# GAS FLOW IN NUCLEPOROUS FILTERS

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Membrane filters in which particle precipitation takes place on the frontal surface have been widely used recently for studying hydrosols and aerosols. In contrast with membrane filters having a complex structure of sinuous polydisperse pores, the so-called nucleporous filters [1] are a transparent thin film of thickness $l \sim 15\,\mu$ with circular channels of identical diameter from 0.25 to $8\,\mu$, arranged primarily perpendicular to the filter plane; the filter porosity is about 5%.

The filter material (polycarbonate, density 0.95 g/cm$^3$) is chemically stable to many reagents and does not lose its high strength up to 140°C. The channels are obtained by chemical etching of the film after irradiation by high-energy heavy particles [2].

Following are the characteristics of four types of filters manufactured by General Electric:

| | Type | $l$, $\mu$ | $N$, cm$^{-2}$ | $r$, $\mu$ | $r^*$, $\mu$ |
|---|---|---|---|---|---|
| 1 | 0.5 | 13.2 | $4.5 \cdot 10^7$ | 0.32 | 0.32 |
| 2 | 1 | 16.5 | $4.8 \cdot 10^6$ | 0.58 | 0.56 |
| 3 | 2 | 13.1 | $3.7 \cdot 10^6$ | 2.1 | — |
| 4 | 8 | 11.6 | $1,6 \cdot 10^5$ | 3,5 | — |

Here N is the number of pores per unit area and r is their radius. For the first three filters, N and r were determined by electron microscope photography of carbon replicas obtained from the surface of the filters (Fig. 1a, filter 1, 17,500X). The measurement of the pores in filter 4 was made using an optical microscope (Fig. 1b, 890X). The thickness $l$ was determined by weighing.

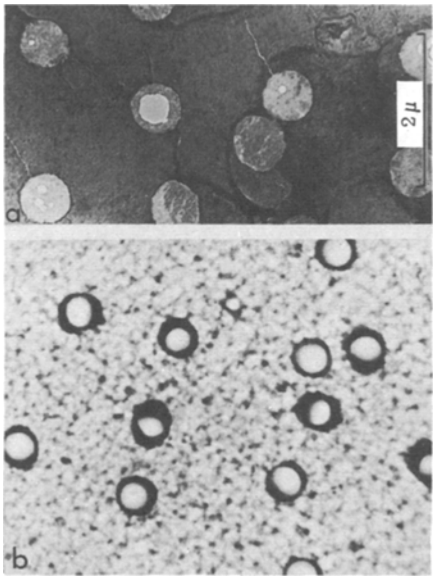

Fig. 1

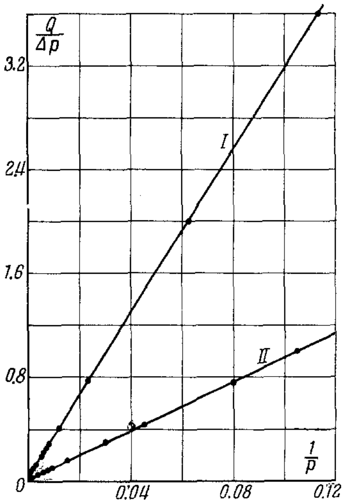

Fig. 2

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Moscow. Prague. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, Vol. 10, no. 3, pp. 109-112, May-June, 1969.

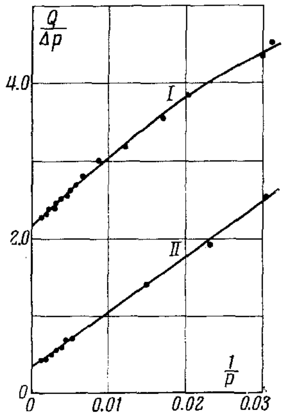

Fig. 3

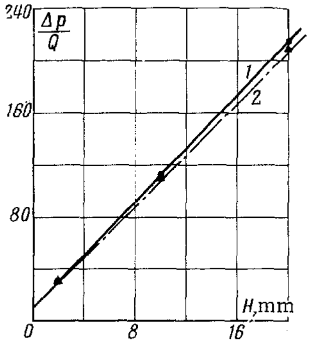

Fig. 4

To study the nature of air flow through the pores, we measured the hydraulic resistance of the filters with various pressures p from 7 to 745 mm Hg. Figure 2 shows the results of measurements of filtered air penetrance ($Q/\Delta p$) through filters 1 (I) and 2 (II) as a function of $1/p$, where Q is the air flow rate in $cm^3/sec$, $\Delta p$ is expressed in cm dibutylphthalate column (density 0.95 $g/cm^3$), and p is in mm Hg.

