OPTIMIZATION OF THE OSCILLATORY DRYING PROCESS

V. A. Sheiman

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The fundamental conditions are formulated and relations are obtained for calculating the parameters of the optimal oscillatory drying regime in a fluidized bed.

The drying of various materials and products in the oscillatory regime is becoming increasingly common in present-day practice. The application of the method is particularly effective in the case of thermodynamically labile materials, which do not submit readily to the use of a heat-transfer agent having a high initial temperature.

Some researchers tend to think of the oscillatory regime primarily in terms of obtaining a high-quality product. However, this is only a one-sided view of the effect and only part of what can be attained in the given regime.

The intensity of convective drying is known [1] to be approximately described by the relation

$$\gamma_m = \frac{\alpha}{r}(t-\vartheta_s) = a_m \rho_0 (|\nabla u| + |\delta \nabla \vartheta|)_s. \tag{1}$$

The right-hand side of Eq. (1) represents the quantity of moisture brought to the surface of the material subjected to drying. It follows from (1) that the efflux of moisture can be accelerated by increasing α and t. However, the possible increase of the external heat transfer is limited by the internal mass transfer and the danger of overheating of the material. Overheating of the surface causes deeper penetration of the moisture-evaporation zone, increases the phase-conversion criterion ε, shrinks the pores and capillaries, and causes dry-out of the top layer of the product, thereby increasing the density of that layer and its resistance to internal diffusion, so that the net effect is an overall reduction in the rate of evaporation. Moreover, surface overheating can in a number of situations have undesirable consequences such as denaturation of albumins, degradation of enzymes and vitamins, the death of living cells, the formation of a moisture-permeable film due to the hydrolysis of starch or pectin or due to the caramelization of sugar, etc. [2].

Consequently, to prevent such unwanted effects it is necessary to equalize the rate of external mass transfer and internal diffusion of moisture. Since, as a rule, the external heat transfer is easily intensified, the process must be organized in such a way as to increase the rate of internal moisture diffusion. This objective can be achieved by increasing a_m and ∇u. But, as we mentioned above, increasing ∇u can detract from the quality of the product. As for a_m, it depends to a considerable extent on the temperature of the material; in the case of grain [3], for example,

$$a_m = a_{m0}\left(\frac{T}{273}\right)^k,$$

where k = 8.3 to 18.1 is an empirical coefficient depending on the moisture content and T is the absolute temperature.

It is desirable, therefore, for the temperature of the material to be maintained at the maximum attainable level during drying. In the oscillatory regime during the cooling (or wetting-off) periods a favorable redistribution of moisture takes place inside the solid particle, accompanied by equalization of the moisture-content field and migration of moisture

A. V. Lykov Institute of Heat and Mass Transfer, Academy of Sciences of the Belorussian SSR, Minsk. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 33, No. 1, pp. 137-143, July, 1977. Original article submitted July 19, 1976.

to the surface in liquid form. This fact, coupled with periodic cooling, makes it possible to increase the initial temperature of the heat-transfer medium during the heating periods. Analyzing the possibilities of the oscillatory regime, we arrive at the conclusion that the efficiency of the process in this case is dictated by the following sets of factors:

1) the impulsive action of the heat-transfer agent with a high initial temperature, which greatly exceeds the temperature of the agent for a continuous heat input; the realization of a long-lasting part of the process at the maximum attainable temperature of heating of the material; periodic coincidence of the temperature and moisture gradients; directional redistribution of moisture throughout the cross section of the body; a reduction of the temperature and moisture gradients in the cross section of the body; the creation of periodic positive and negative temperature gradients;

2) the capability of tighter regulation of the process by comparison with continuous heat input due to the variation of the process parameters; the application of diverse hydrodynamic conditions during a single drying operation, for example, periodic fluidization with wetting off in the stationary granular layer (with or without blowing of a colant through the layer [6]); greater flexibility with regard to the application of diverse heat-input methods, for example, convection with impulsive thermal radiation;

3) the acquisition of a high-quality product through more uniform drying and directional moisture transport, along with deep-drying capabilities.

