Influence of air humidity on particle filtration performance of a pulse-jet bag filter

Rachid Boudhan, Aurélie Joubert, Sylvain Durecu, Kamal Gueraoui, Laurence Le Coq

▶ To cite this version:

Rachid Boudhan, Aurélie Joubert, Sylvain Durecu, Kamal Gueraoui, Laurence Le Coq. Influence of air humidity on particle filtration performance of a pulse-jet bag filter. Journal of Aerosol Science, 2019, 130, pp.1-9. 10.1016/j.jaerosci.2019.01.002 . hal-02268100

HAL Id: hal-02268100

https://hal.science/hal-02268100

Submitted on 21 Aug 2019

Influence of air humidity on particle filtration performance of a pulse-jet bag filter

Rachid Boudhan[a,b], Aurélie Joubert[a,*], Sylvain Durécu[c], Kamal Gueraoui[b], Laurence Le Coq[a]

[a] *IMT Atlantique, GEPEA, CNRS, UMR 6144, 44307 Nantes cedex 03, France*
[b] *Faculté des Sciences de Rabat, B.P. 1014 RP, Université Mohammed V de Rabat, Morocco*
[c] *Trédi, Service R&D - Groupe Séché Environnement, 54505 Vandoeuvre-lès-Nancy, France*

Keywords:
Bag filter
Filtration performance
Clogging/unclogging cycles
Submicronic particles
Absolute humidity
Capillary condensation

ABSTRACT

A pulse-jet bag filter, representative of those implemented in waste incineration plants for flue gas treatment, was studied at laboratory scale to evaluate the influence of air humidity on the filtration performance. Several cycles of clogging/unclogging were performed with non-hygroscopic submicronic particles with a nanosized fraction with on-line cleaning at operating conditions as similar as possible to those found in the flue gas treatment of waste incineration plants (150 °C – 73 g/m^3 of absolute humidity), and in dry conditions (150 °C).

The results revealed a significant influence of air humidity on the bag filter performance: faster increase of bag filter pressure drop during clogging in presence of humidity due to water capillary condensation, lower efficiency of particulate cake unclogging and better collection efficiency of particles between 110 and 300 nm in diameter.

1. Introduction

Bag filters are frequently used within industries for flue gas treatment because of their high particle collection efficiency over a wide range of particle sizes. They are designed to treat high particle concentration with an on-line cleaning system. Bag filters are among the most effective and efficient gas/particle separation processes.

Several physical mechanisms contribute to enhance the collection efficiency of particles by fibrous or fabric filters such as bag filters. The main mechanisms are Brownian diffusion, interception, and inertial impaction; for each mechanism, the efficiency depends mainly on the particle size to collect. The particles deposited onto the filter media surface contribute to increase filtration efficiency (Thomas, Pénicot, Contal, Leclerc, & Vendel, 2001). In fact, the collected particles bridge together to form the so-called dust cake on the filter media. The formation and detachment of the dust cake from the filter surface influence the filtration performance of the bag filter. The structural proprieties of the dust cake, and so the ability of dust cake detachment, are influenced by different parameters such as filtration velocity or dust concentration (Cheng & Tsai, 1998; Saleem & Krammer, 2007) and probably the air water content.

The effect of air humidity on filtration performance of filtering media is not fully understood because it depends on several parameters such as the hygroscopicity of the particles, their size, the nature and size of the fibers and their ability to sorb water, or the loaded mass of particles on the filter. The literature (Gupta, Novick, Biswas, & Monson, 1993; Joubert, Laborde, Bouilloux, Callé-

---

https://doi.org/10.1016/j.jaerosci.2019.01.002

Chazelet, & Thomas, 2010; Miguel, 2003; Montgomery, Green, & Rogak, 2015) shows that for a given mass of collected particles, the pressure drop of fibrous filters decreases with increasing humidity; with higher effect with hygroscopic submicronic particles of soda chlorine below the deliquescent point than with non-hygroscopic micrometric aluminum oxide particles. Ribeyre, Charvet, Vallières, and Thomas (2017) studied the influence of humidity on three different nanostructured filter cakes formed in dry air by three different non-hygroscopic nanoparticles and their results showed that the filter pressure drop increases when the relative humidity (RH) increased gradually from 0% to 85% (i.e. around 20 g/m^3 of absolute humidity AH). While Joubert, Laborde, Bouilloux, Chazelet, and Thomas (2011) showed that the exposure to a humid airflow of the loaded cake filter formed under dry conditions (with hygroscopic submicronic and non-hygroscopic micrometric particles) leads to the reduction of the specific cake resistance i.e. a decrease in the filter pressure drop.

