Journal of Engineering Physics and Thermophysics, Vol. 81, No. 6, 2008

CERTAIN REGULARITIES OF THE KINETICS OF MOISTURE AND HEAT EXCHANGE IN DRYING OF MOIST MATERIALS

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UDC 66.047.37

Methods of calculation of the kinetics of drying of moist materials for the period of the falling rate are considered; they are based on the characteristics of the kinetics of drying: the relative drying rate and the generalized and relative drying times.

The process of drying in the falling-rate period is an extremely complex process and is described by the drying and drying-rate curves and by the temperature curves. Its character is dependent on different factors, which makes it difficult to use analytical solutions for practical calculations. Therefore, in drying of different moist materials, researchers widely use experimental empirical dependences based on the most general regularities of the kinetics of the process. Among such methods are those of A. V. Luikov [1], V. V. Krasnikov [2], V. A. Danilov [2], and G. K. Filonenko [3].

In [4], on the basis of solution of the energy- and moisture-balance equation for the period of falling drying rate, we have obtained the dependences for the drying rate and the temperature curve:

$$\left|\frac{d\bar{u}}{d\tau}\right| = NN^* , \tag{1}$$

$$\frac{d\bar{t}}{d\tau} = \frac{r}{c} N \,\mathrm{Rb}\, N^* . \tag{2}$$

V. V. Krasnikov [2] gives Eq. (1) without derivation following the method of generalization of drying curves by the G. K. Filonenko method.

An analysis of numerous experimental data on drying of highly diverse materials by different methods has made it possible to introduce the following characteristics: generalized time $N\tau$ and relative drying rate N^* into the practice of drying; these characteristics are independent of the regime of drying and are just functions of the moisture content $\bar{u}$.

The second method of generalization of drying curves that has been proposed by V. A. Danilov [2] assumes that the quantity τ/τ_{tot}, where τ_{tot} is the total duration of the process of drying, is preserved for a given running $\bar{u}$ with constant initial $\bar{u}_0$ and critical $\bar{u}_{cr}$.

The heat-flux density for the period of falling drying rate can be described, with a sufficient degree of accuracy, as [4, 5]

$$q_{II} = q_I \exp(-m\tau) . \tag{3}$$

Expression (3) is conveniently represented in dimensionless form

$$q^* = \frac{q_{II}}{q_I} = \exp\left(-m\frac{\tau_{II}}{\tau_I}\right) = \exp(-m\tau^*) . \tag{4}$$

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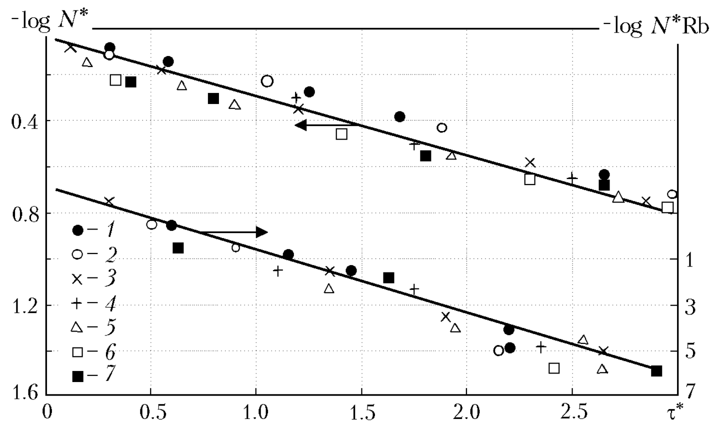

Fig. 1. Quantities log N^* and log N^*Rb vs. relative time τ^* in the process of convective drying of sole leather in the following regimes of drying: 1) t_{med} = 40, v = 5, and φ = 5, 2) 50, 5, and 5, 3) 60, 5, and 5, 4) 60, 3, and 15, 5) 60, 5, and 15, 6) 60, 10, and 15, and 7) 60°C, 15 m/sec, and 15%. δ = 4.5 mm.

