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Modelling the pressure drop across HEPA filters during cake filtration in the presence of humidity

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ABSTRACT

The modelling of the variation in the pressure drop across a HEPA filter during cake filtration in the presence of humidity was studied. A semi-empirical model was developed that considers the pressure drop across the clogged filter as the sum of the pressure drops across the clean filter and across the cake, which is itself decomposed into several successive layers. The pressure drop across each layer of particles depends on its state of equilibrium with the air humidity. The model includes the specific resistance of each layer of particles and its variation when the cake is exposed to a flow of moist air. This model applies for relative humidity below the deliquescent point of the aerosol if it is hygroscopic. The results show good agreement between the calculated values and experimental values for flat filters clogged with aluminium oxide and sodium chloride test aerosols. The model also revealed the influence of filtration time on the evolution of the pressure drop across a clogged filter in the presence of humidity, especially with a hygroscopic aerosol.

1. Introduction

Air cleaning is a major concern in many sectors of industry. In the nuclear industry, aerosols are the main vectors of contamination and they are captured by pleated High Efficiency Particulate Air (HEPA) filters. These filters are used to maintain containment of radioactive substances in nuclear facilities and provide the final barrier before discharge to the external environment both under normal operating conditions and under accident conditions. Some accident scenarios can lead to a significant increase in the humidity of the gaseous effluent. A line break with steam release or the use of water spray for fire extinction, leading to the emission of aerosols, are two examples. It is therefore essential to be able to predict the behaviour of the filters in terms of performances and particularly the evolution of their pressure drop in humidity conditions, as this could be detrimental to maintaining containment in nuclear facilities.

The presence of humidity during the clogging of flat HEPA filters, constituted of glass fibres, was studied experimentally by Gupta et al. [1]. The conclusions of this study, confirmed by Miguel [2] using polyester-fibre filters, have revealed the influence of the hygroscopicity of the aerosols on the evolution of the pressure drop across the filters. First, for a non-hygroscopic aerosol or a hygroscopic aerosol when the air humidity is below its deliquescent point, the linear increase in filter pressure drop during the build-up of a cake at the surface of the filtering medium is much lower than when the air humidity is high. According to Gupta et al. [1], the effect of humidity on the evolution of the pressure drop across the filter can be attributed to an increase in the particle-to-particle adhesive forces as the air humidity increases. Thus, during cake formation, the particles tend to form a more open structure giving a lower pressure drop for the same mass of collected particles. Experimental study realized prior to this modelling work [3] has confirmed the results of Gupta et al. [1] and highlighted that influence of humidity is more significant with the decreasing of particle diameter. The hypothesis proposed to explain this behaviour is associated with the adsorption of water vapour on the surface of the particles deposited. Indeed, liquid water is formed by capillary condensation of the vapour into capillaries or fine pores of the particles. According to Butt and Kapple [4], liquid water can be formed even far above the dew point of the surrounding atmosphere. Thus, water modifies the adhesive force between particles leading to a restructuring of the deposit (to a structure with a smaller specific surface area or to a non-homogenous structure due to the local creation of preferential passageways by the formation of aggregates) which causes a reduction in the specific resistance. This effect is more significant when the diameter of the particles is smaller because the structure of the deposit with submicron-sized particles presents a larger specific surface area due to the dendritic structure of the deposit [5]. Thus, this structure allows the adsorption of a greater

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Nomenclature

a	adjustment coefficient for the model, kg s m^{-1}
b	adjustment coefficient for the model, kg m^{-1}
d_p	particle diameter, m
k	variable of the number of layers in the cake (comprised between 1 and N)
K_c	specific cake resistance, m kg^{-1}
MMAD	mass median aerodynamic diameter, m
m_s	particle mass collected on the filter, kg
N	number of layers in the cake
RH	relative humidity of air, %
S_f	filtration surface area, m^2
t	time, s
t_f	total filtration time, s
V_f	filtration velocity, m s^{-1}
x	variable for the model
z_c	cake thickness, m
Δm_s	particle mass in each layer of cake, kg
ΔP	pressure drop across the filter, Pa
ΔP_0	pressure drop across the clean filter, Pa
ΔP_c	pressure drop across the cake, Pa
ΔP_k	pressure drop across the layer k of the cake, Pa
Δt	time required for the formation of each layer of particles in the cake, s
Δz_c	thickness of each layer of particles in the cake, m
ε_c	cake porosity
μ	gas dynamic viscosity, Pa s
ρ_p	particle density, kg m^{-3}
σ_g	geometric standard deviation of a size distribution

quantity of water for the same mass of deposited particles and thus allows a greater restructuring of the deposit. Furthermore, for a hygroscopic aerosol when the air humidity is above its deliquescent point, the aerosol is liquid and the pressure drop of the filter increases exponentially after a certain mass of droplets collected. In this case, the evolution of the pressure drop across a flat filter is characteristic of clogging with a liquid aerosol [6].

The majority of studies uses flat filters but the two geometries of filters, flat and pleated, do not exhibit similar pressure drop change when being clogged. Indeed, studies performed in moderated air humid conditions [7–9] have showed that flat and pleated HEPA filters have two common filtration stages of first depth filtration, corresponding to a deposit of particles inside the medium, and next cake filtration due to the development of a cake on the surface of the medium leading to a linear increase in the filter pressure drop. The pleated filters get an additional filtration stage of reduction of the filtration surface which follows the cake filtration stage and leads to an exponential increase in the pressure drop across the filter.

