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DRYING IN HEATED GAS FLOWS

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A study has been made of the drying of a body by passage of a drying agent; various structures have been used. A simple mathematical model is presented for this type of drying.

Much attention is being given to the drying of gas-permeable bodies by passage of a heat carrier through a planar layer of material [1-4]. Usually, such a material has large internal channels and pores, in which the hydraulic resistance is quite low [2]. It has been found that the drying is then considerably more rapid than convective drying.

Particular interest attaches to research on drying of this type for materials differing considerably in structure and type of water binding. We have examined various materials (felt, cardboard, nonwoven fabrics, sheet asbestos, woven asbestos strip, and the like), which differ in nature and hydraulic resistance. The measurements were made over a wide temperature range with widely varying pressure differences, the main working unit for the purpose being that shown in Fig. 1, which consists of two sections 1 and 2, which are separated by the perforated baffle 3. Leakage around the edge is prevented by the sealing ring 4, which is compressed by the cover 5. The drying is performed as follows. The wet specimen 6 of diameter 100 mm is set up in section 1 on the perforated baffle 3, with a vacuum set up in section 2. The gas at a set temperature is supplied to the surface of the specimen and passes through it as a result of the pressure difference.

Figure 2 shows results for felt, cardboard, and woven asbestos strip at 100°C and a pressure difference of 65,000 N/m^2. The kinetic curves indicate the mode of drying in the different groups of materials, which differ considerably in structure.

The felt had coarse pores with low hydraulic resistance; the woven asbestos strips were much denser and bound the water in a different fashion. Cardboard is a typical colloidal porous material dominated by small capillaries, and it has the highest hydraulic resistance. Curve 1 reflects the drying of felt of thickness 10 mm and has three prominent parts. The first is rapid mechanical displacement of the water by the gas, while the second and third are drying proper. About half of the water is eliminated during the first period. Curve 2 represents the asbestos strip of thickness 10 mm, which takes the form of a classical curve with two periods. Here mechanical displacement plays no definite part. Curve 3 indicates the drying of cardboard of

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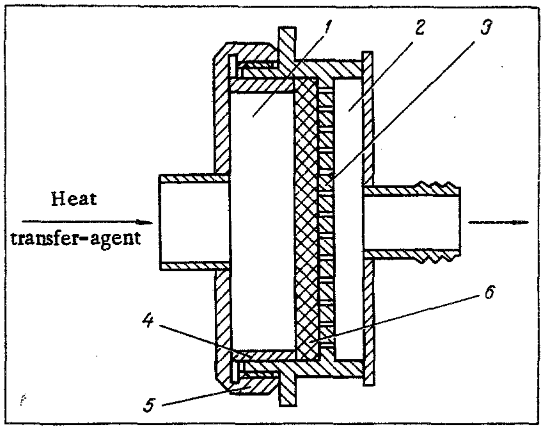

Fig. 1. The drying chamber.

thickness 8 mm. It is clear from curve 3 that the derivative of W with respect to τ increases during the process, which is due to systematic increase in the flow rate (speed) of the gas arising from increase in the effective porosity as the water content falls for a constant pressure difference. Figure 2 also shows that the structure had a decisive influence on the drying, particularly at the start. The drying can be represented as a convective process within the capillaries, in which the temperature and concentration profiles move along the line of the pressure gradient. Figure 2 shows that the drying occurs mainly in the constant-rate period, whereas the rate falls mainly in the range from $W = 8\%$ to W_p, which can be neglected, since the technical conditions specify that the water content should not be reduced to this level. The differential equations for drying and conservation of matter takes the form

$$\frac{\partial x}{\partial Z} + m\frac{\partial W}{\partial \tau} = 0, \tag{1}$$

$$-\frac{\partial W}{\partial \tau} = n(1-\varphi), \tag{2}$$

$$x = \frac{0{,}662\varphi P_s}{\Pi - \varphi P_s},$$
$$m = \rho F/100M, \quad n = SKP_s. \tag{3}$$

Equation (1) represents the water balance for an elementary volume (the gas increases in water content at the expense of the moist material). Equation (2) is a kinetic equation corresponding to the constant-rate period.

These equations can be transformed to

$$\frac{\partial \varphi}{\partial Z} = a(1-\varphi), \quad \frac{\partial W}{\partial \tau} = n(1-\varphi), \quad a = \frac{\Pi mn}{0{,}622P_s}, \tag{4}$$

whose solution is

$$\frac{W}{W_0} = 1 - \tau\alpha\exp(-aZ), \quad \alpha = \frac{1-\varphi_0}{W_0}n. \tag{5}$$

Equation (5) is the final result from the above; it is necessary to determine the kinetic coefficients α and a in order to use this analytical relationship, and for this purpose we convert (5) to the form

$$1 - \frac{W}{W_0} = \alpha\exp(-aZ)\,\tau, \tag{6}$$

$$\lg y = \lg\alpha - aZ\lg l, \quad y = \frac{1-\dfrac{W}{W_0}}{\tau}. \tag{7}$$

$$1 - \frac{W}{W_0} \text{ and } \frac{\tau}{T}\exp\left(-\frac{Z}{h}\right), \quad T = \frac{1}{\alpha}, \quad h = \frac{1}{a}.$$