Here, unlike the V. A. Danilov method, the dimensionless time τ^* is represented in the form of the ratio $\tau^* = \tau_{II}/\tau_I$, where τ_{II} is the running drying time in the second period, which is reckoned from zero, and τ_I is the drying time in the first period. It also preserves the properties of independence from the regime of drying and is a generalized variable. The method of generalization of drying curves yields that the generalized time $N\tau$ and the relative time τ^* are functions of the moisture content $\bar{u}$, i.e., $N^* = f_1(N\tau)$ and $N^* = f_2(\tau^*)$.

An analysis and processing of numerous experimental data on drying of different materials have shown that, whatever the technique of drying, the processing of results of experimental investigations is expediently sought in the form of two dependences [5, 6]:

$$N^* = \exp(-m\tau^*) , \tag{5}$$

$$N^* = \exp(-aN\tau) . \tag{6}$$

It is well known that, when kinetic drying curves are processed, especially if the drying-rate curves belong to the 2nd or 3rd types of curves according to the A. V. Luikov classification [1], we can use the power-law dependence for the drying rate (P. A. Zhuchkov method). Therefore, a generalized dependence of the type (5) can also be represented in the form of the power law

$$N^* = (N\tau)^{-k} , \tag{7}$$

where k is the constant characterizing the properties of the material.

The basic equation of the kinetics of drying of A. V. Luikov [1], which establishes the interrelation between the heat exchange q^* and the moisture exchange N^*, has the form

$$q^* = N^* (1 + \mathrm{Rb}) = N^* + N^*\mathrm{Rb} . \tag{8}$$

An analysis of numerous experimental data on drying of different materials has shown that the product of two generalized parameters N^*Rb can also be expressed by empirical relations analogous to expressions (5) and (6):

$$N^*\mathrm{Rb} = \frac{1}{N}\frac{d\bar{u}}{d\tau}\frac{c}{r}\frac{d\bar{t}}{d\bar{u}} = A \exp(-m\tau^*) , \tag{9}$$

$$N^*\mathrm{Rb} = B \exp(-aN\tau) . \tag{10}$$

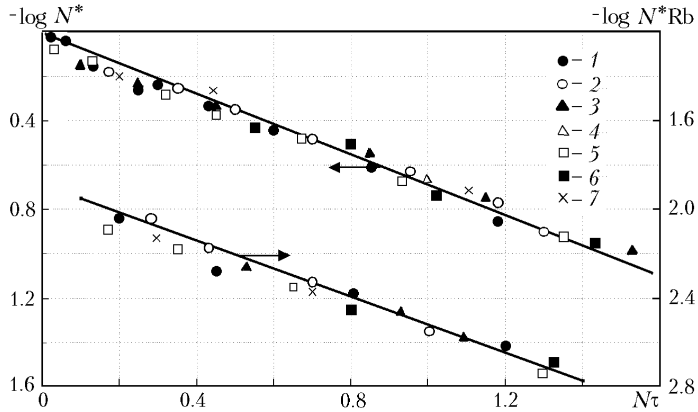

Fig. 2. Quantities $\log N^*$ and $\log N^*\text{Rb}$ vs. generalized time $N\tau$ in the process of convective drying of wool felt in the following regimes of drying: 1) $t_{med} = 90$, $v = 5$, and $\varphi = 5$, 2) 120, 5, and 5, 3) 150, 5, and 5, 4) 120, 3, and 5, 5) 120, 10, and 5, 6) 120, 15, and 5, and 7) 120°C, 20 m/sec, and 5%.

