FILTRATION DRYING KINETICS OF GAS-PERMEABLE ARTICLES

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The drying process under conditions of filtration of a drying agent through a porous structure of a moist article is considered. The existence of three dehydration stages is established: 1) mechanical displacement of water; 2) elimination of moisture in the form of a gas-liquid emulsion; 3) drying. A kinetics equation is derived for each stage. Combination of all the three stages provides a high rate of the total process exceeding the drying rate by tens of times when flowing around an object as a unit.

During the technical realization of filtration drying it is necessary to push a drying agent through a porous object and to overcome its hydraulic resistance. This may be accomplished via pressure induced by a compressor or vacuum produced by a vacuum pump. The pressure gradient resulting in this case favors the mechanical displacement of that part of the moisture which fills coarse pores and which is not firmly bonded to the article material.

With a high original moisture content we may eliminate up to 70% of all the moisture contained in the object in such a manner. The mechanical displacement time of the moisture can be estimated qualitatively by the Darcy law for a variable pressure gradient

$$-\frac{dH}{dt}=\frac{k}{\varepsilon\mu}\frac{\Delta P}{h},$$

whence it follows that

$$t_n=\frac{\varepsilon^*\mu H^2}{2k\Delta P}. \tag{1}$$

The computations made using this formula and the experimental data indicate that time t_n is several seconds and depends on factors contained in (1).

Further dehydration occurs during the stage of elimination of the moisture in the form of a gas-liquid emulsion. As compared with the previous process, this one is more prolonged but its role decreases steadily with time. Here the moisture elimination rate may be taken to be proportional to the amount of moisture which remains in the object and which can be removed by the described manner

$$-\frac{dw}{dt}=k_1w;\quad w=w_0\exp(-k_1t), \tag{2}$$

while coefficient k_1 should be sought in the form: $k_1 \simeq v/H$.

The duration of the mode under consideration at v = 1 m/sec and H = 0.036 m (drying of woolen grinding disks) is t_n= 20 sec. The longer period is associated with the drying process course in the usual understanding of this word. As is known, the drying time while the external drying agent flows around the object depends on the size of this object. In the constant-rate period this time is proportional to the size of the wet object, and in the falling-rate period to the square of the size [1]. Under filtration drying conditions the drying agent flows around the fine-scale structural elements of which it consists and which are hundreds of times less than the object itself. For this reason the critical moisture content decreases considerably, and the drying process takes place mainly at a constant drying rate. To this must be added the high inner surface of interaction between phases, exceeding by hundreds (and sometimes thousands) of times the outer geometrical surface of the drying object.

L'vov Polytechnic Institute. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 63, No. 6, pp. 708-713, December, 1992. Original article submitted October 16, 1990.

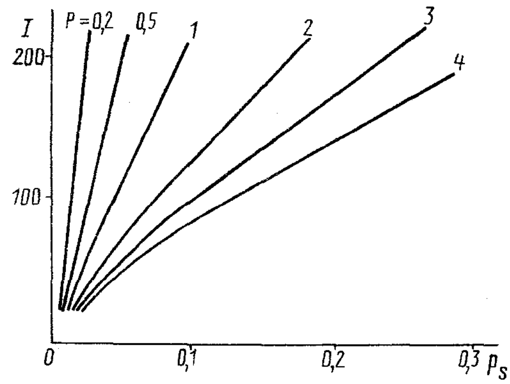

Fig. 1. Dependence of heat content on saturated vapor pressure at different pressures. I, kJ/kg; p_s, atm.

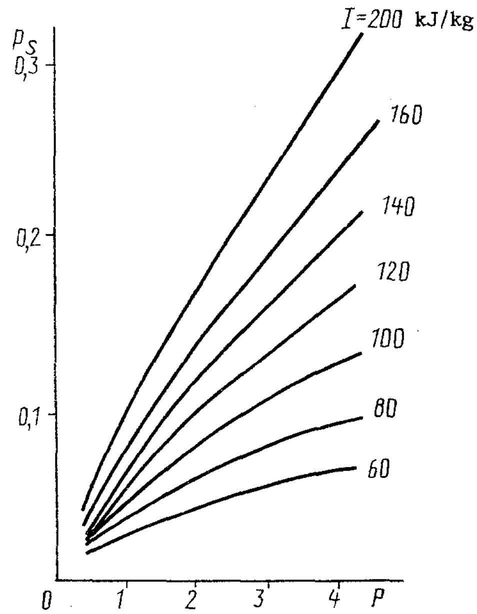

Fig. 2. Dependence of saturated vapor pressure on pressure at different heat contents of the drying agent. P, atm.