Regarding the influence of humidity on filter collection efficiency, Kim, Bao, Okuyama, Shimada, and Niinuma (2006) tested the filtration of NaCl nanoparticles (diameters ranged between 3 and 70 nm) by a fiberglass filter. The results demonstrated no significant influence of humidity on the filtration efficiency for RH between 1% and 92% (i.e. 0.2 and 16 g/m^3 AH). However, Miguel (2003) observed an increase of fibrous filter efficiency with an increase of air humidity during the collection of aluminum particles in the size range of 0.8 – 6 μm.

In the literature, the influence of humidity on aerosol filtration was mainly investigated with fibrous filters of HVAC systems in flat or pleat geometries. We inventoried no study about the influence of humidity on bag filter performance during clogging with submicronic particles at the operating conditions found in flue gas treatment of waste incineration plants i.e. high temperature of 150 °C and high absolute humidity of around 73 g of water vapor /m^3 of air (i.e. 3% RH).

This study focuses on the influence of air humidity on the filtration performance of a bag filter at the beginning of the filter lifetime before stabilizing the residual filter pressure drop resulting from previous filtration cycles. The study aims to investigate the influence of air humidity on experimental pressure drop evolution, particle collection efficiency and cake detachment.

2. Material and methods

2.1. Experimental set-up

To investigate the evolution of pressure drop and filtration efficiency of a pulse-jet bag filter, an experimental set-up was developed and described by Boudhan et al. (2017), so as to be representative of the bag filter unit in flue gas treatment of waste incineration in terms of temperature, humidity, filtration velocity, aerosol size distribution and load, and the on-line pulse-jet unclogging system.

To study the influence of air humidity on the filtration performance, the set-up operated at two conditions, namely (150 °C - 0% RH), and (150 °C - 3% RH), i.e. absolute humidity of 0 and about 73 g/m^3 AH, with a filtration velocity of 1.9 cm s^{-1} and 10 successive clogging/unclogging cycles. For high temperatures, relative humidity is not the most relevant parameter to illustrate the quantity of water vapor in the air, which is why we used absolute humidity (AH) giving the water vapor in the air, regardless of temperature and expressed in mass of water vapor per cubic meter of air (g/m^3).

The experimental set-up is illustrated in Fig. 1. In particular, in area 2, the air is heated up to 80 °C and moistened by steam countercurrent injection (steam generator semiautomatic NEMO 1.6 kW). The RH of air is measured with a capacitive hygrometer. In area 3 the air temperature is up to 150 °C. The pulse-jet cleaning of the bag is ensured by short pulses of compressed air (0.3 s at 6 bar). A filter pressure drop controller which manually triggers the cleaning operation once the maximum pressure drop is reached, set at 150 Pa for this study.

2.2. Aerosol

A non-hygroscopic carbon aerosol, representative of the particle size and concentration in flue gas of waste incineration plants, was generated upstream of the bag filter from DNP-2000 generator (Palas) with carbon electrodes. The applied discharge at high temperature between carbon graphite electrodes leads to the evaporation of carbon producing high number concentration of nanosized particles (primary particles of 3–10 nm) which coagulate to produce agglomerates. The size of the agglomerates increases with increasing spark frequency. The particle size distribution and numerical concentration of the aerosol during the tests were determined by adjusting the generator characteristics to be representative of particle emission from carbon nanowaste incineration in a lab-scale furnace described by Le Bihan et al. (2014). The particle size distribution of the carbon particles expressed in number, determined by SMPS (Grimm) measurements upstream of the bag filter for the two operating conditions studied, are presented in Fig. 2. The particle concentration, median diameter and geometric standard deviation of the distributions are summarized in Table 1. The morphology of the carbon nanoparticles, sampled with a glassfiber filter, was identified from SEM observations. The results in the Fig. 3 confirm that the carbon particles are generated as agglomerates from the DNP-2000 (Palas) generator.

2.3. Tested filter

The tested bag filter, supplied by Trédi, was dismantled from the industrial bag filter unit of a waste incineration plant. The tested bag filter was a used filter with residual particles inside. It was received with a height of 5 m and reduced to 0.44 m for the experimental set-up in the laboratory with a diameter of 0.15 m. The filter media is a non-woven structure composed of Teflon fibers (Polytetrafluoroethylene, PTFE). The main structural parameters of the filter are: thickness of 1256 ± 31 μm, fiber median diameter