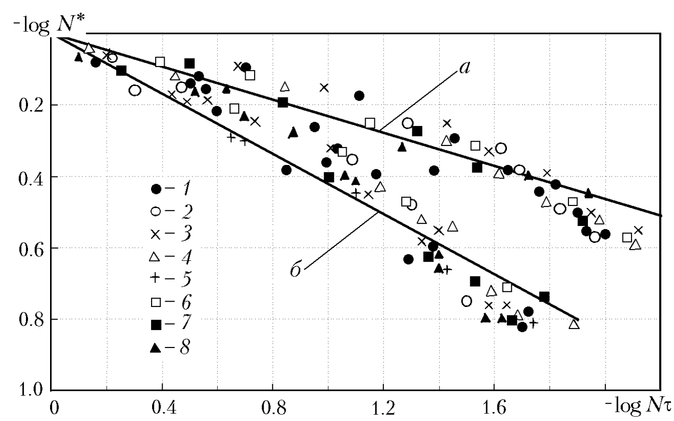

Fig. 3. Quantity $\log N^*$ vs. $\log N\tau$ for asbestos (a) and felt plate (b) in the process of convective drying: 1) $v = 3$ and $t_{med} = 120$, 2) 5 and 120, 3) 10 and 120, 4) 15 and 120, 5) 20 and 120, 6) 20 and 90, 7) 20 and 150, and 8) 10 m/sec and 150°C. $\delta = 6$ mm.

Figures 1 and 2 give the dependences $N^* = f(\tau^*)$, $N^*\text{Rb} = f(\tau^*)$, $N^* = f(N\tau)$, and $N^*\text{Rb} = f(N\tau)$ for drying under forced-convection conditions for sole leather and wool felt in a wide range of the regime parameters. Figure 3 gives the dependences $N^* = f(N\tau)$ calculated from Eq. (7) for felt and asbestos sheet in drying under forced-convection conditions.

Processing of our numerous experimental data and the use of many drying curves and temperature curves on drying of a diversity of capillary-porous colloidal materials in different methods of energy supply in a wide range of the regime parameters from [7–11] have made it possible to establish the dependences for determination of the constants a, m, and k appearing in Eqs. (5)–(7). The results of processing of the experiments are given in Table 1, whereas Figs. 4 and 5 give the dependences from which we have obtained equations for computations of a, m, and k:

$$a = \frac{8 \cdot 10^{-3}}{\bar{u}_{cr}}, \tag{11}$$

$$m = 0.67 \frac{\bar{u}_0}{\bar{u}_{cr}} - 0.35, \tag{12}$$

TABLE 1. Values of the Constants m, a, and k for Certain Materials

Material No.	Material	Regime of drying			δ, mm	m	a	k	Literature source	Kind of energy
		t_{med} °C	v, m/sec	φ, %						
1	Asbestos sheet	90—150	3—25	4	4—12	1.25	0.04	0.42	Data of the authors	Convective
2	Wool felt	90—150	3—25	5	8—18	0.6	0.012	0.22	The same	»
3	Sole leather	40—60	3—20	15	4.5	0.65	0.014	0.24	»	»
4	Cardboard	90—130	3—25	5	4.5	0.5	0.017	0.35	»	»
5	Porous ceramics	90—150	3—25	5	5—20	1	0.085	0.57	»	»
6	Clay	90—150	3—25	5	10—50	1	0.080	0.57	»	»
7	Peat slab	150	4	5	35	0.42	0.0016	0.2	»	»
8	Felt	50	0.5—1	24—75	2—3	1.9	0.025	—	»	»
9	Baker's yeast	40—70	2.9	24	—	0.25	0.004	0.1	[8]	Combined fluidized bed
10	Stem of grasses, ρv = 2.65 kg/(m^2·sec)	120—400	—	—	—	3—4	0.015	0.17	[9, 10]	Fluidized bed
11	Sunflower	100—160	2.2	—	—	0.18	0.03	—	[7]	Convective, radiative, combined
12	Bread	80—125	1.4—3.6	5—16	—	0.006	0.014	—	[7]	Convective
13	Pasta	36—45	2.3—8	50—65	—	0.37	0.03	—	[7]	»
14	Karagandinka wheat	50—90	0.1—1.5	5—25	—	0.03	0.025	—	[7]	Convective, blown-bed thickness 5–50 mm
15	Cut vegetables (beets, potatoes, and carrots) ρv = 6 kg/(m^2·sec)	90—220	—	—	—	0.04	0.002	—	[7, 11]	Fluidized bed
16	Microbiological mass (lysine). Filler-to-lysine ratio 1:1	100	2	—	15	0.4	—	0.38	Data of the authors	Convective
17	Carrots (thickness 10 mm)	80	5—10	5—10	10	0.04	0.002	—	the same	»

$$k = 0.2 + \frac{0.042}{\bar{u}_{cr}} . \tag{13}$$

For materials dried without a constant-rate period, the value of $\bar{u}_{cr}$ is replaced by $\bar{u}_0$. Thus, the constants a, m, and k are physically analogous to the relative drying coefficient χ which is also a function of the moisture content $\bar{u}$ and are dependent only on the properties of the material dried.

