

ANALYTICAL METHODS
FOR DETERMINATION OF AEROSOLS
BY MEANS OF MEMBRANE ULTRAFILTERS. XVIII.*

AEROSOL SAMPLING
UNDER EXTREME GAS CONDITIONS

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Gas temperature and gas pressure have an important influence on the filtration properties of pore filters (membrane ultrafilters and nuclear pore filters). Both of these quantities have an influence on the filter efficiency and on the pressure drop. The impaction and diffusion separation of a pore filter depend on the gas viscosity and on the mean free path of gas molecules. Both of these quantities therefore depend on the gas pressure and gas temperature, too. Using the former filtration theory for pore filters, the pressure drop and the efficiency as functions of temperature and pressure were calculated, measured and discussed.

The different equations of the pressure drop¹ and filter efficiency^{2,3} are valuable mostly for normal thermodynamic conditions. Now there are also in the practice many extreme conditions under which gases should be filtered and aerosol sampling should be done. Among these extreme conditions are to be understood *e.g.* low and high gas pressures and low and high gas temperatures.

There are not many publications in this field. Concerning the gas temperature dependence for fiber filters, there are papers by Pich, Binek⁴ and Benarie, Quetier⁵. First paper on the theoretical and experimental gas pressure dependence for fiber filters (both, gas pressure drops and filter efficiencies) published in 1960 Stern, Zeller and Schekman⁶. They had studied efficiency and pressure drop dependences of a fiber filter under low pressures. Some remarks about filtration under high temperature and high gas pressure are also in the publication by Strauss and Lancaster⁷.

Nowadays fiber filters are used in practice under low and high gas pressures very often (*e.g.* in jet-planes, space vehicles, submarines, nuclear power stations, compressors *etc.*). The same is valid in the field of aerosol sampling. Therefore the filtration theory of pore filters should be also extended to the filtration under extreme conditions. This is also the point of this paper.

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THEORETICAL

In preceding papers it has been pointed out that the theory of aerosol filtration of pore filters is in good quantitative agreement with the experiment in case of nuclear pore filters³ and in qualitative agreement in case of membrane filters². This theory is used for calculation and forecasting of the filtration and hydrodynamical properties of an analytical pore filter working under normal thermodynamic conditions and can be extended for calculation of those properties under extreme conditions, too.

Temperature Characteristics

The equations for the pressure drop¹ and for the filtration efficiency^{2,3} show that these both quantities are a function of gas temperature. The pressure drop as well as the partial efficiencies of impaction and diffusion separation are a function of gas viscosity and of the mean free path of gas molecules³. Both of them are a function of temperature⁵.

$$\eta = A \sqrt{T} \left(1 + \frac{a}{T} \cdot 10^{-c/T} \right), \quad (1)$$

where $A = 1.448 \cdot 10^{-5}$, $a = 122.1$ and $c = 5.0$ (See also the Table I, $\eta = \varphi(T)$ for nitrogen), and

$$l = 0.75kT/\pi s_M^2 p. \quad (2)$$

From the equations for gas pressure drop¹, $\Delta p = f(T)$ it is clear, that if gas temperature is rising, also the pressure drop has reason to rise (Fig. 1). From the equations for the total filtration efficiency^{2,3} it was possible to count (by means of computer) the temperature characteristics $E = F(T)$. An example can be introduced in the Fig. 2.

Gas Pressure Characteristics

The pressure drop is a function of the gas pressure because the quantities η and l have a pressure dependence⁸⁻¹¹.

$$\eta = \eta_0 b \varrho_g [(1/b \varrho_g \chi) + 0.8 + 0.761 b \varrho_g \chi], \quad (3)$$

where

$$b = \frac{4}{3} \pi s_M^3 / m_M, \quad \varrho_g = M p / RT,$$

$$\chi = 1 + 0.6250(b \varrho_g) + 0.2862(b \varrho_g)^2 + 0.1150(b \varrho_g)^3.$$

An example for $\Delta p = f'(p)$ is in the Fig. 3 (measured and calculated values). The gas pressure makes also an important influence on two filtration mechanisms: on the impaction and diffusion separations. The partial efficiency of impaction³ is a function of dimensionless parameter Stk and the diffusion separation³ is a function of dimensionless parameter N_D . Both of them are functions of η and l :

