Penetration of nanoparticles in 5 nm to 400 nm size range through two selected fibrous media

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Abstract. Due to the strong development of nanotechnologies, ultrafine particles could represent a growing hazard for workers health. When it is not possible to reduce the risk at its source, filtration systems are one of the means used to limit the exposure to hazardous substances such as airborne particles. The aim of this study is to measure the penetration of nanoparticles on a very large diameter range, from the nanometer size to the most penetrating particle size (MPPS). Here we present experimental results obtained for three different types of nanoparticles. Measurements of nanoparticle penetration through two low efficiency fiberglass media are carried out using two test benches presented in this article. Penetration values for carbon, copper and NaCl nanoparticles decreases with particle size, as predicted by theory. The value of the most penetrating particle size is situated between 100 and 300 nm. No thermal rebound was observed in this particle size range. The penetration values will be used, in further studies, to determine a global penetration model.

1. Introduction

The use of nanoparticles in the industrial world has increased since the 1990s. These particles, with at least one dimension less than 100 nm, are exploited for their special properties and can cause new cases of occupational exposure. Because of their dimension, they may deposit in the lungs and are also liable to reach the nervous system via the nasal cavities. The scientific community is therefore most concerned about the impact of these particles on the environment and health. The filtration system is one of the means used to reduce aerosol exposure.

The work presented in this paper concerns filtration efficiency for two filters used in filtration systems tested with three different types of nanoparticles and using two different test benches. In the first part, the article describes the two experimental setups. In the second part, a comparison between both test benches allows us to compile the penetration values. The properties of the tested filters are described in the third part of this paper. Finally, experimental results are plotted and penetration data are presented and discussed.

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2. Material and methods

2.1. Description of FANA test bench

The nanoaerosol filtration test bench FANA [1] was developed at the Institute for Radiological Protection and Nuclear Safety (IRSN) in order to measure filter penetration as accurately as possible, for particle sizes ranging from 2.5 to 50 nm. FANA is presented in figure 1.

![FANA experimental setup for nanoparticles (FANA 1)](image)

**Figure 1.** FANA experimental setup for nanoparticles (FANA 1)

FANA’s production of nanoparticles is based on the work of Bartz et al. [2]. NaCl aerosol produced by an atomizer Collison TSI is evaporated using a tube furnace. The gas particles are then condensed in a nanometer size by mixing with cold air. The particle size distribution produced by FANA evolves according to the NaCl concentration, the furnace temperature and the air flow dilution.

For a furnace temperature of 750 °C and an air dilution of 30 L/min, the count median diameter of the generated distribution is 8.5 nm, the geometric standard deviation is 1.5 and the total concentration is $9 \times 10^6$ particles per cm$^3$ (figure 2). This aerosol size distribution has been characterized using a Scanning Mobility Particle Sizer (SMPS). This includes a source of $^{85}$Kr and a nano-DMA (Differential Mobility Analyzer). The $^{85}$Kr source neutralizes the aerosol to the Boltzmann equilibrium state.

Observations by transmission electron microscopy show that the generated NaCl particles are single particles and have a cubic shape (figure 3).
Once the aerosol has been characterized, all particles are sent to the filter holder. After the selection of particles by their electrical mobility, the experimental penetration of filters is determined according to the detection of the particles at the inlet and outlet of the filter holder.

To avoid artefact measurements, the same Ultrafine Condensation Particle Counter 3025A (UCPC) is used for measurements upstream and downstream of the filter holder. This UCPC is used in counting mode for a duration measurement of 60 minutes on average. The experimental penetration is then calculated by the ratio of the downstream number of particles to the upstream number of particles for the same volume sampled.

Temperature, pressure and relative humidity are monitored and a Condensation Nuclei Counter is installed at the exit of the nanoparticle generation system to control the stability of the generation. The filtration velocity through the filter is regulated during the test at 5.3 cm/s.

In order to measure penetration in the range of the Most Penetrating Particle Size (MPPS), the test bench was modified to generate larger nanoparticles (50-500 nm). In this case (figure 4), the generation system is composed of the atomizer Collison TSI and the dryer only.

![Figure 2. Particle size distribution produced by FANA test bench](image2)

![Figure 3. TEM picture of a NaCl nanoparticle](image3)

**Figure 2.** Particle size distribution produced by FANA test bench

**Figure 3.** TEM picture of a NaCl nanoparticle

![Figure 4. FANA experimental setup for larger particles (FANA 2)](image4)

**Figure 4.** FANA experimental setup for larger particles (FANA 2)
This generation system produces an aerosol with a count median diameter of 70 nm, a geometric standard deviation of 1.7 and a total concentration of $1.10^6$ particles per cm$^3$ (figure 5).

**Figure 5.** Particle size distribution produced by FANA test bench for larger particles

In order to avoid potential clogging problems during the measurement of penetration, the DMA is moved upstream of the filter holder. As described before, the same UCPC is used in counting mode for a duration measurement of 60 minutes on the average. The experimental penetration is calculated by the ratio of the downstream number of particles to the upstream number of particles for the same volume sampled. The filtration velocity through the filter is regulated during the test at 5.3 cm/s.

2.2. Description of MEFIANCE test bench

This experimental setup (figure 6) was developed at LRGP [3, 4].

**Figure 6.** MEFIANCE experimental setup

The generation of aerosol on this test bench is obtained using the nanoparticle spark-generator PALAS GFG-1000. The particles are produced by electrical discharge between two electrodes. The size of the nanoparticles varies depending on the operating spark frequency of the generator. The particles are then selected according to their electrical mobility by the same type of nano-DMA as in...
the FANA test bench. These particles are brought to the Boltzmann equilibrium by the use of a source of $^{85}$Kr.

The particles used in this experiment are generated using two types of electrodes, namely carbon and copper electrodes (figure 7 and 8). When using copper electrodes, the count median diameter is about 7 nm whereas, for carbon electrodes, it is about 70 nm.

![Figure 7. Particle size distribution produced by copper electrodes](image)

![Figure 8. Particle size distribution produced by carbon electrodes](image)

Then, particles are sent to the filtration system which is made up of two identical lines. Filtration velocity is regulated through filter at 5 cm/s. Only one Condensation Particle Counter (CPC) is used to remove artefacts. The 3022A CPC is used in the single count concentration mode. The experimental penetration is then calculated by the ratio of the outputs from the two lines.

3. **Comparison of the two experimental setups**

Because the two test benches are not operating in the same laboratory there are differences between the two experimental setups and protocol measurements. In this section, we will enumerate the differences in order to evaluate their potential influence on penetration measurement.

First, the configurations of the two filtration systems are not the same. Either the penetration is calculated by an alternative measure of the concentration upstream and downstream of the filter holder, with controlling of the stability of the total concentration generated, or the penetration is calculated by measurements using a double line. These two configurations were presented by Heim et al. [5], who concluded that using both of them helps to limit artefacts in measurement.

Secondly, the selection of particle size is carried out upstream of the filter holder or at the filter inlet and outlet: both configurations have been studied by Michielsen et al. [1] in the case of measuring the penetration of screens. The authors do not notice differences between the two measurement methods.

Thirdly, one can see that measurements of penetration are performed at a filtration velocity of 5.3 cm/s on the FANA test bench and a filtration velocity of 5 cm/s on the MEFIANCE test bench. This range of filtration velocity is the most commonly encountered in the literature [7, 8]. According to existing models [10], the influence of a 0.3 cm/s increase in velocity is negligible on the calculated penetration.

We can also notice that the two test benches do not use identical filter holders: the diameter of the filtration surface in FANA is 30.6 mm and the diameter of the filtration surface in MEFIANCE is 60.0 mm. Again, this should not make any differences on the results.

At last, the two test benches have been tested with calibrated screens in order to compare our penetration measurements with theoretical model [6]. The results obtained are in good agreement with the theory for both experimental setups. Figure 9 shows the penetration values through a screen as a function of particle diameter obtained with the FANA test bench.
This validation allows us to combine penetration data on a very large diameter range for different nanoparticles.

4. Penetration results and discussion

4.1. Filter media properties
Two different commercial fibreglass filters are tested. They have a low efficiency and the table 1 shows their specifications. Physical properties have been investigated in order to determine the thickness, the pressure drop, the solidity, the Davies diameter and the geometric fiber diameter. The thickness is given by an average of microscopic observations. The solidity, \( \alpha \), is obtained by the following equation:

\[
\alpha = \frac{G}{\rho_f Z}
\]  

(1)

where \( G \) is the filter’s mass per unit area, \( Z \) is the thickness and \( \rho_f \) the fiber density.

The Davies fiber diameter, \( d_{\text{Davies}} \), is the fiber diameter calculated from the pressure drop measurements with the following formula:

\[
d_{\text{Davies}} = \sqrt{\frac{64 \mu U Z \alpha^3}{\Delta P}} \left(1 + 56 \alpha^4\right)
\]

(2)

where \( \mu \) is the air viscosity, \( U \) is the filtration velocity and \( \Delta P \) the pressure drop.

The standard filter media are composed of fibers of different sizes and random orientations. The average geometric fiber diameter is obtained by observations with a TEM.

Figure 9. Penetration through a calibrated screen using FANA test bench
4.2. Media penetration and discussion
Penetrations are plotted in figure 10 and 11 for the two fiberglass filters and the three different nanoparticles as a function of the electrical mobility equivalent diameter.

![Figure 10](image-url)

**Figure 10.** Spectral penetration of nanoparticles through filter 1

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**Table 1.** Physical properties of media tested

|                        | Filter 1       | Filter 2       |
|------------------------|----------------|----------------|
| **Average thickness (µm)** | 552 ± 50       | 427 ± 45       |
| **Solidity**           | 0.05           | 0.064          |
| **Davies fiber diameter (µm)** | 4.23           | 3.25           |
| **Average geometric fiber diameter (µm)** | 3.19 (GSD=1.76) | 5.14 (GSD=2.84) |
The data-gathering allows to obtain the penetration spectrum of the two filters studied for particle sizes ranging from 5 to 400 nm and for different kinds of particles. Each test bench generated two groups of measurements of penetration; and for each bench, the series overlap.

As expected by theory [9], the penetration decreases when diameter decreases. The value of the most penetrating particle size is situated between 100 and 300 nm. One can see that the penetration through filter 1 is slightly greater than the penetration through filter 2.

However, we can notice that there is a difference between the penetration values for NaCl nanoparticles and for C and Cu nanoparticles. One can see that, for filter 1 and diameters of 5 and 20 nm, the values of penetration for NaCl particles represent about 29 % of the values of penetration for copper particles. For filter 2, the penetration values of NaCl particles are about 23 % of the values of penetration of copper particles for diameters of 6 and 30 nm.

The morphologies of the particles are different and this may explain the gap between penetration for NaCl cubic nanoparticles and penetration for metal nanoparticles. But differences in morphology between Cu and C nanoparticles are also expected, and we do not see penetration differences. In addition, one can also notice that filters tested with FANA test bench and filters tested with MEFIANCE test bench are coming from different batches.

5. Conclusions and perspectives
After describing the two test benches used in this study, penetration measurements were performed for two different fiberglass fiber filters and three different types of nanoparticles: carbon, copper and NaCl nanoparticles.

First, the data-gathering allowed to obtain the penetration spectrum of filters studied for a very large diameter range from 5 nm to 400 nm. The penetration decreases when diameter decreases even below 10 nm. The most penetrating particle size is situated between 100 and 300 nm and the penetration through medium 1 is greater than the penetration through medium 2.
However, a comparison of the values of penetration showed a significant difference between NaCl nanoparticles and C and Cu nanoparticles penetration. Differences in the experimental protocol have been listed and did not explain the gap observed in penetrations. The difference in morphology between particles cannot be the unique cause of penetration differences. We have to keep in mind that the filters tested in this work are coming from different batches. This can also yield variations in the measured penetration.

This study gives reliable data on the penetration values on a very large diameter range. In parallel, filter characterisation have been studied. From now on, these data will be used to test existing models and to develop a penetration model.

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