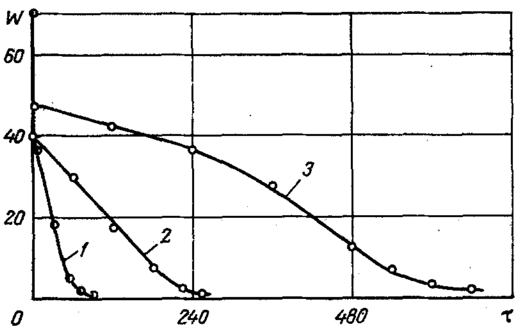

Fig. 2

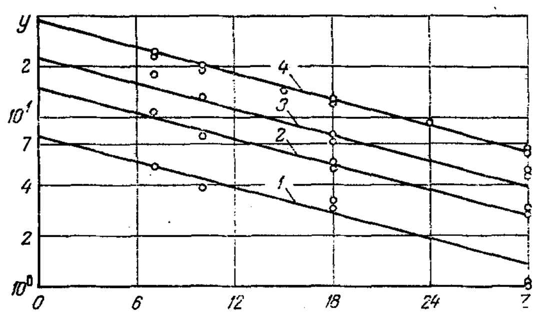

Fig. 3

Fig. 2. Drying curves: 1) felt; 2) asbestos strip; 3) cardboard; W in % and τ in °C.

Fig. 3. Determination of kinetic coefficients for felt at T (°C): 1) T = 50°C; 2) 75; 3) 100; 4) 125.

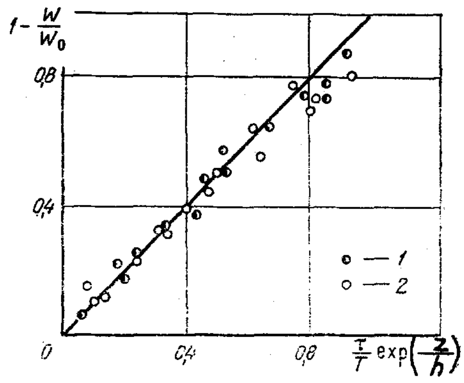

Fig. 4. Comparison of observed and calculated values for dimensionless quantities for: 1) felt; 2) asbestos strip.

Figure 3 shows data on felt processed in accordance with (7), and it is clear that the straight lines are almost parallel. These results for felt and other materials show that α is dependent on the parameters of the process, whereas a is the constant for a given material and is dependent only on the structure (a = 0.058 for felt, as against 0.0182 m^{-1} for asbestos strip). Figure 4 indicates the justification for using (5), since it has been constructed from data for the various materials in the coordinates used in (7). The coefficient of variation does not exceed 14%. It is clear from (5) that α serves to characterize the performance for a given material in relation to drying conditions, since it increases with the rate. Quantitative description requires a knowledge of α as a function of T and ΔP.

Numerous studies have shown that the gas temperature affects α considerably; Fig. 3 confirms this for felt (α is determined as the intercept on the ordinate). The pressure difference and thus the gas speed also appreciably influence the value of α, which tends to increase with the pressure difference.

However, α is independent of the material thickness; the effects of thickness Z on the drying rate are represented by (5). As α is dependent only on the nature of the material and not on the thickness, we can use α = f(T, ΔP) in order to describe the drying quantitatively.

The values for α for the above materials were represented as

$$\alpha = K_0 T^{m_0} \Delta P^{n_0}. \tag{8}$$

Table 1 gives values for K_0, m_0, and n_0 for the various materials.

TABLE 1. Values of Constants K_0, m_0, and n_0

Material	Constant		
	K_0	m_0	n_0
Asbestos strip 10 mm thick	$31\cdot10^{-5}$	1,00	0,226
Felt	$12,8\cdot10^{-5}$	1,31	0,74
Asbestos cloth	$33,6\cdot10^{-5}$	1,00	0,123
Bonded felt	$400\cdot10^{-5}$	2,35	0,870

From (5) and (8) together with K_0, m_0, and n_0 one can readily derive a general relationship for the current water content as a function of τ, T, Z, and ΔP. The studies were based on materials that are difficult to dry industrially not only from the viewpoint of rate but also from the viewpoint of energy consumption. The above style of drying accelerates the process by a factor 10 by comparison with convective drying. The reasons for the acceleration vary from one material to another. An appreciable part is played by direct displacement of the water by the gas, although there are effects from the increase in the surface area and the direct heat and mass transfer in the capillaries.

For instance, the drying of asbestos strip is accelerated by comparison with convective drying by almost a factor of 60, the corresponding factors for cardboard being 18-20, and for felt more than 100. There is also a reduction in the energy consumption and an improvement in the quality of the product.

These measurements and theoretical conclusions can serve as the basis for high-performance drying systems.

NOTATION

x	is the absolute humidity;
Z	is the thickness of material;
W	is the moisture content;
τ	is the drying time;
φ	is the relative humidity;
P_s	is the saturation vapor pressure;
Π	is the barometric pressure;
ρ	is the density of air;
F	is the cross section of sample;
M	is the mass;
S	is the evaporation area;
K	is the coefficient of proportionality;
α and a	are the kinetic drying coefficients for air;
φ_0	is the relative humidity at $\tau = 0$;
W_0	is the initial moisture content.

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