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EFFICIENCY OF UTILIZATION OF HEAT IN THE PROCESSES OF CONVECTIVE DRYING AND AN EQUILIBRIUM ANALYSIS

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A method for evaluating the efficiency of convective dryers from the viewpoint of heat consumption has been proposed; the method is based on a comparison of the characteristics of the dryers to a standard: the process with an efficiency maximum possible under given conditions. The so-called equilibrium analysis assuming the absence of the internal heat and moisture gradients in the dried product is used. It has been shown that gradient-free processes limiting for all modes of phase contact with decrease in the drying intensity to zero possess the highest intensity. The basic rules of organization of economical drying have been formulated.

Introduction. Drying of moist materials is highly power-intensive, which is related to both the large volumes of evaporating moisture and the large specific heat of its evaporation (about 2450 kJ/kg). But the main problem is the very low efficiency of utilization of the consumed heat. Thus, in the food industry, according to the data of [1], the total expenditure of heat for evaporating 1 kg of moisture is 5000–7000 kJ/kg, which is nearly twice as high as the heat of evaporation. As a result the thermal efficiency of many modern dryers amounts to 40–50% at best, i.e., more than half the consumed heat escapes into the atmosphere.

There are a lot of causes for this situation but the first, as we believe, is the absence of clear rules of organization of drying, without which it is difficult to look for economical regimes. Therefore, we primarily attempt to formulate requirements that must be met by the process of drying with a minimum heat consumption. We represent the parameters of the phases contacting in the dryer as follows: air — L, x_1, and t_1 at entry and L, x_2, and t_2 at exit; the solid phase — G, u_1, and θ_1 at entry and G, u_2, and θ_2 at exit.

The parameters of the solid phase u_1, θ_1, G, and u_2 are considered as being prescribed, and the objective of the search is determination of the inlet parameters of the gas L and t_1 ensuring the necessary outlet humidity of material with a minimum expenditure of heat and on condition that the superheating of the material is absent ($\theta_2 \le \theta_{\max}$). As a result we may assume five parameters — L, t_1, t_2, x_2, and θ_2 — to be known, i.e., we must have five coupling equations.

In the absence of any information on the process, one usually uses: a) the equation of material balance of moisture and b) the equation of thermal balance (enthalpies). As a result we have an open system (five unknowns for two couplings) which has an infinite set of solutions. Therefore, the problem is traditionally solved by arbitrary selection of the t_1 and t_2 values for a prescribed θ_2 [2–14]. The drawbacks of such an approach are evident.

What is most important is that the temperature of the dried product θ_2 is dependent on the drying regime, i.e., on L, t_1, and t_2. This dependence is unknown, as a rule; therefore, one predominantly uses data taken from practice that cannot, in principle, ensure high economy. The equation of heating of material is required; the process should be considered in the context of combined heat and mass transfer and be controlled not only by entry and exit but also in dynamics. Consequently, additional information is required for solution of the problem posed.

Substantiation of Investigation Methods. The system of equations proposed in [15] is used as an analysis tool. For the cocurrent flow and countercurrent flow, we have

$$c_{\text{sol}} \frac{d\theta}{du} = r - \frac{\alpha}{\beta} \frac{t - t_{\text{surf}}}{x_{\text{surf}} - x} - q_{\text{ad.sol}} \,, \tag{1}$$

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$$c_g \frac{dt}{dx} = -\frac{\alpha}{\beta} \frac{t - t_{surf}}{x_{surf} - x} + c_{st} (t_{surf} - t) + q_{ad.g} , \tag{2}$$

$$\frac{G}{L} du = \pm dx , \tag{3}$$

where

$$r = r_0 - c_{liq}\theta_{surf} + c_{st}\theta_{surf} + q_b , \quad c_g = c_{dr.g} + c_{st}x ; \tag{4}$$

$$q_b = R_{st} (\theta_{surf} + 273) \ln (p_{sat}/p_{surf}) . \tag{5}$$

Expression (1) characterizes the intensity of heating of the product, whereas (2) and (3) are the balance equation in differential form. Direct use of equations of moisture equilibrium on the interface of the form $x_{surf} = x(u_{surf}, \theta_{surf})$ is an advantage of this system. The system contains no time in explicit form and enables us to do without the equation of drying kinetics. Although system (1)–(3) contains three couplings of the five required, we cannot do without selecting the parameters here, too. However, now we can prescribe either t_1 and t_2, not both parameters simultaneously. The quantity θ_2 is assumed to be unknown.

