SOME PROBLEMS OF DESICCATION IN A FLUIDIZATION BED WITH HEAT CYCLING

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Several variants of the desiccation process in a fluidization bed with heat cycling are considered, and a method is developed for determining the desiccation factor during the periods of heating and cooling; relations are also derived for the design of the desiccation process in various modes of operation.

The variety of desiccation modes with heat cycling (periodic heating and cooling) in a fluidization (bubble) bed stems from both the different specific conditions of the fluidization process and the different modes of heat cycling. In this study we will consider only the few variants which are important, in the author's view, noting that the individual problems have already been dealt with in the technical literature [1, 2, 3].

Generally not only the initial temperature of the heat carrier varies with time but also its water equivalent is different during the periods of heating and cooling. This is a consequence of the necessity to ensure uniform and identical hydrodynamic conditions of bed fluidization during the periods of heating and cooling, when also a maximum but not higher than allowable temperature of the product is maintained. Since desiccation treatment in the cyclic mode involves heat sensitive materials, hence of greatest concern is, of course, the decreasing-rate period of the process. During this period the desiccation rate is accurately enough proportional to the excess moisture content [4]. The proportionality factor (desiccation factor) is generally also different during heating and during cooling, i.e., it varies with time. Moreover, also the specific heat of the product material varies during the desiccation process.

We will limit our analysis of the desiccation process to disperse materials with a negligible temperature gradient across the particles and, on the basis of these comments, write the following system of equations for the decreasing-rate period:

$$W(\tau)\left[t(\tau)-\vartheta(\tau)\right]d\tau = G\left(c_{\text{м}}+c_{\text{L}}\bar{u}\right)d\vartheta - rGd\bar{u}, \tag{1}$$

$$-\frac{d\bar{u}(\tau)}{d\tau} = k(\tau)\left[\bar{u}(\tau)-\bar{u}_{\text{e}}\right], \tag{2}$$

$$t(\tau) = \begin{cases} t_{\text{н}}, & \tau_{\text{н}}(n+n\nu) \leqslant \tau \leqslant \tau_{\text{н}}\left[(n+1)+n\nu\right], \\ t_{\text{C}}, & \tau_{\text{н}}\left[(n+1)+n\nu\right] \leqslant \tau < \tau_{\text{н}}\left[(n+1)(\nu+1)\right] \end{cases} \tag{3}$$

$$(n=0,\ 1,\ 2,\ 3\ \ldots),$$

$$k(\tau) = \begin{cases} k_{\text{G}}, & \tau_{\text{н}}(n+n\nu) \leqslant \tau \leqslant \tau_{\text{н}}\left[(n+1)+n\nu\right], \\ k_{\text{A}}, & \tau_{\text{н}}\left[(n+1)+n\nu\right] \leqslant \tau < \tau_{\text{н}}\left[(n+1)(\nu+1)\right] \end{cases} \tag{4}$$

$$(n=0,\ 1,\ 2,\ 3\ \ldots),$$

$$W(\tau) = \begin{cases} W_{\text{G}}, & \tau_{\text{н}}(n+n\nu) \leqslant \tau \leqslant \tau_{\text{н}}\left[(n+1)+n\nu\right], \\ W_{\text{A}}, & \tau_{\text{н}}\left[(n+1)+n\nu\right] \leqslant \tau < \tau_{\text{н}}\left[(n+1)(\nu+1)\right] \end{cases} \tag{5}$$

$$(n=0,\ 1,\ 2,\ 3\ \ldots).$$

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The initial conditions are

$$\vartheta(\tau)|_{\tau=0} = \vartheta_0 = \text{const}, \quad \bar{u}(\tau)|_{\tau=0} = \bar{u}_{\text{cr}} = \text{const}. \tag{6}$$

For convenience, in subsequent calculations we will use the following relations:

$$0 \leqslant \tau' \leqslant \tau_H; \quad 0 \leqslant \tau'' \leqslant \tau_C. \tag{7}$$

