The dependence (2) for isoamylbutyrate is shown in Fig. 1. As is seen from the figure, a slight stratification in the isotherms generalizing the dependence is observed. It is insignificant at low temperatures. It should be noted that such stratification is observed quite rarely for organic fluids.

Processing was conducted for ρ = 772.7-558.2 kg/m^3 and $\Delta\lambda$ from 0.028 to 0.083 W/(m·deg).

The equation of the generalizing curve has the form

$$\Delta\lambda = b_0 + b_1\rho + b_2\rho^2, \tag{3}$$

where $b_0 = 0.277$; $b_1 = -0.00092$; $b_2 = 86 \cdot 10^{-8}$.

We can calculate λ_T at different temperatures and pressures by using (3) for known ρ and λ with a 3% error in the range of ρ mentioned.

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SOME FEATURES OF HEAT AND MOISTURE TRANSFER AND APPROXIMATE METHODS OF CALCULATING THE DRYING KINETICS OF MOIST MATERIALS

P. S. Kuts and A. I. Ol'shanskii

UDC 66.047.37

Approximate methods of calculating the drying kinetics of moist materials, derived from an analysis of experimental data, are discussed.

Drying is a complex heat- and mass-transfer process taking place within a material and close to its surface. The nature of the drying process depends on the thermophysical, physicochemical, and structural-mechanical properties of the material, the method of supplying power, and so on. The relationships between internal and external heat and mass transfer are so complex that the obtaining of analytical relationships for the drying kinetics of a specific material presents great difficulties.

Hence, the possibility of obtaining approximate, sufficiently reliable relations with a minimum number of constants to be experimentally determined is of great interest for drying calculations in engineering. The most advanced methods are those based on a study of the general laws of drying kinetics and the correlation of a large amount of experimental data [1-3].

We examine some features of the drying process and approximate methods of calculating heat-transfer kinetics on the basis of an analysis of experiments on the drying of a whole series of capillary-porous and colloidal capillary-porous materials to which heat is supplied in various ways.

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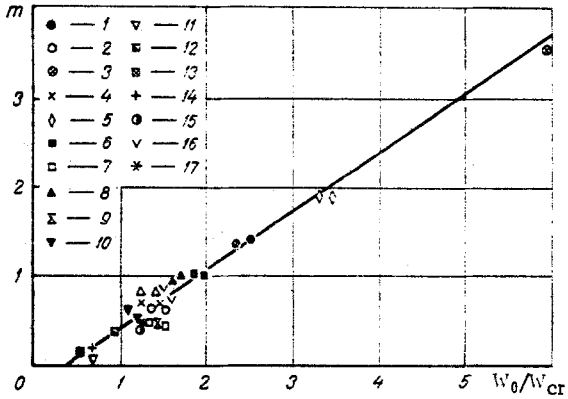

Fig. 1. Determination of constant m in Eq. (5): 1) asbestos; 2) felt-matting; 3) grass stalks; 4) skin; 5) felt; 6) ceramic; 7) cardboard; 8) clay; 9) slab peat; 10) baker's yeast; 11) carrot; 12) sunflower; 13) potato; 14) beetroot; 15) cement stone; 16) macaroni; 17) lysin.

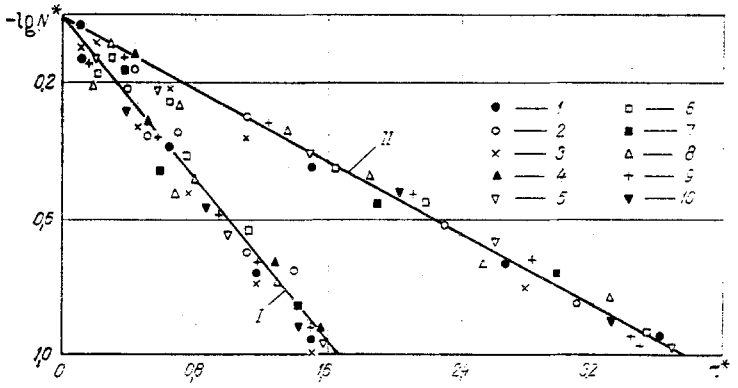

Fig. 2. Plot of log N* against τ* during forced-convection drying of asbestos (I) and felt-matting (II) sheets: 1) t_a = 90°C; 2) t_a = 120°C; 3) t_a = 150°C (v = 5 m/sec, φ = 5%, δ = 8 mm); 4) v = 3 m/sec; 5) v = 10 m/sec; 6) v = 15 m/sec; 7) v = 20 m/sec; 8) v = 25 m/sec (t_a = 120°C, φ = 5%, δ = 8 mm); 9) δ = 6 mm; 10) δ = 12 and 18 mm (t_a = 120°C, v = 3 m/sec, φ = 5%).

