A NEW METHOD OF CALCULATION OF CONVECTIVE DRYING OF THIN MATERIALS

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A description is given of a new method of designing drying equipment for thin materials. It allows calculation of the size of the equipment, as well as of the kinetics of variation of temperature and humidity of the material, with the aid of a single empirical coefficient.

Design of periodic or continuously operating drying equipment must include determination of the time required to remove the moisture from the material, from an initial mean moisture content $\bar{u}_i$ to a final mean moisture content $\bar{u}_f$, under assigned values of the process parameters (one of the most important of which is the material temperature).

The overwhelming majority of materials of organic origin cannot be heated, in the process of removing their moisture, above some temperature or other that is characteristic for each specific drying objective, without an appreciable degradation in the quality of the final product. Important examples are cereals [1], yeast [2], biological preparations, and even peat [3].

It should be noted that in previously published papers this aspect of the question has not been given the necessary attention, and that the efforts of investigators have been directed only toward a description of the kinetics of removal of moisture from the material [1, 4–6].

There has been very little study of the influence in convective drying of the relative direction of motion of the heat transfer agents (air and material). The results of some papers dealing with this aspect of the problem [8–11] do not permit calculation of the temperature of the material at the end of drying.

An exception is [7], in which an account is given of a method which permits calculation of the temperature of the material under varying conditions, but only for drying processes in which the heat expended in heating the material is small in comparison with the total amount of heat transmitted to the moist material by the drying agent.

The rigorous analytical theory developed in [12–14] allows one to obtain the temperature and moisture fields in bodies of classical shape at any instant of time from the solution of a system of differential equations describing the heat and mass transfer processes in the material being dried with the appropriate boundary conditions. However, the use of these results in design practice at present faces difficulties connected with the inadequate amount of test data on the numerical values of the coefficients of mass transfer and their dependence on the moisture content and temperature.

For this reason there is a need for new approximate methods of calculation, with the aid of which one might determine the temperature and the humidity of bodies of arbitrary shape at any instant of time in any section of the drying equipment.

The establishment of an analytical relation between the temperature of a material and its humidity is also very important for arranging for the automatic control of drying processes with respect to one parameter only—temperature, for which there are commercially available sensors and regulators, whereas control of the humidity of a material has not as yet gone beyond the level of laboratory testing [20].

By considering a drying equipment to be a modified regenerative equipment, one may not only determine what the humidity and temperature of the material will be at various stages of drying, as well as the duration of these stages, but also calculate the magnitude of the area which must take part in the heat and mass transfer, and therefore the size of the drying installation.

In distinction from the ordinary regenerator, the heat transfer process in a drier is accompanied by mass transfer, i. e., by transfer of moisture from the material being dried to the surrounding space. Evaporation of the moisture from the material requires the expenditure of heat, which may be transmitted to the material by various means.

The heat of phase transformation may be regarded as going to a heat sink, or, which is the same thing, as coming from a negative internal heat source.

If the material being dried possesses characteristics such that under the chosen or assigned environmental parameters the Bi number is small enough, there will be considerable nonuniformity in the temperature field (due both to thermal resistance of the body, and to displacement of the heat sink inside the body owing to penetration of the evaporation zone).

It should be noted, however, that when there are heat sources in the body, the value of Bi does not uniquely determine the temperature gradient, an example being heating of an infinite plate with uniformly distributed internal heat sources of strength q.

Using the relations given in [15], it may be shown that the variation in temperature at the center of the plate will be 10% less than the variation of its mean temperature, when the condition

$$|q| = \left| 0.1\lambda (t' - t'') \left[1 - \exp(-\mu_1^2 \mathrm{Fo})\right] \Big/ R_2 \left\{ 0.2 + \frac{0.1}{\mathrm{Bi}} \times \right.\right.$$
$$\left.\left. \times \left[1 - \frac{\mathrm{Bi}}{\mu_1^2} \exp(-\mu_1^2 \mathrm{Fo}) \right] \right\} \right| \qquad (1)$$

holds. Given the heat transfer conditions and the thermophysical properties of a body, there is no difficulty in calculating the right side of the inequality (1) and in determining the maximum value of the intensity of evaporation, in doing which it may be considered that the process of heating the moist material occurs with small temperature gradients, the material being thin.