To describe the drying kinetics we use a set of equations [1, 2]:

$$-\frac{\partial w}{\partial t} = 100\beta\sigma(p_s - p)\frac{P_a}{P}; \tag{3}$$

$$G\frac{\partial x}{\partial z} = -\frac{F\rho_m}{100}\frac{\partial w}{\partial t}, \tag{4}$$

$$p = P\frac{x}{0{,}622 + x} \approx \frac{Px}{0{,}622} \quad \text{at} \quad x \ll 0{,}622,$$

$$-\frac{\partial w}{\partial t} = \alpha\frac{p_s - p}{P}; \tag{5}$$

$$-\frac{\partial x}{\partial z} = m\frac{\partial w}{\partial t}, \quad \alpha = 100\beta\sigma P_a, \quad m = \frac{F\rho_m}{100G}. \tag{6}$$

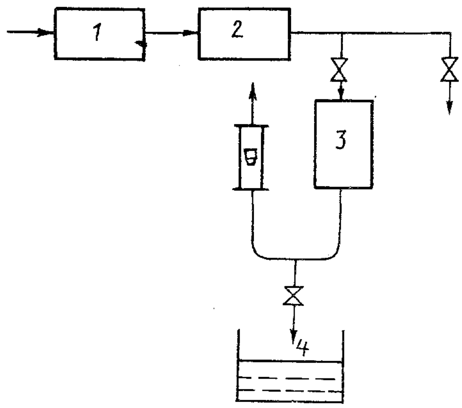

Fig. 3

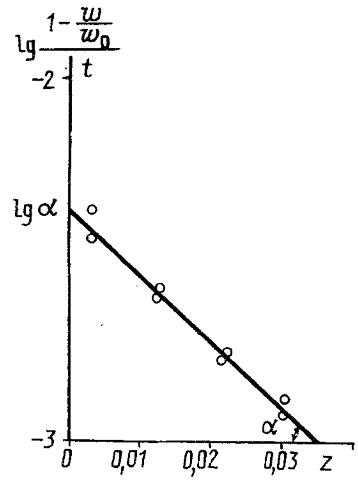

Fig. 4

Fig. 3. Schematic of the experimental setup: 1) compressor; 2) air heater; 3) drying chamber; 4) detector of mechanically displaced water.

Fig. 4. Identification of Eq. (15) with the experimental data. z, m.

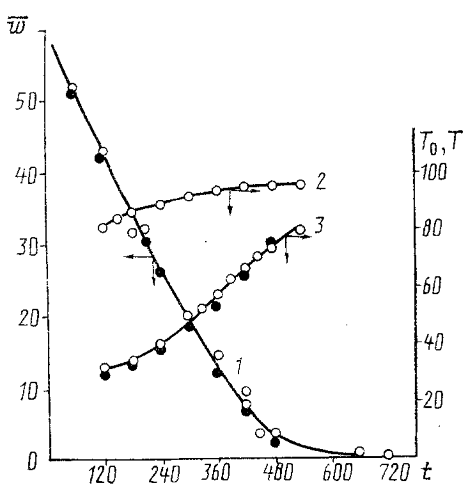

Fig. 5. Filtration drying kinetics: points are experimental data; 1) curve calculated by (20) and (21); 2, 3) variation in the drying agent temperature. $\bar{w}$, %; t, sec; T_0, °C.

The set of (3) and (4) includes kinetics equation (3) and balance equation (4) [3, 4].

Now we turn to the more detailed analysis of kinetics equation (5), giving special attention to the moving force $(p_s - p)/P$. Specific features of its determination lie in the fact that in each cross section of the object the overall pressure of the drying agent arises, corresponding to a linear distribution

$$P = P_i - (P_i - P_f)\frac{z}{H}, \tag{7}$$

and parameters p_s and T_s inherent to this cross section.

Motion of the drying agent through the porous object structure may be considered as the throttling process for which heat content I is kept constant with variation in the temperature and in the moisture content

$$I = 1{,}01T + 1{,}97xT + 2493x =$$
$$= T\left(1{,}01 + 1{,}225\frac{p}{P-p}\right) + 1511\frac{p}{P-p}. \tag{8}$$

In the vicinity of the phase interface, parameters p and T correspond to conditions $p = p_s$ and $T = T_s$. In order to determine them we employ, in addition to (8), the coupling equation on the saturation line [5]:

$$T_s = \frac{2224{,}4}{5{,}9778 - \lg P_s} - 273. \tag{9}$$

Using (8) and (9), the graphs (Figs. 1, 2) are constructed. The latter gives relation $p_s = f(P)$ used for determining the moving force. To obtain the analytical solution to the system of (5) and (6), it is convenient to approximate this relation as

$$p_s = P(A - BP), \tag{10}$$

or more roughly

$$p_s = AP, \tag{11}$$

where constants A and B are the heat content functions.

