Nanoparticles Filtration by Leaked Fibrous Filters

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Abstract. The aim of this work is first to measured nanoparticles penetration through three different fiberglass filters intentionally-pierced with calibrated needles at different filtration velocity. Then a semi-empirical model based on the air flow resistances of the new and perforated filter media and on the mechanism of Brownian diffusion for the collection of ultrafine particles by the media enables to well predict the efficiency observed for all tested operating conditions. Results show that the increase of particles penetration is all the more important that the pinhole is large and that the particle diameter is low. Another result is that the filtration efficiency of the new filter media controlled the penetration. A high efficiency filter with a high resistance to air flow will be more damaged than a low efficiency filter when being perforated.

1. Introduction

For the last few years, numerous works have been carried out dealing with the efficiency of undamaged filters in the ultrafine particle size range [1- 3]. In contrast, very few have been done about the performances of media presenting pinhole towards the filtration of particles under 30 nm. It is however known that the performances of filters can be dramatically changed because of leakages.

So, we measured nanoparticles penetration through three different fiberglass filters intentionally-pierced with calibrated needles, at 5 and 15 cm/s. The test monodisperse aerosols of copper nanoparticles, the electrical mobility diameter of which was varied from 4 to 30 nm, were produced from a commercial spark-generator and a TSI® nano-DMA 3085 for diameter selection. The effect of the filtration velocity, the particle diameter, the properties of the filter media are studied experimentally.

On the other hand, we developed a semi-empirical model based on the aeraulic properties of the filter media which are determined experimentally. The assumption that the only mechanism which occurs during the capture of the nanoparticles by a fibrous filter is the Brownian diffusion allows the development of an expression of the penetration of nanoparticles through a filter media with a pinhole.
2. Materials and Methods

2.1. Experimental Apparatus

In front of the lack of legislation about nanoparticles handling, the precautionary principle has to be applied. That is why the experimental setup of this study was put in an air hood and a part of it was integrated inside a gloves box (schematized in dotted lines on Figure 1).

![Figure 1. Experimental setup](image)

This test bench can be classically divided into three main stages.

The first one consists in generating a polydisperse aerosol of nanoparticles. A Palas® GFG-1000 spark-generator was used for that. Developed by Helsper et al. (1993), this device uses high voltage to produce sparks between two electrodes. The resulting sublimed material condenses into very fine particles, which leave the electrodes chamber thanks to a flow of pure argon inside which they grow in size. An additional flow of air then dilutes the particles. With copper electrodes, the GFG-1000 generator produces an aerosol with a mean diameter of 7 nm.

As a second step, a part of this aerosol is sampled into a TSI® nano-DMA 3085. The particles are separated thanks to an electric field between two concentric cylinders according to their electrical mobility, which is inversely proportional to their diameter. This creates at the outlet of the classifier a monodisperse unipolarly-charged aerosol, which is then globally neutralized – Boltzmann equilibrium – thanks to a $^{85}$Kr ionizing source [4].

The last step is the filtration of the selected particles carried by a dry and clean air stream, the flowrate of which is set according to the desired filtration velocity, through each of the two grounded stainless steel branches of the parallel chambers device alternatively, according to the valves A and B respective positions. Both the empty and the filter chambers are identical and have an internal diameter of 60 mm. Particle concentration at the outlet of any chamber is measured by a TSI®...
CPC 3022. The 1.5 L/min it aspires are isokinetically sampled. Then, the ratio between the particle counts at the outlet of both the filter and the empty chambers respectively is equal to the penetration $P$ of the media put inside the filter chamber.

2.2. Filter media properties
The medias tested in this study are three non woven fiberglass filters. Their physical properties are listed in Table 1.

| Media | Physical Properties |
|-------|---------------------|
| A     | B                   | C                   |
| Mean geometric fiber diameter $d_f$ ($\mu$m) | 4.5 | 3.3 | 1.3 |
| Thickness $Z$ ($\mu$m) | 440 | 420 | 409 |
| Solidity $\alpha$ | 0.060 | 0.065 | 0.078 |

These medias were perforated with calibrated needles of 400, 1320 and 2000 $\mu$m diameter. Pressure drop of these medias were recorded as a function of the air flow rate on the range 0-100 NL/min in both cases: without pinhole and with a pinhole. The curves obtained are linear in each case and resistance to air flow can be deduced from these experiments. Their values are listed in Table 2.

| Pinhole diameter $d_h$ (mm) | Resistance values ($\times 10^3$ cm$^3$) ± $3 \times 10^3$ |
|---------------------------|----------------------------------------------------------|
|                           | media A | media B | media C |
| 0                         | 1.57    | 4.24    | 35.41   |
| 0.4                       | -       | 4.22    | 35.28   |
| 1.32                      | 1.55    | 4.18    | 33.22   |
| 2                         | 1.52    | 3.96    | -       |

Then the filters were loaded by copper nanoparticles the electrical mobility diameter of which was varied from 4 to 30 nm.