Of the great number of solutions, we will just allow for those in which the relative humidity of air at exit from the drier φ_2 amounts to 70%. We can take other values, too, but the problems of condensation of moisture in outlet air ducts arise for $\varphi_2 > 0.7$, and the efficiency of the process is substantially reduced for a lower humidity. As a result we can formulate the *first rule* of economical drying: the used-air humidity must be high as possible.

An analysis with the example of drying of two products — grain (wheat) and potatoes — has been made. The basic assumptions are as follows:

1. The absence of external heat sources and sinks ($q_{ad.sol} = q_{ad.g} = 0$).

2. The absence of internal heat and moisture gradients in the material dried (the internal gradient-free or agradient processes are considered). Then we have $t_{surf} = \theta_{surf} \approx \theta$ and $u_{surf} \approx u$ and the moisture content of air equilibrium with the material surface is characterized by the equation $x_{surf} = x(u, \theta)$.

3. The ratio of the coefficients of interphase heat and mass exchange is expressed as $\alpha/\beta = c_g$. In [5], it has been shown that the resulting error in calculation of the vaporization temperature is no higher than 2^oC up in it; furthermore, the necessary corrections can always be made in the above relation [16].

4. The absence of longitudinal mixing of phases.

As the equation of bound-moisture equilibrium, we use the equation of the desorption isotherm of the material in question (usually for 20^oC):

$$\varphi_{surf} = p_{surf20}/p_{sat20} = \varphi (u) .$$

In particular, for wheat we have used the desorption equation

$$p_{surf20} = 2.34 \{1 - \exp [(- u + 0.025)/0.1953]\} \text{ kPa} ,$$

true in the range $u = 0.16–0.5$ kg/kg.

Conversion to the material's running temperature is carried out according to the available empirical dependences, but in their absence, we carry out conversion based on the Clausius–Clapeyron equation

$$p_{surf} = p_{surf20} \exp \left[\frac{r}{R_{st}} \left(\frac{1}{293} - \frac{1}{\theta + 273} \right) \right] ,$$

where r is determined from (4) at $\theta = 20^oC$. Then we have

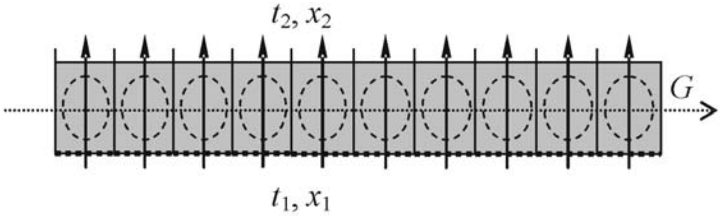

Fig. 1. On definition of cross flow.

$$x_{\text{surf}} = 0.622 \frac{p_{\text{surf}}}{B - p_{\text{surf}}} . \qquad (6)$$

Numerical integration of system (1)–(3) with account for (4)–(6) is carried out with the initial conditions (for countercurrent flow) $\theta = \theta_1 = 20^{\text{o}}\text{C}$, $x = x_2$, and $t = t_2$ for $u = u_1$. We prescribe the temperature t_2 and compute p_2 from the condition $\varphi_2 = p_2/p_{\text{sat}2} = 0.7$ and x_2 using (6). Knowing x_2, we easily determine L/G:

$$L/G = (u_1 - u_2)/(x_2 - x_1) . \qquad (7)$$

The calculation is completed, once the prescribed moisture content u_2 has been attained by the material. The values of the temperatures t and θ at this instant are the unknown quantities t_1 and θ_2.

