KINETICS OF DRYING OF VARIOUS MATERIALS AND CALCULATION OF THE DURATION OF DRYING

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Inzhenerno-Fizicheskii Zhurnal, Vol. 11, No. 4, pp. 482–486, 1966

UDC 66.047

This paper deals with methods of combining the drying curves obtained in different conditions into a single curve, the analysis of the kinetics of the process, and methods of calculating the duration of drying of materials. The proposed method of calculation is a development of Lykov's method.

The drying of many materials takes place in the periods of constant and falling drying rate (the heating period is not considered).

The experimental curves of the kinetics of drying of a specific material under various conditions by a particular method and with the same initial moisture content form a family of curves.

The equation of the drying curve in the first period has the form

$$\bar{u} = \bar{u}_i - N\tau. \tag{1}$$

In Eq. (1) the moisture content can vary in the range

$$\bar{u}_i \geqslant \bar{u} \geqslant \bar{u}_{cr1}.$$

The second drying period begins in all conditions at u_{cr1} and time τ_1, which is equal to the duration of the first drying period and can be taken as the time origin for the second period.

As we know from [1], the drying curve in the second period, plotted in the semilogarithmic coordinates $\lg(\bar{u} - \bar{u}_e)$ and τ, is either a straight line or a line composed of two (or occasionally three) straight portions, which indicates the existence of two (or three) parts in the second period. These straight portions intersect at points corresponding to the critical moisture contents u_{cr2} (and u_{cr3}), which are easily found from the drying curve in semilogarithmic coordinates. The equations of these straight portions are:

For the first part of the second period

$$\lg(\bar{u} - \bar{u}_e) = \lg(\bar{u}_{cr1} - \bar{u}_e) - K_1\tau \tag{2}$$

(here the moisture content lies in the range $\bar{u}_{cr1} \geq \bar{u} \geq u_{cr2}$, and the time τ is measured from the onset of reduction in moisture content in the first part of the second period);

for the second part of the second period

$$\lg(\bar{u} - \bar{u}_e) = \lg(\bar{u}_{cr2} - \bar{u}_e) - K_2\tau \tag{3}$$

(here the moisture content lies in the range $\bar{u}_{cr2} \geq \bar{u} \geq u_{fin}$, and the time τ is measured from the onset of reduction in moisture content in the second part of the second period).

If the second period consists of three parts, the equation of the third part of the second period will be similar to Eq. (3), but with K_3 and $\bar{u}_{cr3}$.

Hence, the curve in the second period is represented by two (three) exponential parts:

$$(\bar{u} - \bar{u}_e) = (\bar{u}_{cr1} - \bar{u}_e)\exp(-2.3K_1\tau), \tag{4}$$

$$(\bar{u} - \bar{u}_e) = (\bar{u}_{cr2} - \bar{u}_e)\exp(-2.3K_2\tau). \tag{5}$$

The coefficients K_1 and K_2, called the drying coefficients, are numerically equal to the tangents of the angles of inclination of the straight portions to the τ axis in the semilogarithmic anamorphosis. The value of these coefficients depends on the kind of moist material, its properties, and the drying conditions and method. The effect of the conditions on these coefficients can be represented by N—the maximum drying rate of the material in the particular conditions in the first period (or the maximum drying rate in the absence of a first period).

We can assume that

$$K_1 = \chi_1 N, \tag{6}$$

$$K_2 = \chi_2 N. \tag{7}$$

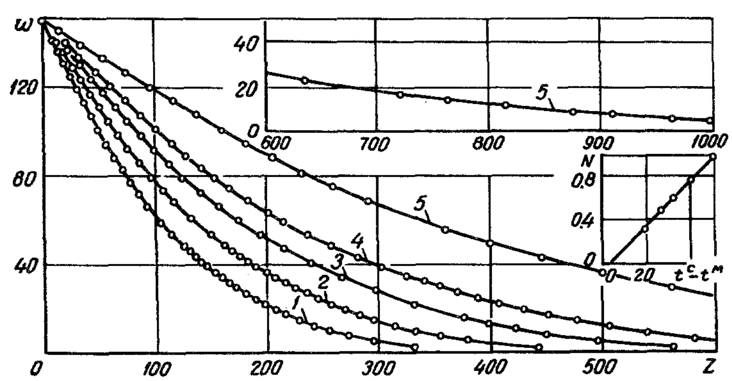

Fig. 1. Dry curves for pressed paper from [3] (w is the moisture content, %, of the material; Z is the time of drying, min): 1–5 for different drying conditions.

In (6) and (7) χ_1 and χ_2, called the relative drying coefficients, are different in the two parts of the second period and their values do not depend on the conditions, but depend on the mode of binding of the moisture with the material, the physicochemical properties (structure, density) of the material, and the method of drying. On substituting Eqs. (6) and (7) in (4) and (5) we obtain

$$(\bar{u}-\bar{u}_e)=(\bar{u}_{cr1}-\bar{u}_e)\exp(-2.3\chi_1 N\tau), \tag{8}$$

$$(\bar{u}-\bar{u}_e)=(\bar{u}_{cr2}-\bar{u}_e)\exp(-2.3\chi_2 N\tau). \tag{9}$$

Expressions (1), (8), and (9) are the equations representing the kinetics of drying in each period.

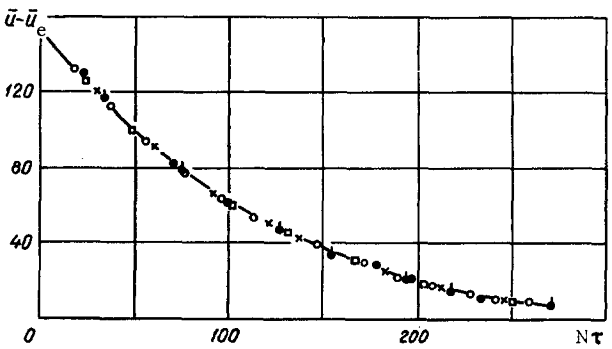

Fig. 2. Generalized drying curve for pressed paper ($\bar{u}-\bar{u}_e$ in % against $N\tau$ in %).

Taking as a new complex parameter the product $N\tau$ instead of τ in Eqs. (8) and (9), we note that in these equations $(\bar{u}-\bar{u}_e)$ is a function of $N\tau$.

If we assume that the critical moisture contents are independent of the drying conditions, then the family of drying curves for the same initial moisture content can be represented by one generalized curve.

The data of several researchers, including the authors, show that the values of the first and second critical moisture contents for many materials vary insignificantly with change in drying conditions. For instance, a change in the temperature of the heating surface from 60° to 154° C (in the drying of cellulose with a specific mass of 100 g/m^2) increase the first critical moisture content by approximately 0.05 kg moist/kg dry [2].

In the drying of pressed paper a change in the air temperature from 60° to 90° C alters the first critical moisture content by 0.018 kg/kg [3].

In the drying of wheat grain a change in the temperature of the drying agent from 60° to 150° C increases the first critical moisture content by approximately 0.3 kg/kg [6]. The effect of the drying conditions on the second and third critical moisture conents is even less.

Figure 1 shows drying curves for pressed paper, taken from [3], and Fig. 2 shows the generalized curve.

Treatment of the drying curves obtained for cellulose, cardboard, paper, cloth, grain, sunflower meal, potatoes, etc., by different investigators, confirmed the validity of this method of generalization.

In fact, the experimental points on the drying curves of a specific material lie on the same curve, irrespective of the drying conditions.

This, in particular, indicates that the kinetic equations of the drying in different periods correctly describe the process and the coefficients χ_1 and χ_2 are independent of the drying conditions.

It follows from the method of generalizing the drying curves [4] that:

a) the generalized drying curve can be plotted from one experimental drying curve obtained in any conditions for a given $\bar{u}_1$.

b) the critical moisture contents and relative drying coefficients can be determined from the generalized drying curve in semilogarithmic coordinates.