An examination of theoretical data [2] showed that the variation in time of the rate of heat transfer in the period of falling rate of drying can be represented sufficiently accurately by the exponential relation

$$q_{II} = q_I \exp(-m_1 \tau_{II}), \tag{1}$$

where τ_{II} is the drying time in the second period, counted from zero.

If the ratio of the heat fluxes in the periods of falling and constant drying rate is denoted by q* and the ratio of the drying times in these periods by τ*, expression (1) can be written in dimensionless form

$$q^*_{(\tau)} = \frac{q_{II}}{q_I} = \exp\left(-m\,\frac{\tau_{II}}{\tau_I}\right) = \exp(-m\tau^*), \tag{2}$$

where m_1 and m are constants that can be determined by experiment.

On the other hand, the main equation of drying kinetics, expressing the relationship between the heat flux q* and moisture flux N*, has the following form:

$$q^*_{(\tau)} = \frac{q_{II}}{q_I} = N^*(1 + \mathrm{Rb}). \tag{3}$$

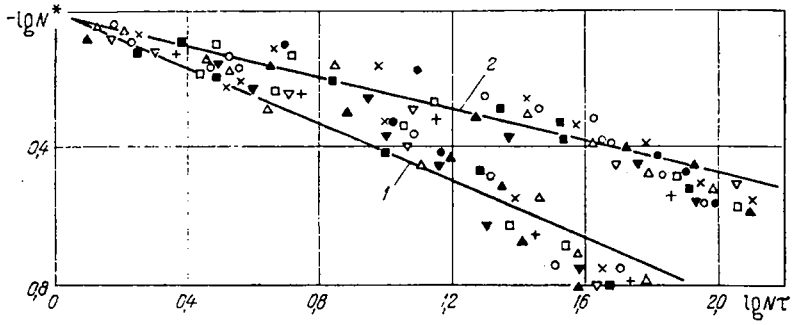

Fig. 3. Relation between log N* and log Nτ, % for asbestos (1) and felt during convective drying (notation as in Fig. 2).

From expressions (2) and (3) we have

$$N^*(1 + \mathrm{Rb}) = \exp(-m\tau^*). \tag{4}$$

The Rebinder numbers for many capillary-porous materials in a large range of moisture contents assume values of 0.01 to 0.3, and the maximum values (0.2-0.3) correspond to the end of the drying process (i.e., to moisture contents close to the equilibrium values) [4]. If we ignore Rb when it has low values, we obtain

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

Treatment of experimental data for the drying of various materials in the form of the relation log N* = f(τ*) showed that the experimental points lie satisfactorily on straight lines in the whole range of regime parameters (t_a, φ, v) and thickness of the material. The constant m in Eq. (5) is a linear function of the ratio of the moisture contents (W_0/W_{cr}) for the whole class of considered moist materials (Fig. 1):

$$m = 0.67\,\frac{W_0}{W_{cr}} - 0.35. \tag{6}$$

Relation (6) is obtained in the range $2 \le v \le 5$; $90 \le t \le 150$°C. Thus, Eq. (5) contains a constant m similar in meaning to the relative drying coefficient $\varkappa$.

Figure 2 shows the relationship between log N* and τ* for asbestos and felt sheets in forced-convection drying; all the experimental points lie on straight lines in the whole range of variation of the regime parameters.

For materials whose drying occurs only in the falling-rate period (carrot, beetroot, potato), we treated the experimental data in the form of the relation

$$N^* = \exp(-m\tau^*). \tag{7}$$

In this case the constant m has the dimensions of 1/time unit.