With (7) taken into account, then, we can write

$$\left.\begin{aligned} &\tau = n\tau_H(1+\nu) + \tau' \quad \text{or} \quad \tau = n\tau_{\text{cy}} + \tau', \\ &\tau = \tau_H[n(1+\nu)+1] + \tau'' \quad \text{or} \quad \tau = n\tau_{\text{cy}} + \tau_H + \tau'', \end{aligned}\right\} \tag{8}$$

where $\tau_{\text{cy}} = \tau_H + \tau_C$, $\nu = \tau_C/\tau_H$.

In (1) and (2) the moisture content $\bar{u}$ is a mean-integral quantity defined by the expression

$$\bar{u}(\tau) = \frac{\Gamma+1}{R^{\Gamma+1}} \int_0^R r^{\Gamma} u(r, \tau)\, dr$$

($\Gamma = 0$, 1, and 2 for a plate, a cylinder, and a sphere, respectively).

The same applies to the temperature of the material ϑ. Integrating Eq. (2) between the respective limits yield

$$\bar{u}(\tau) = (\bar{u}_{\text{cr}} - \bar{u}_0) \exp\left[-\int_0^{\tau} k(\xi)\, d\xi\right] + \bar{u}_{\text{e}}. \tag{9}$$

With (4) taken into account, the integral in (8) can be evaluated as follows:

$$\int_0^{\tau} k(\xi)\, d\xi = \int_0^{\tau_H} \cdots + \int_{\tau_H}^{\tau_H(1+\nu)} \cdots + \int_{\tau_H(1+\nu)}^{\tau_H(2+\nu)} \cdots + \cdots + \int_{\tau_H n(1+\nu)}^{\tau_H[(n+1)+n\nu]} k(\tau)\, d\tau$$

$$+ \int_{\tau_H[(n+1)+n\nu]}^{\tau} k(\xi)\, d\xi = k_G\left[\tau \int_0^{\tau_H} + \tau \int_{\tau_H(1+\nu)}^{\tau_H(2+\nu)} + \cdots + \tau \int_{\tau_H n(1+\nu)}^{\tau_H[(n+1)+n\nu]}\right]$$

$$+ k_A\left[\tau \int_{\tau_H}^{\tau_H(1+\nu)} + \tau \int_{\tau_H(2+\nu)}^{\tau_H 2(1+\nu)} + \cdots + \tau \int_{\tau_H[(n+1)+n\nu]}^{\tau}\right] = k_G(\tau_H n + \bar{\tau}_H) + k_A[\tau - \tau_H(n+1)] = \alpha_n + k_G\bar{\tau}_H + k_A\tau, \tag{10}$$

where

$$\alpha_n = k_G n\tau_H - k_A\tau_H(n+1). \tag{11}$$

We note that (10) will have different values during different periods for which the temperature of the material is calculated. Thus, according to (8), for the heating periods one must substitute $\bar{\tau}_H = \tau'$, $\tau = \tau_H(n + 1 + n\nu)$ (α_n remains constant then) in (10). Instead of (10), we have now

$$\int_0^{\tau} k(\xi)\, d\xi = \tau_H\, n\,[k_G + k_A\nu] + k_G\tau'.$$

For the cooling periods one must substitute $\tau = \tau_H[n(1+\nu)+1] + \tau''$ and, instead of (10), we have now

$$\int_0^{\tau} k(\xi)\, d\xi = n\tau_H(k_G + k_A\nu) + k_G\tau_H + k_A\tau''.$$

After the completion of n full cycles, one must substitute

$$\tau = \tau_H(n+1)(\nu+1)$$

in (10) and, consequently, we have then

$$\int_0^{\tau} k(\xi)\, d\xi = \tau_H(k_G + k_A\nu)(n+1).$$

With (10) taken into account, (9) yields

$$\bar{u}(\tau) = \bar{u}_e + (u_{cr} - \bar{u}_e)\exp(-k_G\tau_\text{н} - \alpha_n - k_A\tau). \tag{12}$$

Inserting now (12) into (1), we obtain a first-order ordinary nonhomogeneous differential equation with variable coefficients. The solution to it which we have obtained under conditions (3)-(6) will not be shown here, owing to space limitations in this article. We will only note that calculations based on this solution are simple but rather lengthy, while the relations we will show here are adequate for computer calculations.

