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ON MAIN METHODS OF DECREASING THE HEAT CONSUMPTION IN PROCESSES OF CONVECTION DRYING

M. M. Razin UDC 664.047(031)

The possibility to substantially decrease the heat consumption in the drying of moist materials by artificial retardation of the process was theoretically substantiated. Main variants of organization of the drying of the indicated materials for the purpose of increasing the efficiency of the process were analyzed.

Keywords: *drying, saving of energy, heat efficiency, rules, retardation, ballast zones, pulsed regime, recirculation, methods.*

Introduction. The problem of decreasing the heat consumption in the convection drying of materials was considered in [1] where three main rules for organization of the process with a small heat consumption were determined. The first of them requires that the humidity of the air at the output of the drier φ_2 be as high as possible. Despite the evidence of this rule, it is ignored in many cases where the value of φ_2 does not exceed 0.3–0.4. Figure 1 demonstrates the influence of the humidity of the outflowing air on the heat consumption in the case were the heat efficiency of the drying of a material η is determined as the ratio between the heat of vaporization (at 20°C) and the real heat consumed for evaporation of 1 kg of moisture in an air heater. We used calculation data obtained for the drying of wheat grains with the use of a countercurrent air flow by the method considered in [1]: the temperature of the air at the input of the drier was 75°C and the maximum temperature of heating of the products was 60°C. Under these conditions, the efficiency of the process increased by a factor of more than 1.5 when φ_2 changed from 0.3 to 0.8 and the air flow rate decreased in the same ratio. In this case, the mass of the material in the drying chamber and, correspondingly, the time of the drying increased by approximately 38%. Consequently, following the first rule requires little effort, and this rule can be easily realized in practice.

The heat consumption in the drying of a material can be further decreased by increasing the drying temperature (the second rule), which, however, can lead to overheating of thermolabile materials. To prevent this overheating, it is recommended to decrease the internal gradients in the material to a minimum (the third rule), which is characteristic of the processes with a decreased drying rate. The principal possibility of decreasing the heat consumption in the drying of materials by retardation of the process will be demonstrated by concrete examples.

Development of Additional Analytical Methods. We will consider any function representing the ratio between the angular coefficient of the moisture-content profile at the surface of a moist particle $-\partial u/\partial n$ and the relative average difference $(\bar{u} - u_{\text{sur}})/R$:

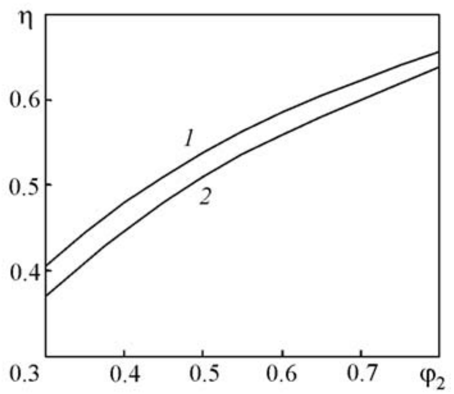
$$k_{\text{f}} = -\frac{\partial u}{\partial n}\frac{R}{\bar{u} - u_{\text{sur}}} . \tag{1}$$

The quantity k_{f} characterizes the relative slope of the moisture-content profile near the surface of the particle. It will be called the coefficient of the form of the profile or, simply, the form factor. We have performed a series of calculations of k_{f} by numerical integration of the linear equation of internal mass transfer for a spherical particle

$$\frac{\partial u}{\partial \tau} = a_{\text{m}}\nabla^2 u \quad \text{at} \quad -\frac{\partial u}{\partial n}\rho_{\text{s}}a_{\text{m}} = \beta\,(x_{\text{sur}} - x) , \tag{2}$$

and the equation of heating of a material [1]

Kazan' State Technological University, 68 K. Marks Str., Kazan', 420015, Russia; email: michrazi@mail.ru. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 83, No. 2, pp. 255–263, March–April, 2010. Original article submitted December 16, 2008; revision submitted April 13, 2009.



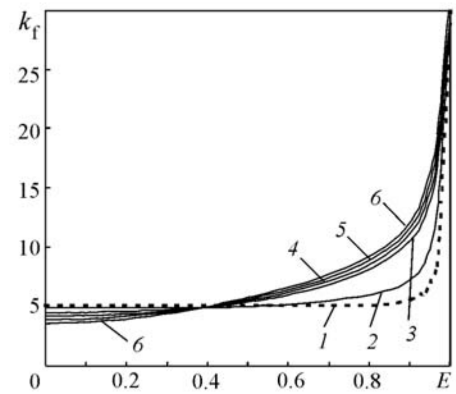


Fig. 1. Dependence of the heat efficiency of the drying of a material on the relative humidity of the outflowing air: $\mathrm{Bi_m}$ = 100 (1) and 500 (2).

