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Impact of relative humidity on a nanostructured filter cake – Experimental and modelling approaches

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HIGHLIGHTS

- Pressure drop and thickness variations of a humid nanostructured deposit are presented.
- An equation allowing porosity determination for a humid nanostructured deposit is proposed.
- The porosity equation was implemented in two pressure drop models.
- A good match between modelled and experimental results was found.

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ABSTRACT

In this paper, three different non-hygroscopic nanostructured powders were dispersed in dry air and filtered to create a nanostructured deposit. The relative humidity was then gradually increased from 0 to 85% and the thickness of the deposit continuously measured using a laser trigonometry device. Experimental results showed that for each sample, the pressure drop of the deposit increases when the relative humidity increases, while the bed thickness decreases.

The modelling of the pressure drop upon increasing humidity was conducted using two pressure drop models available in the literature and specifically developed for nanostructured deposits. The variations in porosity and in cake thickness were included in the pressure drop models. This was achieved using a semi-predictive model of adsorption-condensation on nanoparticle beds developed to calculate the water mass sorbed by a powder. The modified models represent the experimental results with a maximum deviation of 10%.

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1. Introduction

In recent years, nanomaterials have known a strong interest all around the world. This development led to an exposure of a growing part of the population to ultrafine particles. For this reason, in recent decades air quality has emerged as a major public environmental and health issue. Despite numerous scientific publications concerning biological and physico-chemical properties of ultrafine particles, we are confronted with a lack of data about potentially induced toxicological risks (Roco et al., 2010). Thus, in most cases, to protect workers and the environment, institutions use Personal Protective Equipment (PPE) and High Efficiency Particulate Air Filters (HEPA) located in the general ventilation circuits. Nevertheless, almost all the available data correspond to modes with ambient air (ambient temperature and humidity). However, some postulated accident scenarios lead to a high moisture environment (Mocho and Ouf, 2011). The interaction of water vapour with particles may significantly affect the performance of such a filtration system. Indeed, if the pressure drop of the filter increases with humidity, it will lead to a reduction of its mechanical resistance and can eventually cause the rupture of the containment. Yet despite these extreme conditions, the HEPA filters used in industrial facilities must maintain their protective role.

Some laboratory measurements have shown that the evolution of the filter pressure drop during loading is strongly impacted by the presence of moisture and is mainly governed by the hygroscopic properties of the aerosol. For a non-hygroscopic aerosol, or a hygroscopic aerosol below its deliquescent point, Gupta et al. (1993) observed a linear increase of the filter pressure drop with collected mass per unit area for micron-sized aluminium oxide (1.19 μm mass median diameter) and for a submicron hygroscopic aerosol of sodium chloride (0.5 μm mass median diameter). The same observations were reported by Miguel (2003) for large-diameter polyester fibre filters loaded with non-hygroscopic (Al_2O_3) or hygroscopic aerosols (NaCl) below their deliquescent

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Nomenclature

Latin letters

a_0	water activity (–)
Cu	Cunningham coefficient (m)
c_G	GAB energy constant (–)
d_{pp}	primary particles diameter (m)
d_{vg}	mean geometric volume equivalent diameter (m)
Fc	correction factor used in Thomas's model (–)
H	deposit thickness (m)
H_0	initial deposit thickness (m)
h	meniscus demi-width (m)
k	GAB constant (–)
m_{bed}	mass of the dry bed of nanoparticles (kg)
P	pressure (Pa)
r	meniscus demi-length (m)
T	temperature (K)
t	thickness of multi-molecular layer (m)
U_0	gas velocity (m s^{-1})
$V_{particles}$	total volume of the particles (m^3)
V_{total}	total volume of the bed (m^3)
V_{void}	total volume of void inside porous medium (m^3)
V_{water}	total volume of water sorbed (m^3)
$v(a_0)$	water mass per sorbent mass (kg kg^{-1})
v_{mG}	quantity of water needed to cover the solid surface with a monomolecular layer (kg kg^{-1})
Z	coordination number (–)

Greek letters

ΔH	cake thickness variation (m)
ΔL	laser spot variation (m)
ΔP	pressure drop (Pa)
ε	deposit porosity (–)
$\vartheta(\varepsilon)$	void function (–)
γ	angle between laser and surface (°)
μ	gas viscosity (Pa s)
Ω	gas cross-section (m^2)
ρ_l	liquid density (kg m^{-3})
ρ_s	particle density (kg m^{-3})
σ_g	geometric standard deviation (–)
τ	porous medium tortuosity (–)