We write expressions (5), (6), and (7) in the form of the equations for the drying-rate curve:

$$-\frac{d\bar{u}}{d\tau} = N \exp\left(-m\frac{\tau_{II}}{\tau_I}\right), \tag{14}$$

$$-\frac{d\bar{u}}{d\tau} = N \exp(-aN\tau) , \tag{15}$$

$$-\frac{d\bar{u}}{d\tau} = N (N\tau)^{-k} . \tag{16}$$

Integration of Eqs. (14)–(16) for the period of decreasing drying rate between 0 and τ yields

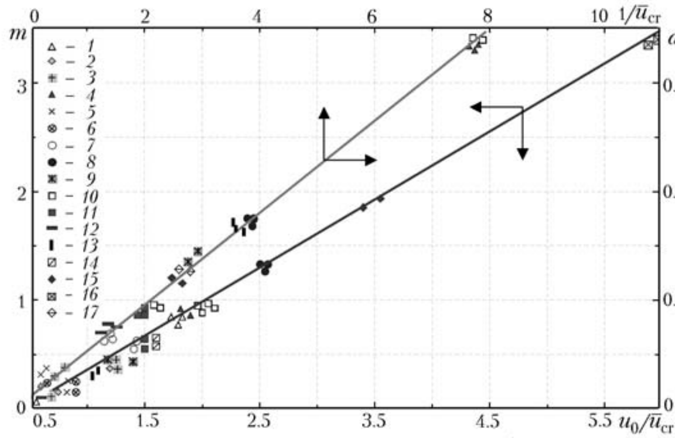

Fig. 4. Constants a and m vs. moisture content for different moist materials (curve Nos. 1–17 correspond to material Nos. in Table 1).

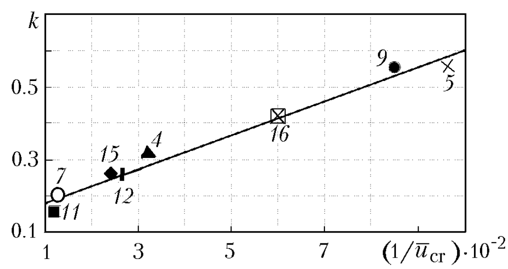

Fig. 5. Constant k vs. moisture content for different moist materials (curve numbers correspond to material numbers in Table 1).

$$\tau_{\text{II}} = -\frac{1}{m}\ln\left(1 - \frac{\left(\overline{u}_{\text{cr}} - \overline{u}\right) m}{N}\right), \tag{17}$$

$$\tau_{\text{II}} = -\frac{1}{aN}\ln\left(1 - a\left(\overline{u}_{\text{cr}} - \overline{u}\right)\right), \tag{18}$$

$$\tau_{\text{II}} = \left(\left(\frac{\overline{u}_{\text{cr}} - \overline{u}}{N^{1-k}}\right)(1-k)\right)^{\frac{1}{1-k}}. \tag{19}$$

The total duration of the process of drying from $\overline{u}_0$ to a prescribed running $\overline{u}$ is found as

$$\tau_{\text{tot}} = \frac{\overline{u}_0 - \overline{u}_{\text{cr}}}{N}\left(1 - \frac{1}{m}\ln\left(1 - m\,\frac{\overline{u}_{\text{cr}} - \overline{u}}{\overline{u}_0 - \overline{u}}\right)\right), \tag{20}$$

$$\tau_{\text{tot}} = \frac{1}{N}\left(\left(\overline{u}_0 - \overline{u}_{\text{cr}}\right) - \frac{1}{a}\ln\left(1 - a\left(\overline{u}_{\text{cr}} - \overline{u}\right)\right)\right), \tag{21}$$

$$\tau_{\text{tot}} = \frac{\overline{u}_0 - \overline{u}}{N} + \left(\left(\frac{\overline{u}_{\text{cr}} - \overline{u}}{N^{1-k}}\right)(1-k)\right)^{\frac{1}{1-k}}. \tag{22}$$