It has been shown [12–14] that the heat expended in evaporating moisture from unit area of a plate is

$$q_F = \alpha (t' - t'') \Big/ \left(\frac{1}{3}\,\mathrm{E\,Bi} + 1\right). \qquad (2)$$

When condition (1) holds, this heat may be considered to be uniformly distributed over the whole volume of the body, and, therefore,

$$q = q_F F/V = \alpha\sigma\rho (t' - t'') \Big/ \left(\frac{1}{3}\,\mathrm{E\,Bi} + 1\right). \qquad (3)$$

On the other hand, the heat absorbed by the material during convective drying is

$$Q = \alpha F (t' - t''). \qquad (4)$$

We will introduce a coefficient of efficiency of external mass transfer

$$\varepsilon_0 = dQ_e / dQ, \qquad (5)$$

which relates to that fraction of the heat supplied to the material going into evaporation of moisture from the material. The larger this coefficient, the more effective the drying process.

It is evident that the value of this coefficient is determined both by the internal and by the external conditions of heat and mass transfer, i. e., it is a generalized coefficient, combining both the structural features of the material, which are taken into account by the transfer coefficients a', λ_m, δ, a, λ, and the capacity of the medium surrounding the material to absorb moisture.

From (5), taking account of (4), and assuming ε_0 to be constant, we obtain

$$Q_e = \varepsilon_0 Q = \varepsilon_0 \alpha F (t' - t'').$$

Relating Q_e to unit volume of the material we obtain an expression for the strength of the internal source ε_0

$$Q_e / V = q = \alpha\rho_2\sigma\varepsilon_0 (t' - t''), \qquad (6)$$

where ε_0 is always negative, since the evaporation process is associated with removal of heat from the material.

Comparing (3) and (6), we obtain

$$\varepsilon_0 = -1 \Big/ \left(\frac{1}{3}\,\mathrm{E\,Bi} + 1\right). \qquad (7)$$

Thus, the coefficient of efficiency of external mass transfer is connected by a simple relation with the phase transformation parameter and the Bi number.

It follows from (7) that the heat supplied to the moist material will be completely expended in evaporation only in the isolated case when displacement of moisture in the material takes place only in the liquid phase ($\varepsilon = 0$). It is evident that ε_0 will then reach its greatest absolute value, equal to unity, this occurring in the constant drying rate period.

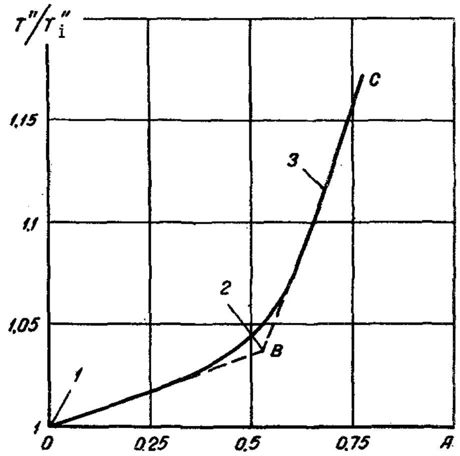

Fig. 1. Graphical illustration of relation (10) for a thin sheet of cellulose according to the data of [17] ($A \equiv \ln[(c_2^d + c_l\bar{u})/(c_2^d + c_l\bar{u}_l)]$): 1) for $\tau = 1.2 \cdot 10^3$ sec; 2) $2.7 \cdot 10^3$; 3) $3.6 \cdot 10^3$.

