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## Abstract

## Full Text

## PHYSICS

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# EXPERIMENTAL INVESTIGATION OF THE FILTRATION OF RAREFIED AIR THROUGH POROUS BODIES IN THE KNUDSEN AND TRANSITION PRESSURE REGIONS

The molecular, or Knudsen, regime of gas flow in porous bodies is known to be the regime of flow in which the mean free path of the gas molecules is much greater than the pore diameter. With increasing pressure the molecular regime of gas flow passes into the viscous regime, in accordance with which the gas flow rate becomes a monotonic and, to a first approximation, linearly increasing function of pressure. The experiments of Knudsen ([1]), Gaede ([2,3]), and other investigators showed that, in the filtration of gas in capillaries of various cross sections, the curve of gas flow rate as a function of pressure has a minimum corresponding to the transition region, in which the mean free path of the molecules is of the same order as the dimensions of the capillaries. Until recently, however, no explanation of this minimum had been given.

A theoretical study of the flow of gases in highly porous bodies in the transition pressure region was carried out by B. V. Deryagin and S. P. Bakanov ([4,5]), who considered the process of gas diffusion through a model of a porous body consisting of spheres located at a considerable distance from one another and rigidly fastened (for example, by means of thin ideally elastic rods). B. V. Deryagin and S. P. Bakanov showed that, in the flow of a rarefied gas in a body of high porosity ($\delta \to 1$) in the region of low pressures, in addition to the molecular (Knudsen) regime of flow and the laminar-viscous regime, there exists a third regime, intermediate between them—the pseudomolecular regime. In this regime of flow, collisions of the gas molecules with one another, despite their large number, do not directly affect the filtration resistance, but only indirectly, by causing the presence of a convective component of the gas motion through the equalization of molecular momenta during their collisions. This causes a slight difference between the resistance in the pseudomolecular regime and the resistance in the molecular regime. At the same time, this difference does not affect the form of the equation relating the gas flow rate to the pressure gradient –

**Fig. 1.** Experiments on the filtration of air through a porous sample

Figure 1. Experiments on the filtration of air through a porous sample
$S = 0.5$ m$^2$/g, $\delta = 0.84$, $D = 6.6 \cdot 10^{-4}$ cm, $\lambda = 12 \cdot 10^{-4}$, $P_{\text{av}} = 3$ mm Hg.

Figure 1: Figure 1. Experiments on the filtration of air through a porous sample $S = 0.5$ m$^2$/g, $\delta = 0.84$, $D = 6.6 \cdot 10^{-4}$ cm, $\lambda = 12 \cdot 10^{-4}$, $P_{\text{av}} = 3$ mm Hg.

Fig. 2

Figure 2: Fig. 2

$S = 0.5$ m$^2$/g, $\delta = 0.84$, $D = 6.6 \cdot 10^{-4}$ cm,
$\lambda = 12 \cdot 10^{-4}$, $P_{\text{av}} = 3$ mm Hg.

···but only reduces the value of the corresponding numerical coefficient, which turns out to be somewhat smaller than for the Knudsen regime. Therefore the gas flow rate through the partition must decrease in the region of low pressures as the pressure increases. On the other hand, at high pressures the gas flow rate through unit cross section must be directly proportional to the pressure (the viscous flow regime). Consequently, the curve of the dependence of the gas flow rate on its concentration or on the gas pressure must pass through a minimum.

**Fig. 2.** Experiments on the filtration of air through insulating cardboard.
$S = 0.006$ m$^2$/g, $\delta = 0.9$, $D = 7 \cdot 10^{-2}$ cm,
$\lambda = 3.8 \cdot 10^{-2}$ cm, $P_{\text{av}} = 4 \cdot 10^{-2}$ mm Hg.

For the final confirmation of the theory it is necessary first to show that the minimum exists in porous bodies with a high porosity coefficient, where the theory is applicable most rigorously. The experiments were carried out on a special apparatus. The porous body was placed in a cylindrical cuvette. After a rarefaction of $10^{-2}$ mm Hg had been reached, a diffusion pump was switched on and the air was evacuated to $10^{-3}$–$10^{-4}$ mm Hg, with a continuous steady flow of air through the specimen. The gas flow rate was measured by means of a capillary rheometer. The pressures on both sides of the specimen were measured by means of two thermocouple manometers or by a differential manometer, depending on the magnitude of the pressure. By varying the pressure with a microvalve, but without changing the rate, one can investigate the flow of air through the porous body at different mean pressures in it.

**Fig. 3.** Experiments on the filtration of air through white-soot powder.
$S = 60$ m$^2$/g, $\delta = 0.7$, $D = 3.4 \cdot 10^{-6}$ cm, $\lambda = 1 \cdot 10^{-5}$ cm, at $P = 365$ mm Hg.

Filtration of air was observed through pressed cotton wool, glass filters, cardboard of various types, and other materials with porosity 0.4–0.9 (Figs. 1, 2, and 3). At high pressures, the flow of gas through the capillaries of a porous

Fig. 3

Figure 3: Fig. 3

body follows the Poiseuille—Darcy law, and the gas flow rate is directly proportional to the mean pressure. Our experiments showed that, for a highly porous body with porosity 0.8—0.9 (Figs. 1 and 2), a minimum is observed on the curve of gas flow rate as a function of pressure; this minimum corresponds to the pressure at which the mean free path of the molecules becomes of the same order as the pore diameter. This minimum corresponds to the pseudomolecular flow regime, which is confirmed by the theory of the latter ([4,5]).

In the graphs (Figs. 1 and 2) there is a rectilinear portion of the curve on which the air flow rate does not depend on the mean pressure.* According to na—

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* If one carefully examines the graphs of gas flow rate as a function of pressure, constructed from the work of Knudsen and Gaede for round and slit capillaries, one can also discover the existence of rectilinear segments parallel to the abscissa axis in the left-hand part of the curves. The authors themselves do not pay attention to this, and the corresponding rectilinear portions are not shown on the graphs they present; only in E. Bloch's book ([3]) are Knudsen's data depicted in such a way that the horizontal portion is noticeable.

According to our calculations, this segment corresponds to the molecular-flow region. Determination of the right-hand boundary of the rectilinear segment, corresponding to the abrupt transition of the molecular flow regime into another, is very important both for theory and for the practice of determining the specific surface area of powdered and porous bodies (6-12). At moderate porosities ($\delta < 0.7$), the horizontal segment passes abruptly into an ascending one, corresponding to the viscous regime (Fig. 3). At high porosities ($\delta > 0.8$), there is a transition region, and a break downward is observed on the curve, corresponding to the transition to the pseudomolecular regime (a minimum on the curve); subsequently the minimum passes into a rectilinear ascending segment of the curve, corresponding to the viscous regime.

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