TABLE 2. Values of C and C' and n and n' in Eqs. (27) and (28) for v = 3–10 m/sec

Material	Regime of drying		C	$C' \cdot 10^3$	n	n'
	t_{med}, °C	φ, %				
Asbestos sheet	90—150	5	0.30	2.3	2	6
Sole leather	40—60	15	0.20	1	2	5
Porous ceramics	90—150	5	0.40	4	9	16
Wool felt	90—120	5	0.18	1.7	1.5	3

The equation for determining the temperature will be obtained from expressions (9) and (10), if they are written in the form

$$\frac{d\bar{t}}{d\tau} = N\frac{r}{c}N^*\text{Rb} = N\frac{r}{c}A\exp(-m\tau^*)\,, \tag{23}$$

$$\frac{d\bar{t}}{d\tau} = N\frac{r}{c}N^*\text{Rb} = N\frac{r}{c}B\exp(-aN\tau)\,. \tag{24}$$

The dependences (23) and (24) establish the interrelation between the heat exchange and the material's temperature in the period of decreasing drying rate for different values of the running moisture content $\bar{u}$. Their integration between $\bar{t}$ and t_{med} for the period of falling drying rate yields the equations of temperature curves

$$\bar{t} = t_{med} - \frac{Ar}{cm}\left(\bar{u}_0 - \bar{u}_{cr}\right)\exp(-m\tau^*)\,, \tag{25}$$

$$\bar{t} = t_{med} - \frac{Br}{ca}\exp(-aN\tau)\,. \tag{26}$$

The coefficients A and B characterizing the properties of a particular material are independent of the regime parameters of the process of drying and are calculated as

$$A = C\exp\left(n\left(\bar{u}_{cr} - \bar{u}\right)\right)\,, \tag{27}$$

$$B = C'\exp\left(-n'\left(\bar{u}_{cr} - \bar{u}\right)\right)\,. \tag{28}$$

The values of C and C' and n and n' for certain materials are given in Table 2.

Thus, the use of the above methods of generalization of the drying curves and temperature curves in different techniques of drying, as an analysis of experimental data for highly diverse materials shows, yields a good agreement of the calculated values of the drying time and the material's temperature from Eqs. (20)–(22) and (25) and (26) with experiment, if the critical moisture content $\bar{u}_{cr}$ is independent of the regime of drying. Investigations show that $\bar{u}_{cr}$ changes with regime only slightly for many materials and this change can be disregarded [1, 2, 5, 6].

We establish the interrelation between the heat-flux density, the temperature of the material, and the moisture content for the period of decreasing drying rate. The basic equation of the kinetics of drying (8) will be written in the form

$$q^* = N^* + N^*\text{Rb} = \exp(-m\tau^*) + A\exp(-m\tau^*) = (1 + A)\exp(-m\tau^*)\,, \tag{29}$$

$$q^* = N^* + N^*\text{Rb} = \exp(-aN\tau) + B\exp(-aN\tau) = (1 + B)\exp(-aN\tau)\,. \tag{30}$$

On the basis of Eqs. (25) and (26), we obtain

TABLE 3. Values of the Parameters c and n in Eq. (36)

Material	c	n
Wool felt	0.435	0.5
Asbestos	0.75	0.5
Peat slab	1.1	0.65
Sole leather	0.8	0.25
Porous ceramics	0.75	0.5

$$q^*(\tau) = (1 + A)\frac{\left(t_{\text{med}} - \bar{t}\right) cm}{\left(\bar{u}_0 - \bar{u}_{\text{cr}}\right) Ar}, \quad (31)$$

$$q^*(\tau) = (1 + B)\frac{\left(t_{\text{med}} - \bar{t}\right) ca}{Br}. \quad (32)$$

The interrelation established between the most important characteristics of the process of drying can be used in selecting the optimum regimes of drying and in developing energy-saving drying equipment and optimizing the drying process. To relate moisture exchange to heat exchange in the process of drying and to confirm the reliability of the equations obtained, we have carried out experimental investigations on the basis of criterial heat-exchange equations.

