Determination of the permeability coefficient in the Darcy formula for liquid molding of thermal insulation products from quartz fibers

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Abstract. The results of water pouring of flat samples from chopped quartz fibers with a diameter of 12 microns and an elongation of 560...1680 are presented. Experimental values of water permeability coefficient through highly porous flat samples were obtained. The constant in the Kozeni-Karman permeability formula is determined depending on the porosity of the fiber layer.

Keywords: Short quartz fibers, material porosity, filtration method, water permeability coefficient

1. Introduction
Difficulties in the development of a process for producing heat-insulating or heat-shielding parts from short chopped or ground elementary glass, quartz or basalt fibers are associated with their small size [1-3] and specific methods of forming products from them [4-7]. The most developed technological process is the formation of a layer of fibers of the required thickness and density according to the shape of the designed part by liquid filtration [8-10]. Liquid technology is widely used in paper and construction industries, in the production of non-woven materials, asbestos cement products [11], as well as in the aerospace industry when creating heat-resistant tiles of the Buran type VKS [12, 13]. However, the permeability of the medium [14-18], which depends on the structure of the fibrous material, its porosity [19-21] and the geometric characteristics of pores, has a great influence on the duration of the filtration deposition of fibers from a sparse pulp.
The aim of the work is to determine the permeability coefficient in the Darcy equation for the transverse filtration of water through a flat sample of chopped quartz fibers of the same diameter and different lengths.

2. Statement of the problem, experiments studied
The permeability of a liquid through a layer of short fibers depends, first of all, on the uniformity of the structure and porosity of the material, the diameter and length of the fibers, as well as the presence of non-fibrous inclusions and components of the bundle (Fig. 1, a). A great influence on the permeability is exerted by the direction of fluid flow around the fibers — along the fiber axis or across the fibers (Fig. 1, b). Transverse flow around a fiber with a viscous liquid can be accompanied by a separation of the jet from its surface with the formation of stagnant regions [11].
Figure 1. Microscopic view of the crushed superthin basalt fiber under the microscope (a) and the scheme of fluid flow through the porous fiber layer (b): 1 - fiber; 2 - interfiber pore space

The rate of filtration or fluid flow through a porous layer of already deposited fibers (Fig. 2a) is determined by Darcy's law [8, 10]:

$$U_x = \frac{K}{\eta L} \Delta P$$

Where, $K$ is the coefficient of permeability of the fluid through the porous medium, $m^2$; $\Delta P = P_0 - P_{out}$ is the fluid pressure drop across the fiber layer, Pa; $\eta$ is the dynamic viscosity of the filtered fluid, Pa·s; $L$ is the thickness of the permeable layer of fiber sediment, m. To determine the permeability coefficient, technical water spills were carried out according to the scheme of Figure 2, and through the sediment layers of different thicknesses (Figure 2, b) from chopped quartz fibers with a diameter of 12 μm, a length of 20.1; 13.4 and 6.7 mm with fiber elongation of 1680 - 1120 - 560.

Figure 2. Scheme of pouring plant (a): 1 - pump; 2 - counter; 3 - vacuum gauge; 4 - valve and (b) - a layer of quartz fibers

When samples were spilled with water, the pressure drop across the layer was measured $\Delta P = P_2 - P_1$ by vacuum gauge, fiber layer thickness $h_f$ and fluid flow rate $Q = F_{smpl} \cdot U$, cm$^3$/s - by flow meter, where $F_{smpl} = 220$ cm$^2$ is the area of the sample. The porosity of the fibrous sample was determined from the equation:

$$n = 1 - \frac{M_{smpl}}{F_{smpl}h_f \rho_f}.$$

Where, $M_{smpl}$ is the mass of the dry sample, $h_f$ is the thickness of the fiber layer, $\rho_f = 2.19$ g/cm$^3$ is the density of quartz fibers. The permeability coefficient in the Darcy equation was determined by the formula (2), and the calculation results in the form of experimental points are presented in Figure 3, a.
\[ K_D = Q L \eta Lq / (F_{smpf} \Delta P) \]  

(2)

3. Results and discussion

The permeability coefficient is inherently a structural characteristic, determined mainly by the geometry of the pore space and according to I. Czerny’s hypothesis [10] depends on the specific volume of open pores \( n = V_p / V_b \) in a cube divided by the square of the specific surface of fibers \( S_y \) in a porous material slowly flowing around with a liquid:

\[ K_D = c_k n^3 / S^2 = c_k n^3 / (S_0 \vartheta f)_2^2 = 0.5 d_f^2 n^3 / 16 (1-n)^2, \]  

(3)

Where, \( S_0 = S_f / f_t = 4 / d_f \), \( 1/m \) – specific surface of one fiber; \( d_f \) - average (efficiently streamlined) fiber diameter, m; \( \vartheta f \) - volumetric fiber content in the sediment layer, \( \vartheta f = 1 - n \).

The coefficient \( c_k \) in the Cozeny-Karman formula (3), determined from the solution of the hydrodynamic equation for the flow of viscous liquid around round fibers along their axis, is \( c_k = 0.5 \). However, when the fluid flows across the fibers (Fig. 1, b), this coefficient obtained from experiments is many times smaller than the theoretical one and depends, first of all, on the surface of the flow around round fibers with the formation of stagnant regions and on the porosity of the fiber layer. Processing of experimental data made it possible to determine the value of the coefficient \( c_k \), which linearly depends on the porosity \( n \) (Fig. 3, b)

\[ c_k = 0.76 (1 - n) \]  

(4)

In fig. Figure 3a shows the dependences of the permeability coefficient \( K_D \) on the porosity of the fibrous material (curve 1), calculated by formula (3) for \( c_k = 0.5 \). Curve 2 is an approximation of the experimental values of the coefficient \( K_D \) on porosity, constructed according to formula (3) taking into account dependence (4):

\[ K_D = 0.76(1-n) d_f^2 n^3 / 16 (1-n)^2. \]  

(5)

From the analysis of Fig. 3a, it follows that dependence (5) agrees relatively well with the results of spilling of fibrous samples from short quartz fibers with a diameter of 12 \( \mu \)m.
Conclusion

When filtering liquid through a layer of fibers oriented in the plane of the sample, the use of the coefficient $c_k = 0.5$ in the Cozeny–Karman formula is not correct, since a transversely flowing water from the back of the fibers produces a shaded region, an uneven and slowed down fluid flow rate. The linear dependence of the coefficient $c_k = 0.76 (1-n)$ on porosity obtained from processing the results of experimental spills allows the Darcy equation to be used in the calculation of technological parameters for the manufacture of heat-shielding, heat-insulating, and filtration products from short ceramic fibers by liquid filtration.

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