KINETICS AND DYNAMICS OF THE CONDUCTIVE DRYING OF DISPERSE MATERIALS

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An analysis is given of the effect of certain parameters on the intensity and rate of conductive drying, the results are generalized in the form $U = f(N_1\tau/u_0)$, $\bar{t}_M/\bar{t}_{M_1} = f(N_1\tau/u_0)$, and information is given for the thermal calculation of the process.

The drying of finely divided and polydispersed friable materials in various branches of industry is one of the fundamental and often limiting areas of a technological process. For many materials contact with the drying agent is undesirable because of the considerable aerodynamic resistance and is sometimes inadmissible for technological reasons. Examples are the drying of abrasive powders, melted welding fluxes and their components, the components of glass mixtures, vanadium pentoxide powders, easily oxidized and dangerously explosive materials, etc. In such cases it is best to use drying equipment with a dense (fixed or moving) layer of friable material and to introduce the heat from a heated surface. The characteristics of the dryer (its efficiency, size, heat capacity, and cost) largely determine the features of the whole production line and the quality of the finished product. Hence, it is obviously necessary to design efficient multitonnage apparatus for finely dispersed and polydispersed materials.

This problem can only be solved by making use of data on the kinetics and dynamics of drying, the theoretical principles of which are described in [1, 2, 3, 4, 5, etc.]. However, only fragmentary information is given in the literature on a limited number of disperse friable materials (quartz sand [2,3], certain chemical products [6], and certain food products [7]). For the majority of materials (including the above) there is no experimental data, and no comparative analysis or generalization have been made. In this paper we present the results of an experimental investigation of the process of conductive drying in a fixed dense layer of abrasive powders of silicon carbide, corundum, boron carbide, fluorspar, quartz granules, and certain fluxes.

We investigated the effect on the heat and mass transfer during the drying process of the following factors: the properties (nature) of the material, its initial moisture content, the thermal load (temperature) of the heating surface, and the thickness and configuration of the layer. The characteristics of the materials and the limits of variation of certain parameters are shown in the table. The investigation was made on models of the elements of a surface dryer, representing the channel of a ring or slot section, in which the material is placed. On one of the walls of the channel, impenetrable for vapor and heated with an electrical heater, boundary conditions of the second kind were produced (q_W = const, $j_m = 0$), and on the other, penetrable for heat and mass flow, convective heat and mass transfer with the surrounding medium occurred, i.e., boundary conditions of the third kind were produced (in the cylindrical model the inner surface was heated). In the experiments we measured the power and temperature of the heater surface, the average moisture content at different instants of time, the initial moisture content, the porosity of the layer, and the parameters of the surrounding medium. In addition, we measured the temperature distribution and moisture content* over the cross section of the layer. The error in determining the local moisture content did not exceed ±10%, the error in determining the overall moisture content did not exceed ±6%, and the error in measuring the rate of drying did not exceed ±7%.

The main features of the kinetics of drying in a layer for all the materials investigated were the same, and reflect the particular features of conductive heat transfer. We

*The local moisture contents were measured with conductometric sensors.

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TABLE 1. Characteristics of the Materials

Material	Particle size d, mm,	Initial moisture content u_0, kg/kg	Heat flux density $q_w \cdot 10^{-3}$, W/m²	Layer thickness δ, mm	Temp., °C	
					Surface, $\bar{t}_w$,	Layer $\bar{t}_M$
Green silicon carbide						
ring layer	0,02 0,05 0,10	0,05—0,20	5,3; 19,2	50	84—455	65—89
flat layer	0,02 0,05		3,9; 5,3; 8,7		69—237	72—78
Corundum	0,05	0,05—0,16	8,2; 13,2; 19,2	34; 20;	85—264	61—94
Fluorspar	0,08	0,04—0,14			145—535	65—126
Quartz grit	0,38	0,04—0,12			136—523	68—97
Boron carbide	1,50	0,05—0,18			102—325	72—116
Fluxes						
AN-60 pumic type	1,96	0,04—0,14	8,2; 13,2		166—470	63—100
AN-15 glass type	2,18	0,02—0,09			187—431	64—88
AN-348A	2,03	0,03—0,09			220—469	61—100