For pleated filters, experimental results [3] showed that the influence of the air humidity varies according to the filtration stage. During the cake filtration stage, the presence of humidity reduces the specific cake resistance in the same way as for flat filters, but when the stage of reduction of the filtration surface begins, the presence of humidity increases the pressure drop across the filter. When the pleated filter is clogged by a hygroscopic aerosol at humidity above its deliquescence point, the pressure drop varies in the same way as for a flat filter, characteristically to liquid filtration. Gregory et al. [10] studied the influence of humidity on the air flow resistance of HEPA filters with deep pleats when clogged by a stearic acid submicron aerosol. The results showed that the air flow resistance of the filter is lower when clogging occurs under humid conditions. Once saturation is reached, an additional injection of water causes a further decrease in the filter air flow resistance for the same aerosol mass loading.

There are several models in literature to predict the evolution of a flat filter pressure drop during its clogging by solid particles in ambient humidity conditions. For the depth filtration stage modelling, Davies [11], Juda and Chrosciel [12] and Bergman et al. [13] assume a homogeneous distribution of particles into the medium, whereas Letourneau et al. [14], Kanaoka and Hiragi [15] and Payatakes [16] take into account a penetration profile of the particles into the medium. Thomas et al. [5] have developed a depth and surface filtration model based on the distinction between fibres of the filter and deposited submicronic particles resulting in additional fibres inside the filter and on the filter surface. The depth filtration stage being very brief, the modelling of the evolution of the pressure drop across a filter during clogging can be limited to the cake filtration stage for which the model of Novick et al. [17] constitutes the most common approach. It assumes that the pressure drop across the filter ΔP results from two contributions: the pressure drop across the clean filter ΔP_0 and the pressure drop across the cake ΔP_c. Furthermore, the authors assume that the porosity of the particle deposit is constant and independent of cake thickness. Hence, the pressure drop across a HEPA filter during clogging by a solid aerosol is expressed by the equation:

$$\Delta P = \Delta P_0 + K_c \mu \frac{m_s V_f}{S_f} \quad (1)$$

where K_c is the specific resistance of the cake of particles, μ is the dynamic viscosity of the fluid, m_s is the mass of particles deposited on the filter, S_f is the filtration surface area of the filter and V_f is the filtration velocity.

Del Fabbro et al. [9] have developed a model for the evolution of the pressure drop across pleated filters based on a dimensionless approach that only applies for micron-sized particles. Rebai et al. [18] have put forward a numerical model for simulating the clogging of a pleated filter, which was obtained by combining a semi-analytical approach to the airflow in the pleat of the filter with an empirical clogging model for a flat filter. These studies have shown that modelling the clogging of a pleated filter is complex, as numerous parameters must be included. For example, experimental tests [19] revealed that the influence of filtration velocity varies depending on the size-distribution of the aerosol. Thus, there is currently no model that can predict whatever the experimental parameters (especially aerosol size distribution and filtration velocity), even in dry air, the variation of the pressure drop across a pleated filter. Nevertheless, Eq. (1) can be used to model the variation of the pressure drop across pleated filters at the beginning of clogging, before the stage of reduction of the filtration surface begins.

The presence of humidity during the clogging of a HEPA filter has never been studied from a modelling standpoint in the literature. The model proposed by Novick et al. [17] is widely used for flat filters with dry air or moderate humidity. However, this model must be extended to take into account the influence of the humidity of the air. For pleated filters, given the complexity of clogging, the existing models that are valid with dry air or moderate humidity are often difficult to use [9,18]. Moreover, only Ricketts et al. [20] have offered empirical correlations based on experimental results obtained during various experiments with high humidity [21,22]. In fact, the authors studied the behaviour of clean and pre-clogged pleated industrial filters and flat samples subject to a flow of moist air. These correlations, corresponding to a mathematical smoothing of experimental data for some filters, are difficult to use due to the lack of data on the physical parameters characterizing the filters studied.

This paper presents a semi-empirical model developed to predict the effect of humidity on the evolution of the pressure drop