Let us agree on the notion of the efficiency of the process. An objective characteristic of the economical efficiency of drying is the specific consumption of heat by evaporating 1 kg of moisture; it is determined by the expression

$$q = c_{\text{g}} (t_1 - t_{\text{amb}})/(x_2 - x_1) .$$

The factor $c_{\text{g}}(t_1 - t_{\text{amb}})$ represents the heat expended on heating, in the air heater, 1 kg of air from the ambient temperature t_{amb} to the temperature t_1, and the expression $1/(x_2 - x_1)$ is the consumption of air by evaporating 1 kg of moisture. However, it is more convenient to use the relative value in which the heat q is related to a constant basis — the heat of evaporation of water at the temperature of the entering material (20^{o}C in this case) r_{20}:

$$\eta = \frac{r_{20}}{q} = \frac{r_{20}}{c_{\text{g}}} \frac{x_2 - x_1}{t_1 - t_{\text{amb}}} . \qquad (8)$$

The use of another vaporization temperature, including the actual one, is incorrect since the quantity r changes in drying, which may perturb the analysis results. Expression (8) is subsequently used as the definition of the thermal efficiency of drying or simply the efficiency.

We have considered two basic modes of interaction of the phases: countercurrent flow and cross flow. The variant of cocurrent flow was eliminated, since it does not always happen that one is able to obtain the required humidity of the product in the presence of the period of decreasing drying rate and a 70% humidity of the outgoing air.

Since researchers have different opinions as far as cross flow is concerned, we refine its definition. We will consider the ideal process in which the solid phase is ideally mixed along the bed's height (transversely) in the absence of longitudinal mixing. The above method can be visualized as a bed consisting of numerous cells with the ideal mixing of the solid phase in each (Fig. 1). The cells are separated by heat- and moisture-insulating partitions moving with the material. The heat-transfer agent may be supplied individually to each cell, which ensures a versatile regime of drying.

When the cells are numerous, we may disregard the discreteness of the solid-phase flow and consider it as a continuous one-dimensional flow in which the parameters of the material vary only along the bed. The method considered is totally identical to the periodic process in one individual cell, if the coordinate axes are related to it. The properties of such a cell have been considered in [15]. In particular, the equation of heating of the material in it appears as follows:

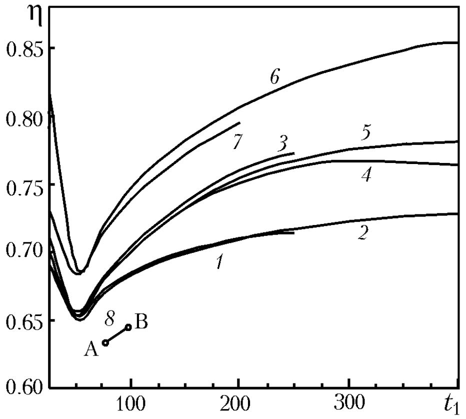

Fig. 2. Thermal efficiency vs. temperature of drying t_1: 1) grain, countercurrent flow without cooling; 2) grain, cross flow without cooling; 3) grain, countercurrent flow with cooling; 4) grain, oscillating regime; 5) grain, cross flow with cooling; 6) potatoes, countercurrent flow; 7) potatoes, cross flow; 8) grain, countercurrent flow at $\mathrm{Bi_m} = 100$. t_1, $^{\circ}$C.

$$c_{\mathrm{g}} \frac{d\theta}{du} = r - c_{\mathrm{g}} \frac{t_1 - \theta}{x_{\mathrm{surf}} - x_1} . \tag{9}$$

Unlike (1), only the parameters of the gas phase at entry into the bed t_1 and x_1 are allowed for here, whereas θ and u refer to the quantities averaged over the bed's height. Expression (9) is easily solved by numerical methods with the initial condition $\theta = \theta_1$ for $u = u_1$ and has a unique solution for constant t_1 and x_1, i.e., the temperature curve $\theta(u)$ in the case of (gradient-free) cross flow is independent of either the bed thickness or the hydrodynamics of the process.

The quantities r and x_{surf} are computed based on (4)–(6). The local parameters of the gas going out of the bed in the case of cross flow are determined from the formulas

$$t_2 = t_1 - k\,(t_1 - \theta)\ ; \quad x_2 = x_1 + k\,(x_{\mathrm{surf}} - x_1)\ . \tag{10}$$

The value of k is selected for a 70% average humidity of the gas going out of the bed. Since the parameters of the outgoing gas vary with motion of the bed in cross flow, the quantity x_2 involved in (7) and (8) must be time-averaged:

$$x_2 = \frac{1}{\tau} \int_0^{\tau} x_2 d\tau = x_1 + (u_1 - u_2)/\psi\ , \quad \psi = \int_{u_1}^{u_2} \frac{du}{x_2 - x_1}\ . \tag{11}$$

Analogously we average t_2 and t_1 (the latter only in the case of a variable drying temperature):

$$\overline{t}_2 = \left(\int_{u_1}^{u_2} t_2 \frac{du}{x_2 - x_1} \right) / \psi\ ; \quad \overline{t}_1 - \overline{t}_2 = \left(\int_{u_1}^{u_2} t_2 \frac{t_1 - t_2}{x_2 - x_1} du \right) / \psi\ . \tag{12}$$

Also, we allow for all cooling zones with their temperature t_1, when present.