Formula (6) may be put in another form,

$$q/\alpha\sigma\rho_2 = \varepsilon_0 (t' - t''),$$

or, going over to dimensionless variables,

$$\varepsilon = \varepsilon_0 (1 - \theta' - \theta''). \qquad (8)$$

Returning to relation (5) and bearing in mind that $dQ_e = -r d\bar{u}$, and $dQ = (c_2^d + c_l\bar{u})dT'' + r d\bar{u}$, we obtain

$$\varepsilon_0 = -r d\bar{u} / [(c_2^d + c_l\bar{u})\, dT'' + r d\bar{u}],$$

or, bringing in the initial values of temperature and moisture content,

$$\varepsilon_0 = -\left[1 + \frac{c_l T''_i}{r}\, d(T''/T''_i) \Big/ d\ln\frac{c_2^d + c_l\bar{u}}{c_2^d + c_l\bar{u}_i}\right]^{-1}. \qquad (9)$$

Thus, to calculate the coefficient of efficiency of external mass transfer it is necessary to know the form of the functional relation

$$\frac{T''}{T''_i} = f\left(\ln\frac{c_2^d + c_l\bar{u}}{c_2^d + c_l\bar{u}_i}\right), \qquad (10)$$

which may be obtained from experimentally determined thermohygrograms of drying, curves of variation of moisture content and temperature of the material with time.

A number of investigations in this direction have been performed by the authors of references [16, 17] under mild drying conditions, and it seems to us that these investigations ought to be extended in the direction of accumulation of appropriate experimental data for various materials under the actual conditions prevailing in driers, this being a basis upon which an approximate design theory could be constructed.

The drying process proceeds in such a way that the period of constant drying rate occurs up to $\bar{u}_{cr}$ =

= 0.45 kg/kg, i.e., $\varepsilon_{0I} = -1$. The next period, which is characterized by a rise in the temperature of the material, may be divided into two stages, as indicated by the straight lines OB and BC in Fig. 1. The slope of each segment is numerically equal to the value of the derivative in (9). Thus, for the next two stages of drying we obtain $\varepsilon_{0II} = -0.963$ and $\varepsilon_{0III} = -0.777$, respectively. Within each period ε_0 is a constant, which considerably facilitates the subsequent analytical calculations.

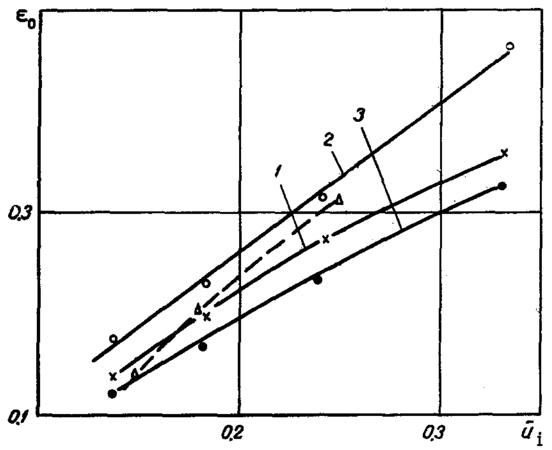

Fig. 2. Dependence of the coefficient of efficiency of external mass transfer ε_0 on the initial moisture content $\bar{u}_i$ for grain drying in a pneumatic pipe according to the data of [18] (solid lines) with $G_1 = 0.146$ kg/sec, and for grain cooling in a bed according to the data of [19] (broken lines): 1) with $G_2 = 0.148$ kg/sec and $t_i' = 190°$ C; 2) 0.437 kg/sec and 190° C; 3) 0.148 and 270.

Figure 1 shows the relation obtained for a constant drying regime, i.e., for constant temperature and moisture content of the surrounding air. It may be shown from simple considerations that in the variable regime the material temperature will always be less than in the constant regime involving a temperature equal to the initial temperature for continuously operating equipment. Moreover, in the constant regime, which is more stable, the final moisture content will be attained at a higher material temperature and in a shorter time than in the case of a variable regime. Therefore, a smaller fraction of the heat supplied to the material will be expended in evaporation. In certain cases, however, the influence of environmental factors on the value of ε_0 is considerable, as may be seen from Fig. 2, which shows curves of the dependences of ε_0 and $\bar{u}_i$ under different conditions of drying of grain. It is noteworthy that values of ε_0 for high-intensity drying processes in the weightless state are not much different from those for a mild regime of grain cooling in a dense bed.