We see from these data that a linear variation of $Q/\Delta p$ as a function of $1/p$ is observed for filters 1 and 2 up to large values of $1/p$. This result is unexpected, since for $1/p = 0.12$ for filter 1 the Knudsen parameter $K = \lambda/r$ is 18, and the gas flow through the pores can be considered free molecular (mean free path of air molecules at p = 760 mm Hg and t = 20°C $\lambda = 6.45 \cdot 10^{-6}$ cm). In this case the theoretically computed value of $Q/\Delta p$ should exceed the experimentally determined value by at least a factor of 1.5 [3].

A similar phenomenon is observed for filter 3 (curve II in Fig. 3) and in the initial segment of curve I for filter 4. For $p < 100$ mm Hg curve I deviates from a straight line in the opposite direction from that expected from theoretical considerations.

This result is apparently explained by the fact that with reduction of the pressure there is an increase of the role of the resistance of the frontal surface of the filter, and this is the faster the larger $r/l$.

As shown in [4], the resistance of a single isolated hole of radius r in an infinitely thin wall for Reynolds numbers $R < 1$ is

$$\Delta p_1 = \frac{3\mu Q}{r^3} \tag{1}$$

where $\mu$ is the viscosity of the air. Thus the over-all resistance of a channel of length $l$ arranged perpendicular to the plane of the wall, with account for the heat loss prior to entry into the channel (neglecting for $R < 1$ the entrance effect in the channel), can be written in the form

$$\Delta p = \Delta p_2\left(1 + \frac{\Delta p_1}{\Delta p_2}\right) = \frac{8\mu l Q}{\pi r^4}\left(1 + \frac{3\pi r}{8l}\right) \tag{2}$$

where $\Delta p_2$ is the resistance of a cylindrical channel.

We see from this formula that the hydrodynamic effect of the front wall can be neglected for $r/l \ll$i.

It should be noted that even in the case with statistically uniform arrangement of the channel holes on the filter plane there is a definite percent (about 10% for the filters studied) of partial overlapping of the channel holes, which leads to a decrease of the differential pressure $\Delta p$.

This reduction is balanced by some increase of the quantity $\Delta p$ as a result of the slight increase of the channel length with deviation from perpendicularity (to the filter plane).

To refine this question we performed model tests by measuring the pressure drop for the flow of a viscous fluid with $R < 1$ (VM-4 vacuum oil, $\mu_{20°C} \approx 5$ poise) through systems of circular parallel channels. The channels with r = 1 mm were made in brass disks of diameter 25 mm and thickness $l$ equal to 2, 10, and 20 mm. Seven channels were used, which corresponded to porosity $\varepsilon \sim 5\%$ of the nucleporous filters.

Parallel measurements were made of the pressure drop through one such channel of variable length; in this case $\varepsilon < 1\%$. The number R did not exceed 0.3, so that the entrance effect, associated with establishment of the parabolic velocity profile in the channel, was small.

Figure 4 shows in the coordinates $(\Delta p/Q, l)$ the data from measurements of the differential pressure for the single channel (1) and for the system of channels (2), converted to a single channel. The intercept on the ordinate axis corresponds to the magnitude of the front wall resistance and for $l = 2r$ amounts to one third the over-all resistance, which corresponds to formula (2). We note that the agreement of curves 1 and 2 in the figure indicates the absence of mutual hydrodynamic influence of neighboring channels.

