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Physics

STUDY ON PHYSICAL REGULARITIES OF A WIDE SPECTRUM AEROSOLS BEHAVIOR AT ITS FILTRATION THROUGH SUPER-THIN MATERIALS

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The behavior of aerosol particles was studied at filtration through super-thin basalt fibers. Diffusion and inertial effects were investigated at the particle sedimentation using theoretical models for fiber filters taking into account the aerosol gas capture factor.

Composition of radioactive aerosols was analyzed over the period of Armenian NPP operation.

***Keywords*:** basalt fiber, aerosol, capture factor, filter**.**

Introduction. It is known that to assure high modern requirements of clearing gases from the suspended aerosol particles, fine-fibered filters are used, which are the most effective means of catching particles in comparison with all other types of filters [1, 2].

Catching (capture) of radioactive aerosols can be carried out by means of fibrous filters, which are macroporous media with very complex geometrical characteristics. The majority of known results on determination of filter operation effectiveness was obtained experimentally and is theoretically not well-examined. The process of filtration of particles depends on a lot of parameters, and it is practically impossible to consider all of them, when carrying out the experimental work. In this connection very important and actual is the mathematical modeling of filtration process to estimate efficiency of filtration at simultaneous variation of a lot of parameters in a wide interval of their variation. The basic equations necessary for mathematical modeling of filtration processes depend on both the sizes of radioactive particles and structural features of the filter [3, 4].

The improvement of these filters is due to the use of super-thin fibers, as the effect of "gas sliding" near the surface of the thin fibers characterized by Knudsen number $Kn=\lambda/a$ (λ is the length of the free path of air molecules, a is the fiber

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radius), is manifested by reduction of the fiber hydrodynamic flow resistance and increase in particle sedimentation on fibers [3].

Sedimentation of submicron aerosol particles from the flow on super-thin fibers at the air (gas) velocity of about several *cm*/*s* occurs as a result of Brownian displacement of particles from flow lines, and with increase of the particle radius their filter blow-off curve goes through a maximum, caused by the influence of particles "own" size on their sedimentation at the expense of "engagement" effect, when the particle centre passes along the flow lines at a fixed distance from the fiber surface (which is smaller than the particle radius).

The maximum of particles blow-off at a fixed air (gas) velocity corresponds to the worst clearing conditions. From evaluation of the penetrating size r^*, the basalt fiber filter efficiency was estimated.

It is known that for modern super-thin filters the radius of the most penetrating particles is close to fiber radius [3], which in it's turn is comparable with free-path length of air molecules λ.

Theoretical study of diffusion sedimentation depending on the penetrating size of particles is insufficient for super-thin basalt fibers. When calculating the particle radius corresponding to the blow-off maximum, it is necessary to consider the "own" size of particles.

In [3–7] the capture factor is calculated for a model filter taking into account the radius of non-diffusing particles and point particles at intermediate Knudsen numbers (*Kn*) and an option of the joint consideration diffusion and engagement of the finite size particles is presented at $Kn=0$. It is known from the general theory of aerosol filtration that one of the main effects influencing sedimentation of dispersed phase is diffusion. It can be stated after detailed analysis of capture mechanisms of aerosol particles that at filtration of aerosols through macroporous dispersion, the aerosol phase is deposited on macrograins at the expense of diffusion and inertial effects.

Results. Calculation of filtration (cleaning) factor of aerosols by macro-granular filters was made without taking into account mutual influence of the above mentioned effects.

For the coefficient factor the following formula was obtained:

$$K = l^{(\lambda_d + \lambda_{in})h}, \tag{1}$$

where λ_d is the coefficient of diffusion sedimentation of aerosols; λ_{in} is the coefficient of inertial sedimentation; h is the capacity of filter layer.