Simplification is possible by introducing the quantities W = const and k = const as the respective averages over the heating periods or the cooling periods. It becomes necessary then, however, to estimate the resulting error. Thus, the validity of calculations by either method can be assessed by comparing the temperatures of the material calculated, respectively, according to the solution to Eqs. (1)-(6) or according to the simpler expression with W = const and k = const [1, 2]. For an analysis of possible discrepancies between the results obtained by using different formulas, one must determine the desiccation factor k during heating and cooling, respectively, and then compare k_G and k_A so as to justify the assumption that k = const. This is also necessary for evaluating the mass-transfer rate during heating and during cooling. A measurement of the desiccation factor in the case of a cyclic process involves considerable difficulties, inasmuch as a desiccation curve must be plotted for each period. Since repeated heating and cooling cycles occur here, the respective periods being very short and usually varying from tens of seconds to a few minutes, hence it is obviously quite difficult in practice to obtain a desiccation curve for each period under such conditions. In order to determine the desiccation factor for a heat cycled fluidization bed by the method proposed here, one compares the temperatures of the material during heating and cooling which have been calculated theoretically for various values of k with those which have been measured. The coefficients k are then determined on the basis of matching temperature curves. In order to reduce the amount of computations and simplify the subsequent analysis, one may use the simpler relation based on W = const. The condition W = const must then be also observed during tests, and this is quite easy.

For the case W = const we may introduce the following dimensionless parameters:

$$T = \frac{t}{t_\text{н}},\quad \Theta = \frac{\vartheta}{t_\text{н}},\quad E = \frac{c_M}{r}t_\text{н},\quad \eta = \frac{Wt_\text{н}}{rG}\tau,\quad \bar{k} = k\frac{rG}{Wt_\text{н}}. \tag{13}$$

For convenience, the dash above $\bar{k}$ will henceforth be omitted. Inserting (13) into (1)-(4) and (6) with the following notation

$$a = \frac{cL}{c_M}(\bar{u}_{cr} - \bar{u}_e)\exp(k_G\eta_\text{н} - \alpha_n),\quad b = 1 + \frac{cL}{c_M}\bar{u}_e.$$

$$C = k_A(\bar{u}_{cr} - \bar{u}_e)\exp(k_G\eta_\text{н} - \alpha_n)$$

will yield

$$\frac{d\Theta(\eta)}{d\eta} + \frac{\Theta(\eta)}{E(b + ae^{-k_A\eta})} = \frac{T(\eta) - Ce^{-k_A\eta}}{E(b + ae^{-k_A\eta})}, \tag{14}$$

$$\Theta(\eta)|_{\eta=0} = \Theta_0. \tag{15}$$

In relations (2)-(4) and (6)-(8), (11) we have changed τ to η and k to $\bar{k}$.

For further convenience and without showing all intermediate steps, we write the solution to (14) under condition (15) separately for the periods of heating and cooling:

for the heating periods $\eta = n\eta_{cy} + \eta'$

$$\Theta_\text{н}(\eta) = \frac{1}{[a + b\exp(k_A\eta)]^s}\Big\{\Theta_0(a + b)^s + T_\text{н}\sum_{i=0}^{n-1}[(a + b\exp[k_A(i\eta_{cy} + \eta_\text{н})])^s$$

$$-(a + b\exp(k_A i\eta_{cy}))^s] + T_\text{н}[(a + b\exp(k_A\eta))^s - (a + b\exp(k_A n\eta_{cy}))^s]$$