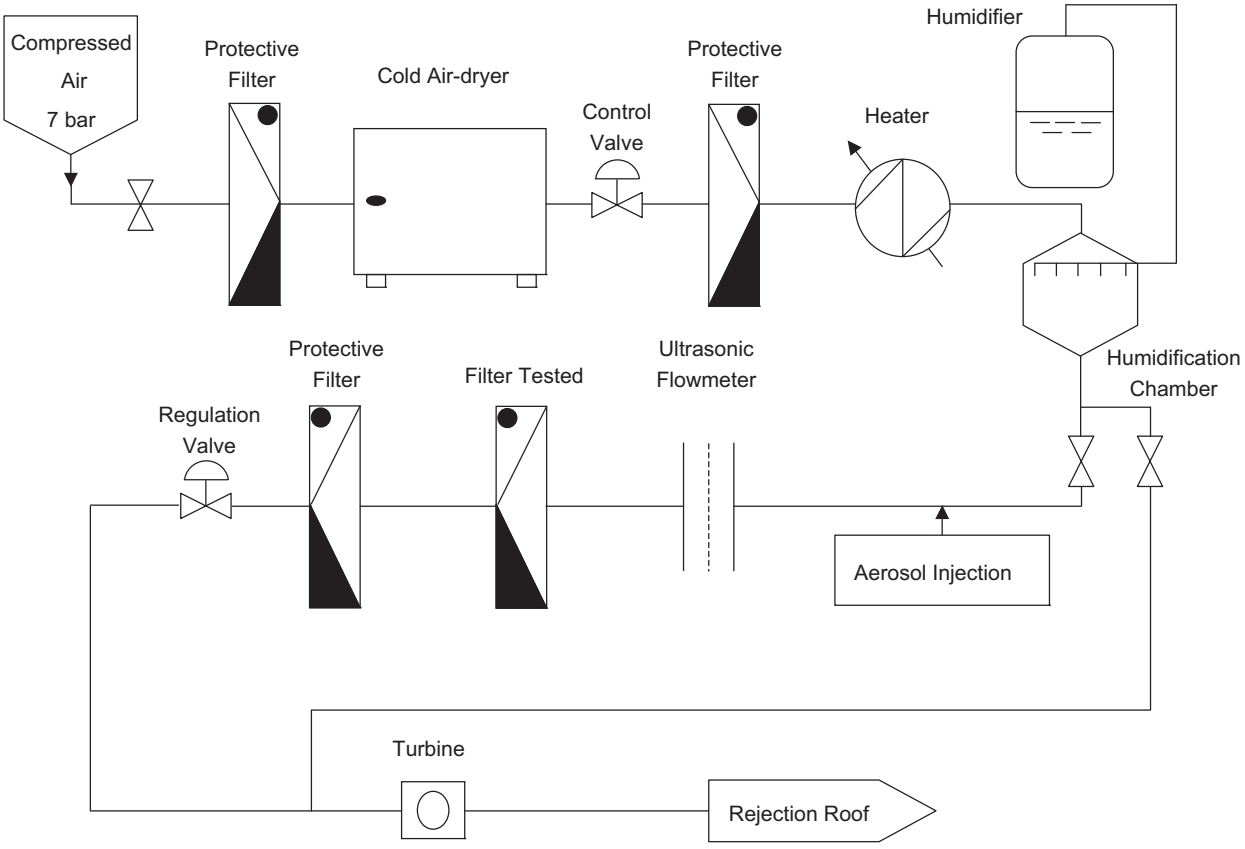

Fig. 1. Schematic diagram of the experimental setup (CATFISH).

across a HEPA filter during the cake filtration stage (common to the flat and pleated filters). The model was developed on the basis of experimental observations, which have never been presented in the literature before, showing that the cakes formed in the presence of humidity may not be in thermodynamic equilibrium with the water vapour in the air.

2. Equipment and method

2.1. Experimental test bench

The model developed during this study is based on experimental data of clogging of flat and pleated filters obtained on a test bench (CATFISH) installed at the *Institut de Radioprotection et de Sûreté Nucléaire* (IRSN, French Radiological Protection and Nuclear Safety Institute) at Saclay in France. The test bench enables the filtered air to be controlled and regulated in terms of flow rate (30–200 $m^3\,h^{-1}$ at 20 °C), temperature (8 °C to 100 °C) and humidity (from a few % to saturation depending on the temperature). Heat trace cables over the entire test bench, insulated in advance, prevent any condensation on the walls. The humidity is measured before and after the filter using capacitive hygrometers and a condensation hygrometer. The experimental test bench, schematised in Fig. 1, has been described in a previous paper [3]. The range of filtration velocities investigated was from 4 to 7 $cm\,s^{-1}$. Relative humidity (RH) was investigated from a few % to near saturation. The temperature was fixed at 25 °C ± 2 °C. The pressure drop through the filter and the flow rate of the generated aerosol were measured continuously during the clogging. Changes in aerosol mass loading were calculated from experimental changes in the flow rate of the generated aerosol and from the weight of the filters (the filters were weighed before and after clogging).

2.2. Filters tested

Two types of filter, made from the same medium, were tested: flat filters with 0.08 m^2 filtering area and pleated filters of 0.42 m^2. The main characteristics of the filter medium are presented in Table 1 (determined from scanning electronic microscopy observations). The diameter of the glass fibres follows a log-normal size distribution. The pleating characteristics of pleated filters are those usually found in the French nuclear industry: height of pleat 27.5 mm and distance between adjacent pleats 2.1 mm; this kind of pleated filters are called mini-pleated filters (in contrast to deep pleat filters with height of pleat above 200 mm).

2.3. Aerosols used to clog the filters

Two types of hygroscopic aerosol with differing diameters were used to clog the filters: a micron-sized, non-hygroscopic, aluminium oxide aerosol and a submicron, hygroscopic, sodium chloride aerosol.

The aluminium oxide aerosol was produced by dispersing powder using a Palas BEG-1000 generator. Changes in generated-aerosol flow rate were recorded during the test. The size distribution of the aerosol was characterized for different RH values between 7 and 90% using a TSI Aerodynamic Particle Sizer (APS), which provides an aerodynamic diameter. At 7% RH, the mass median aerodynamic diameter (MMAD) is 4.2 ± 0.2 μm with a geometric standard deviation σ_g of 1.7; no significant influence of humidity has been observed on the particles diameter in the range of RH studied.

