $B'B''_1$ through the points B' and E to the intersection with the isotherm $t_{B''}$. We obtain the points A''_1 and C''_1 at the intersections of the same isotherm with the I axis and the isenthalpic line $I_{C'}$.

In the second stage we assume that equilibrium is established between the particles and air at the temperature $t_{C''}$. Here the heat-balance equation will be

$$Q''_{C_1} = Q'_C - \Delta Q^{b}_{A'A''}$$

or

$$I''_{ap_1} G''_{ap_1} + I_{B''_1} G_a = I''_{ap} G''_{ap} + I_{B''} G_a - G_p (w'' - w') \bar{q}^{b}_{A'A''} . \quad (16)$$

But

$$G''_{ap_1} = G_a K''_{\mu w_1}, \quad G''_{ap} = G_a K''_{\mu w}, \quad G_p = \mu G_a, \quad I''_{ap_1} = I''_{ap} = c_a t_{B''_1} = c_a t_{B''}.$$

Then, with allowance for the fact that $w''_1 = w'$ by convention, we rewrite (16) in the form

$$I_{B''_1} - I_{B''} = \mu (c_w t_{B''} - \bar{q}^{b}_{A'A''}) (w'' - w'). \quad (17)$$

On the other hand, by definition

$$I_{B''_1} - I_{B''} = c_a t_{B''_1} + x_{B''_1} (r + c_v t_{B''_1}) - c_a t_{B''} - x_{B''} (r + c_v t_{B''}) = (r + c_v t_{B''})(x_{B''_1} - x_{B''}), \quad (18)$$

since $t_{B''_1} = t_{B''}$. Owing to the evaporation of moisture from the material being dried, $x_{B''_1} > x_{B'}$. From (17) and (18) we obtain

$$x_{B''} = x_{B'} + \frac{\mu (\bar{q}^{b}_{A'A''} - c_w t_{B''})}{r + c_v t_{B''}} (w'' - w'). \quad (19)$$

In the coordinates w—x a graph of $x_{B''} = x_{B''}(w'')$ constructed from (19) is not a straight line in general, since $\bar{q}^{b}_{A'A''}$ is not a constant.

In practice, we seek the equilibrium parameters of the gas suspension and its components at the exit from the dryer as follows. In the coordinates w—x we draw a curve in accordance with (19), having first determined $\bar{q}^{b}_{A'A''}$. We choose a point B'' on the isotherm $t_{B''}$, we find $\varphi_{B''}$ and we establish w'' on the w—x diagram. From the sorption isotherm for $\varphi_{B''}$ and $t_{B''}$ we determine w''_V. If $w''_e \neq w''$ from the construction, we assign a new point B''. We find the point C'' from the point 0''. The latter is determined at the intersection of the curve $x_{B''}$ of the x—$K_{\mu w}$ diagram with $K''_{\mu w}$ = const. The lines A'A'', B'B'', and C'C'' will characterize the variation of the parameters of the components and the gas suspension in the drying chamber. For a more precise construction we must choose several temperatures intermediate between $t_{C'}$ and $t_{C''}$. Taking each intermediate temperature as the final temperature, we determine the intermediate points and connect them with smooth curves.

Consumption of Heat, Air, and Hygroscopic Dispersed Material

Heat consumed in heating humid air per kilogram of dry air:

$$q_a = I_{B'_1} - I_{B'''}.$$

Heat consumed in heating particles in the gas suspension per kilogram of dry air:

$$q_p = K'''_{\mu w} (I_{A'_1} - I_{A'''}).$$

Heat consumed in heating the gas suspension per kilogram of dry air:

$$q_{gs} = (K'''_{\mu w} + 1)(I_{C'_1} - I_{C'''}).$$

Fresh air consumed in evaporating 1 kg of moisture:

$$l_a = 1/[(x_{B''} - x_{B'}) + \mu (w'' - w')].$$

Heat consumed in evaporating 1 kg of moisture:

$$q_w = \frac{K'''_{\mu w} (I_{A'_1} - I_{A'''}) + (I_{B'_1} - I_{B'''})}{(x_{B''} - x_{B'}) + \mu (w'' - w')}$$

or

$$q_w = \frac{(K'''_{\mu w} + 1)(I_{C'_1} - I_{C'''})}{(x_{B''} - x_{B'}) + \mu (w'' - w')} \ .$$

The method given above can be used to design installations for drying with a gas suspension containing hygroscopic particles and to determine the heat, air, and dispersed material consumed in drying.

NOTATION

c, specific mass heat capacity, kJ/(kg·°C); G, mass flow rate, kg/sec; I, enthalpy per unit mass, Kj/kg; Q, heat, kW; t, temperature, °C; w, moisture content per dry mass, fraction; x, moisture content per unit mass of dry air, kg/kg; μ, specific mass flow-rate concentration of particles, kg/kg of dry air; φ, relative humidity, fraction; r, heat of vaporization of water, kJ/kg. Indices: w, water; v, vapor; a, air; p, particles; ap, air substituting for particles; gs, gas supension; e, equilibrium; b, bound; ¯, average; without primes, at entrance to air chamber; ''', at exit from air chamber; ', at entrance to drying chamber; '', at exit from drying chamber; 1-4, intermediate parameters.

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KINETICS OF ISOTHERMAL EVAPORATION OF A POROUS OR DISPERSED BODY

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We consider the evaporation of a porous body which consists initially of spheres of identical radii. We find the dependence of the velocity of motion of the boundary of the body on the external parameters.

DERIVATION OF EQUATIONS OF MOTION FOR THE BOUNDARY

To simplify the calculations, we confine ourselves in the present work to a model of the porous body which consists of spheres of identical radii r_0 which are positioned at random but uniformly to the right of a plane. The evaporation takes place on account of a difference between the pressure of vapor in equilibrium with the spheres p_0, and the pressure p_1 of the vapor confined on the left of the planar boundary of the body. Below, we neglect the dependence of the equilibrium pressure on the radius of the spheres. After the beginning of evaporation, the radii of spheres are no longer equal. The radii of the spheres which are nearer to the periphery of the body (Fig. 1) decrease more rapidly, and a gradient of radii appears (but not the gradient of concentrations of the spheres) which is directed and decays toward the interior of the porous body. The spheres at the external surface of the body evaporate first.

We consider a steady-state evaporation process during which the external boundary of a dispersed body which corresponds to radii of spheres $r = 0$ moves to the right with a constant, but yet unknown, velocity c. The problem consists of determination of c as a func-

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