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PERMEABILITY OF MOIST POROUS MATERIALS

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Results of an experimental study are presented pertaining to the dependence of the permeability of porous materials on their moisture content during moisturization and desiccation.

Development of a new technology has recently stimulated interest in studies pertaining to filtration of gases through moist porous systems. Interesting is that pulverulent microparticles of the filtered gas are more effectively precipitated in and retained by moist than by dry porous materials. This applies above all to porous filters protecting the environment against contamination by aggressive substances, also to technological processes involving impregnation of porous materials with various fluids and their desiccation by scavenging with warm air. Filtration of gases through porous materials and the permeability of such materials have been studied by many authors. These studies included, e.g., the dependence of the permeability of porous bodies on the hydrodynamic characteristics of the gas flow through the pores [1, 2]. The study of filtration through moist porous materials has only begun [3]. As far as these authors know, the dependence of the permeability of porous materials on their moisture content has not yet been analyzed.

For a study of this dependence there was assembled the experimental apparatus shown in Fig. 1. The cover plate 1 pressed a porous plate 2 tightly against the beaker 3. The rim of the porous plate was coated with an adhesive, to ensure hermetic sealing. Air was fed from a tank 9 through valve 8, manometer 7, and rotameter 4 to one of the beakers fitting under the porous plate. The air was then drained through the porous plate into the atmosphere. The excess pressure under the porous plate was measured with both a water manometer 6 and a reference manometer 5. The rotameter had been precalibrated against the mass flow rate of air. Atmospheric pressure was measured with a barometer. The apparatus was periodically checked for hermeticity.

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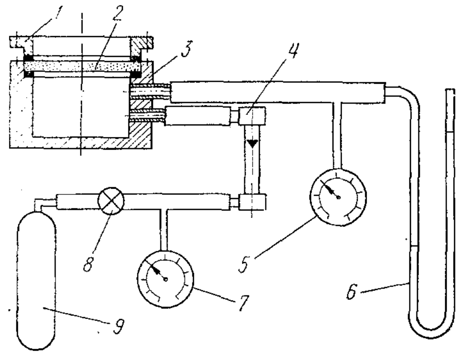

Fig. 1. Schematic diagram of the experimental apparatus.

Experiments were performed with porous plates made of fireclay ceramic, titanium, and nickel, all having approximately the same effective porosity. The titanium plates and the nickel plates (average pore size 5-7 μm) were impregnated with water distillate under a pressure head in a separate apparatus. The ceramic plate (average pore size 2-3 μm) was impregnated with liquid by action of its own capillary potential. The moisture content in the plates was measured by the weighing method with a model ADV-200M analytical balance. The flow characteristics were plotted first during gradual moisturization of a plate and then during its desiccation at room temperature. A definite mass flow rate of air was established by means of rotameter 4 and valve 8 (Fig. 1). At any particular flow rate were then measured the pressure drops and the corresponding moisture contents during moisturization and during desiccation of a plate. Several series of tests, at various mass flow rates of air, were performed with each porous plate. At each selected air flow rate, accordingly, a plate was moisturized to a maximum level U*, the same in each case, at which the air stream flowing at the selected maximum rate would begin to eject particles of the liquid from pores. Moisturization to this level U* was followed by desiccation of a plate. A true moisture content higher than U* cannot be determined accurately at the selected maximum air flow rate. Thus ejection of liquid particles from pores by the air stream limits the hydraulic characteristics of a moist porous plate either with regard to moisture content (at selected air flow rates) or with regard to flow rate (at selected moisture content levels).

The results of experiments with the ceramic porous plate are shown in Fig. 2. According to the graph, the hydraulic characteristics of such a moist porous plate feature a rather appreciable hysteresis between moisturization and desiccation. The hydraulic characteristics of moist porous titanium and nickel plates follow an analogous trend. At a certain mass flow rate of air the pressure drop under the plate with a certain moisture content is larger when this moisture level has been reached during moisturization than when it has been reached during desiccation. In these authors' view, this hysteresis is due to a redistribution of moisture between pores of different sizes in the plate. As is well known, the capillary potential depends on the pore size.

During impregnation of a porous plate with liquid by a pressure head the liquid fills first the macropores, inasmuch as here the capillary potential is lower than in micropores. During impregnation there is not sufficient time to fill the micropores with liquid, inasmuch as moisturization by a pressure head is a rather fast process. Since during filtration of a porous plate most of the air flows through macropores, the permeability of such a plate will sharply decrease during moisturization by a pressure head. During moisturization such a plate becomes, in a way, sealed by the liquid. During desiccation, on the other hand, the liquid from the macropores gradually enters the micropores, where the capillary potential is higher. The amount of moisture in macropores decreases, which immediately affects the pressure drop under the plate while the mass flow rate of air remains unchanged. The permeability of the plate increases. With time, therefore, there occurs a redistribution of moisture between pores, a redistribution which in real porous materials proceeds slower than their impregnation with liquid under a pressure head.