We find the drying rate in the second period from Eq. (5):

$$-\frac{dW}{d\tau} = N\exp(-m\tau^*). \tag{8}$$

Integration of this expression in the prescribed limits gives

$$-(W_{cr} - W) = N\,\frac{\tau_I}{m}\left[\exp\left(\frac{m}{\tau_I}\,\tau_{II}\right) - 1\right]. \tag{9}$$

After simple algebra we obtain the drying time in the falling-rate period:

$$\tau_{II} = -\frac{2.3\tau_I}{m}\,\lg\left[1 - \frac{(W_{cr} - W)\,m}{N\tau_I}\right]. \tag{10}$$

Including the drying time in the first period

$$\tau_I = \frac{W_0 - W_{cr}}{N} \tag{11}$$

the total duration of the process is

TABLE 1. Constants m and k in Eqs. (13) and (23) for Some Moist Materials

Material	Drying conditions			δ, mm	m	k	Limit validity of Eq. (23)	Reference	Energy supply
	T, °C	v, m/sec	φ, %						
Asbestos	90—150	3—25	5	4—12	1,4	0,42	2	Our data	Convective
Felt-matting	90—150	3—25	5	8—18	0,6	0,22	10	The same	The same
Skin of sole	40—60	3—20	15	4,5	0,65	0 24	15	"	"
Cardboard	90—130	3—25	5	4,5	0,5	0,35	10	"	"
Porous ceramic	90—150	3—25	5	5—20	1	0,57	2	"	"
Clay	90—150	3—25	5	10—50	1	0,57	2	"	"
Slab peat	150	4	5	35	0,42	0,2	20	"	"
Felt	50	0,5—0,7	24—75	2—3	1,9	—	—		
Baker's yeast	40—70	2,9	24	—	0,25	0,1	5	[9]	Combined
Grass stalks. ρv = 2,65 kg/(m²·sec)	120—400	—	—	—	3,5	0,17	5	[7]	Fluidized bed
Sunflower	100—160	2,2	—	—	0,18	—	—	[10]	Convective, combined, radiative
Microbial mass (lysin) Ratio of filler to lysin 1:1	100	2	—	15	0,4	0,38	—	Our data	Convective

$$\tau = \tau_I + \tau_{II} = \frac{W_0 - W_{cr}}{N} - \frac{2.3(W_0 - W_{cr})}{Nm} \lg\left[1 - \frac{(W_{cr} - W)\,m}{(W_0 - W_{cr})}\right] \tag{12}$$

or, finally,

$$\tau = \frac{W_0 - W_{cr}}{N}\left\{1 - \frac{2.3}{m} \lg\left[1 - \frac{(W_{cr} - W)\,m}{(W_0 - W_{cr})}\right]\right\}, \tag{13}$$

where W is the instantaneous moisture content of the material.

For materials which do not have a period of constant drying rate, the duration of the process is given by integration of Eq. (7):

$$\tau = -\frac{2.3}{m} \lg\left[1 - \frac{(W_0 - W)\,m}{N}\right], \tag{14}$$

where $N = (dW/d\tau)_{max}$ is the maximum drying rate at the initial instant. A comparison of the calculated data obtained by correlation of the experimental data by means of Eqs. (4) and (5) showed that the constant m is practically independent of the Rebinder number up to values of 0.2-0.3. The only effect is a reduction of the spread of the experimental points, i.e., an increase in the accuracy of the calculations.

In rapid drying processes in "hard" conditions, where the Rebinder number cannot be neglected, the total duration of the process is given by the expression

$$\tau = \frac{W_0 - W_{cr}}{N}\left\{1 - \frac{2.3}{m_0} \lg\left[1 - \frac{(W_{cr} - W)\,m}{(W_0 - W_{cr})}(1 + Rb)\right]\right\}. \tag{15}$$

An important problem of drying kinetics is determination of the temperature of the material at different times. Establishment of the variation of temperature of the material with time is of great practical importance, particularly in the case of drying, since the main technological properties of a material depend on its temperature and the time of subjection to this temperature.

An analysis of experimental data [4] for the drying of various capillary-porous materials led to a simple relation for the surface temperature of the material:

$$T_{sur} = T_a - N^{*0.43}(T_a - T_w). \tag{16}$$

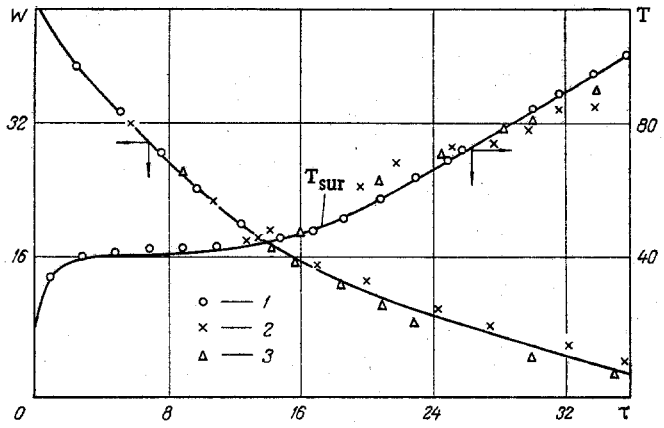

Fig. 4. Comparison of experimental and calculated values of drying time and surface temperature of material during drying of an asbestos plate in the following conditions: $T_a = 120°C$, v = 3 m/sec, $\varphi = 5\%$ [1) experimental points; 2) calculated from Eqs. (13) and (17); 3) from Eqs. (23) and (24)]. W, %; T, °C; τ, min.

If we substitute the value of N* from expressions (5) in (16), we obtain for convective drying

$$T_{sur} = T_a - \exp(-0.43m\tau^*)(T_a - T_w). \quad (17)$$

Thus, for a known value of m we can fairly simply determine the surface temperature of the material from Eq. (17).

We now discuss another method of treating the experimental data, based on the use of the relative drying rate N* and the "generalized drying time" $N\tau$.

The quantity N* is independent of the drying conditions and for a specific material is a function of the moisture content alone for a particular method of drying. This conclusion is derived from G. K. Filonenko's method of reduced drying curves.

The variable $N\tau$ is a stable complex of quantities characterizing the drying process [2].

The method of generalized drying curves enables us to extend the results of a single specific experiment to a large number of cases, corresponding to various regimes, which greatly reduces the number of experiments and allows the results of laboratory research to be applied to industrial plant.

It follows from the method of generalized drying curves that the generalized time $N\tau$, like the relative drying rate N*, is a function of the moisture content, i.e., we can write $N^* = f(W)$, $N\tau = f(W)$ and, hence, $N^* = f_1(N\tau)$.

We know that the kinetic drying curves can be correlated [5] by the use of a power relationship between the drying rate and the moisture content in the second period:

$$-\frac{dW}{d\tau} = \varkappa' N (W - W_e)^n. \quad (18)$$

A test showed that the constant n is independent of the regime parameters and the thickness of the material and depends only on the mode of moisture binding [6]. Hence, if the drying rate curves are of the 2nd and 3rd types, according to Lykov's classification [1], the relationship $N^* = f_1(N\tau)$ should be sought in the form

$$N^* = (N\tau)^k. \quad (19)$$

Figure 3 shows the relationship between the relative drying rate N* and the generalized time $N\tau$ in logarithmic coordinates for felt-matting and absestos in forced-convection drying. It is apparent that changes in the regime parameters and the thickness of the material in a wide range have no effect on the index k, which is negative. The results of treatment of experimental data for some moist materials to which energy was supplied in various ways are given in Table 1.

The drying rate from expression (19), with due regard to the sign of the index k, is

$$-\frac{dW}{d\tau} = N(N\tau)^{-k}. \quad (20)$$

Integration of Eq. (20) in prescribed limits gives the drying time in the falling-rate period:

$$\tau_{II} = \left[\frac{(W_{cr} - W)(1-k)}{N^{1-k}}\right]^{\frac{1}{1-k}}. \quad (21)$$

The total duration of the drying process is

$$\tau = \frac{W_0 - W_{cr}}{N} + \left[\frac{(W_{cr} - W)(1-k)}{N^{1-k}}\right]^{\frac{1}{1-k}}, \quad (22)$$

and we finally obtain

$$\tau = \frac{1}{N}\{(W_0 - W_{cr}) + [(W_{cr} - W)(1-k)]^{\frac{1}{1-k}}\}. \quad (23)$$

A comparison of the experimental values of the drying time with the calculated values obtained from Eqs. (13) and (23) shows that the accuracy of these methods is approximately the same, apart from a small region of the drying curve at a moisture content close to the equilibrium value, where Eq. (23) is inapplicable. This indicates that a power-law relation of form (19) cannot completely cover the drying curve in the second period. As is known, the drying curve in the second period is more accurately represented by two exponential portions [2]. In a number of cases, however, where the drying process terminates before the attainment of W_e, the given method of calculation can be used. There is a slight restriction on Eq. (14) only in the case of vegetable drying. Table 1 shows values of the constants m and k and the limits of validity of Eqs. (14) and (23).

From Eqs. (16) and (19) we can obtain another form of expression for the surface temperature of the material:

$$T_{sur} = T_a - (N\tau)^{-0.43}(T_a - T_w). \quad (24)$$

Equations (17) and (24) for very rapid drying processes have to include the effect of change of the Rebinder number in the process.

The results of calculation from the above relations can be checked from experimental curves. Figure 4 compares the calculated and experimental values. The maximum error in calculation of the drying time and temperature of the material, excluding the effect of the Rebinder number in soft conditions, is 7-10% and 10-15%, respectively, which is permissible in engineering calculations.

The obtained relations are required for determination of the quantitative characteristics of the drying process (drying time, heat-transfer rate, temperature of material).

With the given methods, like the method in [2], the duration of the process and the temperature of the material in any conditions can be calculated from a single drying curve if the rate N in the first period is known.

In conclusion, it should be noted that the discussed methods of treating the experimental data can be derived directly from the known methods of correlation devised by A. V. Lykov and V. V. Krasnikov.

NOTATION

q_{II}, q_I, heat-transfer rates in periods of falling and constant drying rate; τ, instantaneous time; q^*, dimensionless heat-flux density, equal to ratio of heat flux in falling-rate period to heat-flux density in constant-rate period; $\tau^* = \tau_{II}/\tau_I$, ratio of drying time in falling-rate period to drying time in constant-rate period; $N^* = (1/N)(dW/d\tau)$, relative drying rate in falling-rate period; W, instantaneous moisture content; Rb, Rebinder number; N, drying rate in first period; m, n, k, experimental constants; T_a, ambient temperature; T_w, wet-bulb temperature; T_{sur}, surface temperature of material; $N\tau$, generalized drying time; W_{cr}, first critical moisture content; W_0, initial moisture content of material; $dW/d\tau$, drying rate in second period; $\varkappa$, relative drying coefficient; W_e, equilibrium moisture content of material.

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CERTAIN LAWS APPLICABLE TO THE VACUUM DRYING OF ELECTRICAL INSULATION ELEMENTS IN AN INERT HEAT-TRANSFER VAPOR

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Results are given from an experimental study of the heating and drying kinetics of model laminated samples of electrical insulation in petroleum-product vapor.

One of the most progressive and least studied methods for the drying of insulation used in high-voltage electrical equipment (transformers in particular) is the so-called method of vacuum drying in a "vapor phase" atmosphere, i.e., in the vapor of an inert heat-transfer agent (for example, a petroleum product) whose physicochemical and technological properties are compatible with those of insulating materials and liquid impregnating dielectrics [1, 2].

We have carried out an experimental investigation of the vacuum drying of laminated insulation elements in an inert heat-transfer vapor, using a specially designed test stand, the details of which are described in [2]. The investigated objects are cylindrical model samples made from rolled-up type K-120 cable paper with moisture-insulated ends, simulating the most difficult-to-dry elements of electrical insulation structures. The samples are prepared by means of a special device that rolls paper strip of width 160 mm tightly around metal rods with a diameter of 16 mm. For moisture insulation the ends of the cylinder and the free ends of the paper strip in the model samples are coated with an epoxy compound, and then the ends of the cylinder are further packed with bushings of gasoline-resistant rubber by means of a four-bolt clamping mechanism. During fabrication of the model samples the electrodes of a copper — Constantan thermocouple and internal pressure gauges in the form of hypodermic needles connected via thin impulse tubes to the vacuometric system are inserted at one end between the layers of cable paper at various points along the radius. Also, the model samples are fitted with the brass mesh electrodes of local measuring capacitors designed for determining the layer-by-layer values of the dielectric characteristics of the cable paper as they vary during the experiment (these measurements are performed only in the final stage of vacuum drying of the insulation). The testing and measuring equipment and experimental procedure are described in [2]. The thicknesses of the laminated insulation of the model samples are 20, 30, and 40 mm. A typical cyclic schedule of the experiments is planned with regard for the actual technological process of insulation drying in an inert heat-transfer vapor and comprises the following:

a) heating and drying of the (pre-evacuated) samples in petroleum-product vapor for prescribed and strictly regulated regime parameters (temperature level of the process, pressure in the working chamber,

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