will analyze the kinetics of the temperature field and of the moisture content during the drying process on the basis of their local values. Figure 1 shows the variations with time of the temperature and moisture content at distances of 8 mm, 25 mm, and 42 mm from the heating surface in a plane layer (δ = 50 mm) of silicon carbide (d = 20 μm) for one of the modes of operation: the heat flux density $q_w = 5.3 \cdot 10^3$ W/m², and an initial moisture content u_0 = 0.15 kg/kg. Here we have plotted the mean volume temperature of the material and the mean (overall) moisture content. Its values, determined from the local quantities, i.e., from the readings of the moisture sensors and direct weighing of the specimen, agree quite well with each other. On all the curves (local and integral) periods of increasing (0), constant (I) and decreasing (II) drying rates (typical for capillary-porous materials), can be seen. The first critical moisture content u_{cr1} corresponds to the beginning of the second period, and the curves of the second period have a point of inflection corresponding to the second critical moisture content u_{cr2}.

Analysis of the drying curves shows that the initial warmup period is characterized by minimum duration (10–15%) and minimum relative moisture removal (5–12%). The duration of the periods of constant and falling rate of drying are approximately the same (35–55%), but the main part of the moisture (55–75%) is removed during the constant-rate period. The critical moisture contents which define the limits between the zero and first periods (u_{cr0}), the first and second periods ($\bar{u}_{cr1}$), and also the value of u_{cr2} are practically independent of the modes of drying (q_w, $\bar{t}_M$), and the geometrical parameters (δ, d), and the nature of the material, and are determined solely by the initial moisture content u_0. The dependence of the critical moisture contents on the initial moisture content for all the materials investigated can be approximated by the following equations:

$$U_{\mathrm{cr}0} = 0.92;\ U_{\mathrm{cr}1} = 0.22;\ U_{\mathrm{cr}2} = 0.11. \tag{1}$$

The kinetics and dynamics of the variation of the temperature and moisture-content fields can be seen in Figs. 1 and 2. Figure 2 shows the temperature and moisture-content distribution over the thickness of the plane layer of silicon carbide in the warm-up period, the constant-rate period, and falling-rate period for the same modes of operation. The temperature distribution has a considerable effect on the moisture-content field. A change in the moisture-content begins earliest of all in the most rapidly heated layer, close to the heating surface. In the warm-up period the uniform temperature and moisture-content distribution is destroyed, considerable nonuniformity is then observed, and the drying process takes place in the presence of considerable temperature and moisture-content gradients. The maximum temperatures and temperature gradients in all the periods occur on the heating surface, and in the direction towards the free surface the temperature in the layer decreases monotonically but only slightly. The temperature field in the falling-rate period, when the temperature in the layers close to the walls increases sharply and the evaporation region begins to move into the depth of the layer, is the most nonuniform. The central layers of the material have the maximum moisture content in the first and second periods, and the layers close to the walls have the minimum moisture content. The nonuniformity of the moisture-content distribution during the first period is a maximum and decreases with time. The