The sodium chloride aerosol was produced by aqueous spraying of a 200 $g\,l^{-1}$ NaCl solution. The MMAD of the aerosol, calculated from the distribution of electric mobility diameters obtained by

Table 1
Main characteristics of the filtering medium.

Fibre diameters			Thickness (μm)	Weight (g m^{-2})	Packing density
Geometric median diameter (μm)	Geometric standard deviation, σ_g	Numerical mean diameter (μm)			
0.6	2.2	0.9	521 ± 31	92 ± 2	0.071 ± 0.006

a Grimm Scanning Mobility Particle Sizer (SMPS) and relations involving particle dynamic shape factor and Cunningham coefficient [23], decreases from 0.61 ± 0.04 μm (with σ_g = 2.1) at 5% RH to 0.37 ± 0.05 μm (with σ_g = 1.9) at 87% RH. Note that at a temperature of 25 °C, the RH of deliquescence of sodium chloride particles is 75%.

The variation in the diameter of the two aerosols has been considered for the modelling.

3. Experimental change in pressure drop across clogged HEPA filters during exposure to a humid airflow

3.1. Preliminary experiments

The model described in this paper has been developed on the basis of experimental observations. Two pleated filters were clogged with the sodium chloride aerosol at a filtration velocity of 2.6 cm s^{-1} at two RH (5% and 46%). Once particle generation was stopped, the flow rate of humid air was maintained through the filters in order to study the time-variation of their pressure drop. The variations of the ratio $(\Delta P - \Delta P_0)/V_f\mu$ (corresponding to the airflow resistance of the particulate cake) of the two pleated filters as a function of permeation time during and after clogging are presented in Fig. 2. In both cases, the clogging ends during the cake filtration stage, with a surface mass of particles collected of approximately 15 g m^{-2} at the end of particle generation.

The results show that, for clogging at 5% RH, maintaining the air flow at the same humidity after clogging does not change the pressure drop across the filter. Whereas for clogging at 46% RH, maintaining the same humidity after clogging causes a gradual reduction in the pressure drop across the filter: the ratio $(\Delta P - \Delta P_0)/V_f\mu$ drops from 80×10^7 to 50×10^7 m^{-1} in just over 15 h of exposure. This drop can't only come from change in the air physical properties. Indeed, according Tsilingiris [24], the dynamic viscosity of the air at a temperature of 25 °C varies little as a function of RH: 1.844×10^{-5} Pa s in dry air compared with 1.810×10^{-5} Pa s in saturated air. The reduction can be explained by the adsorption of water vapour contained in the air onto the surface of the particles

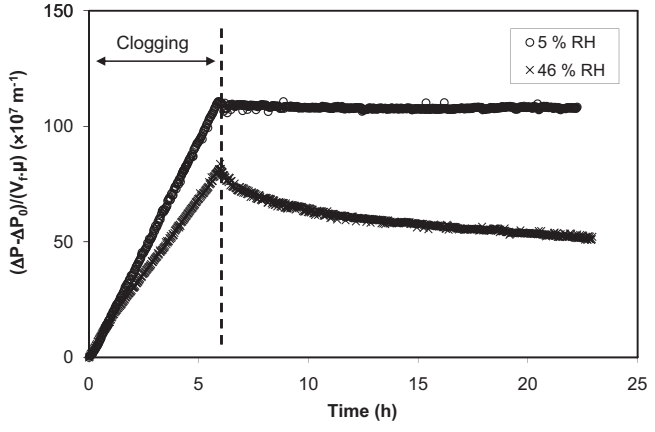

Fig. 2. Time-variation in pressure drop across two pleated filters during and after their clogging (15 g m^{-2}) with sodium chloride aerosol at two different rates of RH of 5 and 46%.

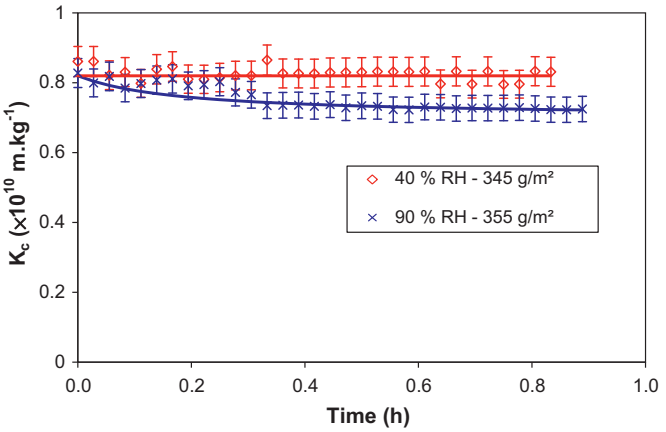

Fig. 3. Time-variation of the specific resistance of aluminium oxide cakes, formed in dry air, during their exposure to an airflow at various levels of RH.

that form the cake, leading to a restructuring of the deposit (which reduces the specific surface area or creates preferential passageways). Thus, these results demonstrate that a cake formed in the presence of humidity may not be in thermodynamic equilibrium with its environment.