The solution to the system of (5), (6), and (10) under boundary conditions $x|_{z=0} = x_i$, $w|_{t=0} = w_0$ takes the form

$$x = 0{,}622\frac{p_{si}}{P_i} + \psi(nz - 1) - \left(0{,}622\frac{p_{si}}{P} - \psi - x_i\right)\exp(-nz), \tag{12}$$

$$w = w_0 - \left[\frac{\psi}{0{,}622} + \left(\frac{p_{si}}{P_i} - \frac{\psi + x_i}{0{,}622}\right)\exp(-nz)\right]\alpha t, \tag{13}$$

where

$$\psi = 0{,}622B\frac{P_i - P_f}{nH}; \quad n = \frac{m\alpha}{0{,}622}; \quad p_i = P_i(A - BP_i).$$

The simpler but less exact model is realized when we use (11) instead of (10)

$$x = 0{,}622A - (0{,}622A - x_i)\exp(-nz); \tag{14}$$

$$w = w_0 - \left(A - \frac{x_i}{0{,}622}\right)\exp(-nz)\,\alpha t. \tag{15}$$

From Eqs. (13) and (15) it follows that at the time instant

$$t^* = \frac{w_0}{\alpha\left(A - \frac{x_i}{0{,}622}\right)}$$

at point $z = 0$, $w = 0$. At the time $t > t^*$ $w < 0$ at point $z = 0$ and at other points, but this has no meaning. Therefore, Eqs. (12)-(15) are applicable only in the $0 < t < t^*$ range.

For conditions $t > t^*$, instead of (14) and (15) we suggest another solution, which also satisfies (5) and (6)

$$x = 0{,}622A - (0{,}622A - x_i)\exp(-n(z - l)); \tag{16}$$

$$w = w_0 (1 - \exp(-n(z - l)));$$ (17)

$$l = \frac{1}{n}\left(\frac{t}{t^*} - 1\right).$$ (18)

From (18), it is possible to define the time of the drying process course, assuming that l = H

$$t^{**} = t^* (1 + nH).$$ (19)

In conclusion we establish the averaged values for the moisture content by application of the known operation

$$\bar{w} = \frac{1}{H}\int w dz; \quad \bar{w} = w_0 - \alpha\left(A - \frac{x_i}{0{,}622}\right)\frac{1 - \exp(-nH)}{nH} t, \quad t \leqslant t^*;$$ (20)

$$\bar{w} = w_0\left[\left(1 - \frac{l}{H}\right) - \frac{1 - \exp(-n(H - l))}{nH}\right], \quad t > t^*.$$ (21)

The experimental part was performed on a setup whose scheme is depicted in Fig. 3. The woolen grinding disk was the object of drying; its original moisture content (w_{0i} = 250%) decreased rapidly to w_0 = 60% due to the mechanical displacement of the water and to the next stage of the gas-liquid emulsion. The further reduction of the moisture content was achieved by drying (evaporation of the moisture). Over the course of the drying process a mass flux of the drying agent increased somewhat (rate v = 1.1-1.3 m/sec) because of the resistance drop as the drying object was dried out. During the experiment the drying disk was tested as a unit (H = 0.036 m) or was cut into four parts (each was 0.009 m thick) and then dried completely with the subsequent definition of the moisture content in each part. The experimental data presented in Fig. 4 allow us to determine filtration drying constants n and t^*:

$$\lg\frac{1 - \frac{w}{w_0}}{t} = -\lg t^* - 0{,}434nz, \quad n = 44{,}77\ 1/\text{m}; \quad t^* = 209\ \text{sec}.$$

Used here are the test data at moments t = 120 and 209 sec, i.e., at the time when the whole object is filled with water, while the region, being devoid of the water, is not yet formed. The time of the whole drying process is determined by (19)

$$t^{**} = 209(1 + 44{,}77 \cdot 0{,}036) = 546\ \text{sec}.$$

In Fig. 5 the experimental results on the drying kinetics of the whole object are compared with Eqs. (20) and (21).

NOTATION

h, the height of a moist object filled by liquid with an original moisture content during mechanical displacement, m; μ, liquid viscosity, Pa·sec; t, time, sec; ε^*, the object porosity; k, the penetration coefficient, m^2; P, the total pressure of a drying agent, Pa; P_a, the atmospheric pressure, Pa; p_l, the partial pressure of steam in a drying agent, Pa; p_s, the saturated vapor pressure, Pa; P_i, the drying agent pressure at inlet to the drying chamber; P_f, the drying agent pressure at outlet from the drying chamber, Pa; H, the drying object thickness, m; w, the moisture mass eliminated in the mode of a gas-liquid emulsion, kg; v, the drying agent filtration rate, m/sec; w, the moisture content of the object to be dried, %; β, the mass transfer coefficient, m/sec; σ, the sample surface per weight unit, m^2/kg; G, the mass flow rate of a drying agent, kg/sec; x, the drying agent moisture content, kg/kg; f = $\pi d^2/4$; d, the sample diameter, m; ρ_m, the dried sample density, kg/m^3; z, the coordinate in the rate vector direction, m; T, the drying agent temperature, °C; I, the drying agent heat content, kJ/kg; A, B, constants determining the dependence of the saturation vapor pressure on the total pressure; n, the filtration drying constant, 1/m; α, the filtration drying constant, 1/sec; w_0, the original moisture content in the course of drying, %; x_i, the original moisture content of a drying agent, kg/kg.

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