Fig. 2. Change in the form factor in the process of drying of the grain: $\mathrm{Bi_m}$ = 5 (1), 15 (2), 40 (3), 70 (4), 100 (5), and ∞ (6).

$$c_s \frac{d\bar{\theta}}{d\bar{u}} = r - \frac{\alpha}{\beta}\,\frac{t - \theta_{sur}}{x_{sur} - x} - q_{ad.s} \quad \text{with the initial condition } \theta = \theta_1 \ \text{ at } \ \bar{u} = u_1 \tag{3}$$

with the use of the equation of equilibrium (desorption) of the material $x_{sur} = x(u_{sur}, \theta)$ [1]. It is assumed that the temperature distribution in a particle of the material is homogeneous: $\bar{\theta} = \theta = \theta_{sur}$. The term $q_{ad.s}$ in (3) accounts for the heat from additional sources (sinks) that are external relative to the material, including the heat losses. In this case, $q_{ad.s}$ is assumed to be equal to zero.

The results of calculations carried out for constant values of t and x are presented in Fig. 2 in the form of the dependence of k_f on the dimensionless moisture content E at different values of $\mathrm{Bi_m}$. The object of investigation is a wheat grain. It was established that the value of k_f is practically independent of the drying parameters t and x and changes from ∞ at $E = 1$ to any constant value characteristic of regular regimes. A series of similar dependences of k_f on E was obtained at $\mathrm{Bi_m} \geq 30$, which makes it possible to use, instead of this series, a general computational dependence:

$$k_f = 3.9 \quad \text{at} \quad E < 0.133 \quad \text{and} \quad k_f = 2.8\,(1 + 7.8E_1^4 + \exp(0.019)\,(1 - E_1))\,, \tag{4}$$

where $E_1 = (E - 0.133)/0.867$ at $E > 0.133$.

With the use of the expression for the form factor (1), the boundary condition (2) can be written as

$$\frac{\bar{u} - u_{sur}}{x_{sur} - x} = \frac{\mathrm{Bi_m}}{k_f}\,. \tag{5}$$

To determine the possibility of using the general dependence (4), we compared analogous dependences obtained by different methods: by numerical integration of Eqs. (2) and (3) and with the use of the form factor determined from Eqs. (3)–(5) at different temperatures. The results obtained were in more than satisfactory agreement. It is interesting that expression (4) can be used at $\mathrm{Bi_m} < 20$ too. Practically analogous results were also obtained for variable values of a_m.

The existence of dependence (4) for any drying regime, revealed by the author in [2], was called the quasi-regularity property. As for the form of expression (4), it is individual for each material and is determined by the state of equilibrium (desorption) of its surface, defined by the equation $x_{sur} = x(u_{sur}, \theta)$, as well as by the initial humidity of the material.

In the present work, the form factor is used only as an additional means because, with it, many effects considered below, which are difficult to represent, are explained simply. However, in what follows we present calculations carried out by traditional numerical methods with the use of (2), (3), and other balance equations, which are individual

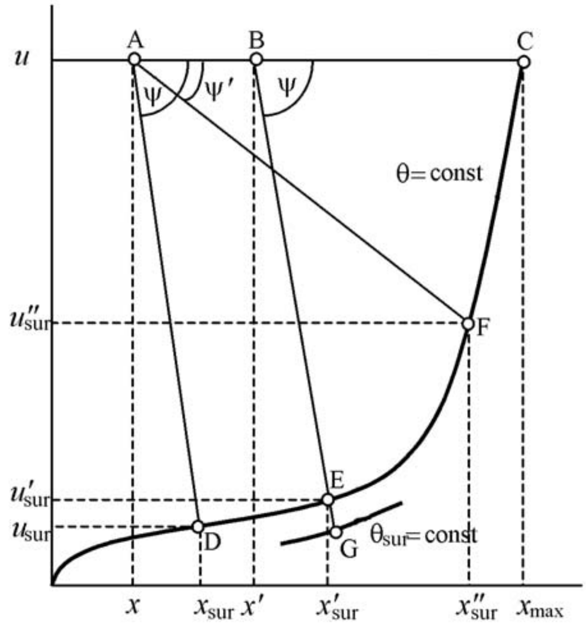


Fig. 3. Graphical representation of the parameters of the surface of moist particles.

for each of these methods. The main of them are presented in [1]. The material being investigated is a wheat grain with an initial moisture content of 20% (u_1 = 0.25 kg/kg) and a finite moisture content of 14% (u_2 = 0.162 kg/kg). In all the cases, the humidity of the outflowing gases was maintained at 70%, and the temperature of the material at the end of the drying was 60°C.

We will consider, by way of example, the state of the surface of moist particles under different conditions (Fig. 3). Let a particle with mean-volume parameters $\bar{u}$ and θ contact with a gas whose moisture content is x. The general state of the particle is represented by point A in Fig. 3. The curve θ = const represents the isotherm of desorption of the material at a given temperature. For drying processes free of gradients [1] (infinitely slow drying), the state of the surface of a particle with a maximum moisture content x_{max} independent of the current value of x is represented by point C. The state of the surface of a particle with internal gradients is presented by point D with parameters x_{sur} and u_{sur} on the isotherm. The position of this point is determined by expression (5), according to which the angular coefficient of the beam AD forming the angle ψ with the horizontal AC is equal to Bi_m/k_f.