$$+ T_0\sum_{i=0}^{n-1}[(a + b\exp[k_A\eta_{cy}(i + 1)])^s - (a + b\exp[k_A(i\eta_{cy} + \eta_\text{н})])^s] - \frac{C}{E}\int_0^\eta[a + b\exp(k_A\xi)]^{s-1}d\xi\Big\}. \tag{16}$$

and for the cooling periods $\eta = n\eta_{\mathrm{cy}} + \eta_{\mathrm{H}} + \eta''$

$$\Theta_0(\eta) = \frac{1}{[a + b\exp(k_{\mathrm{A}}\eta)]^s}\Big\{\Theta_0(a+b)^s + T_{\text{н}}\sum_{0}^{n}[(a + b\exp[k_{\text{в}}(n\eta_{\mathrm{cy}} + \eta_{\text{н}}))^s$$

$$- [a + b\exp(k_{\mathrm{A}}n\eta_{\mathrm{cy}})]^s + T_{\mathrm{C}}\sum_{i=0}^{n-1}[(a + b\exp[k_{\mathrm{A}}\eta_{\mathrm{cy}}(i+1)])^s$$

$$- (a + b\exp[k_{\mathrm{A}}(i\eta_{\mathrm{cy}} + \eta_{\text{н}})])^s] + T_{\mathrm{C}}[(a + b\exp(k_{\mathrm{A}}\eta))^s$$

$$- (a + b\exp[k_{\mathrm{A}}(n\eta_{\mathrm{cy}} + \eta_{\text{н}})])^s - \frac{C}{E}\int_{0}^{\eta}[a + b\exp(k_{\mathrm{A}}\xi)]^{s-1}d\xi\Big\}, \tag{17}$$

where $s = 1/bEk_{\mathrm{A}}$.

When calculating the temperature of the material for any period n, we change only those terms that contain the quantity η (i.e., for any one period we perform calculations with different values of η' and η'' only). With different values assigned to the desiccation factors k_{G} and k_{A}, therefore, it is possible to calculate the temperature of the material during each heating and each cooling period with W = const. If these values agree with test data, it becomes possible to determine the true values of the desiccation factors k_{G} and k_{A}. If now $k_{\mathrm{G}} \approx k_{\mathrm{A}}$, then one may assume that k = const and continue the calculation according to the simplified formulas.

If the desiccation process already begins with periodic heating and cooling, then the maximum allowable temperature of the product is reached only at the end of the process [3] at a moderate temperature of the heat carrier. Otherwise, the product will inevitably overheat. In this way, during the entire desiccation process the temperature of the product remains below the maximum allowable and this, naturally, reduces the dehydration rate. It is well known [4, 5] that the hygrodiffusivity a_{m} increases appreciably with rising temperature of the material and that, consequently, the desiccation process must be designed so as to occur entirely at a temperature as close as possible to the maximum allowable mean temperature for the product. This is achieved by preheating the product. Increasing the desiccation rate by preheating the product before other methods of desiccation are used has been discussed by several authors [6, 7, 8].

Preheating before cyclic desiccation means that the product is first heated up to its maximum allowable temperature by a heat carrier at a constant temperature, whereupon the product is periodically cooled and heated. In this case, instead of (3), we have now in terms of (13)

$$T(\eta) = \begin{cases} T_{\text{н}}, & 0 \leqslant \eta \leqslant \eta_{\text{н}}^{m}, \\ T_{\text{о}}, & \eta_{\text{н}}^{m} + \eta_{\text{н}}n(1+\nu) \leqslant \eta \leqslant \eta_{\text{н}}^{m} + \eta_{\text{н}}[n + (n+1)\nu], \\ T_{\text{н}}, & \eta_{\text{н}}^{m} + \eta_{\text{н}}[n + (n+1)\nu] \leqslant \eta \leqslant \eta_{\text{н}}^{m} + \eta_{\text{н}}(n+1)(\nu+1) \end{cases} \tag{18}$$
$$(n = 0,\ 1,\ 2,\ 3\ \ldots).$$

Here $\eta_{\mathrm{H}}^{\mathrm{m}}$ denotes the dimensionless heating time after which the product reaches its maximum allowable temperature at a constant temperature of the heat carrier.