3.2. Time-variation of the specific cake resistance when exposed to a humid airflow

Experimental tests were performed to study the influence of a humid airflow on the pressure drop across a cake formed in dry air. Flat filters were clogged with aluminium oxide and sodium chloride aerosols at a filtration velocity of 7 cm s^{-1} in dry air. Then, once particle generation was stopped, the airflow rate across the clogged filters was maintained but its humidity was increased. The time-variations in the specific resistance K_c of the cakes during exposure to humid airflow are given in Figs. 3 and 4, for aluminium oxide and sodium chloride aerosols respectively. The surface mass of particles collected on the filter is given for each test. According to relation (1)

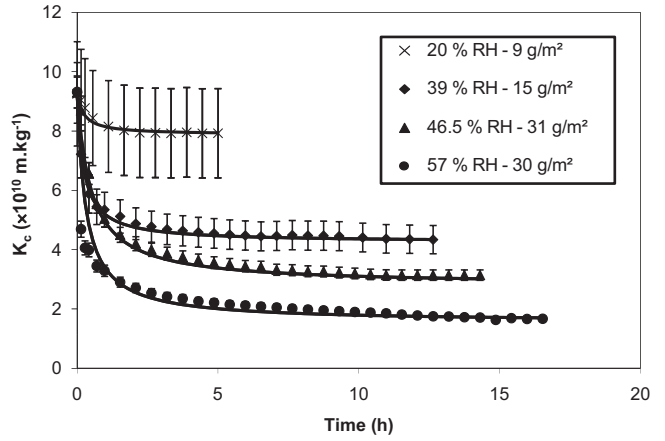

Fig. 4. Time-variation of the specific resistance of sodium chloride cakes, formed in dry air, during their exposure to an airflow at various levels of RH.

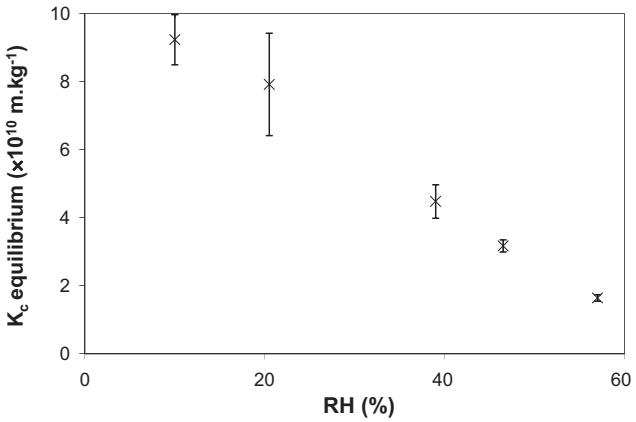

Fig. 5. Equilibrium values of the specific resistance of sodium chloride cakes as a function of the RH of the air.

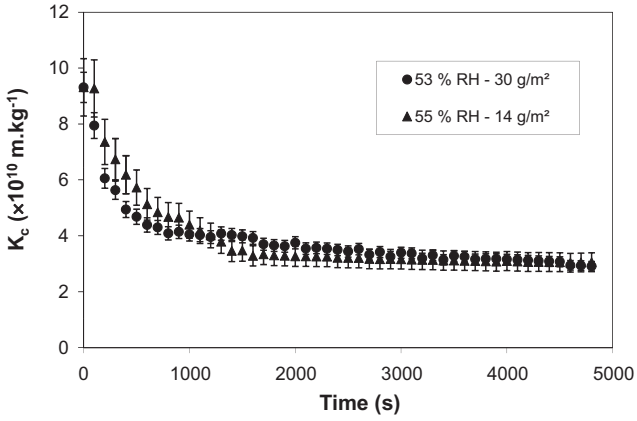

Fig. 6. Influence of the mass of sodium chloride particles deposited on the filter on the time-variation of the specific cake resistance during exposure to a humid airflow at approximately 55% RH.

from Novick et al. [17], the specific cake resistance was calculated using the ratio $(\Delta P - \Delta P_0)/V_f\mu$ divided by the final surface mass of particles collected on the filter.

For the aluminium oxide aerosol, the results show that exposing a filter to an airflow at 40% RH, following its clogging in dry air, does not change its pressure drop (i.e. it does not change the specific cake resistance). For an exposure at 90% RH, a reduction of approximately 10% in the specific cake resistance is observed after several minutes.

For the sodium chloride aerosol, the experimental results highlight a decrease in the specific cake resistance when the filters are exposed to a humid airflow from 20 to 57% RH. The reduction in the specific cake resistance is greater when the RH of the air is higher: a 15% reduction for 20% RH and an 80% reduction for 57% RH. The value of the specific cake resistance obtained at the end of each experiment, once the equilibrium is reached, is reported in Fig. 5 as a function of the air humidity. The results show a linear reduction in the values of K_c at equilibrium as a function of RH over the range of values studied.

3.3. Influence of the air humidity and of the mass of particles collected on the time-variation of the specific cake resistance

The final equilibrium value of the specific cake resistance depends on the air humidity. With regard to the time-variation, two effects were studied: the influence of air humidity when the mass of particles deposited is constant and the influence of the mass of particles deposited when the air humidity is constant.

The time-variation of the specific resistance of two cakes comprising approximately 30 g m^{-2} of sodium chloride particles and exposed to two different levels of humidity (46.5 and 57% RH) is studied in the previous Fig. 4. The results show that, even though the surface mass of particles collected on filters is the same, the time requires to reach equilibrium is different. In fact, with the same volumetric flow rate across the filters, the final equilibrium value of K_c is reached after approximately 10 h of exposure to air at 46.5% RH, whereas more than 15 h are required to reach equilibrium at 57% RH.