Indices

0	related to the initial cake parameters

point. The results indicated that for the same mass of deposited particles, the filter pressure drop is less important when the humidity increases. For a hygroscopic aerosol at a relative humidity above its deliquescent point, the pressure drop of the filter increases exponentially after a certain mass of droplets has been collected (corresponding to the transition from solid to liquid) (Gupta et al., 1993; Joubert et al., 2010). The same trends were observed by Novick et al. (1992) for micron-sized sodium chloride and by Vendel and Letourneau (1994) for a metal fibre filter clogged with sodium chloride and caesium hydroxide aerosols.

However, few studies exist in the literature considering the moisture influence on the pressure drop of a deposit built under dry air. In the case of hygroscopic aerosols, most results are related to micron and submicron-sized aerosols. Joubert et al. (2011) studied flat filters loaded with submicron NaCl particles (0.41 μm equivalent volume median diameter) at 0% RH and crossed by humid air below the deliquescent point. When high humidity (RH = 75%) passed through the cake, the authors denoted a decrease in the cake pressure drop, followed by a stabilization. Furthermore, Montgomery et al. (2015) observed the same trends, but with a depth-loaded filter, a nanostructured NaCl aerosol (approximately 100 nm) and a humidity range between 0 and 60%. For a non-hygroscopic aerosol, Ricketts (1991) and Schröter and Poon (2012) loaded flat filters with a micron-sized atmospheric aerosol (particle size between 100 and 300 nm) and highlighted an increase in the pressure drop after several hours of exposure to a high relative humidity (RH = 90%). Finally, in case of submicron particles, Montgomery et al. (2015) investigated the influence of relative humidity (between 0 and 60%) on the pressure drop of flat air filters depth-loaded with Al_2O_3 particles (approximately 400 nm). After loading at a specified humidity, they exposed the filters to clean air. No change in the pressure drop were seen with relative humidity changes, even when the relative humidity of the clean air for exposure was higher than that during loading for filter media. Experiments were also conducted with mixtures of hygroscopic (NaCl – 100 nm number median diameter) and non-hygroscopic (Al_2O_3 – 400 nm number median diameter) particles to simulate real air systems (atmospheric aerosols). The changes in filter performance characteristics were higher for an aerosol mainly composed of hygroscopic particles than for one that was mainly a non-hygroscopic aerosol. In other words, the change in the pressure drop was lowest for 100% Al_2O_3 particles. The impact of exposure to humidity was a function of filter media and dust loading level, as well as exposure to relative humidity. The authors postulated that particles captured within the filter media while loading at low humidity underwent growth in particle size when exposed to higher humidity. This increase in particle size could impose stress on the structure, resulting in physical restructuring of the particles in the fibers.

Though the studies detailed above have indicated trends in terms of pressure drop for hygroscopic and non-hygroscopic particles, no definite conclusions could be drawn about the effects of relative humidity on the pressure drop of the deposit. Furthermore, the humidity effects are bound to depend on the aerosol material's properties, such as hygroscopicity, and particle size of the aerosol. Thus, the interactions between water vapour and particles composing the cake should be responsible for these variations. However, it is not entirely clear how these phenomena impact the cake pressure drop. Moreover, the studies described above principally concern the submicron or micron-sized aerosols, and almost no information is available in the literature regarding nanostructured particles.

For these reasons, the first objective of this study was to determine the effects of humidity on the pressure drop of a nanostructured deposit formed under dry air by non-hygroscopic particles. The second objective aimed to provide explanations of the observed trends. Hence, part of the study was devoted to the investigation of the thickness and mass variation of the bed under humid conditions. Then, the cake porosity was evaluated using thickness variations and an Adsorption-Condensation Model (ACM) developed in a previous study (Ribeyre et al., 2014). Finally, a pressure drop model that took into account the cake porosity and cake thickness variations under humidity was proposed and compared to experimental data.

2. Experimental part

2.1. Sample characterization

Three kinds of non-hygroscopic agglomerates, consisting of nearly spherical nanoparticles, were used in this study:

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