Here we have not considered cross flow with a dense blown-through bed (without the mixing of the solid phase). In such a bed, stationary particles of the material on the grid are in constant contact with fresh gas. To eliminate their superheating we have to use a gas temperature no higher than $\theta_{\max}$. A low temperature of drying, as we will see further, reduces its efficiency.

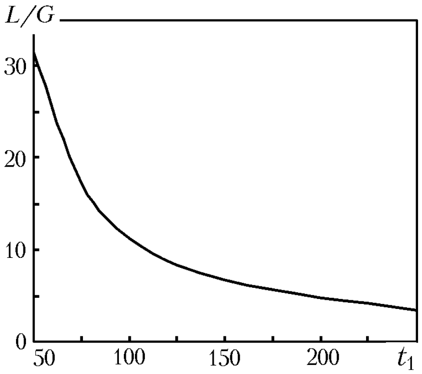

Fig. 3. Relative flow rate of air vs. drying temperature t_1. t_1, $^{\text{o}}$C.

In the considered system (1)–(12), we use no other information on the material than the equilibrium equations. Therefore, the analysis based on gradient-free processes may be called an "equilibrium" one. We believe that it must come before designing industrial dryers, since it enables one to reveal the best mode of phase contact in advance, whatever the specific type of dryer and drying time, or to develop a combined variant.

The results of the equilibrium analysis in the form of the thermal efficiency of drying plotted as a function of the inlet air temperature are given in Fig. 2. The range of variation in the moisture content in drying is (kg/kg) 4.0–0.1 for potatoes and 0.4285–0.162 for grain. The parameters of the ambient air are $t_{\text{amb}} = 20^{\text{o}}$C and $x_1 = x_{\text{amb}} = 0.01$ kg/kg. The maximum temperature of heating of the product θ_{max} is equal to 60$^{\text{o}}$C in all cases.

Discussion of the Results. On all the given curves, we clearly recognize two ranges: low-temperature drying at $t_1 < 50^{\text{o}}$C, when its efficiency grows with reduction in the temperature, and high-temperature drying at $t_1 > 50^{\text{o}}$C. Increase in the efficiency in the temperature range 25–30$^{\text{o}}$ is attributed to the decrease in the ejection of heat with the waste gases, since in this case their temperature is close to the ambient temperature.

A drawback of low-temperature drying is a flow rate of the heat-transfer agent nearly two orders of magnitude higher than that in high-temperature drying. Therefore, the subject of the analysis was the range $t_1 > 50^{\text{o}}$C. In this range, the efficiency of the process increases with temperature, which is attributed to the more rapid growth in x_2 than in t_1 in (8). As a result we can formulate the *second rule*: it is desirable to carry out drying at the maximum possible gas temperature. As the drying temperature grows, the flow rate of air substantially decreases (Fig. 3) to reduce the cost of air pumping and the dryer.

In this case potatoes containing plenty of free moisture show higher values of the efficiency than grain having mainly bound moisture.

Also, grain is characterized by the large share of the expenditure of heat on heating the material. For this reason, the efficiency without cooling the grain after drying (see Fig. 2, curves 1 and 2) is lower than that with cooling. In the latter case drying is incomplete; final removal of moisture is carried out in an individual cooling step [11]. In the case of potatoes the share of heat going for heating the product is comparatively small compared to the total expenditure; therefore, no cooling is used.

We note that the difference in efficiency between countercurrent flow and cross flow is insignificant at the same air temperature t_1. Cross flow allows the use of higher gas temperatures, which enables one to obtain an increased efficiency; this is particularly characteristic of potatoes. The high gas temperature is used only at the beginning of the process; subsequently it is continuously reduced, ensuring the condition $d\theta = 0$. As far as the plots in Fig. 2 are concerned, by t_1 for cross flow we mean the gas temperature at the beginning of drying, i.e., its maximum value.