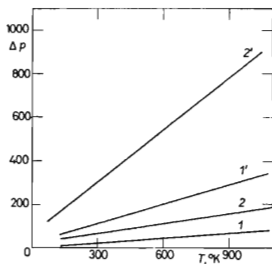


FIG. 1

A Theoretical Dependence $\Delta p(\text{Torr}) - T(\text{K})$; for Two Types of Nuclear Pore Filters

$R = 0.5 \mu\text{m}$, $P = 0.04$, $L = 11 \mu\text{m}$, $q = 5 \text{ cm s}^{-1}$ (1) and $q = 20 \text{ cm s}^{-1}$ (1'); $R = 0.25 \mu\text{m}$, $P = 0.05$, $L = 12 \mu\text{m}$, $q = 5 \text{ cm s}^{-1}$ (2) and $q = 20 \text{ cm s}^{-1}$ (2').

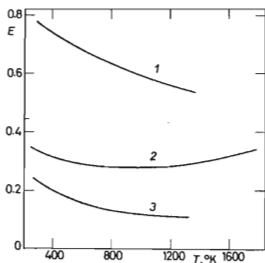


FIG. 2

The Influence of Gas Temperature T (K) on Filter Efficiency E , for Aerosol Filtration by Means of Nuclear Pore Filters

$q = 7.5 \text{ cm s}^{-1}$, $s = 4.0 \text{ g cm}^{-3}$ $R = 2.5 \mu\text{m}$, $r = 1.0 \mu\text{m}$ (1); $R = 0.25 \mu\text{m}$, $r = 0.1 \mu\text{m}$ (2); $R = 1.0 \mu\text{m}$, $r = 0.2 \mu\text{m}$ (3).

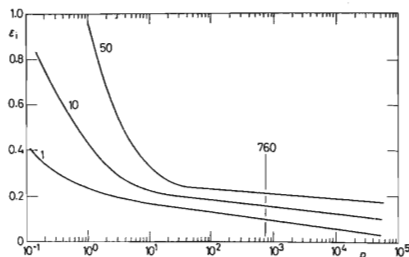


FIG. 3

The Influence of the Gas Pressure p (Torr) on the Impaction Efficiency ϵ_i ; $R = 0.5 \mu\text{m}$, $P = 0.05$, $r = 0.1 \mu\text{m}$, $T = 298 \text{ K}$, $q = 1$; 10 and 50 cm s^{-1} .

$$\text{Stk} = \frac{C}{\eta} \frac{3}{2}(4r^2qs/R), \quad (4)$$

where $C = 1 + 1.246l/r + (0.42 l/r) \cdot \exp[-0.87r/l]$

(see also the Table II and Fig. 5).

$$N_D = LPD/R^2q, \quad (5)$$

where $D = CkT/6\pi\eta r$.

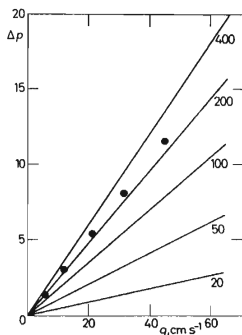


FIG. 4
The Influence of Gas Pressure p (Torr) = 20–400 on the Dependence Filter Pressure Drop Δp (Torr) – Gas Velocity q (cm s^{-1})

Nuclear pore filter $R = 1.5 \mu\text{m}$, $p = 20$ to 400 Torr, $T = 298\text{K}$. Experimental curves and computed values. ($p = 200$ Torr \bullet).

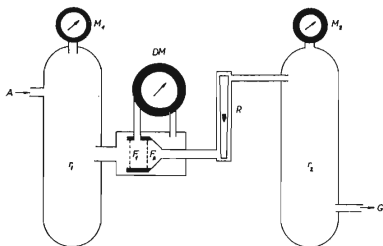


FIG. 5

A Schematic of Equipment for Measurement of Filter Efficiency and Pressure Drop under Low and High Gas Pressures

A Aerosol, G gas, r_1 , r_2 reservoirs, M_1 , M_2 manometers, DM differential manometer (Δp), R flow meter, F_1 , F_2 testing filter and absolute filter.