Fig. 6 presents the variation over time of the specific cake resistance of sodium chloride particles exposed to two levels of humidity that were close (53 and 55% RH), and for a surface mass of particles collected on the filters of 30 and 14 g m^{-2} respectively. The results indicate that, for both tests performed, the final value at equilibrium and the time-change of the specific cake resistance are quite close. Thus, in the present work, it is assumed that the time-variation in the specific cake resistance of a filter exposed to a humid airflow depends on the RH of the air but not on the mass of particles collected on the filter in the cases studied (i.e. for low masses of particles involved).

4. Pressure drop modelling

4.1. Model description

The purpose of this model is to predict the evolution of the pressure drop across a HEPA filter, during the formation of a cake on its surface, as a function of the RH of the air. The model developed has been adapted from Novick et al. [17] for humid airflow. It assumes that during clogging:

- the particles are deposited on the surface of the filter in successive layers of the same thickness and mass;
- the deposit of particles on the fibres inside the filter can be neglected;
- the particles are initially deposited on the filter in the same way regardless of the air humidity. Once particles are collected, the deposit is modified by the presence of humidity due to the interaction between water vapour in the air and the particles that form the cake. Thus, at time t of clogging, each layer of particles is in a different equilibrium state corresponding to the contact time of the particles with the moist air;
- for a pleated filter, the reduction of the filtration surface must be negligible;
- the thickness of the cake is the same regardless of the RH at which it is formed.

The thickness z_c of the cake at the end of clogging is decomposed into N successive layers of the same thickness Δz_c and the same mass of particles Δm_s. Thus, the pressure drop across the clogged filter at time t is given by:

$$\Delta P(t) = \Delta P_0 + \sum_{k=1}^{N} \Delta P_k(t) \quad (2)$$

For a total filtration time t_f, each layer of particles is formed in a time Δt, where:

$$t_f = N\Delta t \quad (3)$$

Interaction between the water vapour and the particles forming the cake is taken into account in the model via the specific resistance of each layer of particles, which changes over time. Thus, the

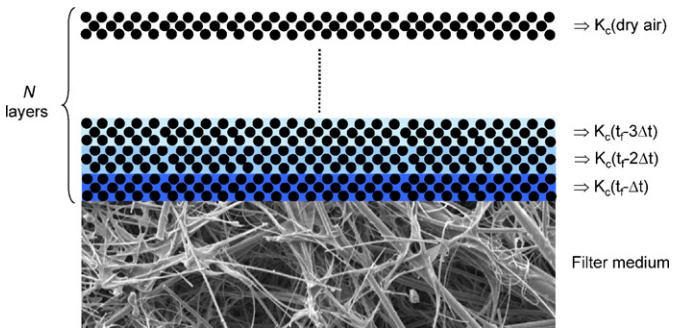

Fig. 7. Schematic diagram of the layer-by-layer deposit of particles on the surface of a filter medium.

pressure drop over a layer k of particles at time t is given by:

$$\Delta P_k(t) = K_c(t)\mu \frac{\Delta m_s V_f}{S_f} \quad (4)$$

The pressure drop across each layer of particles depends on its state of equilibrium with the air humidity, i.e. on the interaction time between the deposited particles and the water vapour in the air (Fig. 7):

- layer N, the last layer of particles deposited on the surface of the filter, is not at equilibrium;
- layer 1 is at a degree of equilibrium that corresponds to time: $t_f - \Delta t$;
- layer K is at a degree of equilibrium that corresponds to time: $t_f - k\Delta t$.

Hence, in this model, the pressure drop across a clogged filter in the presence of humidity is given by:

$$\Delta P = \Delta P_0 + \mu \frac{\Delta m_s V_f}{S_f} \sum_{k=1}^{N} K_c(t_f - k\Delta t) \quad (5)$$

The model requires knowing the time-variation of K_c with the air humidity.

4.2. Determination of the input parameters for the model

The number of layers N that formed the cake is expressed as a function of the thickness of the cake by the equation:

$$N = \frac{z_c}{\Delta z_c} \quad (6)$$

Considering deposit of particles on the surface of the filter to be homogeneous, the thickness of the cake is expressed as a function of the mass of particles deposited on the filter surface by the equation:

$$z_c = \frac{m_s}{\rho_p(1-\varepsilon_c)S_f} \quad (7)$$

where ρ_p is the density of the particles and ε_c the porosity of the cake formed. The cake porosity has been calculated from an empirical correlation developed by Thomas et al. [5] that expresses it as a function of the particle diameter:

$$1 - \varepsilon_c = 0.58\left(1 - \exp\left(-\frac{\text{MMAD}}{0.53}\right)\right) \quad (8)$$

In this equation, MMAD is expressed in μm. Hence, the number of layers of particles forming the cake can be expressed as follows:

$$N = \frac{m_s}{\rho_p(1-\varepsilon_c)S_f \Delta z_c} \quad (9)$$

Table 2
Adjustment coefficients a and b for aluminium oxide and sodium chloride particles as a function of RH of the air.