3. Penetration model

3.1. Description of the modelled system
A schematisation of the filter media with a pinhole is given on Figure 2.
3.2. Expression of the total penetration

A filtration efficiency model that includes the effect of a pinhole inside the media can be derived by differentiating the leakage flow from the one passing through the remaining bed of fibers of the filter. Then, from the mass balance of the system, it can be written:

\[ P_f = \frac{Q_b}{Q_f} P_b + \frac{Q_h}{Q_f} P_h = 1 - E_f \] (1)

where the subscripts f, b and h are for filter, bed and hole respectively. \( P_i \) is the penetration through the object i and \( Q_i \) is the corresponding flowrate. The total flowrate \( Q_f \) is equal to the sum of \( Q_b \) and \( Q_h \). \( E_f \) is the global filtration efficiency. The additional subscript 0 is used to represent the values for the leakage-free filter.

From equation (1) and according to the respective values of \( Q_b \times P_b \) and \( Q_h \times P_h \), the total penetration of the filter is to be directed either by the remaining bed of fibers or by the pinhole or by the both in an intermediate case. Thus and as a first point, \( Q_h \) and \( Q_b \) have to be estimated. It can be done from the measurement of the pressure drop of the filter with and without any hole inside.

The evolution of the pressure drop \( \Delta P_{f,0} \) of the three intact filters are linear as a function of the filtration velocity \( U_f \) (see Table 2). In laminar flow, \( \Delta P_{f,0} \) can be mathematically expressed as:

\[ \Delta P_{f,0} = K \mu U_f = K \mu \frac{Q_f}{S_f} \] (2)

with \( K \), the flow resistance (Table 2) and \( \mu \), the air viscosity (1.8 \times 10^{-5} \text{ Pa.s} \) about in normal conditions). The surface of the filter \( S_f \) is equal to 2.83 \times 10^{-3} \text{ m}^2.

In addition, \( \Delta P_f \) is proportional to the filtration velocity \( U_f \) by a factor \( \mu \times K' \):

\[ \Delta P_f = K' \mu U_f = K' \mu \frac{Q_f}{S_f} \] (3)

The values of \( K' \) are listed in Table 2.

The percentage of leak flowrate increases as the hole size increases. As a consequence, the actual velocity \( U_b \) at which particles pass through the remaining bed of fibers of the filter decreases and is less and less close to \( U_f \) as \( d_h \) is bigger (\( K'/K \) ratio decreases). This difference of real filtration velocity between the filter in intact and leaked state has to be taken into consideration in the determination of the penetration fraction \( P_b \), through the single-fiber efficiency term \( \eta_b \):

\[ P_b = \exp \left( -\frac{4 \alpha Z}{\pi (1 - \alpha) d_f} \eta_b \right) = 1 - E_b \] (4)

where \( E_b \) is the particle removal efficiency of the bed of fibers. When the filter is undamaged, \( E_b \) is equal to \( E_f \), which can also be noted \( E_{f,0} \).

Then, equation (1) resumes to the general expression:

\[ P_f = \frac{S_h K'}{S_f K} \exp \left( -\frac{4 \alpha Z}{\pi (1 - \alpha) d_f} \eta_b \right) + \left( 1 - \frac{S_b K'}{S_f K} \right) P_h \] (5)

It is assumed in the following of this study that the particle penetration through the hole \( P_h \) is total. In other words, \( P_h = 1 \) whatever the particle size \( d_p \) and the flowrate \( Q_h \). Moreover and in regard to the aerosol size range covered by this paper (\( d_p < 30 \text{ nm} \)), it can be considered that the unique mechanism responsible for particle collection is the Brownian diffusion. Then, different models are available in the literature for the calculation of the single-fiber efficiency \( \eta_b \) [5-7]. It was chosen here to use the
recent correlation of Wang et al. [8] since it well fits the nanoparticles penetration values measured for the unleaky filters (Figure 6):

\[ \eta_b = 0.84 \text{Pe}_b^{-0.43} \]  
(6)

where \( \text{Pe}_b \) is the Péclet number of the bed of fibers:

\[ \text{Pe}_b = \frac{d_f \ U_b}{D} = \frac{d_f \ Q_b}{D \ S_b} = \frac{K'}{K} \text{Pe}_f \]  
(7)

with \( D \), the particle diffusion coefficient.