Let us place the indicated particle into a medium with a larger moisture content x'. The state of its surface will be represented by point E (x'_{sur}, u'_{sur}), and the line BE will form the same angle ψ with the horizontal AC. Consequently, the value of x_{sur} changes synchronously with change in the current moisture content of the air, and the inequality $x_{sur} > x$ is conserved.

Analysis of Possible Methods of Increasing the Heat Efficiency of Drying. Wheat grains were used as the material of investigation. In accordance with literature data, the heat-transfer coefficient of wheat grains a_m ranges from 10^{-10} to 10^{-11} m²/sec, which corresponds to the range of change in the mass-transfer Biot criterion 100–1000. Below we use the value of Bi_m = 500 because the characteristics of the drying at Bi_m = 500–1000 differ insignificantly. In this case, the heat efficiency of the drying does not exceed 50% even for φ_2 = 0.7, which is obviously insufficient. Therefore, an effort will be made to determine whether the efficiency of the drying can be increased by a corresponding organization of the process.

Drying with the use of ballast zones. Let the volume of a drying chamber be divided crosswise into two zones: an active zone and a ballast (passive) one. The particles of the products in the active zone are constantly exposed to air. In the ballast zone, exposure to air is absent. An example of such a system is a drum drier with an increased filling factor. In this drier, a material is found during most of the drying period in the dense layer at the bottom of the drum and on the shelves, and the particles are exposed to air predominantly at the instant they are poured. Another example can be a spouting layer with a well-marked active flowing core and a massive peripheral (passive) zone [3].

Let the material be intensively transferred between the zones such that each particle is found in the active zone during the time τ_A and in the ballast zone during the time τ_B, and the time of one cycle of mass transfer between the zones is $\tau_c = \tau_A + \tau_B$. It will be assumed that, because of the intensive stirring of the material, the parameters of the surface of the particles in both zones differ insignificantly. In this case, the boundary condition in (2) for one mass-transfer cycle takes the form

$$-\frac{\partial u}{\partial n} \rho_s a_m \tau_c = \beta \left(x_{sur} - x \right) \tau_A \, . \tag{6}$$

The left side of (6) defines the amount of moisture transferred from within of a particle to its surface during the time τ_c. In the ballast zone, moisture continues to move to the surface of the particle under the action of the internal gradients, despite the absence of contact with air. The right side of (6) defines the amount of moisture removed from the particle during the time of its exposure to air τ_A. We introduce the intensity factor of the process, determined by the formula

$$k_{int} = \frac{\tau_A}{\tau_c} = \frac{F_A}{F} = \frac{m_A}{m} \, . \tag{7}$$

Then (6) can be rewritten with the use of (1) and (7) as

$$\frac{\bar{u} - u_{sur}}{x_{sur} - x} = \frac{k_{int} \, \mathrm{Bi_m}}{k_f} \, . \tag{8}$$

Expression (8) differs from (5) by the presence of the factor $k_{int} < 1$ before $\mathrm{Bi_m}$ in it, which is equivalent to a reduction in the criterion $\mathrm{Bi_m}$ (more precisely, in β). Thus, the drying process in the ballast zone can be calculated on the basis of Eq. (2), in which the product $k_{int}\beta$ should be substituted for β. The point F in Fig. 3 representing the coordinates x''_{sur} and u''_{sur} of the surface of the particle corresponds graphically to the case being considered. The position of point F is determined, according to (8), by the beam AF with an angular coefficient $\tan \Psi' = k_{int}\mathrm{Bi_m}/k_f$. Thus, the larger the size of the ballast zone, the smaller the intensity coefficient and the closer the process to the gradient-free one characterized by point C.

Comparison of this regime with the initial high-rate regime (point D) shows that the quantity x''_{sur} increases substantially as compared to x_{sur} and the motive force of the drying process increases substantially in the active period $x''_{sur} - x$. As a result, although the total rate of the process decreases, the rate of drying in the active zone increases by many factors.

We now address the equation of heating (3). For the case being considered, the difference $x''_{sur} - x$ in the denominator should be substituted for the difference $x_{sur} - x$. This leads to a decrease in the second term determining the slope of the temperature curve θ–u. Consequently, in the case of drying of a material with the use of ballast zones, the material will have a lower temperature, which makes it possible to increase the drying temperature and to decrease the rate of the air flow. The latter is supported by the calculations carried out at $q_{ad.s} = 0$, the results of which are presented in Table 1. These data show that the efficiency of the drying and its permissible temperature t_1 markedly increase with decrease in k_{int}, which, however, leads to an increase in the drying time.

In the case where wheat grains are dried, the heat expended for heating of the material is comparable with the heat expended for evaporation of moisture from it; therefore, the results of the drying without cooling are worse than the results of the drying with a cooling. In the latter case, the product is not dried completely and, after the heating to 60^{o}C, it is cooled by air in the cooling stage where the remaining moisture is removed from the product. The air heated in the process of cooling of the material is fed into the air heater and then into the drying chamber, i.e., the regenerated heat is used.