Curve 5 represents cross flow with an oscillating regime of drying, when the material is successively heated by hot air to 60$^{\text{o}}$C in heating zones and is cooled by 10$^{\text{o}}$C in cooling zones. The indices of the oscillating regimes are slightly lower than the indices of the regular cross flow. The latter is attributed to the decrease in the average inlet gas temperature t_1 with increase in the number of cooling zones. On the plot, t_1 refers to the temperature in the heating zones.

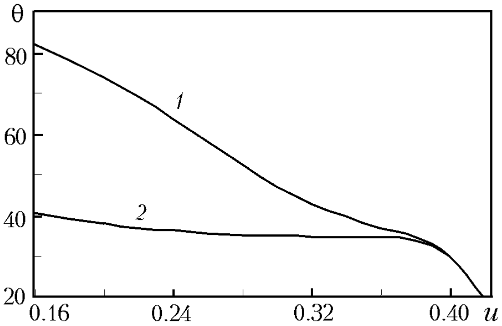

Fig. 4. Temperature curves of drying for grain in different regimes: 1) $\mathrm{Bi_m}$ = 100 and 2) $\mathrm{Bi_m}$ = 0 (gradient free regime). θ, $^{\circ}$C; u, kg/kg.

In the process of analysis, we investigated, for countercurrent flow, regimes with the recirculation of the heat-transfer agent and with the intermediate heating of the gas in the drying chamber. No positive effect compared to the regular countercurrent flow has been established (only gradient-free regimes are dealt with).

Noteworthy are the relatively high values of the efficiency, (about 0.7–0.8) in equilibrium analysis. If industrial dryers had such an efficiency, this would mean an economy of 1.5–2 times in energy carriers. Therefore, it is expedient to analyze the factors that contribute to the reduction in the actual efficiency.

Such well-known factors as the heat loss by walls, nonuniformity of the gas distribution, longitudinal mixing of the phases, etc., can be minimized by using techniques that reduce the nonideal character of the process. Let us turn to the least understood aspect of the problem: the influence of the internal resistance to mass transfer, which is characterized by the mass-exchange number $\mathrm{Bi_m}$ [17].

For a high internal resistance ($\mathrm{Bi_m} >> 0$), the moisture content of a particle is reduced relative to the average value, i.e., $u_{\mathrm{surf}} << u$, which causes x_{surf} to decrease compared to gradient-free processes. Then, with reduction in x_{surf}, Eqs. (1) and (9) yield a higher growth in the material temperature, i.e., the material is heated up to $\theta_{\max}$ much more rapidly. This forces us to reduce the gas temperature with the corresponding reduction in the efficiency of drying. Also, we have an increase in the heat of evaporation of moisture r, since moisture with a higher binding energy evaporates from the particle surface for $u_{\mathrm{surf}} << u$, according to (4)–(5).

To check this proposition we have added, to system (1)–(12), the well-known linear equation of internal mass transfer

$$\frac{\partial u}{\partial \tau} = a_{\mathrm{m}} \nabla^2 u \quad \text{at} \quad -\rho_{\mathrm{sol}} a_{\mathrm{m}} \frac{\partial u}{\partial n} = \beta \left(x_{\mathrm{surf}} - x \right) . \tag{13}$$

Unfortunately, the solution of (13) for an arbitrary form of the equation of moisture equilibrium on the interface is not existent; the problem of internal mass transfer is solved either without equilibrium equations at all or the linear dependence in the form of a constant equilibrium (distribution) coefficient is used [17, 18]. The performed evaluation of the distribution coefficient in drying has shown a variation of more than two orders of magnitude in it in the process; therefore, the solution was carried out by a numerical method. The calculated form of the equation as applied to a spherical particle appears as

$$\delta u_i = [(u_{i+1} - 2u_i + u_{i-1}) + u_{i+1} - u_{i-1})/i]\, N^2 \delta \mathrm{Fo} \quad \text{for} \quad (u_{N-1} - u_N)/(x_{\mathrm{surf}} - x) = \mathrm{Bi_m}/N . \tag{14}$$

Using (14) we determined, on each integration step, the surface moisture content of the particle $u_{\mathrm{surf}} = u_N$ which was subsequently used in (1)–(6) for computation of the running value of x_{surf}. Certain calculation results in the form of the temperature curves of drying of grain in cross flow are presented in Fig. 4 for the same temperature of the heat-transfer agent (100°C) at $\mathrm{Bi_m}$ = 0 and 100.