Thus, the experimental data on the value of the coefficient ε_0 obtained in the laboratory drier under constant conditions may serve as a basis for design in the first approximation, thus ensuring a definite margin of reliability.

We will examine the drying process in some continuously operating equipment as being a heat transfer process between two heat carriers—the drying agent and the material being dried in the presence in the latter (denoted from now on by the subscript 2 or by two primes) of a negative internal heat source. The mathematical description of the problem is given by the system of equations derived in [19], which, taking (8) into account, has the dimensionless form

$$\theta' = 1 - \theta'' \mp \frac{R_{21}}{1+\varepsilon_0} \frac{d\theta''}{dv_x},$$
$$\theta'' = 1 - \theta' - \frac{d\theta'}{dv_x}, \qquad (11)$$

where the lower sign refers to the case of counterflow motion of the heat carrier.

The value appearing in (11) of the ratio of water equivalents of the two heat carriers, R_{21}, is a variable quantity in the drying process. Variation of R_{21} is due to two factors. Firstly, removal of moisture from the material occurs, which causes the specific heat capacity to vary downwards. In addition, the mass of the material being dried changes in the same direction. The result is that the water equivalent W_2 of the material may decrease very considerably. Secondly, some change in the heat capacity and in the mass of the drying agent occurs due to absorption of water vapor. As a rule, these changes are small, and we will assume W_1 = const in what follows.

Since the water equivalent of the moist material is $W_2 = G_2^d(c_2^d + c_l\bar{u})$,

$$R_{21} = W_2/W_1 = c_2^d G_2^d/W_1 + c_l G_2^d \bar{u}/W_1 = R_{21}^d + R_{21}^* \bar{u}, \quad (12)$$

where the superscript "d" refers to absolutely dry material.

The amount of moisture evaporated from the material may be expressed as follows:

$$G_2^d(\bar{u}|_{x=0} - \bar{u}) = -\frac{\varepsilon_0}{r}\int_0^x \alpha s(t' - t'')\,dx,$$

or, going over to dimensionless variables,

$$\bar{u}|_{v_x=0} - \bar{u} = \triangle\bar{u} = -[\varepsilon_0 W_1(t_i'' - t_i')/rG_2^d]\int_0^{v_x}(\theta'' + \theta' - 1)\,dv_x.$$

Replacing the expression in parentheses according to the second of Eqs. (11) and integrating, we obtain

$$\bar{u}|_{v_x=0} - \bar{u} = \frac{c_l\varepsilon_0(t_i'' - t_i')}{rR_{21}}\theta'. \qquad (13)$$

After replacing $\bar{u}$ in (12) by its value from (13), we find an expression for

$$R_{21} = R_{21}^d + R_{21}^*\bar{u}|_{v_x=0} - c_l\varepsilon_0(t_i'' - t_i')\theta'/r,$$

substitution of which in the first equation of (11) and solution of that with respect to θ' gives

$$\theta' = \frac{1 - \theta'' - \lambda(d\theta''/dv_x)}{1 - \varkappa(d\theta''/dv_x)}, \qquad (14)$$