Thus, the oscillatory regime makes it possible to obtain a high-quality product and to intensify the process.

As the foregoing discussion implies, the given effect is achieved only with intelligent planning of the process, namely, through optimization of the parameters. Not only is this problem the most important aspect of the oscillatory regime, it is simultaneously the most complex problem. We need merely point out that so far, despite abundant research on the subject, no one has even stated the conditions for the optimal process regime. Kozlova's dissertation [4] appears to be the only analytical study published on the subject. The heat- and mass-transfer processes associated with drying of a plate under boundary conditions of the second kind are analyzed to obtain a relation for determining the period of oscillation, but this relation does not tie in the parameters of the process with the transport of energy and matter in the interior of the body.

The fundamental optimization principle is guided by a single objective, to intensify the process while ensuring high quality of the end product and minimal energy expenditures. In each specific instance, however, the mathematical formulation embodying this principle posits a concrete expression and in general depends both on the hydrodynamics of the process and on its conditions of evolution. Attention must also be given to the presence or absence of temperature and moisture gradients in the cross section of the body or, more precisely, the necessity of taking them into account or the admissibility of neglecting them. We now examine the conditions for one possible mode of organization of the process, namely, oscillatory fluidized-bed drying, for which the gradients in the particle cross section can be neglected. In this case the controlled system is described by ordinary differential equations and is characterized by the following lumped parameters: the initial temperatures T_H and T_C of the heating and cooling heat-transfer agents; the heating time η_H and cooling time η_C and their ratio $\nu = \eta_C/\eta_H$. We now formulate the fundamental conditions for the optimal process regime.

1. It has been shown [5] that the process is best organized with preliminary warmup (Fig. 1). In this case a large portion of the process can be implemented at the maximum attainable temperature of heating of the material and so for a large value of a_m. This condition is satisfied when after a certain time the tangent to the temperature curve is parallel to the horizontal axis, i.e., when

$$\frac{d\Theta}{d\eta} = 0. \tag{2}$$

2. The maximum temperature of the material in the heating periods must not be greater than the allowable limit Θ^*:

$$\Theta_{\text{H}}^{f} \leqslant \Theta^*. \tag{3}$$

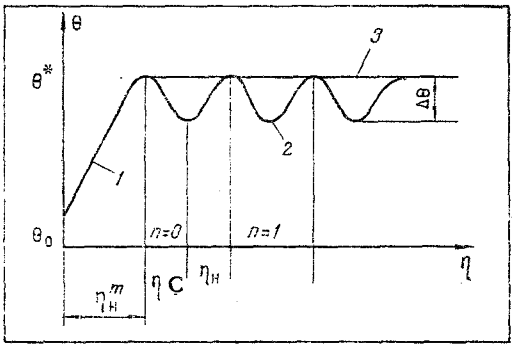

Fig. 1. Temperature variation of material. 1) Preliminary warmup; 2) main drying process; 3) tangent to temperature curve.

3. The net heat flux during any period is proportional to the difference between the maximum and minimum temperatures of the material; this quantity must therefore be bounded and, insofar as possible, specified beforehand, i.e.,

$$\Theta_H^f - \Theta_C^f = \Delta\Theta = \text{const.} \tag{4}$$

The author has previously derived an expression (Eq. (20) in [5]) for calculating the temperature of the material at the end of any heating period with allowance for preliminary warmup:

$$\Theta(n) = (a + b^* \exp[k(1+n)\eta_H])^{-p}\Big[T_m + T_H \sum_0^n (a + b^* \exp[k(1+n)\eta_C])^p -$$

$$-(T_H - T_C)\sum_0^n (a + b^* \exp[k(n\eta_C + \eta_C)])^p - T_C \sum_0^n (a + b^* \exp kn\eta_C)^p - cb\int_{t_1}^{t_2} \frac{dt}{t^p - a}\Big], \tag{5}$$

where $T_m = (\Theta_0 - T_H)(a + b)^p + T_H(a + b^*)^p$; $b^* = b \exp k\eta_H^m$; and the dimensionless time η is expressed in terms of the number n of cycles:

$$\eta = \eta_H^m + (1+n)\eta_C = \eta_H^m + \eta_H(1+n)(1+\nu). \tag{6}$$

Calculations show that the integral term in (5) does not amount to more than 5% relative to the other terms in all cases, and so we neglect it hereinafter. The quantity T_H is dimensionless, and always $T_H = 1$. As far as the temperature T_C of the coolant air is concerned, it is practically equal to the ambient air temperature and is difficult to regulate in real situations. The quantities to be determined, therefore, are η_H, η_C, and ν for given T_H and T_C. Using condition (2), we find the derivative $d\Theta(n)/dn$ from (5) and set the numerator equal to zero. After appropriate transformations we have

$$-pb^* \exp[k\eta_C(1+n)]\, k\eta_C[\sim] + (a + b^* \exp[k(1+n)\eta_C])\times$$

$$\times\Big\{\sum_0^n p(a + b^* \exp[k(1+n)\eta_C])^{p-1} k\eta_C b^* \exp[k\eta_C(1+n)] - \Omega\Big\} = 0, \tag{7}$$

where [~] denotes the bracketed expression in Eq. (5) and

$$\Omega = (1 - T_C)\sum_0^n p(a + b^* \exp[k(n\eta_C + \eta_C)])^{p-1} b^* k\eta_C \exp[k(n\eta_C + \eta_C)] -$$

$$-T_C \sum_0^n p(a + b^* \exp kn\eta_C)^{p-1} b^* k\eta_C \exp kn\eta_C.$$

Equation (7) is valid for any n, so that, putting n = 1 and recognizing that $\eta_C = \eta_H(\nu + 1)$, we obtain from (7)

$$\eta_H(\nu + 1) = \frac{1}{2k} \ln \frac{(a + b^* \exp 2k\eta_C)\{\sim\}}{pb^* k\eta_C[\sim]}, \tag{8}$$

where {~} denotes the expression in braces in relation (7). We denote

$$m = \frac{1}{2} \ln \frac{(a + b^* \exp 2k\eta_c)\{\sim\}}{pb^* k\eta_c [\sim]}$$

and rewrite (8):

$$\eta_н (1 + \nu) = \frac{m}{k}. \tag{9}$$

Hence

$$m = k\eta_н (1 + \nu), \text{ and } k(\eta_н^m + \eta_н) = k[\eta_н^m + \eta_н (1 + \nu)] = k\eta_н^m + m. \tag{10}$$

Let us consider condition (3). It is valid for any n, so that, putting n = 0, we infer the following equation from (3) and (5) with regard for (10):

$$(\Theta^* - 1)[(a + b \exp(k\eta_н^m + m)]^p - (a + b)^p (\Theta_0 - 1) = (1 - T_C)[s - \\ - (a + b \exp[k(\eta_н^m + \nu\eta_н)])^p], \tag{11}$$

where

$$s = (a + b \exp k\eta_н^m)^p.$$

We denote

$$\Theta_0^* = (\Theta^* - 1)(a + b \exp[k\eta_н^m + m])^p - (a + b)^p (\Theta_0 - 1) \tag{12}$$

and rewrite (11):

$$\Theta_0^* = (1 - T_C)[s - (a + b \exp[k(\eta_н^m + \nu\eta_н)])^p]. \tag{13}$$

On the basis of expression (3) we rewrite condition (4) as follows:

$$\Theta^* - \Theta_C^f = \Delta\Theta. \tag{14}$$

Taking Eq. (19) from [5], we obtain the following for calculation of the temperature of the material after any cooling period, using (14) with n = 0:

$$\Theta^* - [a + b \exp[k(\eta_н^m + \nu\eta_н)]]^{-p} \{(\Theta_0 - 1)(a + b)^p + s + \\ + T_C [(a + b \exp[k(\eta_н^m + \nu\eta_н)])^p - s]\} = \Delta\Theta. \tag{15}$$