A feature of the drying of a material with the use of a countercurrent flow is the condensation of moisture on the cold material in the process of its contact with the outflowing moist air. This additional moisture is removed then; however, in this case, a part of the drying path is not used rationally. At small values of k_{int} this part can comprise half the length of the chamber. To eliminate this disadvantage it is recommended to conduct the heating of the

TABLE 1. Characteristics of Drying with the Use of a Ballast Zone for a Countercurrent Flow

k_{int}	Without cooling				With a cooling			
	η	Fo	t_0	L/G	η	Fo	t_0	L/G
1.0	0.503	0.026	66	9.0	0.630	0.029 (0.029)	68	8.5
0.5	0.513	0.031	75	7.5	0.635	0.033 (0.026)	77	7.1
0.2	0.528	0.040	97	5.1	0.651	0.038 (0.030)	110	4.2
0.1	0.540	0.046	129	3.6	0.682	0.042 (0.031)	142	2.7
0.05	0.558	0.053	186	2.3	0.712	0.050 (0.032)	193	1.9
0.02	0.570	0.068	240	1.7	0.735	0.078 (0.042)	220	1.4
0.01	0.602	0.093	280	1.4	0.758	0.146 (0.081)	242	1.3

moist material at $k_{int} = 1$. All the calculations presented here were carried out with account for the indicated fact (the values of Fo in parentheses were obtained for the drying region without cooling).

Since the mass of the product in the apparatus is related to its drying capacity and the time of treatment of the product in it by the relation $m = G\tau$, we obtain

$$\frac{G}{G_{in}} = \frac{m/m_{in}}{\tau/\tau_{in}}, \tag{9}$$

where the index "in" denotes the initial regime (the first row in Table 1). If the mass of the product does not change with increase in the drying time ($m/m_{in} = 1$), the drying capacity of the apparatus will undoubtedly decrease, and if the mass of the product increases more rapidly as compared to the increase in the drying time, the drying capacity of the apparatus will increase. Let us consider, for example, the row with $k_{int} = 0.05$ in the table (the regime with cooling). In this case, the drying rate decreases by a factor of 20 (from 1.0 to 0.005), the drying temperature increases from 68 to 193^{o}C, and the air rate decreases by a factor of 4.5 (the value of L/G decreases from 8.5 to 1.9). At the same time, the drying time increases by a factor of 1.72 ($\tau/\tau_{in} = \mathrm{Fo}/\mathrm{Fo}_{in} = 0.050/0.029$) and the mass of the product increases, because of the presence of the ballast zone (m/m_{in}), by a factor of 20.

Substituting the determined ratios between the mass of the product and the drying time into (9), we obtain that $G/G_{in} = 20/1.72 = 11.6$, i.e., that the drying capacity of the drier increases by a factor of 11.6 as compared to the high-rate drying at one and the same length of the drying chamber. In this case, the specific heat consumption decreases substantially. If the drying capacity of the apparatus remains unchanged, to obtain the ratio $m/m_{in} = 1.72$, it is necessary to decrease the length of the drying chamber by a factor of 11.6 (in this case, the mass of the product increases by a factor of 20 in the transverse direction).

Thus, ballast zones are effective means for decreasing the heat consumption in the process of drying. A paradox is that such zones are in certain industrial driers, e.g., in drum ones, where k_{in} can comprise 0.2–0.3; however, they are considered as stagnant zones and, therefore, their role is underestimated.

Drying with pulsed blowing. The above-described scheme of drying is characterized by an increased consumption of heat for the stirring of the material. The drying process is realized much simplier in the case where the active and passive zones are separated not in the space but in the time. The case in point is the pulsed regime of air supply. In this case, hot air is supplied to the drier during the time τ_A, and the whole drier represents an active zone. Under these conditions, any profile of the moisture content in the particles of a material is formed. During the time τ_B, air is not supplied and, therefore, moisture is not removed. As a result, the moisture-content profile formed in the active period equalizes gradually.

In the case where the passive period is fairly large, the moisture content can be equalized completely to a uniform distribution where $x_{sur} \to x_{max}$. As a result, in the next active period, the drying begins as though at the beginning and proceeds with a large rate. In order that the condition $x_{sur} \to x_{max}$ be fulfilled, the time of the active period should be minimum to ensure that the deformation of the moisture-content profile be as small as possible. If the time-dependent intensity factor k_{int} determined by expression (7) is introduced, the above-formulated condition will provide the organization of the drying process with a minimum k_{int}.