The heat-flux density in the period of constant drying rate is

$$q_{\text{I}} = r\rho_0 R_V N, \quad (33)$$

and that in the period of falling rate is

$$q_{\text{II}} = \bar{\alpha}\,(t_{\text{med}} - t_{\text{II}}). \quad (34)$$

The heat-exchange coefficient $\bar{\alpha}$ in the second period of drying decreases, gradually approaching the heat-exchange coefficient of a dry body.

From the results of processing of experimental data on heat exchange for the process of convective drying [12], we obtain the ratio

$$\frac{\bar{\alpha}}{\bar{\alpha}_{\text{cr}}} = \left(\frac{\bar{u}}{\bar{u}_{\text{cr}}}\right)^n = (1 + \text{Rb})\,N^{*0.57}. \quad (35)$$

The intensity of heat exchange for the decreasing-rate period is determined from the criterial equation [12]

$$\text{Nu} = c\,\text{Re}^{p_0}\left(\frac{T_{\text{med}}}{T_{\text{w}}}\right)^{m_0}\left(\frac{\bar{u}}{\bar{u}_{\text{cr}}}\right)^n. \quad (36)$$

The exponent for convective drying is independent of the kind of material dried and is equal to $m_0 = 2$; the exponent of the Reynolds number is $p_0 = 0.5$. Table 3 gives the values of the parameters appearing in Eq. (36) for certain materials [12].

In developing and creating drying equipment with allowance for the recent energy-saving technologies, determination of the output of dryers is also an important problem. In [13], on the basis of simultaneous solution of the heat-exchange, heat-balance, and moisture-balance equations, an equation determining the evaporated-moisture output of dryers has been obtained:

$$W = \eta\,\frac{M_{\text{air}}c_p}{r}\,(T_1 - T_2)\,[1 + (1 + \text{Rb})\,N^*]. \quad (37)$$

TABLE 4. Comparison of the Calculated Parameters of the Process of Drying to Experimental Data

Regime of drying													
$\bar{u}$	Rb	N^*_{exp}	τ_{exp}, min	τ_{cal}, min		$\bar{t}_{exp}$, °C	t_{cal}, °C		q*			
				(20)	(21)		(25)	(26)	(8)	(31)	(32)	(4)
*Sole leather**												
0.45	0.069	0.56	11	11.3	10	31.5	29.5	32	0.591	0.57	0.597	0.51
0.36	0.079	0.44	17	16	18	37	38.2	39	0.478	0.53	0.48	0.41
0.27	0.092	0.36	22	19	22	41	42.5	40.5	0.39	0.31	0.29	0.22
0.24	0.120	0.24	27	24	25.7	45	44	44	0.272	0.23	0.24	0.19
*Asbestos sheet***												
0.16	0.053	0.73	11	10.8	11.5	44.5	43.5	45	0.73	0.72	0.657	0.641
0.12	0.112	0.57	13	13.1	12.7	49	51	50	0.65	0.615	0.6	0.55
0.1	0.145	0.46	15	14.1	14.5	55	53.5	54	0.46	0.467	0.53	0.46
0.08	0.173	0.35	16.5	16.8	18	64	60.3	61.5	0.37	0.39	0.43	0.39
0.06	0.210	0.25	18.5	17.7	19	73	69.5	69.5	0.29	0.29	0.33	0.29
*Porous ceramics****												
0.08	0.23	0.68	6	5.9	5.6	62	61	63	0.836	0.94	0.94	0.85
0.06	0.24	0.48	8	6.9	7.1	74	75	73	0.595	0.65	0.69	0.61
0.04	0.29	0.29	10	8.7	9.1	83	84	81	0.374	0.41	0.51	0.5
0.03	0.34	0.22	11	9.8	10.3	91	89	92	0.295	0.36	0.38	0.4

