DISPERSION OF AEROSOL PARTICLES IN INHOMOGENEOUS FIBROUS FILTER MEDIA

Albert Podgórski*[1], Anna Jackiewicz[1], Anna Bałazy[1,2]
[1]Faculty of Chemical and Process Engineering, Warsaw University of Technology,
Waryńskiego 1, 00-645 Warsaw, Poland
[2]Cummins Filtration, Inc., 1801 U.S. Hwy. 51/138, Stoughton, WI 53589-0428, USA

ABSTRACT

Fractional penetration through two different fibrous filters was determined experimentally at various air velocities in the range U=0.08–0.2 m/s. The axial dispersion model was applied to describe the data obtained for multilayer sets of filters composed of up to nine layers of the same filter. This model predicts a non-exponential decrease of the aerosol penetration with a filter thickness increase. The dispersion model contains two parameters, i.e., the filter coefficient, λ, and the axial dispersion coefficient, D_x, which were evaluated on the basis of the experimental data. The ratio of the dispersion coefficient, D_x, to the coefficient of Brownian diffusion, D, was found to be nearly proportional to the Peclet number. The model of axial dispersion was also compared with the classical theory of depth filtration. It was found that the classical theory predicts a higher aerosol penetration than that one observed experimentally.

KEYWORDS

Aerosol, Depth Filtration, Fibrous Filter

1. Introduction

Classical theory of depth filtration of aerosol particles in fibrous filters predicts that the fractional penetration, P, through a clean filter is an exponentially decaying function of the filter thickness, L. Thus, $P=\exp(-\lambda L)$, wherein the filter coefficient, λ, is related to the single fiber efficiency, E, the filter porosity, ε, and the fiber diameter, d_F, according to the formula: $\lambda=4E(1-\varepsilon)/\pi\varepsilon d_F$. This is the result of the fundamental assumptions that all fibers have the same size and they are evenly distributed in the space, ergo, that the deposition efficiency is identical for all fibers. However, real fibrous filtering media are always more or less inhomogeneous. First, the fibrous filters are usually polydisperse, i.e., made of fibers with various diameters. And secondly, the fibers form an uneven net with pores of different sizes. Consequently, there is a “tunneling” of flow through zones of a local higher permeability and a mutual “shadowing” of neighboring fibers. This in turn can create nonuniform fields of local gas velocity and local particle concentration in a given filter cross-section and may be the source of the phenomenon called the mass dispersion, which is usually neglected in the classical theory. In such a case the aerosol penetration would be a non-exponential function of the filter thickness. The aim of this paper is to examine whether the mass dispersion may be a significant phenomenon in the fibrous filters and to determine values of the coefficients of axial dispersion.

2. Materials and methods

Two polypropylene filters made utilizing the melt-blown technique were used to perform the experiments. Their structures were fully characterized and the results are collected in Table 1.

Table 1. Characteristics of the investigated filters

Filter no.	Mean fiber diameter $d_F \pm SD$ [μm]	Thickness L [mm]	Porosity ε [%]	Coefficient of variation CV [-]	Basis weight q_s [g/m^2]
1	11.9±3.8	0.77	93.2	0.32	47
2	15.0±6.2	1.28	84.4	0.41	182

A degree of the fibers' polydispersity can be described by the coefficient of variation, *CV*, defined as the ratio of the standard deviation of the fibers' size distribution, *SD*, to the mean fiber diameter. It can be observed in Fig. 1 that the tested filters have a high level of fibers' sizes polydispersity. The noticeable fractions of fibers thinner and thicker than the mean fiber diameter are present.

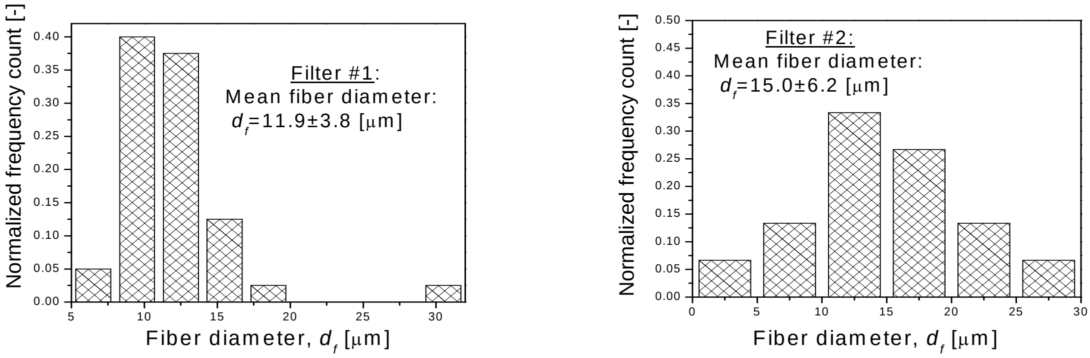

Fig. 1. Fibers' size distributions of the two tested filters.