Calculation of coefficients of sedimentation λ_d and λ_{in} was carried out using "capillary" model on the assumption that diameter of pore channels is defined by the following expression:

$$d = 2K / l\,. \tag{2}$$

Under Prandtl–Taylor hypothesis, according to which the mass transfer of substances in the turbulent flow up to the laminar interlayer is carried out at the expense of turbulent diffusion, and in the laminar interlayer near to the walls of pore channel the mass transfer is carried out at the expense of the molecular diffusion, the following formula was obtained for the coefficient of diffusion sedimentation of aerosols on macrogranular filters:

$$\lambda = \frac{\sigma\sqrt{ml}}{K\sqrt{vU_f}}, \tag{3}$$

where σ is the is coefficient of molecular diffusion of particles; v is the kinematic viscosity of gas; U_f is the velocity in filter.

During the investigation of the diffusion effect an important factor is nuclide composition of the investigated aerosol fractions.

To determine radionuclide composition of aerosols presenting in air of premises and emissions, an historical database characterizing sizes and radionuclide composition of aerosols in air emissions and ventilation systems (see Tables 1 and 2) was created at the Armenian NPP.

Table 1

Nuclide composition and size of emissions during ANPP operation period (10^7 Bq/year)

Year of oper.	Basic radionuclides								
	LLN*	^{131}I	^{137}Cs	^{134}Cs	^{60}Co	^{110m}Ag	^{90}Sr	^{54}Mn	^{51}Cr
1978	16.9	276	0.10	–	7.80	6.40	0.03	5.60	20.0
1979	633	579	17.2	5.10	31.0	–	1.40	19.1	313
1980	428	777	48.6	46.7	18.1	–	0.30	13.6	70.0
1981	214	735	22.4	15.5	26.9	–	0.60	10.7	11.6
1982	341	230	9.5	10.0	62.8	48.5	0.37	22.3	11.5
1983	884	70	5.0	1.70	20.6	4.80	0.06	5.80	0.70
1984	1785	228	66.3	51.0	28.2	37.0	0.04	4.90	4.60
1985	754	151	60.6	33.1	17.2	71.6	0.11	4.0	16.2
1986	794	44	25.0	12.8	21.7	73.4	0.25	8.40	–
1987	259	103	13.4	5.60	34.7	122.0	0.08	7.20	17.2
1988	338	602	14.9	24.0	128	142.0	0.06	26.8	10.2
1989	181	108	10.1	–	29.4	56.60	–	–	–
1990	113	–	8.8	–	12.3	16.10	0.09	–	–
1991	46.0	–	6.2	4.0	8.9	11.80	0	1.30	–
1994	82.0	–	–	–	60.1	–	–	–	–
1995	193.0	9.70	23.3	–	83.7	–	0.15	–	–
1996	121.0	23.5	15.4	0.80	22.4	25.80	0.12	0.80	11.6
1997	278.0	36.7	11.6	1.27	9.0	7.24	0.36	0.33	0
1998	238.4	28.8	9.35	1.32	18.4	7.72	0.29	1.89	21.6
1999	44.43	25.8	10.2	0.89	11.94	10.8	0.44	1.22	–
2000	30.7	26.0	4.20	5.97	17.7	22.60	0.38	8.78	–
2001	31.1	18.8	16.5	5.36	23.5	18.70	0.49	3.42	2.24
2002	9.9	59.6	7.90	2.28	6.6	2.50	0.2	0.16	–
2003	29.3	38.1	26.7	5.0	22.1	25.0	0.23	3.23	–
2004	28.5	97.1	5.59	0.38	14.6	11.3	0.04	1.35	2.53
2005	20.9	3.04**	7.0	0.83	5.10	1.35	0.03	–	–
2006	18.3	3.65	5.12	0.54	9.45	1.77	0.03	–	–
2007	46.0	1.90	4.88	1.60	7.15	1.17	0.05	0.10	–
2008	7.0	0.47	3.82	1.20	23.7	8.0	0.04	1.45	–
% composition excluding ^{131}I and LLN			20.59	1.4	35.08	32.89	0.28	6.83	2.9
% composition excluding LLN		59.7	6.40	3.30	10.9	10.25	0.087	2.14	7.16

* LLN are radionuclides with half-life period more than 24 hours;

** starting from 2005, new and more sensitive equipment and technique of measurement of ^{131}I emission were introduced at ANPP.