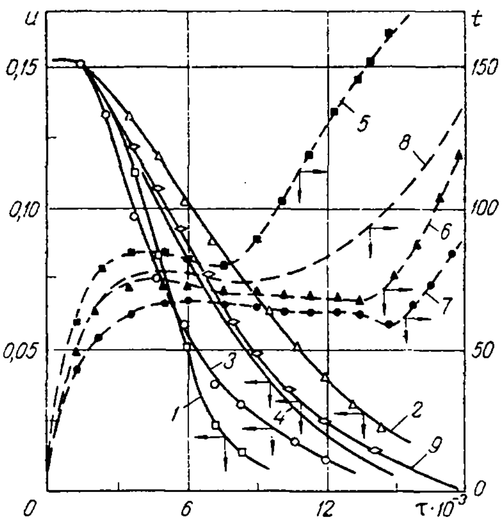

Fig. 1

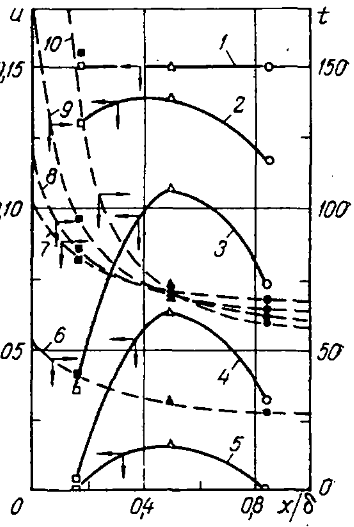

Fig. 2

Fig. 1. Variation of the temperatures and moisture contents in a plane layer of silicon carbide (δ = 50 mm, d = 20 μm, and $q_W = 5.3 \cdot 10^3$ W/m^2). The local values at a distance x from the heating surface are: 1, 5) x = 8; 2, 6) x = 25; 3, 7) x = 42 mm; 4, 8) mean volume values; 9) integral drying curve, the continutous curves are the temperature, and the dashed curves are the moisture content, u, kg/kg, t, °C, $\tau \cdot 10^{-3}$, sec.

Fig. 2. Distribution of the moisture content (1–5) and the temperatures (6–10) in a plane layer of silicon carbide (δ = 50 mm, d = 20 μm, $q_W = 5.3 \cdot 10^3$ W/m^2): heating period – 1, 6) $\tau = 0.6 \cdot 10^3$ sec; 2, 7) $\tau = 3 \cdot 10^3$ sec; period of constant rate – 3,8) $\tau = 5.4 \cdot 10^3$ sec; period of falling rate – 4, 9) $\tau = 9.6 \cdot 10^3$ sec; 5, 10) $\tau = 15.6 \cdot 10^3$ sec.

degree of nonuniformity of the temperature and moisture-content distribution increases as the thermal-flux density and the thickness of the layer increase. The configuration of the layer and its initial moisture content have practically no effect on the nonuniformity. The local rate of drying is a maximum, and the duration of the process is a minimum in the layers close to the heating surface and having the maximum temperature (see Fig. 1). The minimum rate of drying is observed in the central layer, and it is higher in the peripheral layer although the temperatures of the layers differ only slightly. For example, for the mode corresponding to Figs. 1 and 2, in the first period the rate of drying is $1.7 \cdot 10^{-5}$ kg/kg/sec on the heating surface, it is $1.4 \cdot 10^{-5}$ kg/kg/sec in the center, and $1.55 \cdot 10^{-5}$ kg/kg/sec on the periphery (the values correspond to the sections where the moisture sensors are placed).

The nature of the variation in the local and average temperatures and of the moisture content is determined by the mechanism of heat and mass transfer in the layer. The conditions under which the heat is introduced and propagates in the layer and also the heat-exchange conditions on the free surface play an important role. At the initial instants of time, when the temperature perturbations are localized in the first series of particles, the intensity of the heat supply is mainly determined by the contact thermal resistance, which depends on the average thickness of the vapor layer between the surface and the first series of particles. However, under our experimental conditions the time in which the contact resistance plays a decisive role is very small (for d ≤ 10^{-3} m, $\tau_{min} \approx 1$ sec). As the thermal wave propagates the thermal resistance of the layer itself begins to play a decisive part; this increases due to the reduction in the temperature gradients on the wall, and as the depth of penetration of the thermal wave increases until it reaches the free surface. The heat is then dispersed in heating the material and in evaporating the moisture, and is partially dissipated into the surrounding medium. As is well known, when there is no mass transfer the heat in the dense layer is transmitted mainly by conduction, the part played by convection and radiation being negligibly small. When there is mass transfer there is an additional heat-transfer mechanism. In the warm-up period this is transfer with liquid-type moisture, displaced due to concentrational diffusion and thermal diffusion, and in the first and second periods convective transfer by vapor, which travels through the layer due to the

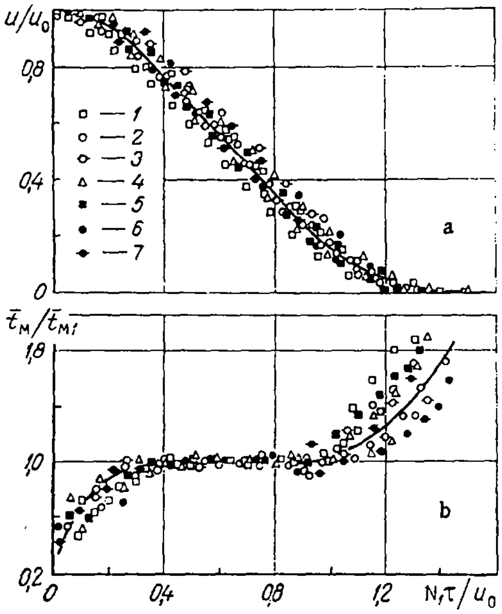

Fig. 3. Generalized modified drying curve (a) and temperature curve of the material (b) for silicon carbide powders: a cylindrical layer — 1) u = 0.05 kg/kg; 2) 0.10; 3) 0.15; 4) 0.20; a plane layer — 5) u = 0.05 kg/kg; 6) 0.10; 7) 0.15.