Hence

$$[a + b \exp[k(\eta_н^m + \nu\eta_н)]]^p = \frac{(\Theta_0 - 1)(a + b)^p + s(1 - T_C)}{\Theta^* - \Delta\Theta - T_C}. \tag{16}$$

Substituting (16) into (13), we obtain

$$\Theta_0^* = (1 - T_C) \frac{s(\Theta^* - \Delta\Theta - 1) - (\Theta_0 - 1)(a + b)^p}{\Theta^* - \Delta\Theta - T_C}. \tag{17}$$

All quantities on the right-hand side of (17) are known, and so Θ_0^* is readily evaluated. From (12) we obtain

$$m = \ln \frac{1}{b} \left\{ \left[\frac{\Theta_0^* + (a + b)^p (\Theta_0 - 1)}{\Theta^* - 1} \right]^{1/p} - a \right\} - k\eta_н^m. \tag{18}$$

From (9) we have

$$\nu\eta_н = \frac{m}{k} - \eta_н. \tag{19}$$

Substituting (19) into (13) and carrying out suitable transformations, we find

$$\eta_н = \frac{1}{k} \ln \frac{b \exp(k\eta_н^m + m)}{\left(s - \frac{\Theta_0^*}{1 - T_C}\right)^{1/p} - a}. \tag{20}$$

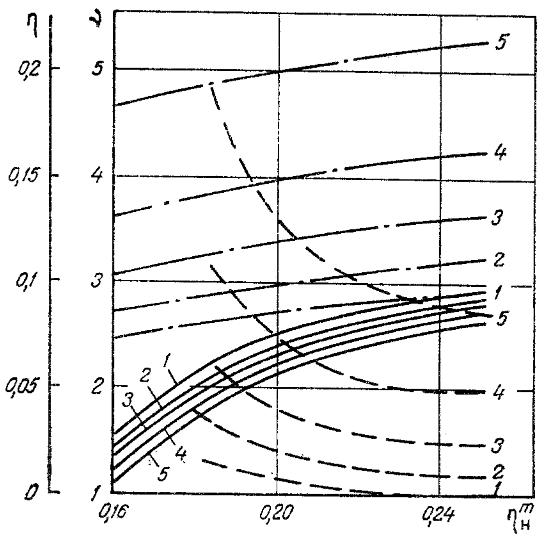

Fig. 2. Graph of η_H (solid curves), η_C (dot-dash curves), and ν (dashed curves) versus η_H^m. 1) T_C = −0.2; 2) −0.1; 3) 0; 4) 0.1; 5) 0.3.

We obtain an expression for ν from (9):

$$\nu = \frac{m}{k\eta_H} - 1. \tag{21}$$

In the foregoing relations $k = k^*(rG/W_h t_H)$, where k^* is the proportionality factor in the well-known expression

$$-\frac{du}{d\tau} = k^*(u - u_e).$$

The results of some calculations are given in Fig. 2. The relations derived above are reasonably simple and do not require large-volume or high-speed storage, so that a suitable program can be written for the Mir computer. With an increase in the preliminary warmup time η_H^m the value of η_H also increases (Fig. 2). Inasmuch as the maximum attainable temperature in every case is considered to be the same, $\Theta^* = 0.401$, the physical implication here is a variation (increase) of the heat capacity of the material.

The term "optimal" is generally understood to mean better control in some definite sense. In the present article the optimization goal has been to determine the parameters that would ensure intensification of the process in combination with minimum expenditure of heat and a high-quality product (the quality of the latter is characterized by the maximum attainable temperature of heating). It is conceivable that each of these assets taken separately might be achieved more auspiciously for other process parameters, but the sum-total of the above-mentioned factors is achieved only for a very definite choice of process parameters.