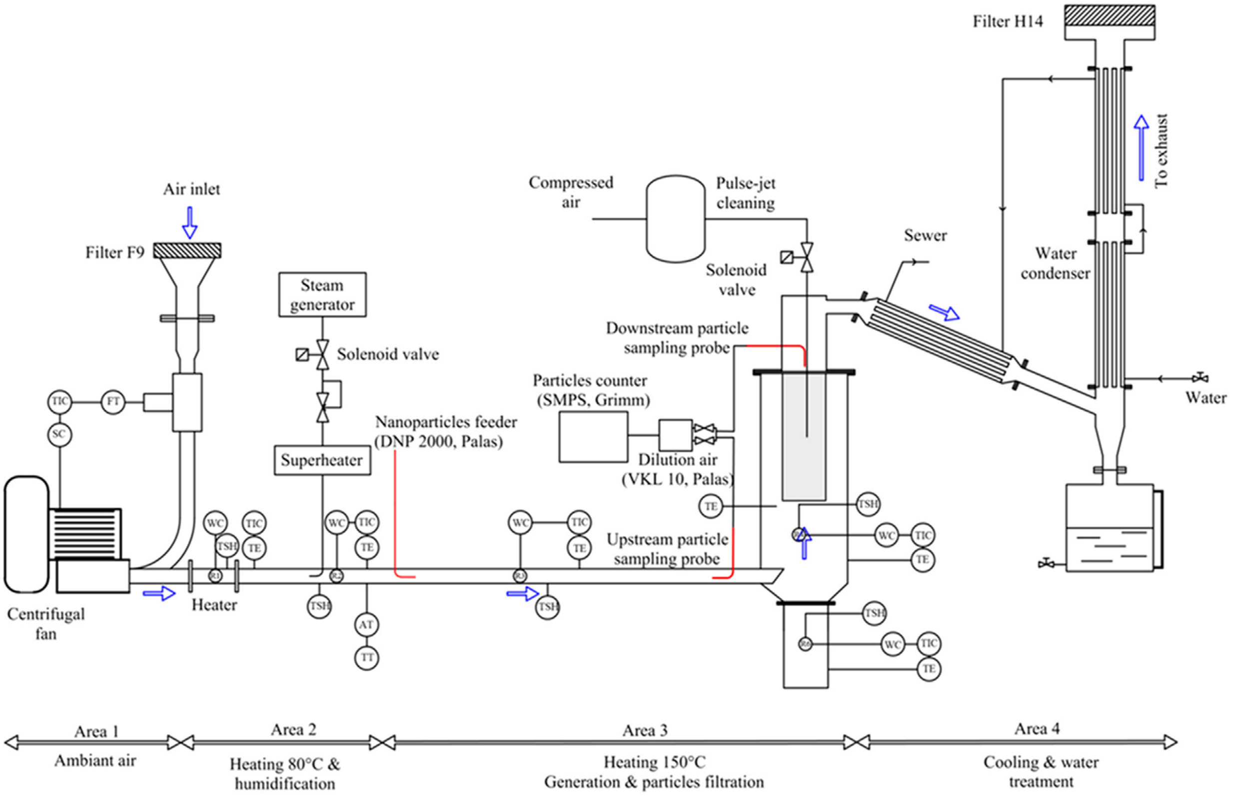

Fig. 1. Experimental set-up for bag filter clogging tests (adapted from Boudhan et al. (2017)).

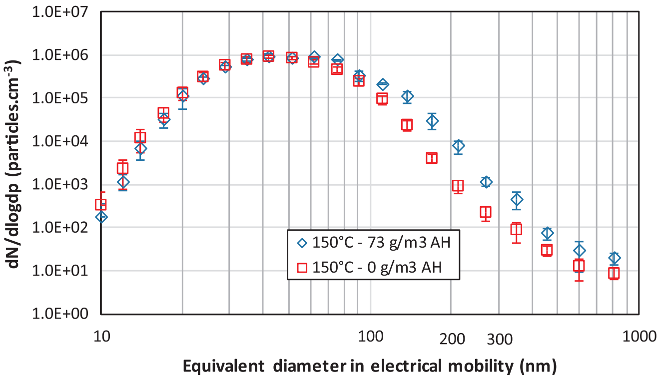

Fig. 2. Particle size distribution of carbon particles upstream of the bag filter for the two operating conditions (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH).

Table 1

Particle concentration, particle median diameter and geometric standard deviation for the two operating conditions.