It is seen from the Table 1 that the greatest percentage contribution to aerosols activity is made by the radionuclides of corrosion origin (^{60}Co and ^{110m}Ag) as well as uranium fission product ^{137}Cs.

Table 2

Concentration of radionuclides in ventilation systems (10^{-7} Bq/l)

Ventilation systems	Max					Min				
	^{137}Cs	^{60}Co	^{110m}Ag	^{54}Mn	^{134}Cs	^{137}Cs	^{60}Co	^{110m}Ag	^{54}Mn	^{134}Cs
2007										
B1C	215.3	26.1	–	–	–	6.7	–	–	–	–
2B2	85000	8000	182	–	90000	28.2	27.3	37.0	–	73.8
B3	12.9	98.0	111.0	–	–	7.4	55.9	74.4	–	–
2B4	31005	1260	–	–	72005	185	–	–	–	111
2008										
B1C	127.1	109.4	–	–	–	52.7	54	–	–	–
2B2	117.8	236.9	70.9	–	–	95.7	–	–	–	–
B3	60.6	380.5	–	–	–	–	–	–	–	–
2B4	81.9	1619	475.6	209.5		41.5	110	–	–	–

In 2009 the measured concentration of ^{58}Co in 2B4 was max=$193\cdot10^{-7}$ *Bq/l.*

When analyzing the contents of radioactive aerosols, it is necessary to take count on the diffusion effect caused by impurity transport in direction of smaller concentrations. When taking samples from flow, it is necessary to follow a series of conditions. The sampling tube axis should be parallel to flow lines in air duct (the coaxiality condition). Otherwise, when following correct sampling speed, concentration of aerosol in sample C_i will be lower than in investigated aerosol C_e, and the aspiration coefficient $a' = C_i / C_e$ will be below 1. The average flow velocity in nozzle U_i should be equal to low velocity U_e in corresponding flow line (which passes the tube axis) in the gas duct (the isokinetic condition, Fig. 1).

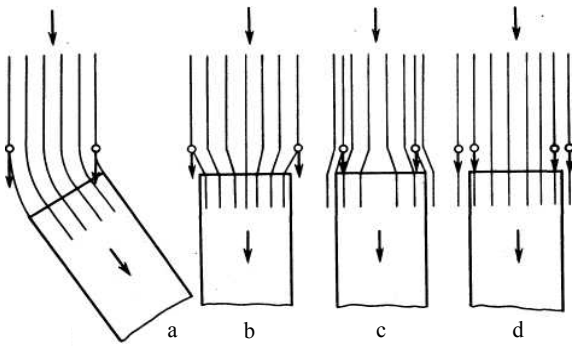


Fig. 1. Aspiration of aerosol. a – violation of coaxiality (at correct sampling velocity); b – increased sampling velocity; c – decreased sampling velocity; d – correct sampling velocity.

At $\omega = U_i / U_e < 1$ flow lines diverge prior to the tube input; the particles - displace from the flow line to the tube axis under the influence of inertia, and as a result the concentration in sample becomes higher than the real one($a' > 1$).

At $\omega > 1$ the situation is vice versa and $a' < 1$ (Fig. 1, c).

At last, to the two above conditions it is necessary to add the third one: the sampling tube walls (nozzle) should be infinitely thin.

Errors due to non-coaxiality of sampling of particles with diameter d at small angles v between the flow direction in air duct ($\omega = 1$) can be taken into account by formula (3):

$$a' \approx 1 - 4 \sin v S_t / \pi , \tag{4}$$

where $S_t = U_e \tau / D_t$ is the Stokes number; $\tau = p_{ch} d^2 / 18\mu$ is the particle relaxation time; p_{ch} is the particle density; μ is the dynamic viscosity of air; D_t is the internal diameter of the sampling tube.

The errors due to violation of isokinetic conditions of sampling can be estimated using empirical Beljaev-Levin formula:

$$a' = 1 + \frac{\left(\omega^{-1} - 1\right)\left(2 + 0.62\omega\right) S_t}{1 + \left(2 + 0.62\omega\right) S_t}, \tag{5}$$

where $-0.2 < \omega^{-1} < 5$.