In the case where the number of cycles is not less than 300, the regime being considered does not differ radically from the above-described variant of drying with the use of a ballast zone. Graphically the state of the surface of

TABLE 2. Characteristics of Drying with Air Recirculation for a Countercurrent Flow (with a cooling of the material)

k_{flow}	η	Fo	t_0	t_1	L/G	L_0/G
1	0.503	0.0290	68	68	8.5	8.5
0.5	0.671	0.0300	97	66	10.1	5.1
0.2	0.684	0.0335	151	64	14.1	2.8
0.1	0.703	0.0369	201	63	19.5	1.9
0.05	0.723	0.0407	254	62	28.8	1.5
0.02	0.743	0.0472	304	61	56.2	1.1

the particles of the material being dried is represented by the same point F in Fig. 3. However, since, in this case, the exact values of τ_A and τ_B are known, it is best to perform calculations individually for each period. The drying process in the active period is described by Eqs. (2) and (3) as an ordinary short-time drying. The equalization in the passive period is described by Eq. (2) too; however, the boundary condition is different in this case: $\partial u/\partial n = 0$, $\overline{u} =$ const, $\theta =$ const.

Our calculations have shown that both the above-considered drying regimes are close in their parameters. However, the data obtained for the pulsed regime are also dependent on the pulsation frequency: the time of the drying decreases with increase in the pulsations. In this case, the drying time is smaller by a factor of 1.5–2 than that presented in the table. This is explained by the fact that the drying time increases by many factors at the beginning of each active period as compared to the steady-state process. Since, in this case, the mass of the product in the apparatus does not increase, in accordance with expression (9), at $m = m_{in}$ the drying capacity of the drier decreases. To make up for this deficiency, it is necessary to increase the mass of the feed in proportion to the value of τ/τ_{in}. It should be also noted that, in the active period, the air-flow rate exceeds the air-flow rate averaged over the drying time by a factor of $1/k_{int}$.

Drying with the use of a cross flow. The use of a cross flow in the process of drying makes it possible to regulate the rate of drying of the material by changing the height of its layer. We will consider the ideal cross flow by the version of [1]. In this case, the parameters x_{sur} and θ are assumed to be unchanged along the height of the layer and the local moisture content of the gas emerging from it is determined by the exponential law

$$x_2 = x_{sur} - (x_{sur} - x_1) \exp(-b) ,$$

where $b = \beta f m_{lay}/(w\rho_g)$. The average motive force of the external mass transfer along the height of the layer is determined by the expression

$$(x_{sur} - x)_{av} = \frac{1}{b}\int_0^b (x_{sur} - x)\, db = (x_{sur} - x_1)\, \frac{1 - \exp(-b)}{b} . \tag{10}$$

Here, the multiplier $(1 - \exp(-b))/b = k_{int}$ plays the role of the intensity factor (in relation to a thin layer with a height in one particle). For a cross flow, $(x_{sur} - x)_{av}$ should be substituted for $x_{sur} - x$ in (2); then, substituting (10) into (2) and using (1), we obtain Eq. (8) that involves x_1 instead of x. As in the previous cases, in Fig. 3, the state of the surface of a particle at an arbitrary instant of time is characterized graphically by the point F with an angular coefficient of the beam AF in accordance with Eq. (8). By increasing the mass of the layer on the grill m_{lay} or decreasing the velocity of the air w, one can approach the establishment of the gradient-free regime, characterized by the point C, as close as desired. The aforesaid is supported by the characteristics calculated for the drying with the use of a cross flow in [1].

The majority of the shaft grain driers used in practice can be considered with certain reservations as apparatus with cross flows of phases; in this case, the parameter b takes a value of about 10. At $b = 10$, the calculated heat efficiency is equal to 0.487 for drying without cooling and 0.567 for drying with cooling. These values are close to the real ones and are limiting for the driers being considered. The characteristics of these driers can be substantially improved (their efficiency can be increased to 0.74 and the flow rate of the air can be decreased by a factor of 2.5) by increasing the value of b to 50, which, however, increases the drying time by almost a factor of 2.

The oscillating drying regime. In the regime of oscillating drying, the product is alternately exposed to hot and cold air. However, unlike the above-considered regime of pulsed air blowing, in the oscillating regime the heat removal is continued in the process of cooling of the material; therefore, the moisture-content profile is not equalized and the process is not retarded. Because of this, it is unlikely that this method can provide a high efficiency of drying.

A numerical experiment carried out for drying with the use of cross flow at b = 10 and t_0 = 350°C in the hot zones of the drier has shown that, as compared to the previous method, the drying time decreases by a factor of 1.5, i.e., the oscillation intensifies the process. This is explained by the fact that the material in the hot zone is heated at a higher rate. However, the oscillating heating practically does not differ in efficiency and total air flow rate from drying with the use of an ordinary cross flow, i.e., it does not provide a marked decrease in the heat consumption. This can be explained by the fact that the values of the temperature of the air t_1 at the input to the layer of the material being dried are practically equal in both variants (for the oscillating regime, the average temperature of the air is considered and the existence of the cooling zones is taken into account).