We will continue the analysis of the desiccation process during its decreasing-rate period, considering only the case W = const and k = const.

With the following notation

$$b = 1 + \frac{c_{\mathrm{L}}}{c_{\mathrm{M}}}\bar{u}_{\mathrm{e}},\quad a = \frac{c_{\mathrm{L}}}{c_{\mathrm{M}}}(\bar{u}_{\mathrm{cr}} - \bar{u}_{\mathrm{e}}),\quad C = k(\bar{u}_{\mathrm{cr}} - \bar{u}_{\mathrm{e}}),$$

and with (13), Eqs. (1) and (2) yield an equation analogous to (14) with the following solution for conditions (18):

for any cooling period $\eta = \eta_{\mathrm{H}}^{\mathrm{m}} + n\eta_{\mathrm{cy}} + \eta'$

$$\Theta_{\mathrm{C}}(\eta) = \left(\frac{a+b}{a + b\exp(k\eta)}\right)^p\left[\Theta_0 + \frac{1}{(a+b)^p}\Big\{T_{\text{н}}[(a + b\exp(k\eta_{\text{н}}^{m}))^p\right.$$

$$-(a+b)^p+\sum_{1}^{n}[(a+b\exp[k(\eta_{H}^{m}+n\eta_{cy})])^p$$

$$-(a+b\exp[k(\eta_{H}^{m}+n\eta_{cy}-\eta_{H})])^p]]+T_{C}\sum_{i=0}^{n-1}[(a+b\exp[k(\eta_{H}^{m}$$

$$+i\eta_{cy}+\eta_{C})])^p-(a+b\exp[k(\eta_{H}^{m}+i\eta_{cy})])^p]$$

$$+T_{C}\left[(a+b\exp(k\eta))^p-(a+b\exp[k(\eta_{H}^{m}+n\eta_{cy})])^p-\frac{C}{E}\int_{0}^{\eta}(a+b\exp(k\xi))^{p-1}d\xi\}\right], \qquad (19)$$

and for any heating period $\eta = \eta_{H}^{m} + n\eta_{cy} + \eta_{C} + \eta'$

$$\Theta_{H}(\eta)=\left(\frac{a+b}{a+b\exp(k\eta)}\right)^p\left[\Theta_0+\frac{1}{(a+b)^p}\{T_{H}[(a+b\exp(k\eta_{H}^{m}))^p\right.$$

$$-(a+b)^p+\sum_{i=0}^{n-1}[(a+b\exp[k(\eta_{H}^{m}+(i+1)\eta_{cy})])^p$$

$$-(a+b\exp[k(\eta_{H}^{m}+i\eta_{cy}+\eta_{0})])^p]+(a+b\exp(k\eta))^p$$

$$-(a+b\exp[k(\eta-\eta')])^p]+T_{0}\sum_{0}^{n}[(a+b\exp[k(\eta-\eta')])^p$$

$$\left.-(a+b\exp[k(\eta_{H}^{m}+n\eta_{cy})])^p]-\frac{C}{E}\int_{0}^{\eta}(a+b\exp(k\xi))^{p-1}d\xi\}\right], \qquad (20)$$

where $p = 1/bkE$.

The temperature after the completion of n cycles is also calculated according to Eq. (20) with $\eta = \eta_{H}^{m} + (n+1)\eta_{cy}$.