The equations (4) and (5) point out, that the aerosol filtration by means of pore filter is influenced by gas temperature and gas pressure through the parameters η and l .

EXPERIMENTAL

The experimental measurement of temperature and pressure characteristics is not simple. The dependences $\Delta p = f(T)$ and $E = F(T)$ were not measured as the membrane ultrafilters and nuclear pore filters are made of organic material and are not stable over 100°C. The dependences $\Delta p = f'(p)$ were measured in one of previous publications¹ (see also Fig. 4).

The dependences $E = F'(p)$ were measured by means of a special equipment (Fig. 5), and by means of a radioactive labelled aerosol^{1,2} as a testing material. The reservoirs (r_1 and r_2) were used for the measurement of filter efficiencies at low as well as at high pressures.

Radioactive labelled aerosols of selenium were prepared in a special generator^{1,2} and were introduced into the reservoir 1 under low pressure (≈ 10 Torr). Then the gas pressure (in this reservoir) was increased to the desirable pressure and aerosol was sucked through two filters (F_1 and F_2). The gas velocity was measured by means of a flow meter R . The total filter efficiency was found by measuring the radioactivity of both filters F_1 and F_2 . The curves $E = F'(p)$ were also calculated by using the published theory³ (Fig. 6).

RESULTS AND DISCUSSION

The influence of gas pressure on the filter pressure drop (Fig. 1) is important and the function $\Delta p = f(T)$ is linear. Therefore it should be also possible to use some types of pore filters, e.g. silver membrane filters and mica membrane filters, for temperature measuring of gases^{1,3}.

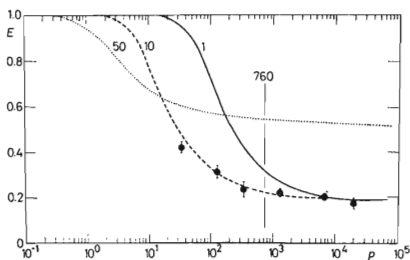


FIG. 6

The Influence of Gas Pressure p (Torr) on the Total Filter Efficiency E

($R = 0.5 \mu\text{m}$, $P = 0.05$, $r = 0.1 \mu\text{m}$, $T = 298\text{K}$, $q = 1$; 10 and 50 cm s^{-1}). Computed curves and experimental values ($q = 10 \text{ cm s}^{-1}$, ●).

TABLE I
Gas Viscosity as a Function of Gas Temperature

T, K	η, Poise	T, K	η, Poise
150	$101.12 \cdot 10^{-6}$	750	$341.76 \cdot 10^{-6}$
200	$129.91 \cdot 10^{-6}$	800	$356.00 \cdot 10^{-6}$
250	$156.13 \cdot 10^{-6}$	850	$369.76 \cdot 10^{-6}$
300	$180.21 \cdot 10^{-6}$	900	$383.09 \cdot 10^{-6}$
350	$202.53 \cdot 10^{-6}$	950	$396.02 \cdot 10^{-6}$
400	$223.36 \cdot 10^{-6}$	1 000	$408.58 \cdot 10^{-6}$
450	$242.92 \cdot 10^{-6}$	1 050	$420.81 \cdot 10^{-6}$
500	$261.40 \cdot 10^{-6}$	1 100	$432.72 \cdot 10^{-6}$
550	$278.94 \cdot 10^{-6}$	1 150	$444.33 \cdot 10^{-6}$
600	$295.66 \cdot 10^{-6}$	1 200	$455.68 \cdot 10^{-6}$
650	$311.65 \cdot 10^{-6}$	1 250	$466.77 \cdot 10^{-6}$
700	$327.00 \cdot 10^{-6}$	1 300	$477.62 \cdot 10^{-6}$

TABLE II
Values of Kn , C , Stk and ϵ_i for Different Gas Pressures ($R = 0.5 \mu\text{m}$, $P = 0.05$, $r = 0.2 \mu\text{m}$,
 $s = 1 \text{ g cm}^{-3}$, $q = 50 \text{ cm s}^{-1}$, $T = 298\text{K}$)