action of the total-pressure gradient. Filtering transfer leads to considerable intensification of heat transfer, and its effect can be interpreted as an increase in the effective thermal conductivity of the layer, which can be taken into account, e.g., using the equation given in [8]. The most intense filtering of the vapor is observed during the constant drying rate period, and the rate of filtering increases as the initial moisture content and thermal flux density increases. For the modes used in the experiments, i.e., a vapor velocity v = 0.05–0.7 m/sec and the equivalent Reynolds's criterion Re = 0.3–2.9, the effective thermal conductivity increases by 20–40% compared with the values when there is no filtering. The heat and mass transfer conditions with the surrounding medium have an effect on the moisture content and rate of drying in the peripheral layer.

Generalized processing of the integral data on drying obtained under different conditions is a fairly difficult problem in view of the complexity of the process and the variety of determining factors. Considerable progress in this direction has been made using the method proposed in [3] in the form of the dependence $u = f(N_1\tau)$, which enables one to generalize the experimental data for a specific material for different drying modes. A drawback of this method is the impossibility of generalizing data for different initial moisture contents, and also the dimensional form of the relationship. These drawbacks can be eliminated when generalizing data in the form of the modified dependence $U = f(N_1\tau/u_0)$. Without going into details in analyzing the drying of granular materials in a moving dense layer, which is of independent interest, we note that this method also enables one to take into account such factors as the velocity of motion of the layer.

A generalized modified curve of the kinetics of the drying for granular silicon carbide, shown in Fig. 3a, generalizes the data for all fractions, thicknesses, heat flows, and moisture contents with an error probability of ±12%. Similar graphs are obtained for other materials. A comparison of the generalized curves of the drying kinetics for all the materials investigated shows good qualitative and quantitative agreement between the data, which indicates the analogy between the forms in which the moisture is bound and the transfer mechanisms due to the similar structure of the materials. The single generalized modified curve of the drying kinetics for the materials investigated is described by the following equations:

1) In the constant-rate period ($u_{cr_0} \le u \le u_{cr_1}$)

$$U = 0.92 - 0.89\,\frac{N_1\tau}{u_0}, \tag{2}$$

2) In the falling-rate period for $u_{cr1} \leq u \leq u_{cr2}$

$$U = 0.22 \exp\left(-4.23\ \frac{N_1\tau}{u_0}\right), \tag{2a}$$

for $u_{cr2} \leq u \leq u_p$

$$U = 0.11 \exp\left(-8.13\ \frac{N_1\tau}{u_0}\right). \tag{2b}$$

The time τ is measured from the beginning of the corresponding period or its part.

The effect of the operating and geometrical characteristics on the rate of drying in the first period and for the process as a whole is qualitatively the same. The rate of drying, and, consequently, the specific moisture removal increases considerably when the initial moisture content of the material is increased, which can be explained by the improvement in the heat and mass transfer conditions due to the increase in the effective thermal and mass conductivities of the layer. The heat-flux density and the temperature of the material have a decisive effect on the intensity and rate of drying, which increase considerably as the heat flux increases. The intensification in the process as the temperature increases is also due to the increase in the effective transfer characteristics. As the heat flux and the temperature are increased, the contribution of convective filtering transfer of vapor increases. An increase in the thickness of the layer from 20 mm to 50 mm leads to a considerable reduction in the rate of drying (by a factor of ≈ 4), which is due to the reduction in the mean temperature of the layer and also to the increase in the aerodynamic resistance, which makes it difficult for the vapor formed to escape.

The average drying rate for the whole process and in the first period is described by the following relations, which generalize (with an error probability of ±8%) all the experimental data:

$$N = \mathrm{Ki}_m a_m u_0 / R^2,$$

where

$$\mathrm{Ki}_m = c\,\mathrm{Ki}_q^{0.86} \left(\frac{u_0}{u_{max}}\right)^{-0.6}, \tag{3}$$

in which the coefficient c is equal to 2.6 and 3.2 for the whole process and for the first period, respectively.