Drying with recirculation of air. Countercurrent flow. A recirculation of the heat-transfer agent in the drying chamber increases the content of moisture in the air at the input of the drying chamber; in this case, t_1 and x_1 are determined from the expressions

$$x_2 - x_1 = k_{\text{flow}}\,(x_2 - x_0)\,, \quad t_1 - t_2 \approx k_{\text{flow}}\,(t_0 - t_2)\,, \tag{11}$$

where the flow factor k_{flow}, representing an analog of the intensity factor, is determined by the ratio between the flow rate of the fresh air and the total flow rate of the air in the chamber:

$$k_{\text{flow}} = \frac{L_0}{L} = \frac{x_2 - x_1}{x_2 - x_0}\,, \quad L = L_0 + L_{\text{r}}\,. \tag{12}$$

The factor k_{flow} is related to the recirculation ratio K by the relation $k_{\text{flow}} = 1/(K+1)$. In this case, the following scheme of organization of the process is used. The fresh air is heated and resquires parameters t_0 and x_0 at the output of the air heater; then it is mixed with the recirculating air having output parameters t_2 and x_2, and the mixture with parameters t_1 and x_1 enters the input of the drying chamber.

As a result of the recirculation of the air in the drying chamber, its moisture content increases; therefore, in Fig. 3 the state of the surface of the particles is represented by the point E corresponding to the case of an increased moisture content x' and by the point D corresponding to the case where air recirculation is absent. An increase in x'_{sur} in comparison with x_{sur} points to the fact that the air recirculation positively influences the drying process, which is supported by the calculation data presented in Table 2. It should be noted that the efficiency of the drying increases from 0.503 to 0.703 with decrease in k_{flow} by a factor of 10. In this case, the increase in the drying time is 1.14 times smaller as compared to the ballast-zone method. Unlike the previous methods, in which an increase in the efficiency of the drying causes a decrease in the flow rate of the air, in the recirculation method the amount of the air circulating in the chamber increases; however the flow rate of the fresh air is many times smaller in this case.

Cross flow. We will consider a stirring layer of comparatively large height, in which $x_2 \approx x_{\text{sur}}$ and $t_2 \approx \theta$. In this case, expressions (11) will take the form

$$x_{\text{sur}} - x_1 = k_{\text{flow}}\,(x_{\text{sur}} - x_0)\,, \quad t_1 - \theta \approx k_{\text{flow}}\,(t_0 - \theta)\,. \tag{13}$$

In Eq. (8), for a cross flow, the difference $(x_{\text{sur}} - x)_{\text{av}}$ should be substituted for $x_{\text{sur}} - x$, then, using (10) and the first equation of (13), we obtain

$$\frac{\bar{u} - u_{\text{sur}}}{x_{\text{sur}} - x_0} = \frac{k_{\text{flow}} k_{\text{int}}\,\text{Bi}_{\text{m}}}{k_{\text{f}}}\,. \tag{14}$$

Independently of the recirculation ratio, Eq. (14) involves the moisture content of the fresh air x_0 and not the moisture content of the air at the input of the drier x_1. According to (14), the air recirculation decreases the drying rate depending on k_{flow} and increases the mass of the layer of the material being dried depending on k_{int}. Therefore, the action of the air recirculation is analogous to an increase in the mass of the layer.

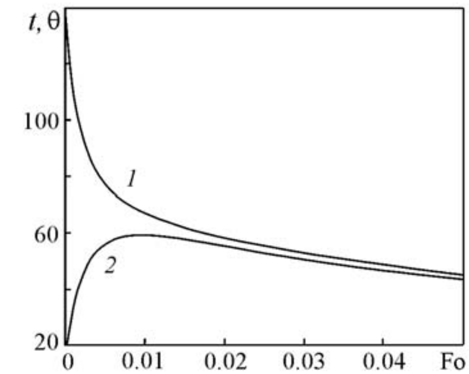


Fig. 4. Change in the temperatures of the gas and the material in the case of parallel-current flows of phases: 1, gas; 2, material.

In the equation of heating (3) for a cross flow the parameters of the air at the input of the layer t_1 and x_1 should be substituted for the current values of t and x; moreover, the relation $\alpha/\beta = c_g$ [4] is undoubtedly fulfilled, and, with the use of (13), we obtain

$$c_s \frac{d\theta}{d\bar{u}} = r - c_g \frac{t_0 - \theta}{x_{sur} - x_0} - q_{ad.s} . \tag{15}$$

In this equation too, independently of the recirculation ratio, only the fresh-air parameters t_0 and x_0 are involved. In the gradient-free processes, the moisture content of the surface of the particles (the point C in Fig. 3) at definite values of θ and u is independent of the current value of x and is equal to x_{max}. Therefore, the value of $x_{sur} - x_{max}$ in (15) is independent of the recirculation ratio and the temperature of the air at the input of the drier t_1; consequently, the behavior of the temperature curve described by Eq. (15) is dependent only on t_0 and will be one and the same for all the recirculation regimes. This condition is a necessary and sufficient prerequisite to the absence of a heat effect from the recirculation of the gas in the gradient-free drying process. Consequently, it does not always happen that the recirculation provides a decrease in the heat consumption.