NOTATION

$T_k = t/t_H$; $\Theta = \vartheta/t_H$; $p = 1/bkE$; $E = (C_M/r)t_H$; $\eta = (Wt_H/rG)\tau$; $a = C_L/C_M(u_f - u_e)$; $b = 1 + (C_L/C_M)u_e$; C_L and C_M, specific heats of the liquid and material, respectively; G, quantity of material loaded into the drier; r, heat of vaporization; t, temperature of heat-transfer agent; u, moisture content of material; W, water equivalent; α, heat-transfer coefficient; ϑ γ_m, mass flow rate; δ, thermogradient coefficient; ρ_0, density of kiln-dry material; ϑ, temperature of material; τ, time. Indices: f, final; m, maximum H, heating; 0, initial; C, cooling; s, surface; e, equilibrium; c, cycle.

LITERATURE CITED

1. A. V. Lykov, Theory of Drying [in Russian], Énergiya, Moscow (1968).
2. V. A. Sheiman, Inzh.-Fiz. Zh., 31, No. 4, 651 (1976).
3. A. S. Ginzburg, V. P. Dubrovskii, E. D. Kazakov, G. S. Okun', and V. A. Rezchikov, Moisture in Grain [in Russian], Kolos (1969).

4. M. S. Kozlova, Author's Abstract of Candidate's Dissertation, Moscoe Technological Institure of the Food Industry, Moscow (1971).
5. V. A. Sheiman, Inzh.-Fiz. Zh., 25, No. 4 (1973).
6. V. A. Sheiman and A. E. Protskii, Izv. Akad. Nauk BelorusSSR, Ser. Fiz.-Énerg. Nauk, No. 4 (1975).

DETERMINATION OF THE LOCAL ANGULAR COEFFICIENT FOR A CYLINDRICAL SURFACE

R. Kh. Mullakhmetov

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Algebraic expressions are obtained and graphs are presented for the determination of the local angular coefficient for a particular orientation of an elementary area relative to a cylinder.

In engineering practice when calculating radiant heat transfer one usually uses the approximation where the problem of determining the angular coefficient between a cylindrical surface (F_2) and a structural surface (F_1) comes down to the problem of determining the angular coefficient between the surface F_2 and a surface of elementary area dF_1.

Let us consider the case when the normal to the center of the elementary area is parallel to the axis of the cylinder.*

The algebraic expression for calculating the local angular coefficient is sought by the method of integration of the basic equation [2]

$$\varphi_{dF_1 \cdot F_2} = \int\limits_F \frac{\cos\theta_1 \cdot \cos\theta_2}{\pi r^2}\, dF_2, \tag{1}$$

which is written in the following form, using $dF_2 = Rd\Phi dy$, $\cos\theta_1 = y/r$, $\cos\theta_2 = (x_1 \cos\Phi - R)/r$ and $r^2 = R^2 + x_1^2 + y^2 - 2x_2 R\cos\Phi$ for the geometry shown in Fig. 1a:

$$\varphi_{dF_1 \cdot F_2} = \frac{2R}{\pi} \int\limits_0^{\Phi_0} (x_1 \cos\Phi - R)\, d\Phi \int\limits_0^{y_1} \frac{ydy}{(y^2+k)^2}, \tag{2}$$

where $k = R^2 + x_1^2 - 2x_1 R\cos\Phi$ and $\Phi_0 = \arccos(R/x_1)$.

The integration of Eq. (2) encounters no mathematical difficulties and is carried out using tables of integrals:

$$\varphi_{dF_1 \cdot F_2} = \frac{1}{\pi} \operatorname{arctg}\left(\frac{x_1 + R}{x_1 - R} \operatorname{tg}\frac{\Phi_0}{2}\right) + \frac{1}{\pi}\, \frac{R^2 - x_1^2 - y_1^2}{\sqrt{AB}} \operatorname{arctg}\left(\sqrt{\frac{A}{B}} \operatorname{tg}\frac{\Phi_0}{2}\right), \tag{3}$$

where $A = y_1^2 + (x_1 + R)^2$ and $B = y_1^2 + (x_1 - R)^2$.

The limiting local angular coefficient is of interest in some cases when the height of the cylinder approaches infinity. From Eq. (3) it follows that

*The solution of the problem for the case when the normal to the center of the elementary area is perpendicular to the axis of the cylinder is presented in [1].

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