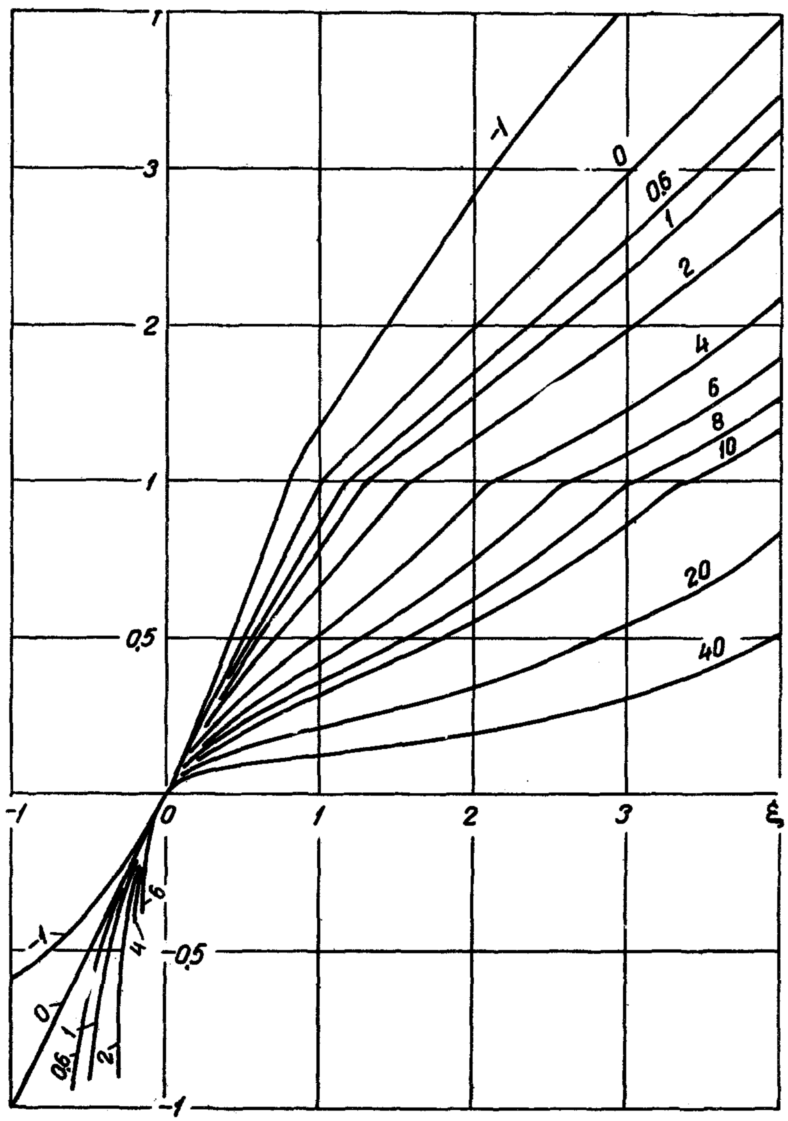

Fig. 3. Graph of the integral $\int_0 d\eta/[1 + B\eta\exp(-\eta)]$ for various values of the parameter B (the figures on the curves).

where

$$\lambda = \pm \frac{R_{21}^{d} + R_{21}^{*}\bar{u}|_{v_x=0}}{1+\varepsilon_0}; \quad \varkappa = \pm \frac{c_l \varepsilon_0 (t_1'' - t_1')}{r(1+\varepsilon_0)} \quad (15)$$

are constants, the actual parameters of the drying process.

Replacing θ' in the second equation of (11) by its value from (14), we obtain, after transformation,

$$\left[1 + \frac{1}{\varkappa(1-\theta'') - (1+\lambda)}\right] \frac{d^2\theta''}{dv_x^2} - \varkappa\left(\frac{d\theta''}{dv_x}\right)^2 + \frac{d\theta''}{dv_x} = 0. \quad (16)$$

The nonlinear second-order differential equation obtained describes the heating process for a moist, thin (in the sense of (1)) material in a drier with parallel motion of the material and the drying agent, under the assumption of constant ε_0. If there is appreciable variation of ε_0 during drying, then Eq. (16) must be used for a zonal calculation, the value of ε_0 being taken as constant in each zone, equal to its mean value for the given zone.

The solution of (16) must satisfy the following boundary conditions:

for direct flow

$$\theta''\Big|_{v_x=0} = 0, \quad \frac{d\theta''}{dv_x}\Big|_{v_x=0} = \frac{1}{\lambda}, \quad (17)$$

for counterflow

$$\theta''\Big|_{v_x=0} = \theta_f'', \quad \frac{d\theta''}{dv_x}\Big|_{v_x=0} = \frac{1-\theta_f''}{\lambda}. \quad (18)$$

