ANALYSIS OF THE PROCESS OF VAPOR MIGRATION IN CAPILLARY-POROUS BODIES DURING SUBLIMATION UNDER VACUUM CONDITIONS

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The effect of displacement of the phase interface on mass transport in capillary-porous bodies is described and the particular role of molar vapor transport in the over-all mass transfer process is noted. Empirical relations for the motive force of molar vapor transport are presented.

In designing sublimation dryers it is necessary to take into account the specific mechanism of moisture transport in the material and, in particular, the depression of the sublimation zone during drying. This effect is continuously related with the structural properties of the material.

Physically, the depression of the sublimation zone is analogous to processes of displacement of the phase transformation zone at constant moisture content and surface heat flux. A linear law of depression of the evaporation surface was established by Luikov [1], while the problem of the depression of the evaporation zone (Stefan problem type) was solved by Luikov and Pomerantsev [2].

In relation to the sublimation process a linear law of depression of the sublimation zone can be assumed if the moisture content of the frozen part of the material and the surface heat flux are constant.

Starting from these assumptions, we calculated the depression characteristic (distance of sublimation zone from surface of material) from the following equation:

$$\xi = l\left(1 - \frac{U_m}{U_0}\right). \tag{1}$$

An analysis of the parametric criterion ξ/l showed that the depression of the sublimation zone is linear only for the period of constant drying rate ($\xi = b\tau$), while for the period of falling drying rate the law is parabolic ($\xi = b\tau^n$) [3, 4] (Fig. 1).

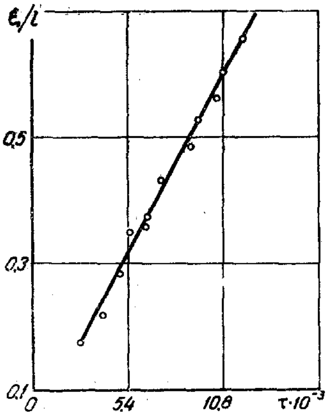

Fig. 1. Variation of the parametric criterion ξ/l with time.

To determine the location of the phase interface during sublimation, we experimentally recorded the pressure and temperature fields in the specimen at various pressures of the vapor-air medium in the sublimator and various heating wall temperatures.

The following experimental method was used to determine the pressure difference between the specimen and the medium. The pressure in the specimen was measured with injection needles ($d_{ex} = 1$ and $d_{in} = 0.5$ mm) distributed over the height of the specimen at intervals of $5 \cdot 10^{-3}$ m from the surface; the pressure readings were registered with an oil U-manometer, the initial pressure at both ends of which was equal to the pressure of the medium. The experiments were performed on quartz sand, which was poured into an insulated plexiglas mold measuring 30 × 30 × 30 mm and then introduced into a vacuum chamber. The heating surface surrounded the specimen on all sides, but heat was supplied only from above, since the lateral surfaces were insulated. The vapor also escaped upward. The experiments were conducted on a laboratory vacuum apparatus (Fig. 2). The initial moisture content was the same, irrespective of the dispersity of the material ($U_0 = 25\%$); the pressure in the chamber was 93.3, 133.3, and 500 N/m^2, and the temperature of the heating wall 45–75° C. The mold containing the sand was mounted on a VTK-500 balance and the loss of moisture measured. The temperature fields were measured with copper-constantan thermocouples $d = 0.1 \times 10^{-3}$ m, stretched over a plexiglas frame at intervals of $5 \cdot 10^{-3}$ m. The thermocouples and needles were under identical isothermal conditions.

As already noted [5], when moist materials are intensely heated, a total pressure gradient develops inside the material. Although in our experiment the temperature of the heating wall was relatively low, maximum 75° C, and the temperature of the material −15° C, nonetheless a total pressure gradient, an important factor in mass transfer, was detected in the material.

The total pressure difference between the specimen and the medium over the height of the material is shown in Fig. 3a as a function of τ at a vapor-air pressure of 133.3 N/m^2 and a heating wall temperature of 55° C for moist quartz sand with a capillary diameter of $0.07 \cdot 10^{-3}$ m. The same graph includes the drying rate curve for the sand. The sublimation drying

