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INVESTIGATION OF THE GASDYNAMIC PERMEABILITY OF A RETICULAR FILTER FOR He, Ar, Xe

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UDC 539.217.082.3

A number of problems in science, engineering, and technology can be solved with the help of fine-pore membranes. In recent years, membranes which are called reticular filters are finding increasing applications. These membranes are obtained by bombarding thin polymeric films with high-energy ions [1]. The distinguishing features of such membranes are: high density and nonoverlapping of pores, almost cylindrical shape of the channels, and small variance of the pores with respect to radius. All of these properties make reticular filters irreplaceable in many cases, because the quality of the filtration in them is higher than for other types of membranes.

There is a large number of papers in the literature concerning the investigation of gas flows with arbitrary Knudsen numbers through capillaries and capillary sieves with controllable geometry. It is shown in these papers that the gasdynamic permeability of different gases is sensitive to the geometry, material, temperature, and roughness of the surface of the channel [2, 4]. There are practically no analogous investigations of reticular filters of the type indicated above, although they are of undoubted interest, because they permit clarifying both the characteristics of the structure of pores in the reticular filters themselves and the physical nature of the interaction of molecules of different gases with one another and with the surface of channels.

In this paper we present the results of measurements of the flows of helium, argon, and xenon through a reticular filter in a wide range of Knudsen numbers ($0.5 < \mathrm{Kn} < 500$) at a temperature of $T = 293°\mathrm{K}$.

The measurement procedure and the schematic of the setup used to perform the investigations are described in detail in [4]. The method of stationary flow, based on determining the rate of change of the volume of the system at constant pressure p, was used. The gas flowing through the reticular filter discharged into a vacuum. The filter under study was prepared from a polyethylene terephthalate film $L = (1.00 \pm 0.05)\cdot 10^{-3}$ cm thick. The pore density of the filter was $N = (4.0 \pm 0.1)\cdot 10^{7}\ \mathrm{cm}^{-2}$, the average radius of the input cross sections of the pores was $\langle R_0\rangle = (1.25 \pm 0.30)\cdot 10^{-5}$ cm, the average radius of the outlet openings was $\langle R_L\rangle = (2.6 \pm 0.3)\cdot 10^{-5}$ cm. The quantities N, $\langle R_0\rangle$, $\langle R_L\rangle$ were estimated from photographs of the filter, obtained with the help of an electron microscope.

The experimental results for different gases were compared in terms of the relative flow rate ω as a function of the rarefaction parameter δ related to the Knudsen number by the relation

$$\delta = \frac{\sqrt{\pi}}{2}\frac{\langle R\rangle}{\lambda} = \frac{\sqrt{\pi}}{2}\frac{1}{\mathrm{Kn}}, \tag{1}$$

Sverdlovsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 67-69, January-February, 1984. Original article submitted December 14, 1982.

0021-8944/84/2501-0061$08.50

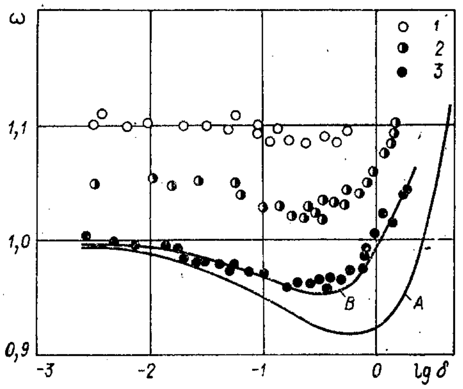

Fig. 1

where <R> is the average radius of the channels in the reticular filter and λ is the average mean-free path length of gas molecules.

The relative flow rate of gas ω_i was calculated from the formula

$$\omega_i = \frac{Q_i}{Q^0_{\mathrm{Xe}}}\left(\frac{\mu_i}{\mu_{\mathrm{Xe}}}\right)^{1/2},$$

where Q_i is the volume flow rate of the gas under investigation; Q^0_{Xe} is the volume flow rate of xenon in the free-molecular flow regime; and μ_i and μ_{Xe} are the molecular weights of the gas under study and of xenon, respectively.