It follows from these model experiments that in the nucleporous filters for commensurate r and $l$ we must take into account the influence of the frontal surface. This influence was also significant in measuring the diffusional precipitation of highly disperse NaCl aerosols with particle radius $r_0 < 0.02\,\mu$, obtained by spontaneous condensation of supersaturated salt vapors [5]. The average particle diffusivity $\langle D \rangle$ was determined from the aerosol flow through a slotted battery or a standard fibrous filter [6]. Here are presented the results of measurements of the particle flow $(n/n_0)_1$ through filter 4, which are considerably below the values of $(n/n_0)_2$ calculated theoretically for identical cylindrical channels [7]:

| Q, $cm^3/sec$ | $\langle D \rangle$, $cm^2/sec$ | $(n/n_0)_2$, theor. | $(n/n_0)_1$, exper. |
|---|---|---|---|
| 30 | $3.3 \cdot 10^{-3}$ | 0.19 | 0.12 |
| 11.5 | $5.1 \cdot 10^{-4}$ | 0.46 | 0.33 |
| 1.4 | $4.6 \cdot 10^{-5}$ | 0.53 | 0.39 |
| 1.4 | $3.8 \cdot 10^{-5}$ | 0.61 | 0.47 |

This implies that part of the aerosol precipitates on the frontal surface of the filter ($S = 5.7\ cm^2$ is the filter area).

In conclusion we note that since the channel radii are practically the same for each filter type, the quantity $r^*$ for $r/l \ll 1$ can be found from Figs. 2 and 3, using the Poiseuille formula with slip correction

$$\frac{Q}{\Delta p} = \frac{\pi r^{*4} N}{8 \mu l}\left(1 + 4\frac{\xi}{r^*}\right), \qquad \xi = \frac{\xi_0 p_0}{p} \tag{3}$$

Here $\xi_0$ is the gas slip coefficient for t = 23°C and p = 760 mm Hg. Substituting into the expression for the slope of this straight line, which expresses the dependence of $Q/\Delta p$ on $1/p$, the value of N found from the intercept on the ordinate axis, we obtain

$$r^* = \frac{4\xi_0 p_0}{p}\left[\frac{Q/\Delta p}{(Q/\Delta p)_0} - 1\right]^{-1} \tag{4}$$

The values of $r^*$ for filters 1 and 2, calculated using (4), are presented above, where $\xi_0 = 8.2 \cdot 10^{-6}$ cm [8].

The authors wish to thank I. Rudysheva for preparing the electron microscope pictures, and also I. B. Stechkina and N. A. Fuks for joint discussion of the results.

## LITERATURE CITED

1. K. R. Spurny and J. P. Lodge, "Die Aerosolfiltration mit Hilfe der Kernporenfilter," Staub Reinhaltung der Luft, vol. 28, no. 5, p. 179, 1968.
2. R. L. Fleischer, P. B. Price, and R. M. Walker, "Method of forming fine holes of near atomic dimensions," Rev. Scient. Instrum., vol. 34, no. 5, p. 510, 1963.
3. M. Devienne, "Frottement et échanges thermiques dans gaz rarefiés," Paris, Gauthier-Villars, 1958.
4. H. Hasimoto, "On the flow of a viscous fluid past a thin screen at small Reynolds numbers," J. Physical Soc. Japan, vol. 13, no. 6, p. 633, 1958.
5. N. A. Fuks and A. G. Sutugin, "Highly disperse aerosols," Kolloidn. zh., vol. 26, no. 1, p. 110 (1964).
6. A. A. Kirsch and N. A. Fuchs, "Studies on fibrous aerosol filters — III: Diffusional deposition of aerosols in fibrous filters," Annals of Occupational Hygiene, vol. 11, no. 4, p. 299, 1968.
7. P. G. Gormley and M. Kennedy, "Diffusion from a stream flowing through a cylindrical tube," Proc. Roy. Irish. Acad., Sect. A — 52, no. 12, pp. 163-169, 1949.
8. R. A. Millikan, "Coefficients of slip in gases and the law of reflection of molecules from the surfaces of solids and liquids," Phys. Rev., vol. 21, no. 3, pp. 217-238, 1923.