A much different situation arises in the case where internal gradients arise in the process of drying. According to expression (14) and Fig. 3, the value of x_{sur} increases with decrease in k_{flow}, which, in accordance with Eq. (15), leads to a decrease in the heating of the material. This makes it possible to increase the temperature of the fresh air t_0 and decrease its flow rate L_0, which, according to the above-described rules, provides an increase in the efficiency of the drying. A recirculation of the heat-transfer agent in a cross flow can be easily realized in periodic processes.

Drying with a parallel-current flows of phases. A specificity of the drying regime with a parallel-current flow is that in it, as compared to the drying with a countercurrent flow, the temperature of the air at the input of a drier can be higher; therefore, if at $\varphi_2 = 0.7$ a parallel-current flow is allowable, the parameters of the process can be increased. Calculations of the drying of wheat grains with the use of a classical parallel-current flow (without cooling) have given the following results: $\eta = 0.56$, $t_0 = 135^{o}C$, $L/G = 3.1$, Fo = 0.034, $\varphi_2 = 0.7$. Comparison of these data with the analogous data obtained for drying with a countercurrent flow (the first row in Table 1) allows the conclusion that, in this case, drying with a parallel-current flow has an indisputable merit, which is achieved at the cost of an increase in the drying time.

Calculations have shown that, in the drying of the material being investigated with the use of a parallel-current flow, not the material at the output of the drier but the material at any distance from its input is heated to the maximum temperature, and the temperature of the material decreases as it moves to the output (Fig. 4). Therefore, control of the temperature of the material at the output of the drier did not assure the absence of its overheating. The characteristics of drying with a parallel-current flow can be additionally improved with the use of the above-considered methods. For drying with the use of a ballast zone at $k_{int} = 0.1$ (without cooling) $\eta = 0.60$, $t_0 = 250^{o}C$, $L/G = 1.5$, Fo = 0.056, and $\varphi_2 = 0.7$.

Driers with regulated heating of the material. This method allows one to additionally improve the characteristics of the drying of a material with the use of a countercurrent flows of phases. For this purpose, the product is

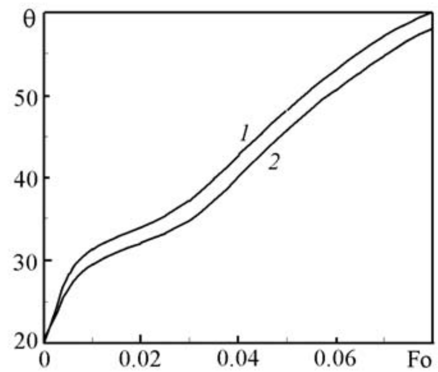


Fig. 5. Influence of the temperature of the surface of the particles of the material on the kinetics of its heating (cross current): 1, calculation at $\theta_{sur} = \theta$; 2, calculation at $\theta_{sur} = \theta + 3$; θ, ^{o}C.

rapidly heated and then its temperature is held constant, close to the maximum temperature. The air is heated not only by the outer air heater but also heated by the inner heaters in the process of its movement along the drying path. The power of the heaters and their arrangement should provide a required near-isothermal regime of heating of the material. Calculations of the drying with a countercurrent flow and seven intervening stages of heating of the air (without cooling of the material) have given the following results: $\eta = 0.519$, Fo = 0.0225, $L/G = 4.29$, $\varphi_2 = 0.7$, and $t_e = 95^{o}$C.

These data point to a higher efficiency of the drying regime being considered as compared to drying with a classical countercurrent flow (the first row in Table 1), especially in respect to the values of L/G and Fo. Here, the temperature t_e represents the temperature of the air at the input of an ordinary drier, the air heater of which has a power equal to the power of the drier being considered (with account for the power of the inner heaters) at one and the same value of L/G. This effect is provided in accordance with the second rule of drying by an increased equivalent temperature, as compared to the temperature t_1.

It should be noted that the time of the drying decreases in the variant being considered (Fo = 0.0225) relative to the initial one (Fo = 0.026). This is explained by the fact that the temperature of the material averaged over the length of the drier is increased as compared to that of the ordinary drying, which causes a shift of the isotherm θ = const to the right in Fig. 3. As a result, the motive force of the drying $x_{sur} - x$ increases, which causes a decrease in the drying time.

When in the drying regime being considered a pulsed air supply with $k_{int} = 0.2$ is additionally used (without cooling of the material), we obtain the following parameters of the drying: $\eta = 0.574$, Fo = 0.0267, $L/G = 1.3$, $\varphi_2 = 0.7$, and $t_e = 280^{o}$C. It should be noted that fairly good characteristics of drying were obtained in this case practically with no increase in drying time (Fo = 0.0267 and 0.0260 in the case of a classical countercurrent flow). Here, along with the increased temperature of the material, the high rate of drying at the beginning of each active period has served its purpose.