Operating conditions (temperature – absolute humidity)	Particle concentration (Part.cm^{-3})	Electrical mobility median diameter d_{50} (nm)	Geometric standard deviation σ_g (-)
150 °C – 73 g/m^3 AH	5.09E+ 06	51	1.5
150 °C – 0 g/m^3 AH	5.79E+ 06	45	1.5

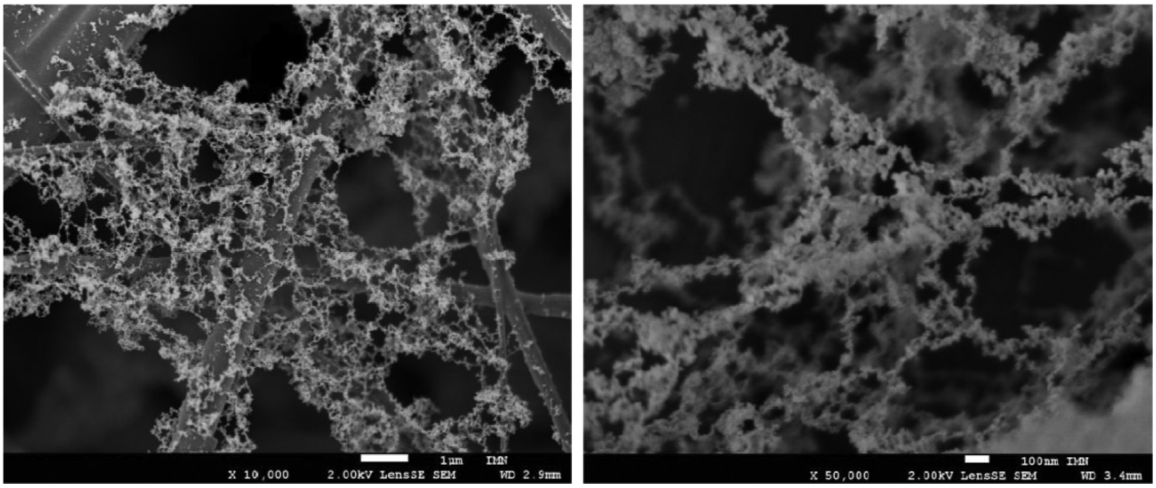

Fig. 3. SEM observations of the carbon nanoparticles generated by the DNP-2000 (Palas).

of 20 µm, total porosity of 0.64 and basis weight of 750 g m^{-2}. Note that a new clean filter was also provided by Trédi and used to quantify the initial filter pressure drop ΔP_0 at the temperatures and humidities tested.

2.4. *Filter performance measurement*

2.4.1. *Filter pressure drop*

The evolution of the pressure drop generated by the gas flow through the filter during clogging is measured by a pressure sensor (FCO model 332), with a pressure measuring range of 0–200 Pa and measuring accuracy $<$ 0.5%.

2.4.2. *Filter particle collection efficiency*

Filter efficiency was calculated from particle sampling and counting with SMPS (Grimm) in the set-up. VKL diluter was implemented before the SMPS particle counter, to decrease temperature and humidity of the air.

In order to avoid a systematic error of calculated filtration efficiency of the bag filter, we considered the large number of particles deposited on the walls of the filter holder. Thus, the results were expressed with the fractional efficiency determined as:

$$E_{d_p}(t) = \frac{\overline{N}_{upstream,d_p} - N_{downstream,d_p}(t)}{\overline{N}_{upstream,d_p}}$$

With $N_{downstream,dp}$ the number of particles of diameter d_p measured downstream of the tested filter whose value varies as a function of filtration time.

$\overline{N}_{upstream,dp}$ is a constant value (for given temperature and humidity conditions) pre-determined before the filtration tests and representing the upstream number of particles of diameter d_p determined from particle counting in the experimental set-up without bag filter at the downstream filter particle sampling location.

Error bars regarding efficiency were calculated considering $\Delta N_{downstream} = 5\% \times N_{downstream}$ the accuracy of the SPMS for single

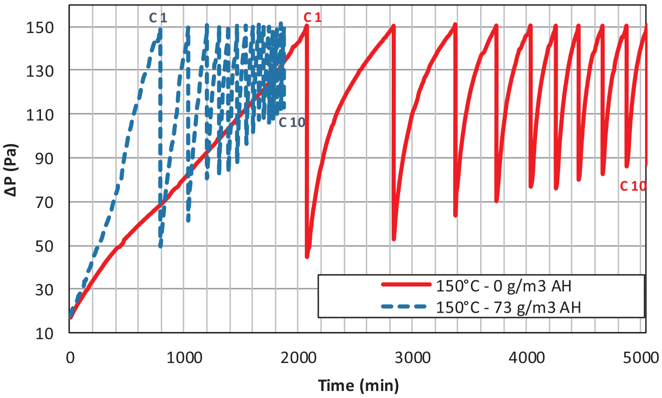

Fig. 4. Evolution of filter pressure drop during 10 clogging/unclogging cycles at (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH).

particle counting. As $N_{upstream,dp}$ is a constant value (for a given d_p) determined from preliminary experiments, $\Delta N_{upstream,dp}$ is obtained from the experimental uncertainty of the particle counting measured for 6 samplings carried out.