Making the solution of (16) conform to boundary conditions (17) and (18), we obtain

$$v = I_i - I_f = \int_0^{\xi_i} \frac{d\xi}{1 + B\xi e^{-\xi}} - \int_0^{\xi_f} \frac{d\xi}{1 + B\xi e^{-\xi}}, \quad (19)$$

where $\xi = \varkappa(1-\theta'') - \lambda$ and in the case of direct flow

$$\xi_i = \varkappa - \lambda, \quad \xi_f = \varkappa(1-\theta_f'') - \lambda, \quad (20)$$

in the counterflow case

$$\xi_i = \varkappa(1-\theta_f'') - \lambda, \quad \xi_k = \varkappa - \lambda, \quad (21)$$

while

$$B_{\text{dir}} = \frac{1}{\lambda}\exp(\varkappa - \lambda), \quad B_{\text{ctr}} = \frac{1}{\lambda}\exp[\varkappa(1-\theta_f'') - \lambda]. \quad (22)$$

We compiled a table of the integral I, the results being shown graphically in Fig. 3, by using which, for known $\varkappa$, λ and θ_f'', we may determine the value of the dimensionless coordinate v (negative values of B in Fig. 3 refer to the counterflow case).

From the relations given above we may find the connection between the dimensionless temperatures of the drying agent and of the material; because of limitations of space we omit the intermediate calculations, and give only the final result:

for direct flow

$$\theta' = \frac{\lambda}{\varkappa}[1 - \exp(-\varkappa\theta'')], \quad (23)$$

for counterflow

$$\theta' = \frac{\lambda}{\varkappa}\{1 - \exp[\varkappa(\theta_f'' - \theta'')]\}. \quad (24)$$

Thus, in constrast with the usual regenerators, which are characterized by a linear relation between the temperatures of the heat carriers, this relationship is exponential for drying.

Whereas the material temperature in counterflow may attain, in the limit, the temperature of the drying agent, the highest temperature of the material in direct flow is $t_f'' \le t_f'$ or $1 - \theta_f' \ge \theta_f''$.

Substituting θ_f' from (23) in the last expression, we obtain the inequality

$$1 - \theta_f'' \geqslant \frac{\lambda}{\varkappa}[1 - \exp(-\varkappa\theta_f'')], \quad (25)$$

from which, for known constant values of λ and $\varkappa$, we may find the limiting permissible temperature for direct flow of the heat carriers.

If the water equivalent of the drying agent is infinitely large ($W_1 \to \infty$), which corresponds to the condition that its temperature remains constant, then, after introducing the new independent variable $u_x = \alpha F_x/W_2^d = R_{12}^d v_x$, and replacing v_x in (16), we obtain, according to this relation, letting R_{21} tend to zero and assuming $\lambda = 0$, as may be seen from (15)

$$\left[1 + \frac{1}{\varkappa(1-\theta'') - 1}\right] \frac{d^2\theta''}{du_x^2} - \varkappa\left(\frac{d\theta''}{du_x}\right)^2 = 0. \quad (26)$$

The solution of (26), satisfying the boundary conditions

$$\theta''\Big|_{u_x=0} = 0, \quad \frac{d\theta''}{du_x}\Big|_{u_x=0} = \frac{1+\varepsilon_0}{1 + c_l/c_2^d}, \quad (27)$$

will be

$$u = \frac{\varkappa(1 + c_l/c_2^d)}{1+\varepsilon_0}[\mathrm{Ei}(\xi_i) - \mathrm{Ei}(\xi_f)], \quad (28)$$

where

$$\xi_i = \varkappa, \quad \xi_f = \varkappa(1-\theta_f''). \quad (29)$$

Replacing θ' in (13) by its value from (23), we obtain an expression for the removal of moisture from the material with direct flow of the heat carriers

$$\bar{u}_i - \bar{u} = (c_2^d/c_l + \bar{u}_i)[1 - \exp(-\varkappa\theta'')] \quad (30)$$

and with counterflow, taking into account that R_{21}^{*} changes its sign in (13),

$$\bar{u} - \bar{u}_f = (c_2^d/c_l + \bar{u}_f)\{1 - \exp[-\varkappa(\theta_f'' - \theta'')]\}, \quad (31)$$

i. e., the decrease of moisture content during drying is an exponential function of temperature.