The first three terms, the integral, and the coefficient before the brackets in (20) determine the temperature to which the material is heated by a heat carrier at a constant temperature. For a given maximum allowable temperature Θ_m with $W = \text{const}$, $k = \text{const}$, and $t = t_H = \text{const}$, Eqs. (1) and (2) yield an expression for η_{H}^{m} (with the notation according to (13)):

$$\eta_{H}^{m}=\frac{b'}{a'N^*}\left[1-\left(\frac{T_m-\Theta_m-N^*}{T_m-\Theta_0-N^*}\right)^{a'EN^*}\right], \qquad (21)$$

where

$$N^*=N\frac{rG}{Wt_{H}};\quad a'=\frac{c_L}{c_M};\quad b'=1+\frac{c_L}{c_M}u_0;\quad u_0=\bar{u}(\tau)|_{\tau=0}.$$

If the desiccation rate is constant during the preheating period, or if the decrease in the moisture content is negligible, then expression (21) can be simplified.

The main problem of desiccation with heat cycling is the proper selection of the operating mode in which the temperature of the material will fluctuate slightly about its maximum allowable level. The results of computer calculations based on formulas (19) and (20) are shown in Fig. 1. After preheating, according to the graph, desiccation can be made to proceed in such a way that the mean temperature of the product is approximately equal to the maximum allowable, with the subsequent heating period then generally not being equal to the cooling period (curve 6), however. Moreover, a certain time ratio t_H/t_C must then be maintained. Such a trend of the temperature curve is possible for such materials and such process modes where the evaporation zone does not deepen; otherwise, the cycling cannot be continued in the same mode throughout the process.

In other modes with preheating (curves 2-5) one notes a continuously rising temperature of the material, above the maximum allowable, but the rate of rise decreases as the ratio $\nu = \tau_C/\tau_H$ is increased (curves 2 and 4) and as the ratio t_C/t_H is decreased (curves 3 and 5). As ν is increased from 1 to 2, for

