DETERMINATION OF THE THERMAL AND THE MOISTURE DIFFUSIVITY IN A POROUS BODY FROM THE KINETIC CHARACTERISTICS OF THE DRYING PROCESS

P. P. Lutsik, E. A. Strashkevich, and M. F. Kazanskii

UDC 678.029.71:532.72

A method is proposed for simultaneously determining the thermal and the moisture diffusivity in a porous body during drying. The results of such a determination are presented, together with the Lykov number for drying cellulose.

For the calculation of heat and mass transfer processes as well as for an explanation of the mechanism of internal heat and mass transfer, it is important to know how the thermal and the mass diffusivity of a substance that has been adsorbed by a disperse, porous body depend on the concentration and the temperature of the body.

Most methods now in use yield either the thermal diffusivity or the mass diffusivity, without accounting for the interrelation between the processes of heat and mass transfer.

The present article proposes a combination method of determining, by a single test, both the thermal and the moisture diffusivity of a capillary-porous material, as functions of the temperature and the moisture content during convective drying.

In order to determine these diffusion parameters, experimental curves of local moisture and temperature kinetics for two layers of the test material and the integral curve of drying rates are used. The calculation formulas have been derived by solving the system of differential equations of one-dimensional molecular mass transfer at negligible temperature gradients inside the material.

The equations of heat and mass transfer with constraints corresponding to the convective drying of a moist body have been solved by Lykov [1, 2]. After the initial heating stage there will prevail in the body a quasisteady temperature and moisture distribution which can be described by the following simplified expressions:

$$\frac{u_0 - u(x, \tau)}{u_0} = \int_0^{\tau} \frac{j_m(\tau)}{R\gamma_0 u_0} d\tau - \mathrm{Ki}_m(\tau) \frac{R^2 - 3x^2}{6R^2}; \tag{1}$$

$$\frac{t(x, \tau) - t_0}{t_c - t_0} = 1 - \mathrm{Ki}_m(\tau)\,\mathrm{Ko}\,\mathrm{Lu}\,\frac{t_c}{t_c - t_0}\left[\frac{\varepsilon}{2}\left(1 - \frac{x^2}{R^2}\right) + \frac{1}{\mathrm{Bi}_q}\right]. \tag{2}$$

At two sections (having coordinates x_1 and x_2) of a plane body let us measure the moisture content and the temperature throughout the entire drying process. Writing Eq. (1) for each of these two coordinates, and considering that

$$\mathrm{Ki}_m(\tau) = \frac{j_m(\tau) R}{a_m \gamma_0 u_0}, \tag{3}$$

Engineering Institute of Light Industry, Kiev. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 22, No. 4, pp. 635-639, April, 1972. Original article submitted June 29, 1971.

TABLE 1. Diffusivities a_q, a_m and Lykov Number Lu as Functions of the Moisture Content and the Temperature during Convective Drying of Cellulose

u, %	t, °C	$a_q \cdot 10^8$, m²/sec	$a_m \cdot 10^8$ m²/sec	Lu
10,5	53,0	3,4	0,05	0,015
11,1	52,7	4,2	0,05	0,013
12,0	52,7	5,1	0,06	0,012
12,6	52,6	6,4	0,07	0,010
14,0	52,6	8,7	0,09	0,010
15,0	52,5	8,9	0,09	0,010
15,9	52,4	8,9	0,09	0,010
16,6	52,3	8,9	0,09	0,011
17,4	52,2	8,4	0,10	0,012
18,3	52,2	8,0	0,10	0,012
19,6	52,1	8,2	0,10	0,012
20,4	52,0	7,7	0,10	0,014
21,6	52,0	7,5	0,11	0,014
22,5	52,0	7,9	0,11	0,014
23,4	52,0	7,9	0,11	0,014
24,6	52,0	8,0	0,12	0,014
26,1	52,0	8,3	0,12	0,014

we obtain, after subtracting Eq. (1) from Eq. (2):

$$u(x_1, \tau) - u(x_2, \tau) = \frac{j_m(\tau)}{2a_m\gamma_0 R}(x_2^2 - x_1^2). \qquad (4)$$

With the moisture current density expressed in terms of the integral drying rate

$$j_m(\tau) = \gamma_0 R \frac{du_v(\tau)}{d\tau},$$

Eq. (4) will finally yield the sought moisture diffusivity:

$$a_m = \frac{\frac{du_v(\tau)}{d\tau}(x_2^2 - x_1^2)}{2[u(x_1, \tau) - u(x_2, \tau)]}. \qquad (5)$$

In order to find the thermal diffusivity, we subtract from Eq. (2) in the x_2 coordinate the same equation in the x_1 coordinate:

$$t(x_2, \tau) - t(x_1, \tau) = \mathrm{Ki}_m(\tau)\,\varepsilon\,\mathrm{Ko}\mathrm{Lu}\,t_A \frac{x_2^2 - x_1^2}{2R^2}. \qquad (6)$$

Using the Kirpichev number (3), the Kossovich number, and the Lykov number

$$\mathrm{Ko} = \frac{r(t)\,u_0}{c_q(t_A - t_0)};\ \mathrm{Lu} = \frac{a_m}{a_q},$$

we derive from (6) the calculation formula for the thermal diffusivity:

$$a_q = \frac{t_A \varepsilon r(t)(x_2^2 - x_1^2)\frac{du_v(\tau)}{d\tau}}{2c_q(t_A - t_0)[t(x_2, \tau) - t(x_1, \tau)]}. \qquad (7)$$

Formulas (5) and (7) apply to any instant of time during the drying process, except the initial heating stage.