We note a stronger heating of the product in the presence of the internal resistance to mass transfer (curve 1), which is heated up to 82°C by the end of the drying. Consequently, a drying temperature of 100°C or higher is un-

TABLE 1. Characteristics of the Process of Drying in Cross Flow at $\mathrm{Bi_m} = 100$ as Functions of the Parameter b

b	k_{in}	L/G	Fo	φ_2	η	t_1
0.1	0.951	252	0.082	0.051	0.045	75
0.5	0.786	53	0.086	0.093	0.20	80
1.0	0.632	28	0.091	0.169	0.347	85
2.0	0.432	15	0.103	0.353	0.522	99
5.0	0.198	7.9	0.129	0.670	0.667	140
10	0.100	5.1	0.167	0.827	0.711	195
20	0.05	3.6	0.236	0.911	0.736	260
50	0.02	3.2	0.520	0.968	0.746	290

acceptable for this product, which confirms the inadmissibility of arbitrary selection of θ_2 in calculations. A temperature t_1 of the order of 75°C is safe.

As far as the thermal efficiency of drying for the case in question (it corresponds to point A in Fig. 2) is concerned, it cannot be high in principle for $\mathrm{Bi_m} >> 0$ because of the low temperature of the gas, second, it is additionally reduced due to the increase in the expenditure of heat on heating the material (82°C instead of 40°C of gradient-free processes).

Recirculation of the heat-transfer agent for $\mathrm{Bi_m} > 0$, unlike gradient-free drying, ensures a certain effect. Thus, the use of a 1.5 fold recirculation enabled us to somewhat increase the efficiency due to the increase in the air temperature in the air heater: from 75 to 90°C (point B in Fig. 2).

Thus, the ideal gradient-free processes allowing a high drying temperature possess the highest efficiency of utilization of heat and because of this can serve as peculiar standards using which the potential of actual dryers is conveniently evaluated. Comparing the efficiency of the actual and standard processes that use the same method, we can draw an unambiguous conclusion on the available efficiency reserves. As applied to point A on curve 8 (Fig. 2) with an efficiency of 0.63, we draw the conclusion on the fundamental possibility of increasing the efficiency to 0.773 (last point on curve 3 on the right) in countercurrent flow, if the condition $\mathrm{Bi_m} \to 0$ is ensured.

In actual practice, the gradient-free regime is realized for $R \to 0$, i.e., in drying of finely divided materials or (as is easily established from boundary condition (13)–(14)) for any materials when $\beta \to 0$ or $x \to x_{\mathrm{surf}}$. This corresponds to processes with a very low rate. It paradoxically (at first sight) follows that infinitely slow processes possess maximum economy for $\mathrm{Bi_m} > 0$. The more intense the process, the larger the moisture-content gradient in particles and the higher the expenditure of heat on drying. The influence of the temperature gradient is opposite in character: a particle-surface temperature higher than a gradient-free one leads to a reduction in the heat flux and, accordingly, a decrease in the heating intensity.

For cross flow, decrease in x_{surf}, according to (10) and (11), leads to a corresponding reduction in the local and average values of x_2, which means, in accordance with (8), a sharp decrease in the thermal efficiency even with the high temperature being preserved (the first rule of economical drying is violated).

Consequently, it is necessary to organize the process so that drying can be similar to a gradient-free process as much as possible. We take this statement as the *third rule* of economical drying. Needless to say, it is unlikely that the indices of standard are in full measure attainable, but they can be approached as closely as desired by a reasonable compromise between intensity and efficiency.

Let us show the fundamental possibility of actions of this sort using cross flow as an example. We will use Eqs. (9)–(12) simultaneously with (13)–(14). Since the parameters of the gas in the bed vary with height, in (13)–(14), we should use, instead of the local difference $(x_{\mathrm{surf}} - x)$, its height-average value

$$(x_{\mathrm{surf}} - x)_{\mathrm{av}} = (x_{\mathrm{surf}} - x_1)\, k_{\mathrm{in}}\,, \quad k_{\mathrm{in}} = \frac{1 - \exp(-b)}{b}\,, \quad b = \beta f \frac{m}{w\rho_{\mathrm{dr.g}}}\,.$$

Here K_{in} plays the role of the intensity factor taking on values from unity in an intense process to zero in an infinitely slow process.