RH (%)	a ($\times 10^{-10}$ kg s m^{-1})	b ($\times 10^{-13}$ kg m^{-1})
Aluminium oxide particles		
40	0	∞
90	5500	8500
Sodium chloride particles		
20	645	725
39	165	200
46.5	275	155
57	145	130

An estimate of layer thickness Δz_c can be made on the basis of the diameter of the particles collected using the equation:

$$\Delta z_c = x d_p \quad (10)$$

Since the aerosols used during the tests were polydispersed, the diameter d_p used in this equation is the numerical mean diameter. The value of variable x was set at 5 for the micron-sized aluminium oxide aerosol and at 10 for the submicron-sized sodium chloride aerosol, in order to optimise the number of layers N.

The time step Δt is then set using Eq. (3). Finally, the mass of particles Δm_s deposited on each layer is determined using the equation:

$$\Delta m_s = \frac{\Delta t m_s}{t_f} \quad (11)$$

4.3. Variation in the specific cake resistance over time

According to the results given in Figs. 3 and 4, the variation in the specific cake resistance as a function of the time of exposure to a humid airflow can be expressed as a function of time as:

$$K_c(t) = K_c\,(\text{dry air}) - \frac{t}{a + bt} \quad (12)$$

Given that the model considers each layer of the cake independently, the curve for the time-variation of the specific cake resistance to be used in the model must be that of a layer of cake whose mass is Δm_s. However, it has been shown that variation in K_c depends mainly on RH and very little on the mass of particles deposited on the filter (this has been established up to 30 g m^{-2}). Thus, the curves for the time-variation of K_c obtained for a cake whose mass is m_s will be used to describe the time-variation for a layer of particles of mass Δm_s.

Adjustment coefficients a and b (Table 2) were determined for the various levels of RH studied for aluminium oxide and sodium chloride aerosols using Figs. 3 and 4. The figures give the experimental values for variation in K_c and the adjustment curves. Note that more experimental data are required to establish correlations that would enable the coefficients a and b to be expressed as a function of the diameter of the aerosol and the air humidity.

During clogging in dry air, the evolution of the ratio $(\Delta P - \Delta P_0)/V_f\mu$ for flat filters as a function of the surface mass of particles collected is linear only during the cake filtration stage, i.e. after a limit surface mass of particles has been deposited $(m_s/S_f)_{limit}$, in particular for the aluminium oxide aerosol. During this stage, the specific cake resistance is constant. The adjustment coefficients a and b given in Table 2 have been determined with this constant value of K_c. Before the cake filtration stage, i.e. when the cake is not yet fully formed (depth filtration stage), the variation of $((\Delta P - \Delta P_0)/V_f\mu)$ as a function of the surface mass of particles collected is not linear. In fact, the value of K_c is different from that obtained during cake filtration because it varies as a function of the surface mass of particles collected. Thus, the value of K_c in dry air is not constant over all the clogging. The model developed,

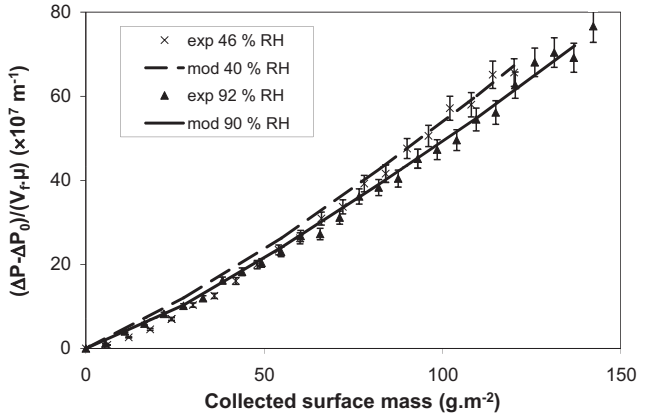

Fig. 8. Comparison between the values from calculation and experiment for the pressure drop across a filter during clogging with aluminium oxide aerosol at various levels of RH.

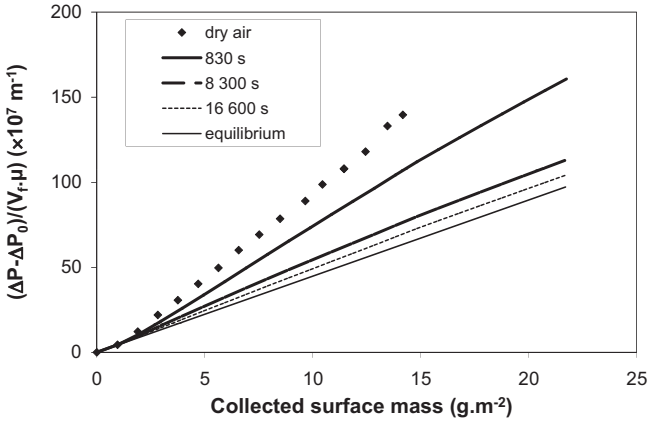

Fig. 10. Influence of the filtration time on the calculated evolution of the pressure drop through a flat filter during its clogging at 39% RH with sodium chloride aerosol.

which requires the value of K_c in dry air as input data, must take into account its variation during clogging. Hence, for values of K_c before the cake filtration stage, the adjustment coefficients a and b must be recalculated. For surface mass collected $(m_s'/S_f)_{limit}$ below limit value $(m_s/S_f)_{limit}$ and corresponding to specific resistance K_c', the adjustment coefficients a' and b' can be calculated using the following equations:

$$b' = \frac{bK_c}{K_c'} \tag{13}$$

$$a' = \frac{aK_c}{K_c'} \tag{14}$$

where a and b are the values given in Table 2, corresponding to the cake filtration stage.