3. Results

3.1. *Influence of humidity on filter airflow resistance*

3.1.1. *Evolution of bag filter pressure drop*

Fig. 4 shows the evolution of bag filter pressure drop with filtration time at the two operating conditions studied: (150 °C - 0 g/m^3 AH) and (150 °C - 73 g/m^3 AH). The results reveal that the pressure drop evolution is influenced by the content of humidity in the air which influences, in turn, the total filtration time per 10 filtration cycles: 1850 min for a bag filter clogged at 73 g/m^3 AH against 5000 min at 0 g/m^3 AH. For both filtration conditions, the duration of the clogging phase decreases gradually with the number of clogging/unclogging cycles.

For the first filtration cycle, the evolution of the filter pressure drop can be assumed from the model of Novick, Monson, and Ellison (1992) where the pressure drop across the filter results from the pressure drop across the clean filter ΔP_0 and the pressure drop across the cake ΔP_{cake} (assuming that the particle deposit inside the filter has a negligible air resistance).

$$\Delta P = \Delta P_0 + \Delta P_{cake}$$

Moreover, assuming that the porosity of the particle deposit is constant and independent of the cake thickness, the pressure drop across the filter during clogging is expressed by:

$$\Delta P_{cake} = w \bullet V_f \bullet \mu \bullet K_c$$

With the specific cake resistance K_c (m kg^{-1}), the areal collected particle mass w (kg m^{-2}), the gas viscosity μ (Pa s), and the filtration velocity V_f (m s^{-1}).

Thus, the ratio $(\Delta P - \Delta P_0)/(\mu \bullet V_f)$ corresponds to the cake resistance to air flow independently of the air viscosity variations with water content.

Fig. 5 compares the evolution of cake resistance $(\Delta P - \Delta P_0)/(\mu \bullet V_f)$ in relation to the number of particles collected by the filter during the first filtration cycle at 150 °C for dry (0 g/m^3 AH) and humid conditions (73 g/m^3 AH). The results indicate a higher increase of cake resistance with particle loading in presence of water vapor in air, suggesting an influence of water content on the structural properties of the particle cake. At the maximum value of particulate cake resistance (3.25×10^8 m^{-1}), the number of particles collected by the filter is significantly higher in dry air (0 g/m^3 AH) as compared to 73 g/m^3 AH, respectively 2.5×10^{15} and 7.0×10^{14} particles. Hence, a significant effect of absolute humidity was observed on the evolution of particulate cake resistance in the two conditions studied despite close relative humidity rates (3% vs. 0% RH).

These results differ from the conclusions of Gupta et al. (1993) and Joubert et al. (2010) regarding the influence of air water content on the evolution of particulate cake resistance during clogging. We assume that the opposite conclusions come from the filtration conditions in terms of temperature (150 °C), humidity, and also aerosol nature and size: the particles should have a good affinity with water molecules for surface interactions considering the high absolute humidity in the present study and the small size of particles (16–310 nm) i.e. high specific surface area of particles which increases their ability of water sorption.

3.1.2. *Influence of air humidity on pulse-jet cleaning of the bag filter*

The influence of air humidity on pulse-jet cleaning efficiency of the bag filter is studied in Fig. 6 with the evolution of the residual particulate cake resistance according to the filtration cycles for the two experimental conditions (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH). The ratio $(\Delta P_{res} - \Delta P_0)/\mu \bullet V_f$ at the beginning of each clogging/unclogging cycle is calculated from the residual pressure

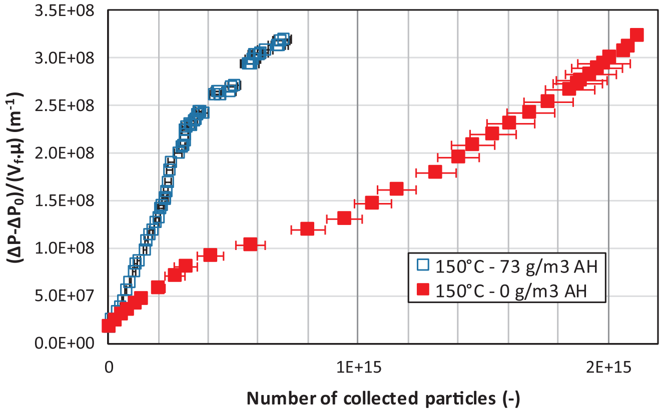

Fig. 5. Evolution of particulate cake resistance as a function of collected particle number during first filtration cycles at (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH).