Diffusion sedimentation of aerosol particles on super-thin basalt fibers was studied using a model of the fiber filter presenting a system of the parallel fibers located normally to the flow direction. The flow field in the system is presented as a cell model with packing density $\alpha = \left(a / b\right)^2$, where a is a fiber radius, b is a cell radius [3, 5–7]. Analytical solution of integral equations is a large amount of work, but as a result we obtain for the total particle flow a relationship reflecting the fact of particle engagement on fibers.

It is determined that for large R_0 / δ capture factors η is equal to

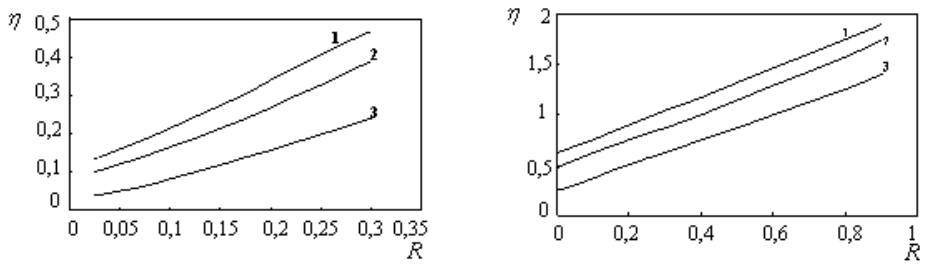
$$\eta = \left(R_0 / \delta\right)\left(1 + R\right) / Pe^{1/2}, \tag{6}$$

where Pe is the Peclet number ($Pe = 2aU / D$, where D is the diffusion, U is the gas flow velocity); R is the dimensionless particle radius; δ is small ($\delta = 1 / Pe^{1/2}$).

Thus, pure engagement effect can be expressed as

$$\eta = R_0\left(1 + R\right), \text{ where } R_0 \sim 1. \tag{7}$$

Fig. 2 (a, b) presents the results of calculations of the capture factor curves for pure engagement and for total capture factor. It is seen from the figure that curves are almost parallel, i.e. sedimentation mechanisms are additive. The effect of aerosol gas sliding near the surface promotes the accelerated movement of particles along the fiber surface that, in turn, leads to reduction of diffusion sedimentation of particles. But, on the other hand, with the increase of sliding velocity, the increase in velocity of the particle radial transport to fiber is possible, which is equivalent to reduction of the particle diffusion sedimentation. The change in the capture factor of point particles depends on these effects ratio.



a b

Fig. 2. Capture factor η dependence on the engagement parameter R for a filter with $\alpha=(1/6)^2$ at different Knudsen numbers. a) δ=0.05(Pe=400); b) 0.3 (Pe=12). Curve 1 corresponds to Kn=10; curve 2 – to Kn=1; curve 3 – to Kn=0.1.

Conclusion. Analysis of the filtration process in real super-thin basalt filters has shown that it is appropriate to express the existing sedimentation mechanisms of aerosol particles in terms of capture coefficient, depending on the filter parameters and dimensionless parameters characterizing filtration conditions, such as Knudsen number and diffusion Peclet parameter.

The obtained results on aerosol capture modeling can be used to estimate the nanofiber radius by fiber layer gas permeability method, for example, at different absolute pressure of gases.

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Լայն տիրույթի աերոզոլների վարքի ֆիզիկական օրինաչափությունների հետազոտումը, երբ դրանք անցնում են գերբարակ նյութերով

Հետազոտվել է աերոզոլային մասնիկների վարքը բազալտե գերբարակ մանրաթելերով անցնելիս: Տեսական մոդելների միջոցով ուսումնասիրվել են դիֆուզիոն և իներցիոն երևույթները մասնիկների նստեցման ընթացքում գազ-աերոզոլի գրավման գործակցի օգնությամբ:

Կատարվել է Հայկական ատոմակայանի շահագործման ընթացքում ռադիոակտիվ աերոզոլների պարունակության վերլուծությունը: