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Deposition of Aerosol Particles below 10 nm on a Mixed Screen-Type Diffusion Battery

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ABSTRACT

Experimental characterization of a mixed screen-type diffusion battery has been made by using monodisperse neutral particles with diameter below 10 nm. The diffusion battery contained two "composite" grids, each of them consisting of a gold screen sandwiched between two Aluminium screens. The equivalent fiber diameter of the composite grid was obtained by fitting the experimental penetration data for uncharged particles to the Cheng-Yeh model. Once the equivalent or effective fiber diameter is known, the fan filter model of Cheng and Yeh allows accurate prediction of particle penetration through the mixed-screen type diffusion battery.

Keywords: Nanoparticle; Diffusion; Wire screen; Single fiber efficiency; Equivalent fiber diameter.

INTRODUCTION

The most important filtration mechanism for neutral ultrafine airborne particles is diffusive deposition. Uncharged particles with diameter below 100 nm are collected due their Brownian motion. Single fiber efficiency due to diffusion is described by the following expression by Lee and Liu (1982):

$$\eta_d = 2.58\left(\frac{1-\alpha}{K}\right)^{\frac{1}{3}} Pe^{-2/3} \tag{1}$$

where α is the packing density of the filter (solid volume fraction), K is the hydrodynamic factor and Pe is the Peclet number.

Traditionally, the experimental test of the above equation (or of others derived from it) has been done using either a single well-characterized wire screen or a series of screens separated a certain distance from each other (diffusion battery). A large number of reports on penetration of particles through wire screens are available in the literature (Kirsch and Fuchs, 1968; Cheng and Yeh, 1980; Cheng *et al*., 1980). This theory has been experimentally verified for particle sizes, $d_p > 0.5$–8 nm (Cheng and Yeh, 1980; Cheng *et al*., 1980; Yeh *et al*., 1982; Scheibel and Porstendörfer, 1984; Holub and Knutson, 1987; Yamada *et al*., 1988; Ramamurthi, 1989; Cheng *et al*., 2000; Heim *et al*., 2005; Kim *et al*., 2007; Heim *et al*., 2010). Cheng and Yeh (1980) showed a theory developed for fiber filters worked for predicting aerosol penetration through 635-mesh wire screens to facilitate the use of wire screens. A special type of diffusion battery for measuring the particle size of aerosols is the so called graded screen array (GSA) and was first developed by Holub and Knutson (1987) in the 1980s, in which several screens differing in their geometric characteristics (wire diameter, screen thickness, opening and solid volume fraction) are arranged in series within a filter holder (e.g., Solomon and Ren, 1992). GSAs were used in several studies of radon decay product behavior (e.g., Strong, 1988; Ramamurthi and Hopke, 1989; Ramamurthi *et al*., 1990; Winklmayr *et al*., 1990; Hopke, 1991; Li and Hopke, 1991; Hopke *et al*., 1992; Solomon and Ren, 1992; Cheng *et al*., 2000). The Cheng-Yeh wire screen penetration theory in the molecular cluster size range was confirmed the validity by Ramamurthi *et al*. (1990) using a well-defined and radioactive 218PoO_x cluster aerosol, highly disffusive D_{avg} = 0.078 ± 0.003 cm^2/s (dp ≈ 0.6 nm). An assessment of wire screen penetration theory for two low mesh number wire screens indicated good agreement with the diffusion theory within the domain of $Re_f < 1$ (Scheibel and Porstendörfer 1984; Cheng *et al*., 1990). However, in all the past works employing multiple wire screens, the screens were separated from each other by a certain distance, thus ensuring that the aerosol flow just before each screen is uniform throughout the whole cross section of the filter. Under these circumstances, the overall penetration can be calculated as the product of the penetrations through each individual screen.

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According to the current literature there are no reports concerning the validity of the diffusion battery equations when the screens are in contact (i.e., no separation distance in between). In this case, penetration through the composite grid array is no longer given by the product of the individual penetrations because the aerosol flow approaching the second and successive screens does not cover the whole cross section as it is partially "screened" by the wires of the precedent mesh. Furthermore, no experimental data has been found for the case when the contacting screens have different geometric characteristics.

The present work tries to increase the current mixed screen-type diffusion battery knowledge. Specifically, the penetration of sub 10 nm particles through two composite grids placed in series has been studied. A set of experiments has been performed at different aerosol flow rates. Each composite grid consists of a gold mesh sandwiched between two aluminium meshes. All three meshes are in contact one with each other.

While the geometric characteristics of the individual screens as fiber diameter, solid volume fraction and thickness are well-defined, it is difficult to assign *a priori* a proper value to the fiber diameter of the composite grid.

However, it is possible to define an equivalent fiber diameter for the composite grid from experimental penetration measurements using the fan filter model correlation of Cheng and Yeh (1980):

$$P = \exp(-nS\eta_d) \tag{2}$$

$$\eta_d = 2.7Pe^{-2/3} \tag{3}$$

In Eq. (2) n is the number of grids and S is the screen parameter, which involves all the relevant geometric characteristics of the screen. The thickness of the composite grid has been experimentally measured and therefore the global solid volume fraction was obtained from the packing density values of the individual screens. Yamada *et al*. (2011) pointed out that the single fiber collection efficiencies of nanoparticles through wire screens are in good agreement with those predicted by Kirsch and Fuchs (i.e., Eq. (3)), but the dependence of real filters on Pe is somewhat smaller than –2/3 and in agreement with $\eta_d = 0.84Pe^{-0.43}$ (Wang *et al*., 2007). Guillaume *et al*. (2009) and Podgorski (2009) also found the exponent of smaller dependence on Pe. Despite the fact that the Cheng and Yeh correlation is strictly valid when $Re_f < 1$ (Scheibel and Porstendörfer 1984; Cheng *et al*. 1990), it has been applied for fiber Reynolds number ranged between 2.3 and 9.1 because, as the experimental results show, no systematic effect of flow rate (i.e. Reynolds number) on penetration has been found.

EXPERIMENTAL METHOD

Fig. 1 shows the experimental setup employed for the measurement of particle penetration. A polydisperse evaporation-condensation NaCl aerosol was charged in a circular tube containing two thin foils of ^{241}Am, each with an activity of 0.9 μCi, and size-classified with a differential mobility analyzer (DMA, TSI short column, length = 11.11 cm; electrodes radii = 0.937 and 1.958 cm). The DMA was operated in open mode, i.e. no sheath recirculation, at aerosol (= sampling) flow rate of 2 L/min, and sheath (= excess) flow rate of 20 L/min. The singly-charged monodisperse particles, with mobility-equivalent diameter selected between 3.3 and 9.1 nm, leaving the DMA were passed through another ^{241}Am neutralizer, with the same characteristics as the former, and an electrostatic precipitator (ESP). The uncharged monodisperse particles were subsequently fed to the filter system. The ESP consisted of a circular grounded tube made of copper, 10 mm ID and 15 cm in length, with a coaxial metal wire to which a DC voltage, high enough to remove all the charged particles, was supplied.

The filter efficiency measuring system consisted of two geometrically identical cylinders made of brass and electrically grounded, one containing a series of wire grids ('test filter' in Fig. 1), the other empty ('reference unit'). Each cylinder, 186 mm long and 8 mm ID, was equipped with a series of rings, 4 mm wide, 14 mm OD and 8 mm ID, placed near the outlet, as sketched in Fig. 2. The grids were held in between consecutive rings, in contact with them. The wire screen exposed to the aerosol flow was thus a circle of 8 mm in diameter. The length of the cylindrical casing assured the attainment of a fully developed parabolic flow velocity profile upstream of the first grid. The test particles were alternately passed through the test filter and the reference unit. Penetration through the grids was determined from comparison of the particle concentrations measured at the outlet of the cylinders. Particle number

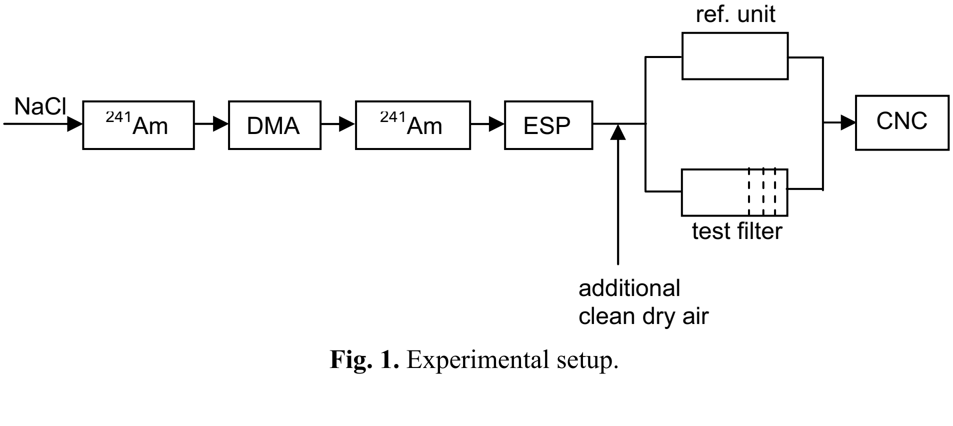

Fig. 1. Experimental setup.

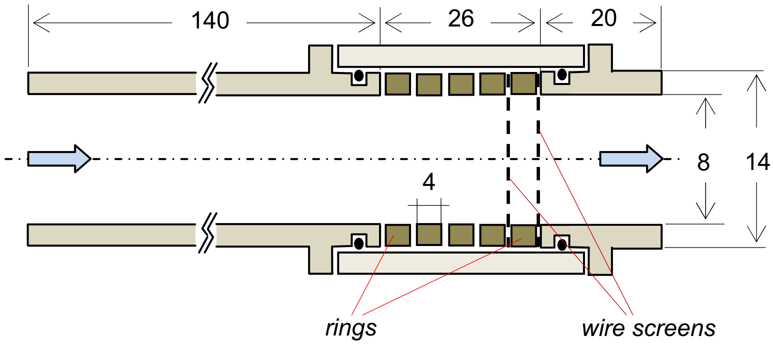

Fig. 2. Sketch of the filtration unit.

concentrations were measured with a condensation particle counter (CNC, TSI model 3025). Shifting between the two routes (filter holder with and without grids) was done by means of a 3-way valve; in order to eliminate the possible effect of any asymmetry between the two exit nozzles of the valve, the connections of the two routes to the valve were interchanged between experiments.

A set of experiments were performed with six Aluminum screens placed in series and separated 4 mm (a ring width) from each other in order to check the accuracy of the experimental setup and the measurement method. This is a 'conventional' diffusion battery comprising a series of single, well-characterized wire screens.

The main series of experiments were carried out with two 'composite grids', also separated by a 4 mm-width ring. Each composite grid consisted of one gold screen sandwiched between two Aluminum screens, as sketched in Fig. 3; optical photographs of the screens are shown in Fig. 4. This is a 'non-conventional' battery in which screens of different geometric characteristics are mixed and, moreover, they are in contact with each other. As far as we know, such a case has not been studied before.

In the case of the Aluminum screens, the value of the fiber diameter used in the calculations was provided by the manufacturer (Goodfellow), the solid volume fraction was determined from the weight of the screen and the known density of the material, assuming a screen thickness equal to twice the fiber diameter (Heim *et al*. 2010). For the "composite" grids, the thickness was measured with a caliper, and the solid volume fraction was calculated from the known solid volume fractions of the separate screens. The fiber diameter of the composite grid is unknown in principle, though it can be expected to lie somehow between the values of the fiber diameters of each of the composing screens. Actually, and this represents the main point of this work, it can be calculated by fitting the experimental penetrations with the Cheng-Yeh correlation.

Measurements of penetration through the composite grids were carried out at aerosol flow rates of 2, 4, 6 and 8 L/min (corresponding mean flow velocities of 66, 132, 198 and 264 cm/s). Each value of penetration reported below is the average of five measurements. For the preliminary series of experiments with single Al screens, additional flow rates well below 2 L/min were also employed so as to examine the possible influence of the fiber Reynolds number on penetration.

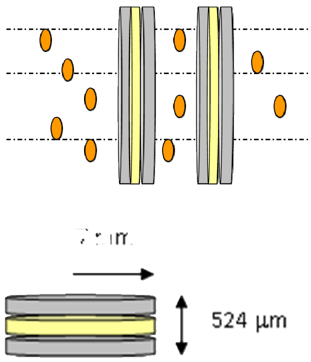

Fig. 3. Sketch of Al-Au-Al composite grid.

RESULTS AND DISCUSSION

Penetration through the Aluminum Screens

The experimentally measured penetrations through the diffusion battery containing six Aluminum screens and those calculated by the Cheng-Yeh model (Eqs. (2) and (3)) are shown in Fig. 5. As could be seen, the measured values are in agreement with the calculated ones, implying that the experimental setup and the measurement method were both correct. Furthermore, the results plotted in Fig. 5 indicate that there is no systematic dependency of penetration on fiber Reynolds number in the range studied (Re_f between 1.1 and 17.6 in the case of the single Al screens).

Determination of the Equivalent Fiber Diameter for the Composite Grid

The 'equivalent' fiber diameter of the composite grid was obtained by fitting the experimental penetration data for uncharged particles to the Cheng-Yeh model. Substituting the expression for the screen parameter

$$S = \frac{4\alpha h}{\pi d_f (1-\alpha)} \tag{4}$$

into Eq. (2), and taking Eq. (3) and the definition of Peclet number (5) into consideration,

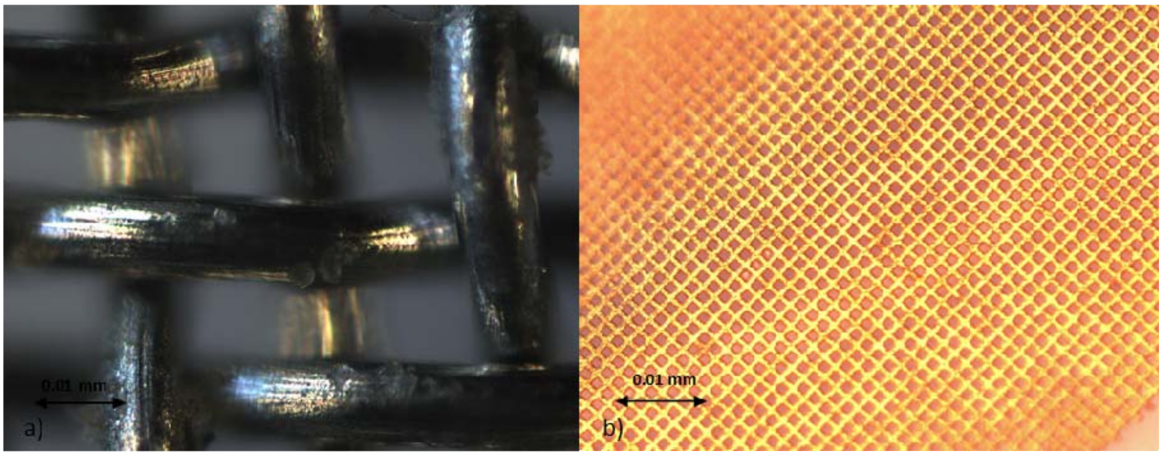

Fig. 4. Optical photographs of a) Aluminum grid and b) Gold grid.

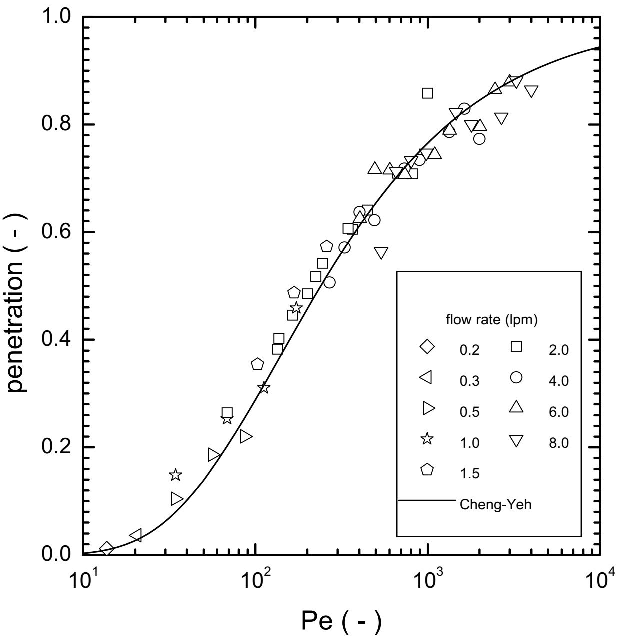

Fig. 5 Comparison between experimental penetration of neutral nanoparticles through a diffusion battery of six Al grids and the Cheng-Yeh correlation.

$$Pe = \frac{ud_f}{D} \tag{5}$$

the diffusional penetration can be expressed as

$$P = \exp\left(-\frac{10.8nh\alpha}{\pi(1-\alpha)}\left(\frac{u}{D}\right)^{-\frac{2}{3}} d_f^{-\frac{5}{3}}\right) \tag{6}$$

where α is the solid volume fraction of the screen, h is thickness, n is the number of screens, u is the mean velocity of the flow approaching the screen, and D is the particle diffusion coefficient. The particle diffusion coefficient was determined from the particle electric mobility Z, as measured by the DMA, and the Einstein's relation

$$D = \frac{kTZ}{e} \tag{7}$$

where k is Boltzmann's constant, T is the absolute temperature, and e is the electron charge.

Therefore, a plot of –ln$P$ against the factor multiplying $d_f^{-5/3}$ in Eq. (6) should yield a straight line passing through the (0, 0) point. An effective or equivalent fiber diameter value of 51.9 µm has been obtained from the slope of the line shown in Fig. 6. This value is within the fiber diameter for each of the composing screens range (100 µm for Al, and 5 µm for Au). Inserting this value into Eq. (4) yields a screen parameter of 6.05, Table 1.

Calculated penetrations with Cheng-Yeh model using composite screen effective fiber diameter were compared with experimentally measured penetrations in Fig. 7.

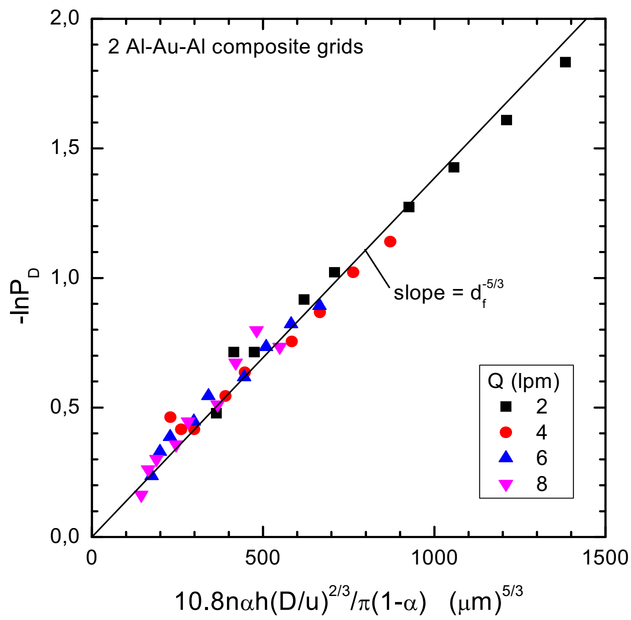

Fig. 6. Determination of the equivalent fiber diameter for the Al-Au-Al composite grid from the experimentally measured penetration for uncharged particles.

Table 1. Characteristics of the grids.

	Aluminum	Al-Au-Al composite grid
Fiber diameter, d_f (µm)	100[1]	51.9[2]
Thickness, h (µm)	200[3]	524[4]
Solid volume fraction, α (–)	0.39	0.32
Screen parameter, S (–)	1.653	6.01

[1] Data provided by the manufacturer; [2] determined from penetration measurements (see text for explanation); [3] taken as $2d_f$; [4] measured.

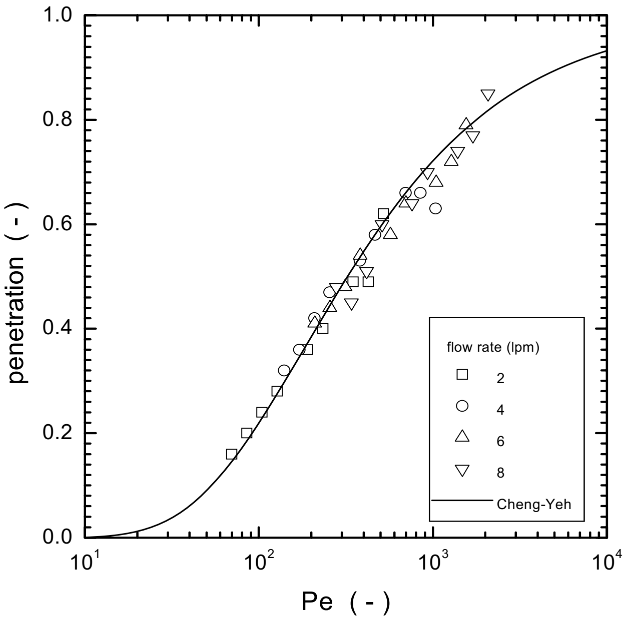

Fig. 7. Comparison between experimental penetration and that calculated with Eqs. (2) and (3) for the Al-Au-Al composite grids.

Experimental data was obtained with different flow rates (fiber Reynolds numbers between 2.3 and 9.1). The results showed that there is no systematic dependence of penetration on the Reynolds number within the range of values tested in agreement with the results shown before for the Aluminiun 'single' screens.

CONCLUSIONS

It has been shown that it is possible to apply the fan filter model equations of Cheng and Yeh to estimate the diffusional penetration of aerosol nanoparticles through composite grids, i.e., a grid system consisting of wire screens having different geometric characteristics in intimate contact with each other. For this, it is first necessary to determine the equivalent fiber diameter of the composite screen from a fitting of Eq. (6) to the experimental penetration data.

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