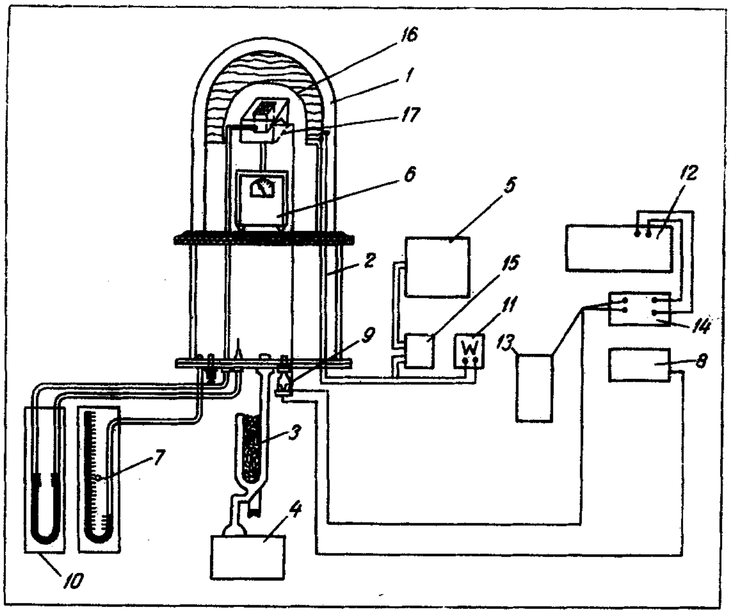

Fig. 2. Diagram of the experimental vacuum apparatus: 1) sublimator; 2) support for sublimator; 3) condenser; 4) VN-1MG vacuum pump; 5) EPP-0.9 MG; 6) VTK-500 balance; 7) mercury U-manometer; 8) thermocouple manometer; 9) LT-2 lamp; 10) oil U-manometer; 11) wattmeter; 12) PMS-48; 13) thermostat; 14) switch; 15) transformer; 16) heater; 17) specimen.

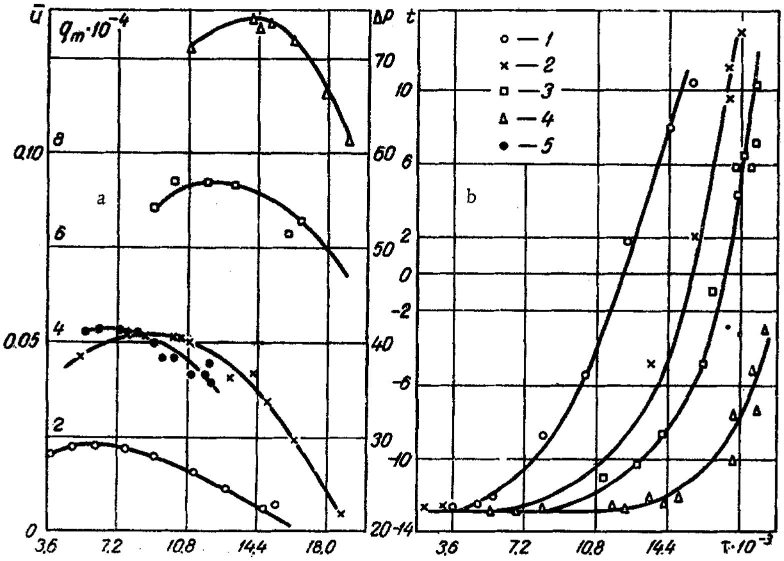

Fig. 3. Pressure difference between specimen and medium over the thickness of the material as a function of τ for quartz sand (a) and the temperature curves for the same conditions (b): 1) $5 \cdot 10^{-3}$ m; 2) $10 \cdot 10^{-3}$ m; 3) $15 \cdot 10^{-3}$ m; 4) $20 \cdot 10^{-3}$ m; 5) $q_m = f(\tau)$.

process as a whole should be examined layer by layer (over the thickness of the material). The maximum value of ΔP relates to the sublimation zone. It is clear from the graph that as the sublimation zone is depressed into the material ΔP increases, which is obviously because the rate of phase transformation exceeds the rate of vapor transport, owing to the increased resistance of the dry layer. The temperature curves for quartz sand with the same parameters are presented in Fig. 3b. As may be seen from the figure, during the period of constant drying rate the temperature of the material also remains almost constant. Then, as the residual moisture is removed and the material heated, its temperature constantly rises and, at the end of sublimation drying, reaches the temperature of the medium. A joint consideration of the temperature and pressure curves clearly demonstrates the pattern of displacement of the phase interface in the specimen. It is clear from Fig. 3a that the period of constant drying rate ends before the material attains a positive temperature over its entire thickness; i. e., the period of constant drying rate and the sub-

Table 1

Experimental Data on the Total Pressure Difference ΔP, Drying Rate, and b/μ Obtained for Various Capillary Diameters Under Different External Conditions

$d\cdot 10^3$, m	$P_{общ}$, N/m²	t_{cp}, °C	$t_{ст}$, °C	$q_m\cdot 10^4$, kg/m²·sec	$b\cdot 10^5$, m/sec	$b/\mu\cdot 10^3$, m/sec	$\xi\cdot 10^3$, m	ΔP, N/m²
0.035	133.3	45	55	5.0	0.278	0.0676	5	32.6
							10	57
							15	81.5
							20	105
0.07	93.53	35	45	3.4	0.2	0.0805	5	28
							10	37
							15	53
							20	70
		45	55	4.44	0.225	0.0854	5	32.7
							10	49
							15	65
							20	82.4
		65	75	4.9	0.278	0.0881	5	41
							10	57
							15	73.5
							20	102
	133.3	35	45	3.05	0.192	0.0815	5	24.4
							10	33
							15	49
							20	65
		45	55	4.16	0.216	0.0846	5	28
							10	41
							15	57
							20	74.8
		65	75	4.58	0.25	0.0866	5	36.7
							10	53
							15	69
							20	89
	500	35	45	2.44	0.185	0.8	5	2.3
							10	12.2
							15	20.3
							20	28.5
		45	55	3.8	0.194		5	16.3
							10	24.4
							15	33.0
							20	45
0.328	133.3	45	55	3.4	0.159	0.12	5	16.3
							10	24.4
							15	33
							20	41
0.5	133.3	45	55	3.0	0.101	0.147	5	12.2
							10	20.3
							15	24.4
							20	33