The hysteresis in the hydraulic characteristics of a porous body impregnated with liquid by its own capillary head is due to a lag, in terms of variation of the wetting angle at the surface, between outflow and inflow of liquid, or which is equivalent, between desiccation and moisturization. The wetting angle is known to be smaller during desiccation than during

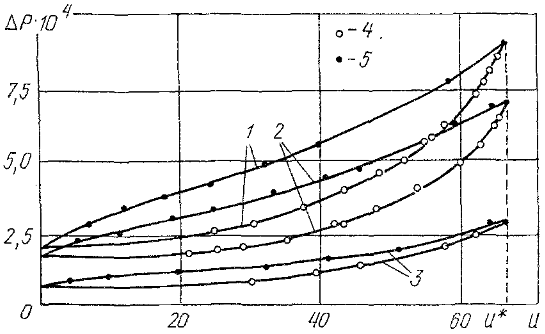

Fig. 2. Experimentally determined dependence of the pressure drop (P, N/m^2) under the ceramic porous plate on its moisture content (U, %), at various mass flow rates of air (q^M, kg/sec): 1) $1.65 \cdot 10^{-6}$; 2) $1.25 \cdot 10^{-6}$; 3) $4.5 \cdot 10^{-7}$; 4) desiccation; 5) moisturization; $U = \Delta m / \Delta m_{max} \cdot 100\%$, Δm denoting the amount of moisture in a plate at a given instant of time and Δm_{max} denoting the maximum amount of moisture with which this plate can be impregnated.

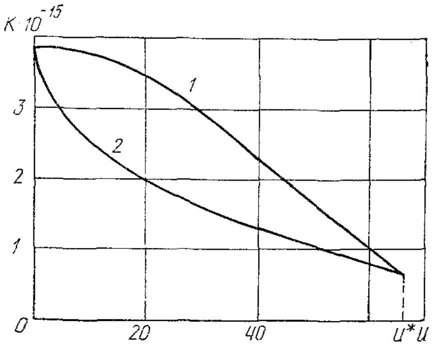

Fig. 3

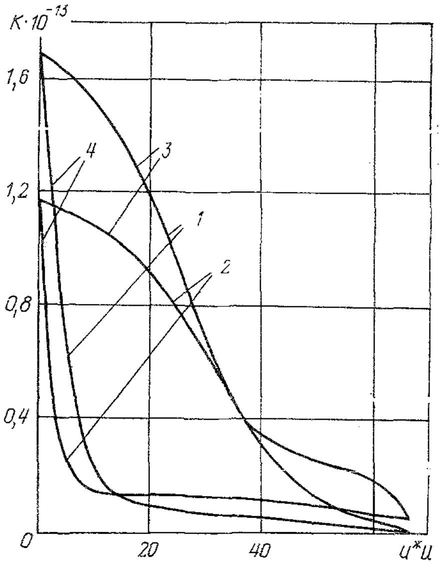

Fig. 4

Fig. 3. Dependence of the permeability (m^2) of the porous ceramic plate on its moisture content (%): 1) desiccation; 2) moisturization.

Fig. 4. Dependence of the permeability (m^2) of 1) the porous titanium plate and 2) the porous nickel plate on their moisture contents (%): 3) desiccation; 4) moisturization.

moisturization. As a consequence, the process of moisture redistribution between pores is more intensive during desiccation. In other words, this angle and thus also the hysteresis in the hydraulic characteristics of porous plates between moisturization and desiccation depend on the wettability of the plate material by the given liquid.

Since in our experiments the rates of air flow through the porous plates were insignificantly low and filtration proceeded under isothermal conditions, Darcy's law for gases [4] can be used for determining the permeability of those plates

$$q_{atm} P_{atm} = \frac{KA}{\mu L} \left(\frac{P_p^2 - P_{atm}^2}{2} \right) . \tag{1}$$

This relation yields the permeability

$$K = \frac{2q_{\mathrm{atm}}P_{\mathrm{atm}}}{P_{\mathrm{p}}^2 - P_{\mathrm{atm}}^2}\frac{\mu L}{A}. \qquad (2)$$

With the aid of experimentally determined hydraulic characteristics and relation (2) we have plotted curves depicting the dependence of the permeability on the moisture content for the various porous plates in this study (Figs. 3 and 4). The hysteresis loop is found to be smallest in the case of the ceramic plate. It is larger for the titanium plate and largest for the nickel plate, in both cases almost two orders of magnitude larger than for the ceramic plate. Such a substantial difference between the sizes of the hysteresis loop can be explained only by different modes of impregnation of the different porous materials with liquid. The hysteresis in the case of a ceramic plate is due to a lag, in terms of variation of the wetting angle at the pore walls, between moisturization and desiccation. In the case of porous titanium and nickel plates, on this hysteresis in terms of the wetting angle there is superposed another hysteresis due to impregnation with liquid by a pressure head. According to the graphs in Figs. 3 and 4, moreover, this additional hysteresis is much larger than the hysteresis in terms of the wetting angle. One can thus conclude that the magnitude of the hysteresis in the relation between permeability and moisture content depends strongly on the mode of impregnation and to a lesser degree on the wettability of the porous material.

On the basis of an analysis of the experimentally determined hydraulic characteristics and of the derived relations for the permeability of porous plates, one can conclude that the permeability of porous bodies depends largely on their moisture content (especially during the first stage of moisturization or desiccation) but also on the mode of its impregnation with liquid.

NOTATION

U, moisture content, %; ΔP, pressure drop under the plate, N/m^2; P_{atm}, atmospheric pressure, N/m^2; P_p, pressure under the plate, N/m^2; q_{atm}, volume flow rate of air under atmospheric pressure, m^3/sec; q^M, mass flow rate of air, kg/sec; K, permeability factor of a porous plate, m^2; A, area of the plate in the plan view, m^2; L, plate thickness, m; and μ, dynamic viscosity of air, $(N\cdot sec)/m^2$.

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