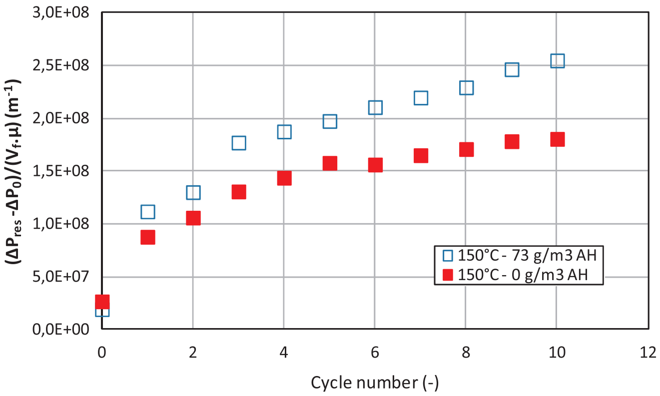

Fig. 6. Evolution of residual particulate cake resistance at the beginning of each filtration cycle at (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH).

drop (ΔP_{res}) resulting from the overall pressure drop across the filter media (ΔP_0) and the residual cake remaining on the filter surface after pulse-jet cleaning.

The results indicated in Fig. 4 that the residual pressure drop of the bag filter ΔP_{res} as a function of filtration cycles at 73 and 0 g/m^3 AH increases respectively from 22 to 111 Pa and from 19 to 87 Pa between cycle 1 and cycle 10. Thus, Fig. 6 confirms that the increase of residual particulate cake resistance with clogging/unclogging cycles is higher in wet conditions of clogging than for dry air, which means that the pulse-jet cleaning system implemented in the study is more efficient to remove the cake formed in dry conditions on the surface of the bag filter.

In fact, the deposited particles on the filter surface are subject to different forces applied by reverse air flow during the unclogging phase, mainly the pressure forces such as pressure-gradient forces and friction forces. We assume that the presence of water on the surface of the particles by capillary condensation leads to the formation of liquid bridges between them (Feng & Yu, 1998) and therefore to a capillary condensation at the meniscus of pore size formed by two or more neighboring particles which increases the particle-particle adhesion forces. Consequently, the cake becomes more resistant to the forces applied by air flow and cake removal with the pulse-jet method becomes more difficult. Moreover, the humidity may also influence the particles penetrating in-depth the fibrous filter by increasing the particle-fiber adhesion forces.

3.2. Discussion of the results

The presence of humidity between two neighboring solid surfaces causes an attractive force called the capillary force (Butt & Kappl, 2009). This adhesion force may lead to an agglomeration of particles when flowing in a gas at high particle concentration and reduce the distance between particles when deposited on the filter surface and lead to the formation of a compact particulate cake on the surface media. Hence, this can explain the faster increase of pressure drop with clogging in humid air conditions compared with dry gas. SEM observations of carbon nanoparticles generated at 150 °C - 0 g/m^3 AH and 150 °C - 73 g/m^3 AH were performed from sampling with glassfiber filters to illustrate the effect of humidity on the particle deposit (Fig. 7).

Two solid spheres of rough surface get connected by the capillary bridges formed in between surface asperities. The surface asperities can strongly influence the capillary forces between the two particles. Butt and Kappl (2009) distinguished three regimes

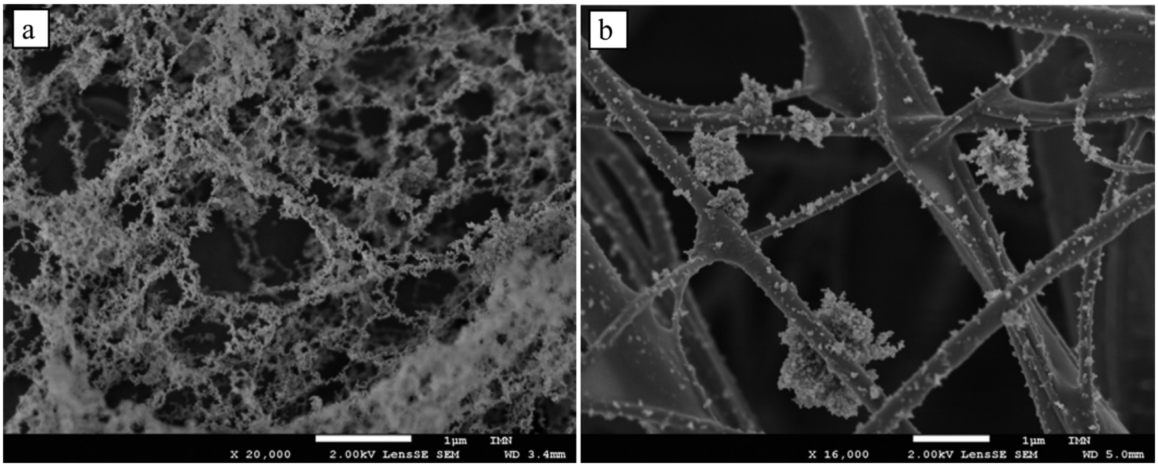

Fig. 7. SEM observations of carbon nanoparticles generated at a) 150 °C - 0 g/m^3 AH and b) 150 °C - 73 g/m^3 AH.