Fractional penetrations of solid aerosol particles with diameters 0.2–10 μm through the many-layer sets of those fibrous filters (Fig. 2) were determined using the modular filter test system (model MFP-2000, Palas GmbH, Germany). The experiments were carried out for several air velocities in the range U=0.08–0.2 m/s.

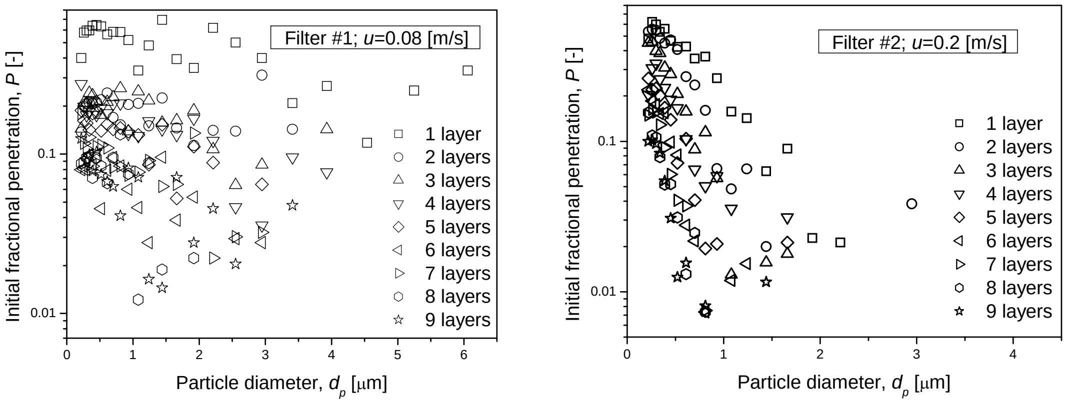

Fig. 2. Influence of the filter thickness on the initial fractional penetration for multilayer sets of the filter #1 and the filter #2 composed of up to nine layers of the same filter.

3. Results and discussion

Having determined values of the penetration as a function of the filter thickness (number of layers) for various gas velocities and various diameters of aerosol particles, the filter coefficients, *λ*, and the coefficients of axial dispersion, D_X, were calculated by fitting the experimental data *P*(*L*) to the solution of the standard axial dispersion model, [1], with the Danckwerts' boundary conditions (see the equation below); six such examples for the filter #1 and #2 are shown in Fig. 3 for various gas velocities and particle diameters.

$$P=\frac{4\sqrt{1+\frac{4d_F\,\lambda}{\mathrm{Bo}}}}{\left(1+\sqrt{1+\frac{4d_F\,\lambda}{\mathrm{Bo}}}\right)^2\exp\left[-\left(1-\sqrt{1+\frac{4d_F\,\lambda}{\mathrm{Bo}}}\right)\frac{L\,\mathrm{Bo}}{2d_F}\right]+\left(1-\sqrt{1+\frac{4d_F\,\lambda}{\mathrm{Bo}}}\right)^2\exp\left[-\left(1+\sqrt{1+\frac{4d_F\,\lambda}{\mathrm{Bo}}}\right)\frac{L\,\mathrm{Bo}}{2d_F}\right]}$$

In the above equation Bo is the Bodenstein number, $\mathrm{Bo}=Ud_F/\varepsilon D_X$.

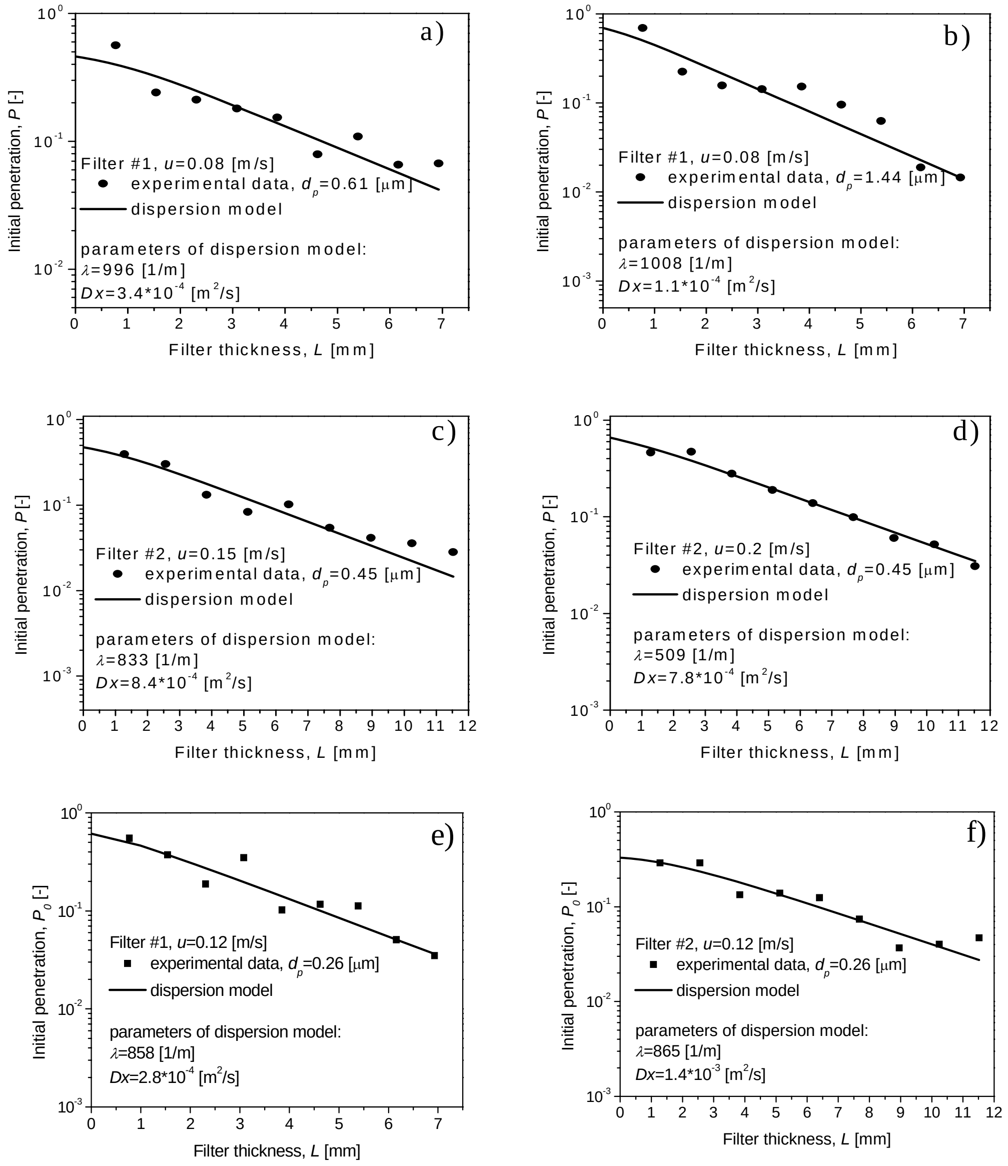

Fig. 3. Examples of determination of *λ* and D_X coefficients for:
filter #1 – a), b) and e); filter #2 – c), d) and f).

As can be seen in Fig. 3, the dispersion model allows one to describe precisely the experimental data of the penetration as a function of the filter thickness. It was found that the coefficients of axial dispersion, D_x, are a few orders of magnitude greater than the values of the Brownian diffusion coefficients, D, determined for the same particle diameters from the Stokes-Einstein formula: $D=k_BTC_c/3\pi\mu_g d_p$, wherein k_B is the Boltzmann constant, T is the absolute temperature, C_C is the Cunningham slip correction factor and μ_g is the gas viscosity. The filter #2, which is more polydisperse (it is characterized by a higher value of *CV*) than the filter #1, has also a greater value of the dispersion coefficient. A good agreement between the axial dispersion model and the experimental results was obtained in each case. The experimental data for the multilayer systems drawn in the plot of logarithm of penetration, P, vs. the filter thickness, L, do not form straight lines. The values of the penetration extrapolated to the filter thickness tending to zero do not reach one, what suggests occurrence of the mass dispersion phenomenon. Plotting the values of the dimensionless dispersivity, defined as the ratio of the dispersion coefficient, D_x, to the coefficient of Brownian diffusion, D, determined for a given filter for various gas velocities and particle diameters, vs. the Peclet number, Pe=Ud_F/D, a linear relationship is observed, Fig. 4, what implies predominance of the convective dispersion mechanism at high Peclet numbers, as could be expected from the theory of Koch and Brady, [2]-[3].

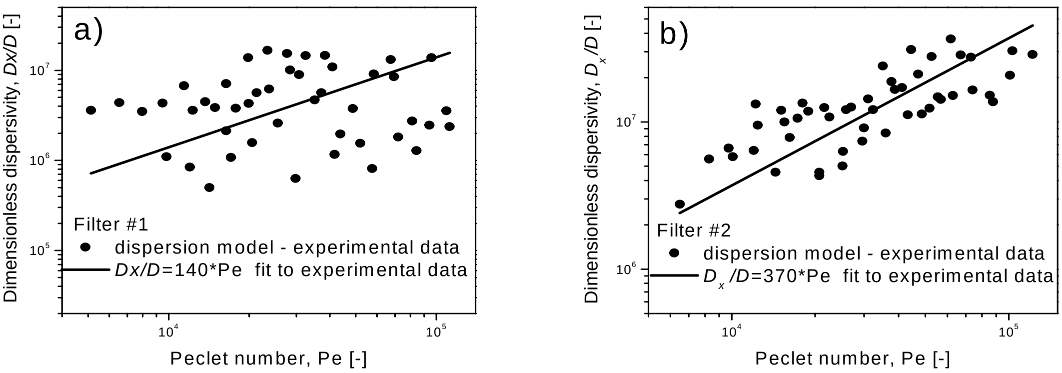

Fig. 4. Linear fit of the dimensionless dispersivity vs. Pe for various gas velocities and particle diameters for: a) filter #1 and b) filter #2.