This equation was validated experimentally on the tested filters without pinholes.

Incorporation of equation (6) into equations (5) finally leads to:

\[ P_f = 1 - \frac{S_b \ K'}{S_f \ K} \left( 1 - \exp \left[ -\frac{3.36 \ a \ Z}{\pi (1 - a) d_f} \left( \frac{K'}{K} \text{Pe}_f \right)^{-0.43} \right] \right) \]  
(8)

4. Experimental Results and Discussion

4.1. Media Penetration

Each point presented in this section is the average of three series of measurements at least. The aerosol concentrations were always lower than \( 10^4 \text{part.cm}^{-3} \) in order to detect particles in the most accurate counting mode of the CPC.

Figures 3 and 4 show the effect of calibrated holes inside media A and media B on their penetration by nanoparticles. It can be seen that the agreement between the experimental points and equation (8) is very good.

![Figure 3](image_url)  
**Figure 3.** Particle penetration through media A as a function of both particle size and leak hole diameter (a): 5 cm/s and (b): 15 cm/s.
As it could be expected, the global efficiency of a filter decreases when this latter is damaged, all the more as the leakage is bigger. It is however notable that penetration increase is more important for fine particles than for larger ones, even for the smallest holes.

Lastly, it is well seen on Figures 3 and 4 that below a given aerosol diameter, which depends upon the leak size, the penetration of particles tends to reach a constant value, like for media C (Figure 5). The aerosol penetration is no longer determined and controlled by the capture through the bed of fibers, but by the leak (leak regime).

Whatever the particle size, media C is always in leak regime, even for the tiniest hole of 400 µm. It can be explained by the fact that this filter is so much efficient in leakage-free state that the slightest leak is enough to significantly increase the particle penetration.

Figures 3, 4 and 5 show that while media C is the most efficient of the three tested filters when they are intact at 15 cm/s, it becomes less effective than media B below 13 nm and than media A below 7 nm when they are 1.32 mm leaked. This point can be explained by the fact that the air flow...
resistance of media C is higher than the resistance of the two other filters. Then, at a given total flow and for a same hole size, the percent of leak flow is likely to be all the more important as the filter is higher flow-resistant. Thus, the lower the pressure drop due to the fibers is, the less significant a leak becomes in allowing particles to penetrate the media. The model well describes this phenomenon.

For a given particle size and as a well-known result, penetration through intact filters increases when the velocity increases, as a consequence of the reduction of diffusional deposition (the Péclet number is higher). In contrast, the penetration through damaged filters progressively becomes less and less velocity-dependent as the hole size increases. This confirms that in leak regime, the particle penetration is no longer influenced by the filtration velocity. Then, the gap between the penetration values for leaked and intact filters decreases as the filtration velocity increases. In a sense, the effect of a leak inside a media is reduced at high velocity.

5. Conclusion and Perspectives
The present study showed that perforation in a filter can result in a strong efficiency decrease, even though the opening percentage is small. On the one hand, these results confirm the important point that air leakage through a hole is all the more consequential as the air flow resistance of the filter is higher (i.e. for filters with higher efficiency). On the other hand, the effect of air leakage is more significant for smaller particles, in the region of 10 nm and below. This might call into question the use of very high filtering facepiece respirators for protection against nanoparticles, since the higher the media efficiency, the higher the leak consequence.

Moreover, it is shown that knowledge of air flow resistance of both new and damaged filter can be used to predict penetration increase. It must be noted that for filters with low flow resistance, air leakage has very little effect on pressure drop, resulting in potential undetected leak. Though, particle penetration can have been dramatically increased and causes the filter to fail efficiency requirements, especially for the finest particles. Consequently, this limits the use of indirect, pressure-based, methods of leakage measurement.

Finally, a study on nanoparticles penetration through leaks into respirators, taking into account the inspiration/exhalation cycle, should be soon carried out to complete this work.

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