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Association of fibrous filters for aerosol filtration in predominant Brownian diffusion conditions

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ABSTRACT

In order to improve the dust retention capacity of air filters and increase their lifetime, the filtration performance of associations of fibrous filters has been investigated. This study highlighted the interest of the addition of a medium or coarse filter, composed of microfibers, upstream of a HEPA filter. Collecting nanostructured particles in the depth of this upstream filter, rather than directly on the surface of a HEPA filter, permits to significantly reduce the pressure drop increase while maintaining a global mass collection efficiency close to the unit. On the one hand, the association of a medium filter and a HEPA filter induces a real energy gain, compared to the implementation of a single HEPA filter. On the other hand, the implementation of a coarse filter, presenting a too low initial collection efficiency, upstream of a HEPA filter leads to mixed results.

1. Introduction

At this time, because of their very high-efficiency, the fibrous filters are the most commonly dedusting systems used for individual and collective protection. High efficiency particulate air (HEPA) filters are used in many applications: containment in medical, pharmaceutical or nuclear facilities, cabin air treatment in automobiles and aircrafts, vacuum and so on. In addition to their high efficiency, these filters, usually non regenerable, may have an important lifetime (i.e. high dust retention capacity) to avoid too frequent replacements.

The performances of these filters are typically measured by the figure of merit (also called quality factor) which represents the ratio of the penetration of particles to the filter pressure drop [1]. A high quality filters are thus characterized by high values of quality factor (i.e. high filtration efficiency and low pressure drop). To further improve the filter performances, a possible solution is to fabricate fibers with diameter lower than 0.5 µm (called nanofibers). Nanofiber filters, generally produced by electrospinning [2], have a small fiber size so that they integrate the advantage of a small pore size as well as large surface collection area. Besides, low basis weight also make nanofiber filtration a promising application [3]. As the collection efficiency is a decreasing function of the collector size, nanofiber filters could generally achieve a high collection efficiency. However, the pressure drop across nanofiber filters is higher than across microfiber filters (all other things being equal) even in the slip regime. Wang et al. [4] compared the performances of nanofiber filters and conventional fiber glass filters and highlighted that nanofiber filters have a better figure of merit for particles larger than 100 nm and a similar one for particles smaller than 100 nm. Furthermore, the authors observed an optimal nanofiber packing density at which the figure of merit is maximal. The characteristics of the nanofiber filters (packing density, fiber diameter) may thus be adjusted according to the size of the particles mostly present in the gaseous effluent.

In practical applications, a thin nanofiber layer is usually placed upstream because of its high filtration efficiency while a downstream microfiber layer provides mechanical strength. Wang et al. [5] studied the initial filtration performance of dual-layers filters composed of monodisperse micrometer fibers and nanofibers. The theoretical calculation of the quality factor for various layer properties (packing density, thickness, fiber diameter) highlighted that an increase of the thickness and the packing density in the nanofiber layer leads to better performances for particles larger than 100 nm and to opposite results for particles smaller than 100 nm. Furthermore, increasing the nanofiber diameter leads to better performances for particles smaller than 100 nm and to worse ones for particles larger than 100 nm; increasing the microfiber diameter induces exactly opposite results. However, initial filtration performances are not sufficient to conclude on the best properties of a filter. It is absolutely necessary to investigate the influence of these layer properties under loading with particles. Within this scope, Przekop and Gradon [6] developed a model estimating the

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temporal performances of bilayer filters consisting of nanofibers in the front layer and microfibers in the rear layer. The highest quality factor was obtained for the smallest nanofibers and microfibers tested and decreased during filter loading. The authors also highlighted that a uniform distribution of nanofibers in the front layer leads to a better quality factor during particle loading. Indeed, in case of thickness heterogeneities, the air flow tends to pass through the thinner (and less resistant) part of the nanofiber layer leading to a decrease of filtration performance. As a means for obtaining a thickness homogeneity of nanofiber mats, Zhang et al. [3] recommend the use of multiple thin layers of nanofibers.

Overall, the solution consisting of adding a thin layer of nanofibers allows increasing the collection efficiency but not countering the pressure drop increase during particle loading and consequently the energy consumption. A possible solution to reduce the pressure drop increase is a better distribution of particles collected within the fibrous filter. Leung et al. [7] performed experimental loading tests with NaCl submicron particles to evaluate the temporal performances of filters composed of two layers; one with nanofibers and another with microfibers. They notably highlighted that placing the microfiber layer upstream leads to more homogeneous deposit in the filter thickness and consequently to a lower pressure drop increase rate. In the specific case of nanoparticle filtration, the morphology and the size of these particles induce, for the same area density of collected particles, a faster increase of the pressure drop during the filter clogging than for submicronic and micronic particles [8]. This further reduces the lifetime of the fibrous filter and makes even more important the optimization of its retention capacity.