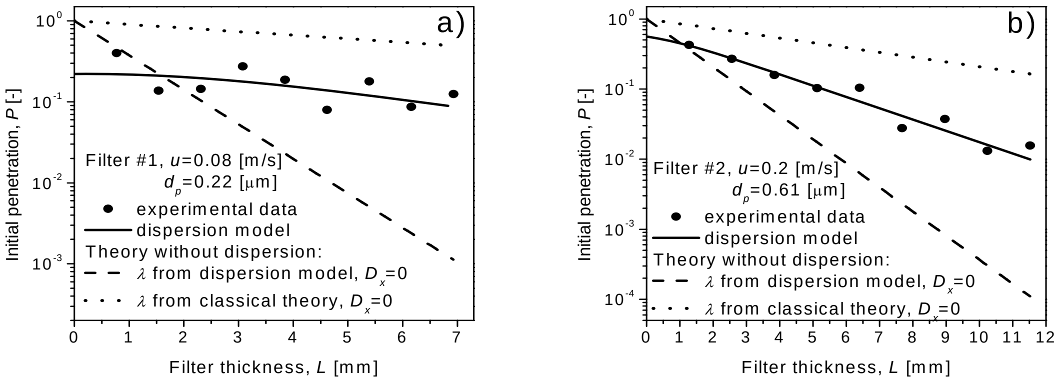

Fig. 5. Comparison of penetration accounting for dispersion (points and solid lines) and neglecting dispersion (dotted and dashed lines – see text for explanation).

Finally, the experimental data of aerosol penetration through multilayer sets of filters were compared with the predictions of the classical theory of depth filtration, which neglects the mass dispersion. Fig. 5 shows two examples of such comparison for both examined filters. When the filter coefficient λ was calculated for the arithmetic mean fiber diameter using available in the literature correlations for the single fiber efficiency for various mechanisms (diffusion, interception, impaction), the aerosol penetration through a filter (dotted lines in Fig. 5) was significantly overestimated. On the other hand, when the penetration was calculated with the use of the values of λ determined by fitting the dispersion model to the experimental data and then neglecting dispersion (D_x=0), i.e., using the formula $P=\exp(-\lambda L)$ – dashed lines in Fig. 5 - the experimental results of penetration were considerably underestimated.

4. Conclusions

- The model of axial dispersion was capable of precisely describing the data of aerosol penetration obtained from the measurements for multilayer sets of fibrous filters composed of up to nine layers of the same filter.
- Extensive experimental studies were carried out in order to determine the axial dispersion coefficients in fibrous filters. It was found that the coefficients of axial dispersion, D_x, are a few orders of magnitude greater than the values of the Brownian diffusion coefficients, D, determined for the same particle diameters.
- The ratio of the dispersion coefficient to the coefficient of Brownian diffusion was found to be nearly proportional to the Peclet number. This suggests predominance of the convective dispersion mechanism in highly porous fibrous filters, which have always more or less inhomogeneous internal structure. Inhomogeneity of the fibrous filters causes a tunneling effect of the aerosol flow. It means that there are preferential flow paths through the areas of a higher local porosity.
- The results of the experiments confirmed that the mass dispersion is important phenomenon in inhomogeneous filters, especially these having a high porosity, a low thickness and a high degree of the structural inhomogeneity.
- We have found that the penetration estimated on the basis of the classical theory for the mean fiber diameter significantly overestimates the penetration measured experimentally in inhomogeneous, polydisperse fibrous filters. This suggests that the real distribution of fibers' diameters should be involved in theoretical calculations.

Acknowledgements

This work was supported by Cummins Filtration Inc., USA, and by Polish Ministry of Science (project 1 T09C 014 30).

References

[1] Podgórski A., *On the Transport, Deposition and Filtration of Aerosol Particles in Fibrous Filters: Selected Problems*, Publishing House of the Warsaw University of Technology, Warsaw, 2002.

[2] Koch D.L., Cox R.G., Brenner H., Brady J.F., *The effect of order on dispersion in porous media*, J. Fluid Mech. 1989, 200, 173.

[3] Koch D.L., Brady J.F., *The effective diffusivity of fibrous media*, AIChE J. 1986, 32, 575.