It is of interest to compare the direct and the counterflow drier. We will make the comparison in terms of the amount of moisture evaporated at equal values of water equivalents, coefficients of efficiency of external mass transfer, and dimensionless temperature of the material.

If we examine the drier as a whole ($\theta'' = 0$), expression (31) may be transformed into

$$\bar{u}_i - \bar{u}_f = \left(\frac{c_2^d}{c_l} + \bar{u}_i \right) \frac{1 - \exp(\varkappa \theta_f'')}{2 - \exp(\varkappa \theta_f'')}. \qquad (31a)$$

Thus, for equal values of the initial moisture contents

$$(\Delta u)_{dir} / (\Delta u)_{ctr} = 2 - \exp(\varkappa_{ctr}\, \theta_f''). \qquad (32)$$

It may be seen from (32), that the left side of this relation is always greater than unity, i. e., the decrease in moisture content in direct flow is greater than in counterflow, if the temperature to which the material is heated in the drier is identical in both cases, and the values of ε_0, which determine the values of $\varkappa$ (see (15)), are also equal. As regards conditions of constant ε_0 in the two variants of mutual direction of motion of drying agent and material, the picture is not quite clear, since transition from one variant to the other is associated with a change in drying regime, other conditions being equal. Thus, in a transition to counterflow in the first stage of drying, the process will proceed under milder conditions (high humidity of the drying agent, low temperature, and a large value of the critical humidity) than in the final stage, which is characterized by more rigorous drying regimes. The total effect over the whole process may be different, but, bearing in mind what has been said about the influence of the regime factors on ε_0, we may assume that no substantial difference in the values of ε_0 will be observed in counterflow as compared with direct flow.

At low values of material moisture content, for which the values of ε_0 and (correspondingly) the value of $\varkappa$ is small, the exponent on the right side of (32) will differ little from unity. The higher the humidity of the material, the greater the advantage of direct flow drying equipment.

These advantages are especially noteworthy when, from technological considerations, the material cannot be heated above some maximum temperature or other.

If there is no such limit, then the effectiveness of counterflow may be appreciably increased by making use of the basic advantage of this variant—the possibility of heating the material to a higher temperature.

The design method described has been verified experimentally by a number of authors who have investigated the drying of disperse materials in the weightless state, as well as of thin pieces and sheets of materials in convective driers of the ordinary type. The results of this verification, which are the subject of a forthcoming publication, have proved the effectiveness of the above method of calculation, the special feature of which is the description of the entire process by only two empirical coefficients, ε_0 and α.

In conclusion, it should be pointed out that the heat transfer coefficient entering into the dimensionless coordinate v_x (or u_x) in the drying process may change quite considerably. One should therefore introduce mean values of this coefficient for each computational zone, determined from the appropriate criterial relations for the moist material, as given in [12]. If we assume the value of α for all the drying stages to be that for "dry" heat transfer, then the result obtained from such a calculation will have a definite margin of reliability.

NOTATION

$\bar{u}$ is the mean moisture content over volume of body; F and V are the area and volume of body; R is the half-thickness of plate; σ is the area of unit mass of material; G is the mass flow rate; c is the heat capacity; α is the heat transfer coefficient; ρ is the density; $W = cG$; $R_{21} = W_2/W_1$; $\theta' = (t' - t_i')/(t_i'' - t_i')$; $\theta'' = (t_i'' - t'')/(t_i'' - t_i')$; $\varepsilon = q/\alpha\sigma\rho_2(t_i - t_i'')$; $v_x = \alpha F_x/W_1$; $R_{21}^* = c_l G_2^d/W_1$; $u_x = \alpha F_x/W_2^d$; r is the latent heat of evaporation; $\varkappa$ and λ—see (15); s is the perimeter of body; x is a coordinate. Subscripts i and f refer, respectively, to the inlet and outlet of the equipment; cr is critical; l is liquid. Superscript d refers to the absolutely dry material; 1 or one prime refers to the drying agent, 2 or two primes—to the material.

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