Hence, from one experimental drying curve it is possible to write the kinetic equation of drying for any conditions and, hence, to construct the drying curves for different conditions, but the same $\bar{u}_i$, without carrying out experiments, if N is known. Since the drying curve is represented by several equations, and not just by one, the drying rate in the second period cannot be calculated analytically from Eqs. (8) and (9) (the derivative of $\bar{u}$ with respect to time changes at the points where the portions meet). The drying rate in the second period can be determined by graphic differentiation of the generalized drying curve. The actual complex curve of the generalized drying rate should be replaced, by Luikov's method, by a straight line intersecting the moisture-content axis at a point corresponding to equilibrium moisture content. Then the equation of the generalized curve of the drying rate in the second period takes the form

$$\left(\frac{d\bar{u}}{d\tau}\right)_{II}=-\chi' N(\bar{u}-\bar{u}_e). \tag{10}$$

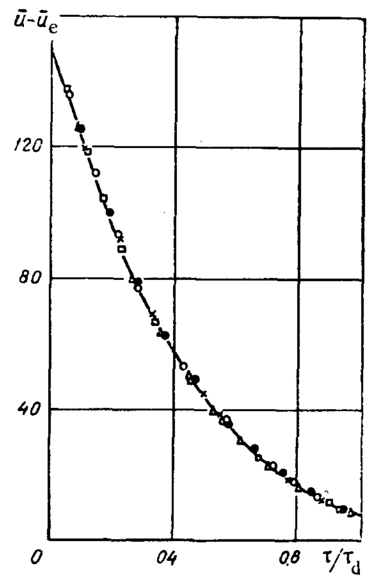

Fig. 3. Generalized drying curve of pressed paper ($\bar{u}-\bar{u}_e$ in % against τ/τ_d).

In (10) χ' is the mean relative drying coefficient, which is numerically equal to the tangent of the angle of inclination of the straightened portion of the curve of the generalized drying rate in the second period to the moisture-content axis.

From the kinetics of drying discussed above we can suggest two methods of calculating the duration of drying on the basis of the generalized drying curves.

The total duration of drying τ_d (without including the heating period) is the sum of the durations of drying in the first period τ_I and in the first (τ_1) and second (τ_2) parts of the second period.

From Eqs. (1), (8), and (9) we can write

$$\tau_d = \tau_I + \tau_1 + \tau_2 = \frac{1}{N}\left(\bar{u}_i - \bar{u}_{cr^1} + \right.$$

$$\left. + \frac{1}{\chi_1} \lg \frac{\bar{u}_{cr1} - \bar{u}_e}{\bar{u}_{cr2} - \bar{u}_e} + \frac{1}{\chi_2} \lg \frac{\bar{u}_{cr2} - \bar{u}_e}{\bar{u}_{fin} - \bar{u}_e}\right) \quad (11)$$

The relative drying coefficients are calculated from the following expressions:

$$\chi_1 = [\lg(\bar{u}_{cr^1} - \bar{u}_e) - \lg(\bar{u}_{cr^2} - \bar{u}_e)]/N\tau_1, \quad (12)$$

$$\chi_2 = [\lg(\bar{u}_{cr^2} - \bar{u}_e) - \lg(\bar{u}_{fin} - \bar{u}_e)]/N\tau_2. \quad (13)$$

If there is no first period the maximum drying rate will be used instead of N in Eq. (11), and u_{cr_1} will be replaced by u_i.

If the temperature of the drying agent is 100° or more, then $\bar{u}_e$ will be practically zero. The proposed method of calculating the duration of drying on the basis of an analysis of the drying kinetics and generalization of the curves allows the calculation of the duration of drying in any conditions from one experimental curve. This method of calculation is a development of Luikov's method.

In the proposed method there is no need to construct the drying rate curve by graphic differentiation and to find the critical reduced moisture content, nor to carry out many experiments in different conditions to find the relative drying rate.

The calculation of the duration of drying from the generalized drying curve is simpler than Filonenko's method based on the reduced drying rate curve.

From the discussed method of generalization of the drying curves and from Eq. (11) we can also derive a method of generalizing the drying curves in coordinates $\bar{u} - \bar{u}_e$ and τ/τ_d and a graphical method of calculating the duration of drying from one experimental value of $\bar{u}$ and τ [5]. Figure 3 shows the generalized drying curve of pressed paper, plotted from the experimental data (Fig. 1).

The proposed analysis of the kinetics of drying, the methods of treating the experimental data, and the methods of calculating the duration of drying save time and material in experimental investigations of the drying of a particular material.

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15 July 1966

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