Figure 1 shows the experimental values of the relative flow rate of He, Ar, Xe (points 1-3) as well as the theoretical dependence $\omega(\delta)$ for long cylindrical channels (A), obtained assuming a completely diffuse reflection of molecules of gas from the walls [5]. The radius in Eq. (1) for calculations of the experimental dependences $\omega_i(\delta_i)$ was chosen based on the best agreement between the experimental values of the relative flow rate of xenon (as the most "diffuse" gas) and curve A. As is evident from Fig. 1, the depth of the Knudsen minimum for xenon is approximately two times smaller than for the theoretical curve A. This difference between the experimental data and the theory cannot be explained either by the existing dispersion of the input sizes of pores or by their conicity. It was verified that the dependence $\omega(p\langle R\rangle)$ for two channels differing in diameter by a factor of 2 (<R> is the average radius of the channel and p is the pressure at the channel inlet) does not differ significantly from the curve $\omega(p\langle R\rangle)$ for a single capillary with radius R = <R>. The form of the curve $\omega(\delta)$ for intermediate Knudsen numbers is likewise insensitive to the conicity of the expanding channel. In a conical channel, as the pressure gradually increases the regime with collisions between gas molecules first arises at the narrowest location due to the approximately linear decrease in pressure along the core. For this reason, the deviation of the dependence $\omega(\delta)$ from the constant free-molecular value with increasing pressure in an expanding channel is determined by the dimensions of its inlet and is virtually independent of the diameter of the outlet.

The experimental and theoretical (B, see Fig. 1) dependences of the relative flow rate on the rarefaction parameter δ could be matched only by taking into account the finite length of the channel ($L/\langle R\rangle \sim 80$). Curve B was obtained using the semiempirical formula obtained by Lund and Berman [6], which permits calculating the flow of gas through short channels. The magnitude of the average pore radius, selected from the condition of best agreement between the theory (B) and experiment, constituted $\langle R\rangle = (1.35 \pm 0.10)\cdot 10^{-5}$ cm, which within the limits of error of the experiment coincides with the radius of the inlet openings of the pores, recorded on the electron microscope. The fractions of the diffusion reflection of gases, which constituted $\varepsilon_{\mathrm{He}} = 0.95$, $\varepsilon_{\mathrm{Ar}} = 0.97$, were calculated from the excess of the relative flows of He and Ar in the free-molecular regime above unity (see Fig. 1). These data coincide, within the limits of error of the experiment (∿1%), with the corresponding values $\varepsilon_{\mathrm{He}} = 0.95$, $\varepsilon_{\mathrm{Ar}} = 0.98$ for fused glass [3].

This agreement indicates the quite high smoothness of the walls of the pores of the polyethylene teraphthalate filter studied, since it is known [4] that roughness eliminates the differences in the relative flow rates of different gases.

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EFFECT OF NONISOTHERMAL CONDITIONS OF SKIN FRICTION IN SUBSONIC TURBULENT CHANNEL FLOWS

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UDC 536.24:532.517.4

A number of different approaches are available in current literature to the theoretical determination of skin friction in nonisothermal flows in channels and pipes. Some of these (e.g., [1-3]) predict an appreciably stronger dependence of skin friction on temperature ratio $\psi = T_W/T_\infty$ (T_W is the wall temperature; T_∞ is the core fluid temperature), than those indicated by experimental results [4-7]. Significantly better agreement with existing experimental results is achieved in [8, 9] based on comprehensive numerical analysis of a system of integrodifferential equations. However, the assumptions they make are not always sound nor physically clear. Besides, the use of numerical methods does not allow the authors to relate their analysis to known limiting laws and simultaneously develop reliable numerical expressions to generalize experimental data. Physically quite clear results have been obtained in [10-12] and, in particular, very simple limiting laws for skin friction have been established. At the same time, it appears that based on the same physically clear assumptions, it is possible to obtain even more general results which agree well with experimental data. Simultaneously, these results which coincide with the limiting values at infinite Reynolds number make it possible to indicate the limits of applicability of these laws and extend them to finite Reynolds number range.

The problem is reduced to the consideration of stable turbulent fluid flow in a channel. In order to simplify the problem it is assumed that laminar and turbulent Prandtl numbers are equal to one and that the specific heat is independent of temperature. The temperature T and velocity v distributions are then described by

$$\tau = \rho(\nu^{\mathrm{M}} + \nu^{\mathrm{T}})|dv/dy|,\ q = -\rho c_p(\nu^{\mathrm{M}} + \nu^{\mathrm{T}})\ (dT/dy), \tag{1}$$

where ν^M and ν^T are molecular and eddy viscosity coefficients; ρ is the density; ν is the shear stress; q is the heat flux. Assume that τ and q vary linearly along the channel section (it will later be shown that this simplifying assumption is quite adequate for the determination of skin friction coefficients):

$$\tau = \tau_w|y|/(h/2),\ q = q_w|y|/(h/2), \tag{2}$$

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 1, pp. 69-76, January-February, 1984. Original article submitted December 14, 1982.