Table 2
Vapor pressure and absolute humidity at different filtration conditions.

Operating parameters (T – RH)	Absolute humidity AH (g water vapor / m^3 air)	Water vapor pressure (Pa)
150 °C - 0% RH	0	0
24 °C - 45% RH	10	1347
150 °C - 3% RH	73	14285

according to the vapor pressure:

- At low vapor pressure, capillary bridges are few between the two solid surfaces. The capillary force is low due to the small curvature radius formed.
- At intermediate vapor pressure, the amount of capillary bridges formed between the asperities of the two solid surfaces is higher.
- At high vapor pressure, the number of capillary bridges between asperities increases and they interact with each other to form a continuous capillary bridge.
  The capillary forces can depend sensitively on the shape of the contact. As the surface structure of the collected particles, formed at the dry and humid cases, are different (Fig. 7), the capillary condensation should be more rely on absolute humidity or vapor pressure rather than the relative humidity.

In terms of comparison, the experimental results of filtration were also investigated at room conditions (24 °C, 45% RH, 10 g/m^3 AH) as an intermediate value of humidity. In Table 2, the water vapor pressure and absolute humidity are reported for the experimental filtration conditions of (150 °C, 3% RH, 73 g/m^3 AH), and (150 °C, 0% RH, 0 g/m^3 AH) and the room conditions.

The water vapor pressure increases with increase of absolute humidity, so that for 150 °C – 73 g/m^3 AH, the vapor pressure is 10 times higher than at (24 °C – 10 g/m^3 AH) increasing the formation of capillary condensation and capillary bridges between the deposited particles. Thus, we assume that in presence of humidity, capillary condensation leads to a decrease in the particulate cake porosity and thus to an increase of the filter resistance to airflow. This hypothesis is in accordance with Fig. 8 reporting the evolution of particulate cake resistance during 10 clogging/unclogging cycles at the three tested conditions (150 °C - 73 g/m^3 AH; 150 °C - 0 g/m^3 AH; and 24 °C - 10 g/m^3 AH). The evolution of particulate cake resistance to air flow with filtration time is higher at (150 °C - 73 g/m^3 AH) than (24 °C - 10 g/m^3 AH).

Further explanation of cake resistance increase at the humid conditions can be enhanced from the SEM observation (Fig. 7), the images show the fluffy nature of generated particles, capillarily-condensed water may have enough surface tension to break the particle microstructure and cause collapse and coalescence of the structure.

3.3. Influence of air humidity on particle collection efficiency

The evolution of fractional efficiency of the bag filter at different values of pressure drop during the first filtration cycle at 150 °C in dry (0 g/m^3 AH) and humid (73 g/m^3 AH) conditions is reported Fig. 9. The three main conclusions are: (1) the most penetrating particle size is 80 ± 10 nm; (2) the fractional efficiency is lower in humid conditions as compared to dry one whatever the particle diameter is (in the studied range) for a given level of filter pressure drop, with minimum efficiency of 96.7% ± 1% for humid conditions (73 g/m^3 AH) against 98.5% ± 0.5% for dry conditions (0 g/m^3 AH); (3) For the two hygrometry conditions, the increase of fractional efficiency with the increase of filter pressure drop is clearly observed whatever the particle diameter is.

The influence of humidity regarding fractional efficiency can be explained by the number of collected particles in the two

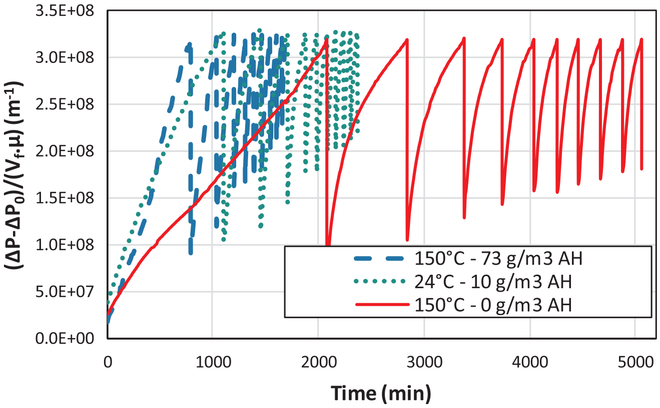

Fig. 8. Evolution of particulate cake resistance during 10 clogging/unclogging cycles at (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH) and room conditions (24 °C – 10 g/m^3 AH).