Estimation of the Influence of the Assumptions Used on the Heat Efficiency of Drying. Since the motion of the phases in all the above-described variants of drying is assumed to be ideal, it is necessary to determine the influence of the possible imperfect conditions on the heat efficiency of the processes. This influence can be easily determined logically without resorting to calculations. The irregularity of the gas distribution, the longitudinal stirring, and overhoots of the gas and solid phases undoubtedly lead to an increase in the drying time, which, from the standpoint of the internal mass transfer, means that the internal gradients decrease (the angle ψ in Fig. 3). In this case, the rate of heating of the material and its temperature at the output of the drier decrease, which makes it possible to increase the drying temperature t_1 and decrease the flow rate of the air. As a result, in the case where this effect is used properly, the heat efficiency of a real drier can be even higher than that of the ideal one.

Great internal gradients are characteristic of high-rate processes; here, we mainly consider processes with a low rate and small humidity gradients, for which the assumption that the temperature of a particle is uniformly distributed along its radius is warranted.

Moreover, it has been established that there exists a negative relation between the temperature of the surface of a particle θ_{sur} and the mean-volume value of this temperature $\bar{\theta}$. Let $\theta_{sur} > \bar{\theta}$. The desorption isotherm for θ_{sur} = const is positioned to the right of the isotherm θ (Fig. 3). Extending the beam BE to the intersection with this isotherm, we will obtain the point G with new surface parameters. It should be noted that the value of x_{sur} at the point G is larger that the value of x'_{sur} at the point E. In this case, the fraction on the right side of the equation of heating (3) for the point G decreases because of the substitution of θ_{sur} for $\bar{\theta}$ in the numerator and the increase in x_{sur} in the denominator. The latter means that the rate of heating of the material decreases, i.e., in the case where $\theta_{sur} > \bar{\theta}$, the temperature curve should lie lower than the temperature curve obtained for the case where $\theta_{sur} = \bar{\theta}$ (Fig. 5).

To put it differently, an increase in the surface temperature of a particle leads to a decrease in the rate of heating of the whole particle on condition that $q_{ad.s} = 0$, i.e., in the case where radiation and convective heat transfer to the material are absent. Therefore, the calculation at $\theta_{sur} = \bar{\theta}$ corresponds to the maximum degree of heating of the material and provides a certain reserve in the temperature in the direction of its overestimation.

Conclusions. Our analysis of different methods of drying of a material with a low drying rate has shown that, theoretically, the heat efficiency of industrial driers can be increased from the traditional values comprising 30–50% to 70% and larger values, which makes it possible to decrease the heat consumption by a factor of 1.5–2. The realization of this direction (all the possible variants of which were not described here) requires, as a rule, an increase in the drying rate in approximately the same ratio. However, the use of processes with a low drying rate can be economically appropriate because, in addition to the economy of the combustible and vapor, this make it possible to decrease the consumption of air by many factors and, correspondingly, the amount of energy expended for its pumping, as well as to decrease the sections of the drying chamber, the blowers, and the dust-suppression apparatus, which serves to decrease the dimensions of the drier and its cost.

NOTATION

a_m, mass-transfer coefficient, m^2/sec; b, additional parameter; $Bi_m = \beta R/(\rho_s a_m)$, mass-transfer Biot criterion; c, heat capacity, J/(kg·K); $E = (\bar{u} - u_{eq})/(u_1 - u_{eq})$, dimensionless moisture content; E_1, intermediate variable; f, specific surface of the material, m^2/kg; F, interphase surface, m^2; $Fo = a_m\tau/R^2$, Fourier criterion; G, flow rate of the solid (absolutely dry) phase, kg/sec; k_f, k_{int}, k_{flow}, form factor, intensity factor, and strength factor; K, recirculation ratio; L, flow rate of the gas (absolutely dry), kg/sec; m, mass of the product; kg; m_{lay}, specific mass of the layer of the product on the grill, kg/m^2; n, coordinate normal to the surface of the particle, m; $q_{ad.s}$, additional heat supplied to the solid phase, J/kg of the evaporated moisture; r, heat of moisture evaporation, J/kg; R, radius of the particle, m; t, temperature of the gas, ^oC; u, $\bar{u}$, local and mean-volume moisture content of the material, kg of moisture/kg of dry material; w, velocity of the gas, m/sec; x, moisture content of the gas phase, kg of moisture/kg of dry air; α, coefficient of interphase heat exchange, W/(m^2·K); β, coefficient of interphase mass exchange, kg/(m^2·sec); η, heat efficiency of drying; θ, $\bar{\theta}$, local and mean-value temperature of the material, ^oC; ρ, density, kg/m^3; τ, τ_A, τ_B, τ_c, current time, time of the active period, time of the passive period, time of a cycle, sec; φ, relative moisture of the air. Subscripts: A, active period, B, passive period; m, mass exchange; max, maximum; sur, surface; f, form; g, gas; ad.s, additionally to the solid phase; int, intensity; in, initial; flow, flow; eq, equilibrium; r, recirculation; lay, layer; av, average; s, solid phase; c, cycle; e, equivalent; 0, parameters of the gas at the output of the air heater; 1, parameters of the material and the gas at the input to the drier; 2, the same parameters at the output of the drier.

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