*t_{med} = 60°C, φ = 5%, v = 3 m/sec, $\bar{u}_{cr}$ = 0.55, $\bar{u}_0$ = 0.86, and ρ_0 = 650 kg/m^3;

**t_{med} = 120°C, φ = 5%, v = 5 m/sec, $\bar{u}_{cr}$ = 0.2, $\bar{u}_0$ = 0.46, and ρ_0 = 770 kg/m^3;

***t_{med} = 120°C, φ = 5%, v = 5 m/sec, $\bar{u}_{cr}$ = 0.11, and $\bar{u}_0$ = 0.2.

Substituting relations (5), (6), (9), and (10) into Eq. (37), we obtain

$$W = \eta \frac{M_{air} c_p}{r} (T_1 - T_2) \left[1 + \exp(-m\tau^*) (1 + A)\right] , \quad (38)$$

$$W = \eta \frac{M_{air} c_p}{r} (T_1 - T_2) \left[1 + \exp(-aN\tau) (1 + B)\right] . \quad (39)$$

Equations (38) and (39) relate both the external parameters of the process of drying (M_{air}, c_p, T_1, and T_2) and the internal parameters (N, τ, m, and a) for a particular dryer.

A comparison of the calculated data obtained from formulas (4), (8), (20), (21), (31), and (32) to experiment for certain materials is given in Table 4, from which it follows that the accuracy of the above methods is virtually identical; the disagreement between the calculations from the formulas and experiment is no higher than 7–10%, except for the small portions of the curves for moisture contents close to equilibrium u_{eq}. These results confirm the fact that the drying curves and the temperature curves are more accurately described by two adjoint parts of the exponents by the V. V. Krasnikov method [2].

Thus, when the considered methods of calculation of the kinetics of drying are used, there is no need to construct the drying-rate curve and to carry out numerous experiments on drying in different regimes. The drying rate in the first period N for a particular regime can be obtained by constructing a triangle with the vertex at the point $\bar{u}_0$, with the base $\tau > 0$, and the ordinate $(\bar{u}_0 - \bar{u})$, where the running moisture content corresponds to a given time τ.

NOTATION

A, B, a, and m, constants determined experimentally; c and c_p, specific heat of a moist material and air, kJ/(kg·°C); $d\bar{u}/d\tau$, drying rate in the second period; $dt/d\tau$, rate of change in the temperature of the material; M_{air}, mass flow rate of air, kg/sec; m_0 and p_0, exponents; N, drying rate in the first period, 1/sec; N^*, relative drying rate; N^*_{exp}, relative drying rate determined experimentally; q_I and q_{II}, heat-flux densities in the first and second periods, W/m^2; q^*, relative heat flux; R_V, ratio of the volume of a perfectly dry body to the surface area, m; Rb, Rehbinder number; Re, Reynolds number; r, heat of vaporization, kJ/kg; T_1 and T_2, temperatures of the heat-transfer agent at entry and exit from the dryer; $\bar{t}$, volume-average temperature of the material, °C; t_{cal}, temperature of the material, calculated from the formulas, °C; $\bar{u}$, moisture content of the material, kg/kg; $\bar{u}_{cr}$ and $\bar{u}_0$, critical and initial moisture content of the material, kg/kg; v, air velocity, m/sec; $\bar{\alpha}$ and $\bar{\alpha}_{cr}$, heat-exchange coefficients in the period of falling and constant drying rate, W/(m^2·°C); δ, thickness of the material, mm; η, efficiency of the dryer; ρ_0, density of a perfectly dry body, kg/m^3; τ, drying time, min; τ_I and τ_{II}, drying time in the first and second periods, min; τ^*, relative drying time; τ_{tot}, total duration of the process of drying; τ_{cal} and τ_{exp}, drying time calculated from the formulas and determined experimentally, min; φ, relative humidity of air. Subscripts: cr, critical; w, wet; surf, surface; med, medium; 0, initial state; air, air; exp, experimental; cal, calculated; V, volume; p, pressure; tot, total.

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