Deposition of Aerosol Particles on Filter Surfaces

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DEPOSITION OF AEROSOL PARTICLES ON FILTER SURFACES

Jiří SMOLÍK[1], Ludmila MAŠKOVÁ[1,2], Naděžda ZÍKOVÁ[1,3], Jakub ONDRÁČEK[1]

[1]Department of Aerosol and Laser Studies, Institue of Chemical Process Fundamentals ASCR, v.v.i.,
[2]Institute for Environmental Studies, Faculty of Science,Charles University in Prague
[3] Department of Meteorology and Environment Protection, Faculty of Mathematics and Physics, Charles University in Prague
email: smolik@icpf.cas.cz

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INTRODUCTION

Airborne particles deposited on cultural heritage artefacts have many negative effects. Beside soiling and abrasion of surfaces particles can also cause material deterioration by chemical reactions. Ultrafine atmospheric particles, penetrating indoors from the outdoor environment, contain soot and organic matter from traffic that are hygroscopic and effective for transport of acids. Fine particles consist of secondary organic matter, ammonium sulphate and ammonium nitrate, and sometimes sulphuric acid. Coarse particles, formed predominantly by resuspended dust, contain crustal elements and in the indoor environment also alkaline particles emitted from concrete structures (Nazaroff et al., 1993, Hatchfield, 2005). Dry deposition is considered to occur by a combination of Brownian and eddy diffusion and gravitational settling (Nazaroff and Cass, 1989, Lai and Nazaroff, 2000) where prevailing deposition mechanism depends on the particle size. Coarse particles are deposited on upward-facing surfaces by gravitational settling and fine particles predominantly by diffusion on surfaces of any orientation. In principle the submicron particles can penetrate by diffusion also between books and even into the gaps between pages and thus can be deposited on the inner surfaces of books. To test this hypothesis we examined deposition of particles on Whatman filters located on the free shelf of the library.

MODELLING AND MEASUREMENTS

In order to characterize indoor particulate matter (PM) in the Baroque Hall of the National Library in Prague and determine penetration of outdoor PM into the indoor environment, we measured size resolved particle number concentrations and mass size distributions of indoor and outdoor PM using Scanning Mobility Particle Sizer (SMPS 3936L, TSI, USA), Aerodynamic Particle Sizer (APS, 3321, TSI, USA), and two Berner type Low Pressure Impactors (BLPI, 25/0.018/2, Hauke Austria). The collected samples were analysed gravimetrically, by Ion Chromatography (IC) and Particle Induced X-Ray Emission (PIXE), giving mass, ionic, and elemental size distributions. The results showed that the average concentrations of size fractions 10 – 100 nm and 100 nm - 1μm of the indoor PM were of the order 10^3 particles/cm^3. The IC analyses revealed that the major water-soluble inorganic component of submicron indoor PM was ammonium sulphate with maximum concentration centred at about 300 nm (Andělová et al., 2010). During the measurement we also performed a simple experiment in which we investigated deposition and possible penetration of submicron particles into gaps between books and even between pages of books. To test it we placed twelve bunches of ten Whatman filters No. 542 (circles, 70 mm), fixed in open Petri dishes on a free shelf of the library. Bunches were exposed for three, six, nine, and twelve months (VII.-IX.2009, VII.-XII.2009,VII.2009-III.2010, and VII.2009-VI.2010). Each bunch contained ten filters, which were gently loosed to increase the distance between them (Fig.1). Exposed filters were examined by Scanning Electron Microscopy (SEM) and Ion Chromatography (IC).

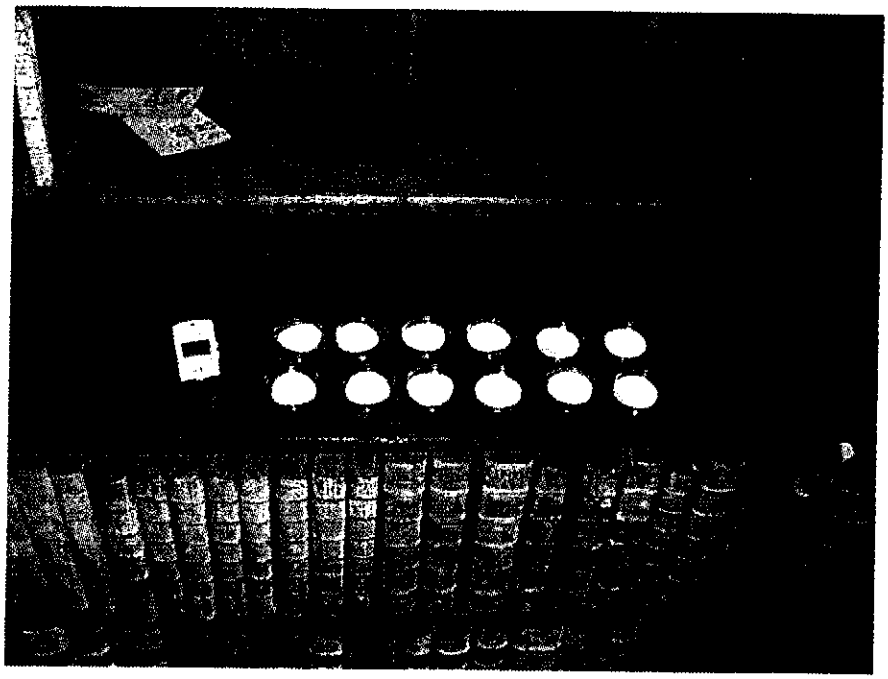

Fig. 1: Whatman filters fixed in Petri dishes

To estimate penetration of particles between filters and subsequent deposition on inner surfaces we modelled transport of particles by Brownian diffusion between two parallel discs (Fig. 2) put into environment with constant particle number concentration n_0. The particle concentration was described by the equation

$$\frac{\partial n}{\partial t} = D\left(\frac{1}{r}\frac{\partial n}{\partial r} + \frac{\partial^2 n}{\partial^2 r} + \frac{\partial^2 n}{\partial^2 z}\right), \qquad (1)$$

where n is the particle number concentration, t is the time, r and z are the radial and axial distances, respectively, and D is the particle diffusion coefficient (Hinds, 1999)

$$D = \frac{kTC_c}{3\pi\eta d_p}, \qquad (2)$$

where k is the Boltzmann's constant, T is the temperature, C_c is the slip correction factor, η is the air viscosity, and d_p is the particle diameter. The slip correction factor C_c is given by

$$C_c = 1 + \frac{\lambda}{d_p}\left[2.34 + 1.05\exp\left(-0.39\frac{d_p}{\lambda}\right)\right], \qquad (3)$$

where mean free path λ for air at standard conditions is 0.066 μm. The solution of the equation (1) with boundary conditions

$$\begin{array}{llllll} n = n_0 & \text{for} & r = R, & z \geq 0 & \text{and} & t \geq 0, \\ n = 0 & \text{for} & r \geq 0, & z = 0 & \text{and} & t \geq 0, \\ n = 0 & \text{for} & r \geq 0, & z = Z & \text{and} & t \geq 0, \\ \dfrac{\partial n}{\partial r} = 0 & \text{for} & r = 0, & z \geq 0 & \text{and} & t \geq 0, \end{array} \qquad (4)$$

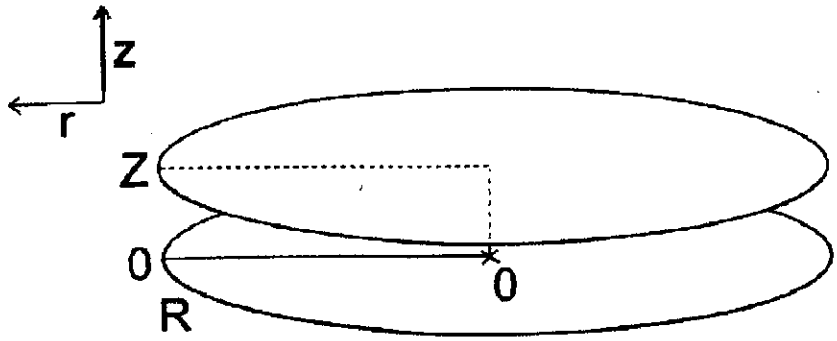

Fig. 2: Diagram of two parallel discs

gives the concentration gradient $\partial n/\partial z$ at filter surfaces $z = 0$, $z = Z$ and using Fick's law the rate of particle deposition per unit area of surface

$$J = -D\frac{\partial n}{\partial z}\Big|_{z=0,z=Z} \cdot \qquad (5)$$

The equation (1) was solved numerically for particle sizes d_p = 10, 100, and 1000 nm, gap width Z = 1 and 5 mm with disc radius R = 3.5 cm and constant particle number concentration $n_0 = 1.10^3$ particles/cm^3. An example of steady state concentration profile of 1000 nm particles in 5 mm gap is shown in Fig 3.

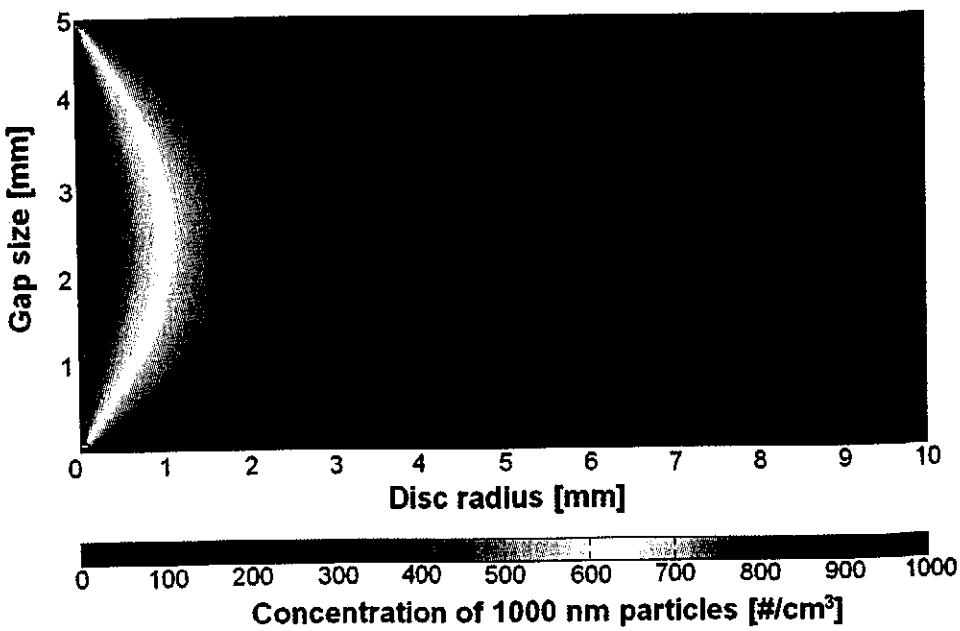

Fig. 3: Concentration profiles of 1000 nm particles in 5 mm gap between filters

From Fig 3 it can be seen that concentration gradient at both surfaces decreases with the distance from the edge of discs. Thus the rate of particle deposition on surfaces and hence also amount of deposited particles decrease with increasing distance from the edge (see Eq. 5). To estimate the deposition of particles and their distribution on discs we calculated the amount of particles deposited on inner surfaces during one year of exposition (i. e. $J.t$), assuming again constant particle concentration $n_0 = 1.10^3$ particles/cm^3 during the whole period. The results are shown for individual cases in Fig 4. As can be seen, smaller particle penetrate faster and deeper between filters by diffusion resulting in higher number concentrations of deposited particles.

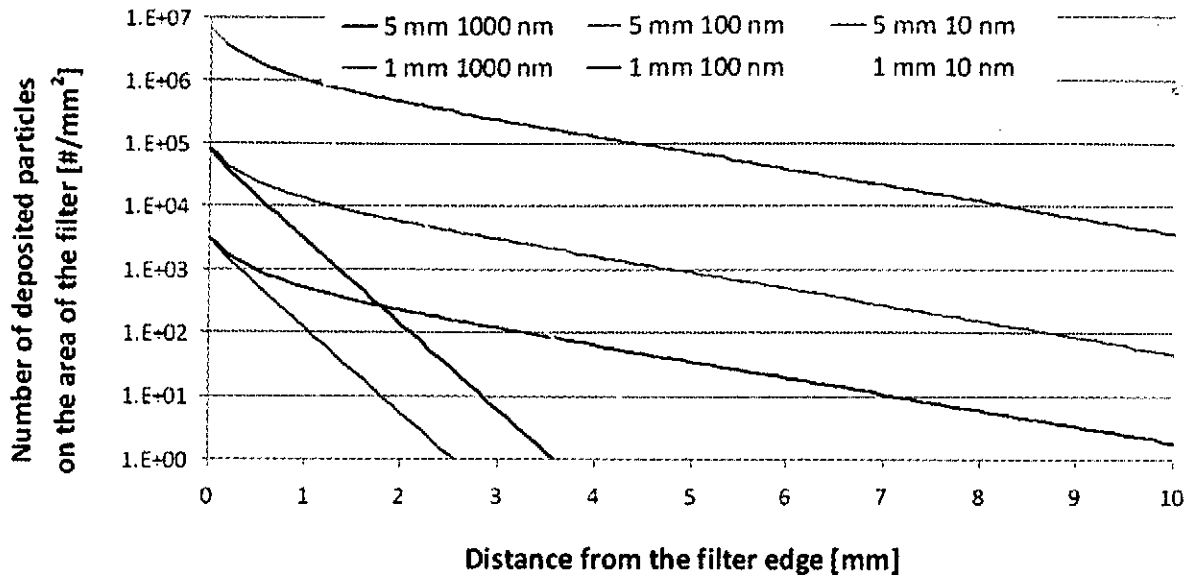

Fig. 4: Number of particles deposited per unit area of surface

But the situation is quite different if we consider mass of deposited particles. Mass of deposited particles, calculated assuming for simplicity spherical particles of unit density, is shown in Fig. 5. In this case more material is transported by larger particles.

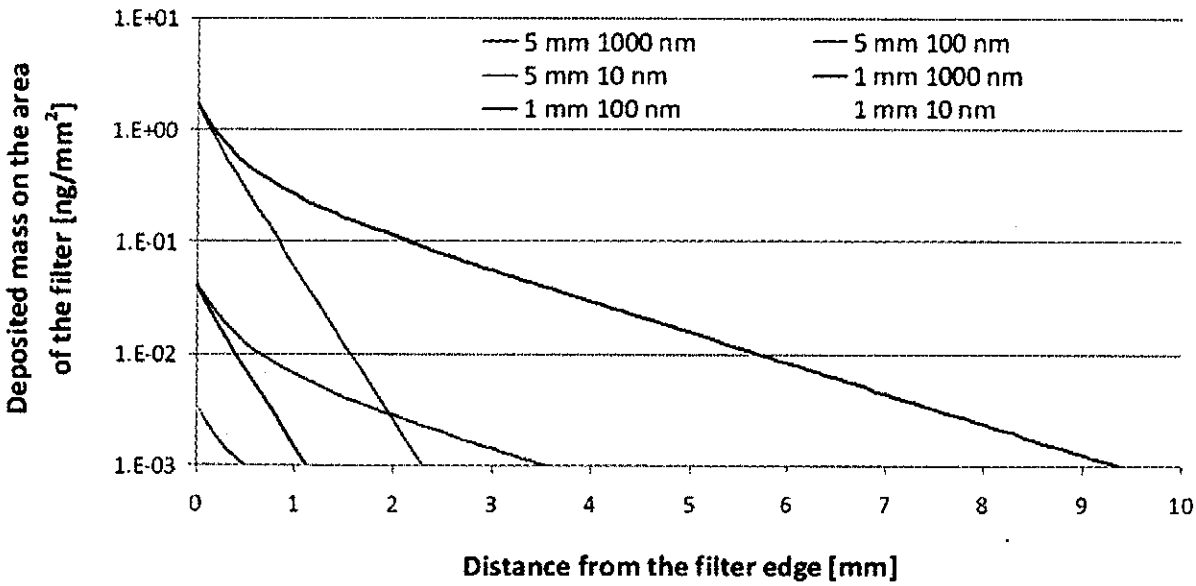

Fig. 5: Mass of particles deposited per unit area of surface

To summarize the results: simple model showed that submicron particles can pentrate by diffusion between two paralell sheets of filter followed by deposition on filter surfaces. The particle penetration and deposition depends on particle size and width of the gap, with the depth of the penetration limited by parallel diffusional deposition on filter surfaces. Smaller particles penetrate faster and deeper resulting in higher particle number concentration of deposited particles but higher mass is transported by larger particles.

Exposed filters were analysed by Ion Chromatography (IC). Since the bunches were not exactly planar but slightly convex the downward-facing surface of the last filter could be exposed as well. Thus, we analysed the top (first), internal (second) and bottom (tenth) filter from two bunches

after each period. Results from the parallel study (Andělová et al., 2010) showed that ammonium sulphate formed up to 60% of mass of water-soluble part of indoor submicron PM. Since the ammonium sulphate is stable compound, sulphate was used as a marker for deposited particles. Results of analyses, corrected for the blank values, are shown in Fig. 6. As can be seen, sulphate concentration on all filters increased with time. Substantially higher sulphate concentrations were found on the top predominantly due to larger exposed area. This results were confirmed by statistical analysis (Wilcoxon test, $p<0.05$), which showed significant differences only between the top and other two filters. The results clearly show that submicron particles penetrated between filters with transport governed at least to the downward-facing surface of the bottom filter by diffusion.

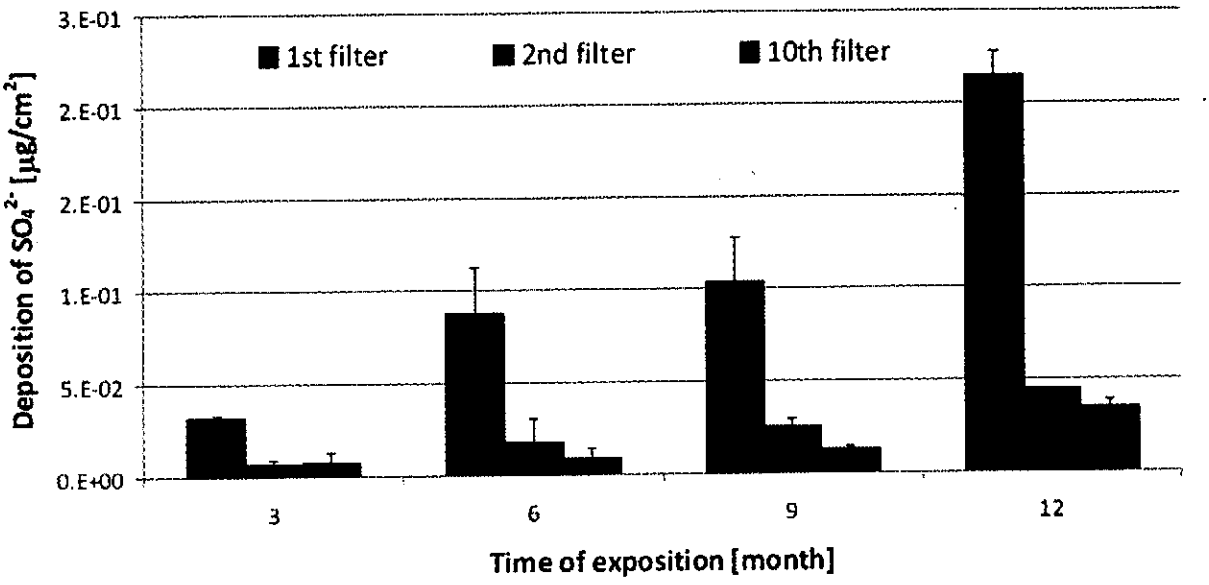

Fig. 6: Concentration of sulphate ion deposited on the top (first), internal (second) and bottom (tenth) filters during three, six, nine, and twelve months long exposition. Average values obtained from two parallel bunches, the bars represent the standard deviations.

CONCLUSIONS

To test if the indoor submicron particles can penetrate by diffusion into gaps between books or even between pages of books, we exposed twelve bunches of Whatman filters to the indoor air fixed in open Petri dishes on a free shelf of the library. Bunches were exposed for three, six, nine, and twelve months and analysed after each period by Scanning Electron Microscopy (SEM) and Ion Chromatography (IC). The penetration and deposition of particles has been modelled assuming Brownian diffusion between two parallel discs. The simple model showed that the particle penetration and deposition depend on particle size and width of the gap, with the depth of the penetration limited by parallel diffusional deposition on filter surfaces. Smaller particles penetrate faster and deeper resulting in higher particle number concentration of deposited particles but higher mass is transported by larger particles. The results of modelling have been qualitatively confirmed by Ion Chromatography using sulphate as marker for deposited particles.

ACKNOWLEDGEMENT

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