In order to determine the coefficients a_m and a_q, therefore, it is necessary to have experimental curves of moisture and temperature kinetics for two layers of the body, the curve of integral drying rates, and the criterial phase-transformation number ε. The remaining quantities in Eq. (7) can be determined without difficulties. In the calculation of a_q there arises a serious problem on account of the phase-transformation number, however, because the latter can vary from 0 to 1 depending on the moisture content and the temperature.

This method was applied in determining the thermal and the moisture diffusivity for cellulose cut into ashfree filter sheets. The specimens built up of cellulose sheets to a 30 mm thickness were placed in a special-purpose vessel. Prior to the test, a specimen was moistened to a definite level. It was then dried by convection at both sides of the plate with heating and evaporation in a symmetrical temperature and a symmetrical hydrodynamic field. The laboratory apparatus and the test procedure have been described in [3]. The moisture content in the specimen layers was measured by the gammascopic method [4] throughout the process without distortion of the pore structures. The temperature in the same layers was measured with resistance thermometers and was recorded automatically.

The criterial phase-transformation number for cellulose during drying, as a function of the moisture content and the temperature, was determined according to the Lykov formula [2]:

$$\varepsilon = \frac{2[t(x, \tau) - t(0, \tau)]\lambda_q R}{r(t)\,x^2 j_m(\tau)}.$$

The data necessary for this had been obtained from preliminary tests. Furthermore, the values of thermal diffusivity for cellulose at various moisture levels were taken from [5] and the heat of evaporation for water at various temperatures was taken from [6]. The heat of evaporation of water from macro- and microcapillaries in filter paper was, moreover, assumed to be the same as that from a free surface.

The specific heat of moist cellulose was defined as a linear function of the moisture content: $c_q = (1.51 + 4.47\,u) \cdot 10^3$ J/kg · °C.

The thermal and the moisture diffusivity as well as the Lykov number for cellulose obtained in these tests from the kinetic characteristics of the drying process are shown in Table 1. The values of moisture content and temperature represent averages for a plate layer between coordinates $x_1 = 0$ and $x_2 = 5$ mm. The local temperatures and moisture contents during the drying process had been measured at these two sections of a plane specimen.

The values of thermal diffusivity obtained for cellulose from kinetic characteristics of the drying process agree fairly well with the analytic data obtained by other separate methods [5, 7]. For instance, at a 15% moisture content (corresponding to the hygroscopic conditions in micropores of filter paper) we obtained $a_q = 8.9 \cdot 10^{-8}$ m^2/sec (see Table 1), while the values in [5] and in [7] were $9.7 \cdot 10^{-8}$ and $7.2 \cdot 10^{-8}$ m^2/sec, respectively. Also the curves of thermal diffusivity vs moisture content according to our kinetic method have the same shape as those obtained by the stationary temperature–time point-by-point method [5]. The $a_q(u)$ curve passes through a maximum within the hygroscopic range of moisture content. As moisture is removed from cellulose during drying, from 14% downward, the thermal diffusivity decreases sharply.

The moisture diffusivity for cellulose decreases during convective drying within the 26–10% range. A sharp decrease of a_m occurs when the moisture content drops from 14 to 11%, when moisture absorption by microcapillaries changes from the capillary to the adsorptive mode.

The Lykov number remains much smaller than unity within the test range of moisture content. It follows that the buildup of the temperature field leads the buildup of the moisture field during drying.

NOTATION

a_m	is the moisture diffusivity;
a_q	is the thermal diffusivity;
$u(x, \tau)$	is the local moisture content in a body;
$t(x, \tau)$	is the local temperature in a body;
x	is the coordinate of a point from the center of a plane body;
τ	is the time from the beginning of the drying process;
u_0, t_0	are the initial moisture content and temperature, respectively;
t_A	is the ambient temperature;
Lu	is the Lykov number;
Ko	is the Kossovich number;
ε	is the phase-transformation number;
Ki_m	is the Kirpichev mass-transfer number;
Bi_q	is the Biot heat-transfer number;
$j_m(\tau)$	is the current density of moisture evaporating from one plate surface;
R	is half the thickness of a plate;
γ_0	is the density of a perfectly dry material;
$du_V/d\tau$	is the integral drying rate;
$r(t)$	is the evaporation of absorbed liquid from a porous material;
c_q	is the specific heat of a moist material.

LITERATURE CITED

1. A. V. Lykov, Heat and Mass Transfer in Drying Processes [in Russian], Gosénergoizdat, Moscow –Leningrad (1956).
2. A. V. Lykov and A. V. Ivanov, in: Heat and Mass Transfer in Evaporation Processes [in Russian], Izd. AN SSSR (1958).
3. P. P. Lutsik, Author's Abstract of Candidate's Dissertation [in Russian], Kiev (1967).
4. P. P. Lutsik, Legka Promyslovist', No. 4 (1967).
5. M. F. Kazanskii, A. N. Kulandina, and P. P. Lutsik, Inzh.-Fiz. Zh., 3, No. 2 (1960).
6. Tables of the Thermodynamic Properties of Water and Steam [in Russian], Gosénergoizdat, Moscow –Leningrad (1952).
7. A. P. Onokhin, in: Proceedings of the Leningrad Technological Institute [in Russian], No. 5 (1958).