4.4. Comparison between model and experimental results

The model (Eq. (5) and the following) was compared with experimental values obtained with flat filters on the CATFISH test bench. Figs. 8 and 9 present the variations in ratio $(\Delta P - \Delta P_0)/V_f\mu$ as a function of the surface mass of particles collected, calculated from the model (noted 'mod') and the experimental values (noted 'exp'), for the aluminium oxide and sodium chloride aerosols respectively. The experimental data correspond to clogging performed at a filtration velocity of 4 cm s^{-1} for the aluminium oxide aerosol and 7 cm s^{-1} for the sodium chloride aerosol.

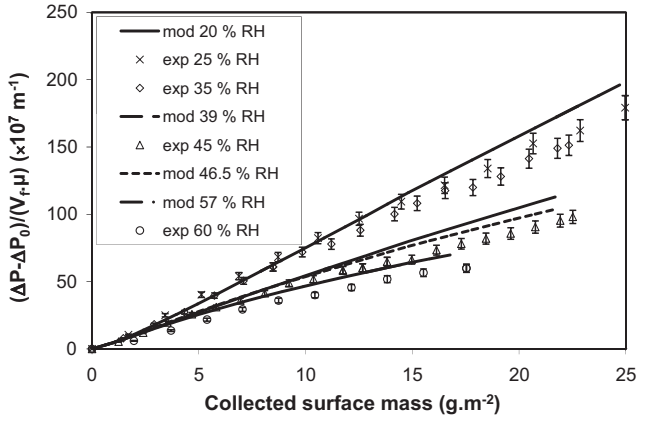

Fig. 9. Comparison between the values from calculation and experiment for the pressure drop across a filter during clogging with sodium chloride aerosol at various relative humidities below the deliquescent point.

For the aluminium oxide aerosol, the results indicate that the curves coming from the model give a good estimate of the experimental variation in ratio $(\Delta P - \Delta P_0)/V_f\mu$ for the two RH values tested. For the sodium chloride aerosol, the model was compared with experimental values for RH between 20 and 60% (i.e. below the deliquescent point). The results reveal that the model satisfactorily describes the influence of the presence of humidity on the evolution of the filters pressure drop. The maximum discrepancy between the experimental results and those from the model is 30%. Note that for a better comparison, the experimental RH conditions should be the same that the RH values used for the model.

4.5. Influence of the filtration time

Since the filtration time is an input parameter in the model developed, it could impact the evolution of the filter pressure drop during the clogging. The influence of the filtration time was therefore studied theoretically for a filter clogged with sodium chloride aerosol. For this study, RH was arbitrarily set to 39%. The mean clogging duration t_f of a filter in the experiments (approximately 8300 s for a collected surface mass of around 22 g m^{-2}) was compared with two other values: $2 \times t_f$ and $(t_f \times 10)$, with the evolution of the pressure drop in dry air and with the curve corresponding to the experimental value of K_c at equilibrium (Fig. 5). The results are given in Fig. 10.

The results highlight a significant influence of the filtration time on the evolution of the pressure drop across the filter. Indeed, for a given surface mass of particles collected, the longer the filtration time, the longer the time of interaction between the particles forming the cake and the water vapour in the air. This causes a greater reduction in the specific cake resistance, until an equilibrium value is reached. This remains true as long as the time step Δt, during which layer of particles is formed, remains shorter than the time required to reach equilibrium at the corresponding RH. This study reveals that filtration time (in other words, the mass flow of particles collected), is an essential parameter to take into account when modelling the clogging of a filter in the presence of humidity, especially with a hygroscopic aerosol.

5. Conclusions

This study focused on modelling the change in the pressure drop across a HEPA filter during cake filtration in the presence of humidity.

The literature review revealed that currently no phenomenological model exists, qualified in dry air, to predict the evolution of the pressure drop across a flat filter and takes into account the

influence of the air humidity. The modelling work therefore focused on finding an overall method for estimating the specific resistance of a cake formed in the presence of humidity. Experiments showed that the particles deposited on the filter may not be in thermodynamic equilibrium with the moist air. The evolutions of the pressure drop consequently do not correspond to an equilibrium state of the system and depend on the operating conditions. The model developed considers the pressure drop across the clogged filter as equal to the sum of the pressure drops across the clean filter and across the cake. The cake is then decomposed into various successive layers. The pressure drop across each layer of particles depends on its state of equilibrium with the moist air. This model requires knowing both the value of the specific cake resistance in dry air conditions and its time-variation as a function of exposure to a humid airflow. The latter parameter is obtained by exposing a filter clogged in dry air to an airflow at the RH considered and studying the time-variation of its pressure drop. The results showed good agreement between the values calculated from the model and the experimental values obtained with flat filters clogged with micron-sized aluminium oxide aerosols and submicron-sized sodium chloride aerosols at levels of RH below its deliquescent point.

Further work could be performed to generalize the empirical correlations proposed to express the reduction in specific resistance of the cake exposed to a humid airflow. For this, more experimental data needs to be obtained, in particular to study the influence of the filtration velocity and of the diameter and hygroscopicity of the aerosol.

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