P, Torr	Kn	C	Stk	ϵ_i
1	700.0	1 160.0	582.8	0.930
5	140.0	232.0	116.8	0.423
10	70.0	116.6	58.5	0.325
50	14.0	23.8	11.9	0.240
100	7.0	12.2	6.1	0.227
200	3.5	6.4	3.2	0.218
300	2.3	4.5	2.2	0.213
400	1.7	3.5	1.8	0.209
500	1.4	3.0	1.5	0.207
600	1.2	2.7	1.4	0.205
700	1.0	2.4	1.2	0.203
800	0.9	2.2	1.1	0.200
900	0.8	2.1	1.0	0.199
1 000	0.7	1.9	0.9	0.198
5 000	0.1	0.1	0.6	0.184
10 000	0.01	0.01	0.5	0.181

The dependence $E = F(T)$ — see Fig. 2 — does not seem to be very important from the practical point of view. These curves have often a minimum. The position of this minimum is a function of particle size and gas velocity. The existence of this minimum can be explained as a superposition of two principal filtration mechanisms. If the gas temperature is increasing, the efficiency of impaction is decreasing, as the gas viscosity increases and the value of Stk therefore decreases. On the contrary, the efficiency of diffusion increases, because η and l and further also N_D are increasing with temperature.

The characteristics $\Delta p = f'(p)$ (see Fig. 6) show, that the pressure drop of a pore filter decreases with a decreasing gas pressure. The agreement between theory and experiment is quite good¹.

The total efficiency of a pore filter increases if the gas pressure is decreasing ($E = F(p)$), especially at low gas velocities. From the Fig. 8 it can be seen *e.g.*, that at a normal gas pressure a filter efficiency is about 22% and at a pressure of 100 Torr it is more than 75%. If aerosol is to be sampled at low gas pressure (*e.g.* in high atmosphere), relatively large pore size filters can be used. But for sampling at high gas pressures the pore filters with small pore sizes should be applied. It seems to be reasonable to sample or to filter aerosols at low pressures, if it is possible. The filter testing at low and high gas pressures is difficult. Nevertheless a practical verification could be done (Fig. 8) and the results had shown, that it was possible to estimate E for different gas pressures by computing only.

LIST OF SYMBOLS

B	aerosol particle mobility $(6\pi\eta r)^{-1}$
b	hard-sphere volume (Enskog coefficient) $[\text{cm}^3 \text{g}^{-1} \text{mol}^{-1}]$
C	Cunningham correction factor
D	aerosol particle diffusivity for Brownian motion $[\text{cm}^2 \text{s}^{-1}]$
E	total efficiency of a filter
k	Boltzmann's constant $(1.38 \cdot 10^{-16})$ $[\text{gcm}^2 \text{s}^{-2} \text{deg}^{-1}]$
Kn	Knudsen number for particles (l/r)
l	mean free path of suspending gas $[\text{cm}]$
L	filter thickness or pore length $[\text{cm}]$
m_M	mass of the molecule $[\text{g}]$
M	molecule mass of gas
N_D	coefficient for diffusion separation
P	filter porosity
p	gas pressure $[\text{dyne cm}^{-2}]$
Δp	gas pressure drop of a pore filter $[\text{dyne cm}^{-2}]$
q	gas velocity in the front of a filter $[\text{cm s}^{-1}]$
r	aerosol particle radius $[\text{cm}]$
R	filter pore radius $[\text{cm}]$
R	gas constant $(8.313 \cdot 10^7)$ $[\text{g cm}^2 \text{s}^{-2} \text{deg}^{-1} \text{mol}^{-1}]$
s	aerosol particle density $[\text{g cm}^{-3}]$

s_M	radius of gas molecule [cm]
Stk	Stokes number (coefficient for impaction)
T	temperature [K]
ϵ_i	partial efficiency of impaction mechanism
η	viscosity of suspending medium [$\text{g cm}^{-1} \text{s}^{-1}$]
η_0	viscosity of suspending medium at normal conditions [$\text{g cm}^{-1} \text{s}^{-1}$]
ρ_g	density of suspending gas [g cm^{-3}]
χ	collision probability increase factor

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