limation period do not correspond, which has also been noted by Guigo [6] for thick materials. In our experiments, the period of constant drying rate corresponds to a depression of the sublimation surface by about 10–15 mm.

Changing the temperature of the heating wall and the pressure in the sublimator leads to a change in the sublimation rate. Increasing the heating temperature with the other conditions fixed leads to an increase in the mass of vapor formed in the material and, hence, to an increase in the total pressure difference ΔP (Table 1). Reducing the pressure of the vapor-air mixture in the sublimation chamber also leads to an increase in ΔP.

On the basis of a generalization of the experimental data we obtained an empirical formula (for specific conditions) for determining the pressure gradient in the specimen, which depends not only on the external parameters (pressure of the medium in the sublimator and heating wall temperature), but also on the capillary diameter:

$$\Delta P = 88.7\, P^{-0.55}\, t^{0.665}\, d^{-0.403}\ (\mathrm{N/m^2 \cdot m}). \qquad (2)$$

The experimental data on the drying rate, the total pressure difference, and the coefficient b/μ for various external conditions and different capillary diameters are presented in Table 1.

It is clear from the table that the coefficient characterizing the rate of depression of the sublimation zone hardly changes with variation of the vacuum in the chamber and depends mainly on the rate of heat supply and the capillary diameter. As a result of the depression of the sublimation zone, the hydraulic resistance of the porous structure increases owing to the increase in the layer of dry material. To analyze this factor, we introduce the ratio b/μ.

On the basis of a generalization of the experimental data, we obtained an experimental relation between b/μ (for our experimental conditions) and the external parameters of the vapor-air mixture in the chamber and the capillary diameter

$$b/\mu = 12\cdot 10^{-7}\, P^{-0.007}\, t^{0.07} d^{0.28}\ (\mathrm{m/sec}), \qquad (3)$$

from which it is clear that the diffusion resistance coefficient (structure factor of the material [3]) μ depends on the pressure and temperature of the surrounding medium less than on the capillary diameter. The coefficient μ is a function of the moisture content [7] and, at U > 10%, of the heating rate. The coefficient μ shows by how many times the coefficient of diffusion (D) of vapor from the free surface into air is greater than the coefficient of internal vapor diffusion (a_m).

This criterion ($1/\varepsilon_n$) was introduced by Luikov [7]:

$$\mu = \frac{1}{\varepsilon_n} = \frac{D}{a_m}.$$

In the first approximation, we calculated μ as the ratio of the rate of evaporation from the surface (q_{m0}) to the sublimation rate for the depressed surface ($q_{m\xi}$). The data for μ as a function of the moisture content of the material are presented in Table 2.

On comparing the internal diffusion resistance coefficient for capillary-porous materials in a vacuum with the coefficient μ obtained by other authors for atmospheric conditions [7], we obtain close agreement.

Table 2

Experimental Data on the Vapor Diffusion Resistance Coefficient for Sand $0.07\cdot 10^{-3}$ m in Diameter at P_t = 133.3 N/m² and t_{av} = 55° C as a Function of the Moisure Content of the Material

U, %	$q_{m0}/q_{m\xi}$	U, %	$q_{m0}/q_{m\xi}$
16.5	1.6	11.5	1.802
15.0	1.6	10.0	1.93
13.3	1.7	8.4	2.04

As for the internal diffusion coefficient (a_m), under vacuum conditions it is much greater than under atmospheric conditions, which is coordinated with a corresponding increase in the coefficient of diffusion D of vapor from the surface into the surrounding medium. Values of D and a_m were obtained from formulas taken from [7, 8].

A knowledge of the resistance coefficient of the dry layer of material in relation to the rate of depression of the sublimation zone is of considerable practical importance: allowance for these factors together with a calculation of the rate of energy supply to the sublimation zone makes it possible to select the thickness of sublimed material.

NOTATION

ξ is the distance between the phase interface and the material surface, m; l is the total thickness of the material, m; U_m and U_0 are the moisture content of the material at the reference time and the initial moisture content, respectively, kg/kg; q_m is the rate of evaporation of ice from the capillary-porous body, $kg/m^2 \cdot sec$; a_m is the internal vapor diffusion coefficient, m^2/sec; b is the rate of depression of the sublimation zone; τ is the time, sec; μ is the vapor diffusion resistance coefficient; P is the pressure in sublimator, N/m^2; d is the capillary diameter, m.

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