The kinetics of the drying process in the second period are best represented by the relative rate of drying $N_2^* = (1/N_1)(du/d\tau)$, the instantaneous values of which can be found directly from the generalized modified drying curve. The relative drying rate is independent of the mode of operation, the geometry of the layer, and the particle dimensions, and is determined solely by the instantaneous values of the moisture content. The equation of the generalized drying-rate curve of all the materials investigated have the form (for the first and second parts of the second period, respectively)

$$N_{2a}^* = 1.54 \exp[0.36(U - U_{cr2})], \tag{4a}$$

$$N_{2b}^* = 3.86 \exp[0.14(U - U_p)]. \tag{4b}$$

The error probability is ±15%.

The generalized modified curve of the heating kinetics for silicon carbide powder is shown in Fig. 3b. This curve generalizes the data for all the operating and geometrical characteristics shown in Table 1. The curves for all the other materials investigated have a similar form. The modified temperature curve of the heating kinetics for the whole drying process is described (with a rms error of ±10%) by the following relation: for $N_1\tau/u_0 \leq 0.32$

$$\bar{t}_M/\bar{t}_{M1} = 0.106 + 4.273\ \frac{N_1\tau}{u_0} - 6.851\left(\frac{N_1\tau}{u_0}\right)^2 + 3.683\left(\frac{N_1\tau}{u_0}\right)^3, \tag{5a}$$

for $0.32 \leq N_1\tau/u_0 \leq 1.0$

$$\bar{t}_M/\bar{t}_{M1} = 1, \tag{5b}$$

and for $N_1\tau/u_0 \geq 1.0$

$$\bar{t}_w/\bar{t}_{M1} = 0.106 + 4.973\left(\frac{N_1\tau}{u_0} - 0.56\right) - 6.851\left(\frac{N_1\tau}{u_0} - 0.56\right)^2 + 3.683\left(\frac{N_1\tau}{u_0} - 0.56\right)^3. \tag{5c}$$

The values of the mean-volume temperature in the constant drying rate period which occur in Eq. (5) are given (with a rms error of ±15%) by the expression

$$T = \frac{\bar{t}_{M1} - t_f}{t_f} = 3.5\,\mathrm{Ki}_q^{0.28}(R/D)^{-0.36}, \tag{6}$$

which holds for $0.8 \le \mathrm{Ki}_q \le 12.3$; $1.8 \le R/D \le 7.8$.

Hence, the data obtained in the conductive drying of all the materials we investigated for different initial moisture content, and operating and geometrical characteristics, are described by single modified curves of the kinetics of drying and heating. The results obtained may provide a basis for designing apparatus and choosing the optimum parameters of the drying process. In addition, they are also of interest for comparison with data for a moving layer.

NOTATION

$a = 6(1 - \varepsilon)/d$, particle surface per unit volume; a_m, moisture diffusion coefficient in the layer; c_m, specific isothermal mass capacity of the material; d, particle size; D and F, diameter and area of the heater; ε, layer porosity; q_w, heat-flux density; j_m, mass-flux density; N, rate of drying; R = V/F, determining linear dimension; t, temperature; r, specific heat of vaporization; $u = c_m\theta$, moisture content; V, volume of the layer; v, velocity of the vapor; δ, layer thickness; θ, moisture transfer potential; λ_q, effective thermal conductivity of the layer; λ_m, mass transfer coefficient of the layer; ν, coefficient of kinematic viscosity of the vapor; τ, time; $\mathrm{Ki}_q = q_wR/\lambda_q t_f$; $\mathrm{Ki}_m = j_m r/\lambda_m u_0$; Kirpichev's number; $N_2^* = (1/N_1)(du/d\tau)$, rate of drying number; $\mathrm{Re} = 4\bar{v}/\nu a$, Reynolds's number; $U = u/u_0$, moisture-content number; and $T = (\bar{t}_{M_1} - t_f)/t_f$. The indices used are as follows: f, surrounding medium; M, material; m, mass transfer; q, heat; cr, critical; p, equilibrium; and w, on the heating surface.

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