As nanofibers may present a health risk [9,10] and potentially a social acceptability risk, our approach is quite different and consists in a series association of microfiber filters with various properties (packing density, mean fiber diameter).

2. Materials and methods

The fibrous filter or the association in series of fibrous filters were placed downstream of a spark generator (GFG1000, Palas) producing graphite nanostructured particles. Their number size distribution was measured by a SMPS (Scanning Mobility Particle Sizer, nanoDMA 3085 TSI + CPC 3776 TSI). The particle size distribution presents a number median diameter (expressed in electrical mobility-equivalent diameter) of 60 nm and a Geometric Standard Deviation (GSD) of 1.6. The total number concentration was close to 4.5 10^7 cm^3. Control valve allows to check the filtration airflow rate whose acquisition is insured by a flow sensor placed downstream of a safety filter.

The characteristics of the fibrous filters are summarized in Table 1.

Table 1
Characteristic properties of tested fiber filters.

	Filters					Measurement method
	HEPA	Medium (M)		Coarse (G)		
	A	B	C	D	E	
Mean fiber diameter d_f (µm)	1.6	5.1	2.2	26.8	16.9	SEM
Material	glass	glass	PP*	PET*	PET*	-
Mean packing density α (-)	0.076 -	0.074 0.069	0.050 0.048	0.241 0.284	0.217 0.254	LTM IM
Thickness Z (µm)	411 -	373 367	387 401	606 681	422 602	LTM IM
Pressure drop at 2.5 cm/s (Pa)	147.0	6.3	7.0	3.2	5.2	-
Symbol	A	B	C	D	E	-

* PET: Polyethylene terephthalate; PP: polypropylene.

The analysis of scanning electron microscope (SEM) pictures, performed on about 300 fibers (per filter) permits to obtain the mean fiber diameters. The thickness and packing density of each filter have been determined by two methods:

- A laser trigonometry method (LTM), inspired by the study of Altmann and Ripperger [11], allows obtaining the filter thickness by the measurement of the displacement of a laser between two pictures. For more details, readers may refer to Ribeyre et al. [12]. The packing density may be deduced from this thickness and the weighing of a filter with a known surface.
- A impregnation method (IM), inspired by the method of Schmidt [13], followed by an analysis of SEM pictures allows a local measurement of the properties of filters embedded in an epoxy matrix. A numerical analysis tool have been developed to analyze SEM pictures of the embedded filters. After a binarization and a noise removal process based on filtration operations, the ratio of black and white pixels has been plotted along the filter thickness. The thickness and the mean packing density have been extracted from this profile. For more details on the filter preparation and properties measurement, readers may refer to Bourrous and al. [14].

The two methods lead to similar results except for the thickness measurement of the filter E. This difference may be explained by a loose fiber network and a possible reflection of the laser on the polyethylene terephthalate fibers.

The filters are supported by a grid presenting a negligible collection efficiency and pressure drop. When they are associated in series, the HEPA filter (called filter A) is systematically placed downstream of the medium or coarse one (filter B, C, D or E). The filter pressure drop is continuously recorded during the particle loading. The number particle size distributions are intermittently (every 30 min) measured upstream and downstream of the filter (or the series association of filters) using a Scanning Mobility Particle Sizer to obtain the temporal evolution of the fractional number efficiency.

Upstream and downstream fractional number concentrations ($C_{n,i}$) may be converted into fractional mass concentrations ($C_{m,i}$) according to Eq. (1).

$$C_{m,i} = \frac{\pi . \rho_P}{6} . C_{n,i} . d_{V,i}^3 \quad (1)$$

where ρ_p is the density of the raw particle material, $d_{v,i}$ the volume equivalent diameter and $C_{n,i}$ the measured fractional number concentration.

As graphite airborne particles are agglomerated and not spherical, the volume equivalent diameter differs from the electric mobility equivalent diameter (with is measured by the SMPS). The effective density, defined as the ratio of aggregate mass to equivalent mobility volume, allows converting the volume equivalent diameter into an electric mobility equivalent diameter and consequently calculating the fractional mass concentrations (cf. Eq. (2)). An experimental protocol, described in details in Charvet et al. [15], provides the relationship between the effective density of the graphite agglomerates and the electric mobility equivalent diameter (cf. Eq. (3)).

$$C_{m,i} = \frac{\pi . \rho_{e,i}}{6} . C_{n,i} . d_{m,i}^3 \quad (2)$$

$$\rho_{e,i} = 20.135 . d_{m,i}^{-1.02} \quad (3)$$

where ρ_e is the effective density of the graphite agglomerates and $d_{m,i}$ the electric mobility equivalent diameter. It should be noted that in (3), the mobility equivalent diameter is expressed in nm and the effective density in g/cm^3.

It was therefore possible to obtain the total mass collected per unit of filter area ($m_{c,t}$) during a set period of time (Δt):