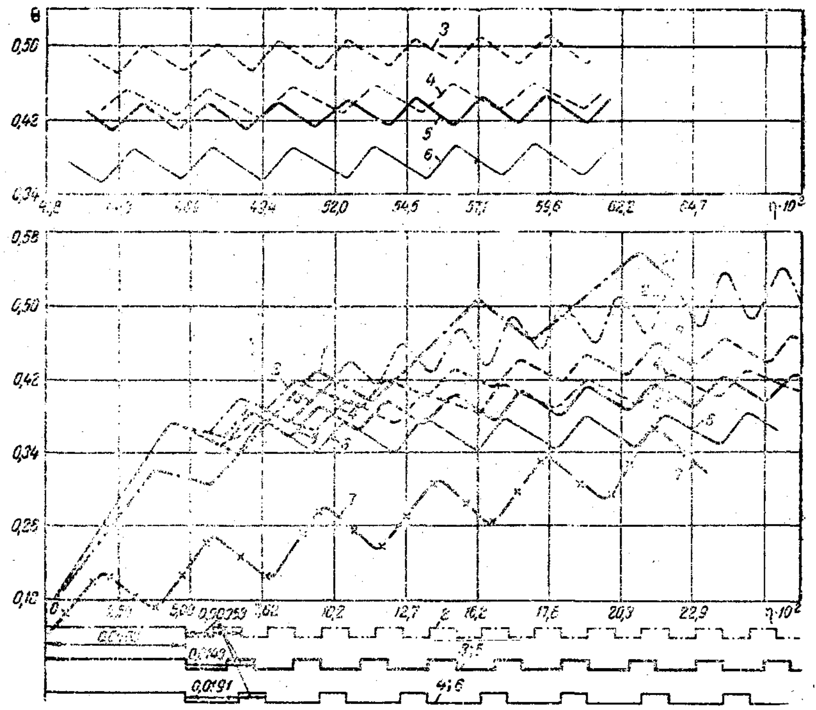

Fig. 1. Temperature of the material, as a function of time, during various cycling modes: 2-6) with preheating; 1, 7) without preheating; 1) $t_C = 36°C$, $\tau_H = 120$ sec, $\tau_C = 60$ sec, $\nu = 0.5$; 2) $t_C = 36°C$, $\tau_H = \tau_C = 30$ sec, $\nu = 1$; 3) $t_C = 36°C$, $\tau_H = 30$ sec, $\tau_C = 45$ sec, $\nu = 1.5$; 4) $t_C = 36°C$, $\tau_H = 30$ sec, $\tau_C = 60$ sec, $\nu = 2$; 5) $t_C = 20°C$, $\tau_H = 30$ sec, $\tau_C = 45$ sec, $\nu = 1.5$; 6) $t_C = 20°C$; $\tau_H = 30$ sec, $\tau_C = 60$ sec, $\nu = 2$; 7) $t_C = 36°C$, $\tau_H = \tau_C = 60$ sec, $\nu = 1$; on the bottom is shown the temperature of the heat carrier, as a function of time.

example, in the first case (curve 2, $\nu = 1$) the temperature of the material reaches $\Theta = 0.525$ (78.6°C) within the period $\eta = 0.221$ ($\tau = 11.5$ min, n = 9 cycles) or in the second case (curve 4, $\nu = 2$) it reaches $\Theta = 0.423$ (63.5°C) within $\eta = 0.219$ ($\tau = 11.5$ min, n = 6 cycles), the difference between both cases being quite appreciable. With other conditions remaining the same, decreasing the ratio t_C/t_H from 0.240 to 0.133 results in lowering the temperature from 0.458 (68.5°C, curve 3) to 0.416 (62.5°C, curve 5) within $\eta = 0.216$ ($\tau = 11.3$ min, n = 7 cycles).

Meanwhile, with an efficient design of the process (curve 6), the temperature of the material remains approximately constant and equal, for example, to $\Theta = 0.38$ (57°C) during the same period of time $\eta = 0.219$ ($\tau = 11.5$ min, n = 6 cycles), i.e., approximately equal to the temperature $\Theta = 0.373$ (56°C) reached by preheating.

During heat cycling without preheat, as has been mentioned earlier, the temperature of the material during a long process time will either exceed the maximum allowable (which is not permissible, curve 1) or remain far below it (which is not expedient, curve 7).

Thus, only a definite combination of ν and t_C/t_H will ensure a most efficient desiccation process. A higher cycling frequency, up to a definite limit, will result in only a smaller amplitude of temperature fluctuations in the material about the maximum allowable, which is quite desirable. An increase in the frequency is limited by the technical aspects of realizing such a process.

We note that the computer calculations and curves in Fig. 1 are based on the following values of the parameters: $\bar{u}_{cr} = 0.218$ kg/kg, $\bar{u}_e = 0.12$ kg/kg, $c_M = 0.37$ kcal/kg·deg, $\vartheta_C = 25°C$, $\bar{u}_C = 0.238$ kg/kg, $c_e = 0.25$ kcal/kg·deg, $t_H = 150°C$, bulk velocity of gases $v_G = 1.8$ m/sec, load density on the distributor grid $G/F = 340$ kgf/m², $k = 0.6$ g/h, and $r = 560$ kcal/kg.

NOTATION

c_M is the specific heat of the material;
c_L is the specific heat of the liquid;

G	is the amount of dry material in the apparatus;
k	is the desiccation factor;
N	is the desiccation rate during the constant-rate period;
r	is the heat of evaporation or the radius of a particle;
R	is the characteristic dimension of a particle;
t	is the temperature of the heat carrier;
u	is the moisture content in the material;
W	is the water equivalent;
ϑ	is the temperature of the material;
τ	is time.

Subscripts

A	denotes the air;
G	denotes the gas;
cr	denotes critical;
H	denotes heating;
C	denotes cooling;
e	denotes equilibrium;
cy	denotes cycle.

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