The results of numerical calculations for grain (without a cooling step) as functions of the parameter *b* at the same outlet temperature of the product $\theta_2 = 60^{\circ}C$ are presented in Table 1. The value of *b* is changed by variation of the height (mass *m*) of the bed or the velocity of the gas *w*.

The value $b = 0.1$ corresponds to the process in a thin bed (one grain thick). The intensity of the process k_{in} is reduced with increase in *b* but the internal gradients decrease, too, to increase the permissible inlet temperature t_1; this largely compensates for the decrease in the drying rate. Let us compare, e.g., the line $b = 0.1$ and the line $b = 20$. In the latter, the bed's mass is increased 200 times and the intensity factor is decreased nearly 20 times; the permissible temperature grew from 75 to 260°C, which has led to an increase from 0.045 to 0.736 in the efficiency. Simultaneously the L/G ratio has sharply decreased from 252 to 3.6; this means an increase of nearly 80 times in the capacity compared to the thin bed (for the identical flow rate of air) or the same reduction in the air flow rate for the identical capacity.

As far as the drying time is concerned, its increase is by no means proportional to the growth in *b*. In the case in question, the time has increased only 2.88 times (according to the ratio of Fo numbers: 0.236 and 0.082), which is quite acceptable. Thus, the last columns of the table correspond to virtually gradient-free regimes of drying.

The above example clearly shows that gradient-free processes represent quite a realistic standard rather that an abstraction far removed from practice. Approximating them is not only possible but also economically attractive. In this example, the action of all the three rules of economical drying is pronounced. The given method of bringing the process closer to gradient-free ones is not unique. Unfortunately, we cannot consider all methods within the framework of the work.

Conclusions. We have presented the new concept of organization of convective drying with a minimum heat consumption; it is based on the use of the limiting values of thermal efficiency of drying (standards) and the set of basic rules of construction of economical processes. The use of the developed rules and recommendations in calculating, designing, and modernizing industrial dryers enables one to substantially reduce the consumption of energy carriers (1.5–2 times in some cases). The effect of reduction in heat consumption with decrease in the drying rate has first been noted; in this connection, low-intensity processes are desirable in practice.

NOTATION

a_m, mass-transfer coefficient, m^2/sec; $Bi_m = \beta R/(\alpha_{sol}\alpha_m)$; *B*, atmospheric pressure, Pa; *c*, heat capacity, J/(kg·deg); $Fo = \alpha_m\tau/R^2$; *G*, flow rate of the (absolutely dry) solid phase, kg/sec; *i*, interval No.; *k*, coefficient of utilization of the heat-transfer agent; *L*, flow rate of the (absolutely dry) gas, kg/sec; *m*, mass of the dry product per 1 m^2, kg/m^2; *N*, number of subdivision intervals; *n*, coordinate normal to the particle surface, m; *p*, partial pressure of the steam, Pa; *q*, specific heat, J/kg; q_b, binding energy of moisture with the material, J/kg; *r*, heat of evaporation of moisture, J/kg; r_0, the same, at 0°C; *R*, particle radius, m; R_{st}, gas constant of the steam, J/(kg·K); *t*, gas temperature, °C; *u*, moisture content of the material, kg of moisture/kg of dry material; *w*, gas velocity, m/sec; *x*, moisture content of the gas phase, kg/kg of dry air; α, coefficient of interphase heat exchange, $W/(m^2 \cdot K)$; β, coefficient of interphase mass exchange, $kg/(m^2 \cdot sec)$; θ, material temperature, °C; ρ, density, kg/m^3; τ, time, sec; φ, relative humidity of air. Subscripts: g, gas; ad.g, and ad.sol, additional, to the gas and the solid phase respectively; liq, liquid; in, intensity; m, mass-exchange; max, maximum; sat, saturated; surf, surface; st, steam; amb, ambient medium; b, bound; dr.g, dry gas; av, average; sol, solid phase; 1, inlet; 2, outlet; 20, parameter at a temperature of 20°C; (+), countercurrent flow; (−), cocurrent flow.

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