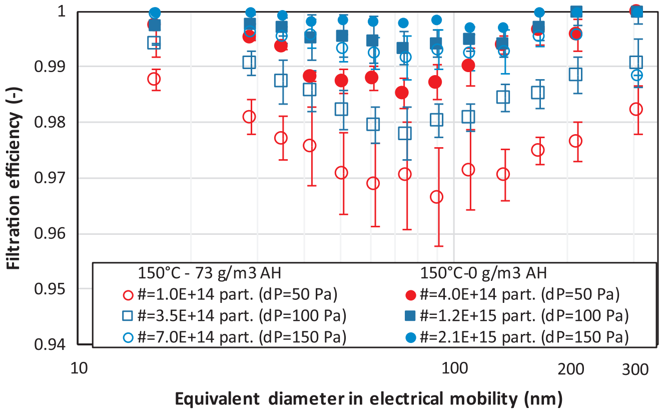

Fig. 9. Fractional efficiency of bag filter for different filter pressure drop levels during the first clogging cycle with carbon nanoparticles at (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH).

operating conditions. For example, at filter pressure drop of ΔP = 50 Pa, the number of collected particles at 73 g/m^3 AH is 1.0 × 10^{14} against 4 × 10^{14} at 0 g/m^3 AH. As the particles deposited on the filter surface contribute to collection efficiency, this can explain the results in Fig. 9.

The evolution of fractional efficiency for the same number of collected particles, in humid (73 g/m^3 AH) and dry (0 g/m^3 AH) conditions, is plotted in Fig. 10. The results indicate two ranges of particle diameter: particle size range between 16 and 100 nm with no significant influence of humidity in fractional efficiency observed; submicron particles higher than 110 nm in diameter with higher filtration efficiency reported at high humidity conditions (73 g/m^3 AH) compared with dry air (0 g/m^3 AH), for collected particle numbers equal to 1.0 × 10^{14} and 3.5 × 10^{14} (i.e. beginning of clogging).

Note that the cake structural properties are different in the case of humid and dry gas, which certainly lead to a different contribution of particle cake to particle capture efficiency once the filter surface is sufficiently charged.

3.3.1. Discussion of the results

For particles with a diameter above 110 nm, their collection is dominated by the inertia impaction mechanism. We assume that the capillary force leads to increase the adhesion forces between the aggregates and to decrease in particular the distance between them during their transportation in the gas flow (as observed in Fig. 2) of particle size distribution upstream of bag filter: for particles with a diameter higher than 100 nm, there is a slight increase of concentration at (150 °C - 73 g/m^3 AH) in comparison to (150 °C - 0 g/m^3 AH) probably due to the formation of clusters of aggregates. Thus, we assume that particle density, which is a key parameter affecting the particle collection by inertial impaction mechanism, is influenced by capillary condensation. Indeed, due to their high inertia, the heavier particles tend not to follow the deviation of the streamline of the carrier gas where they get close to the collector, which leads them to touch the latter and be captured (Ramskill & Anderson, 1951). Thus, by increasing the particle density, the presence of water vapor in air increases the particle collection efficiency by an impaction mechanism with non-hygroscopic carbon particles.

The results of this study are consistent with the literature findings (Kim et al., 2006; Miguel, 2003) regarding the influence of humidity on fiber filter efficiency on the two particle size ranges.

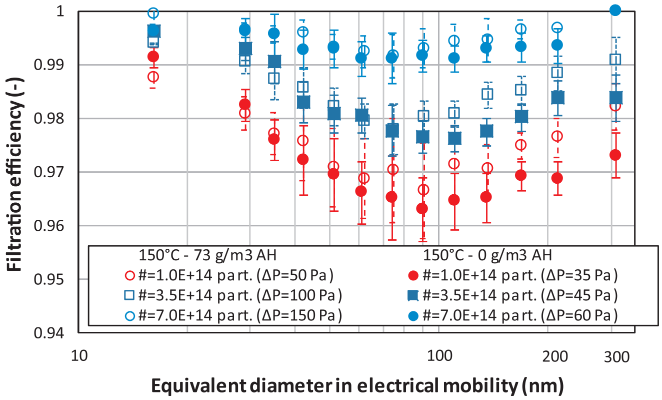

Fig. 10. Fractional efficiency of bag filter for different numbers of collected carbon nanoparticles during the first clogging cycle at (150 °C – 73 g/m^3 AH) and (150 °C – 0 g/m^3 AH).

4. Conclusion

The experimental results showed that the presence of water vapor in the treated gas has a significant influence on bag filter performance at 150 °C even for low relative humidity (3%) demonstrating that absolute humidity is a more relevant parameter than relative humidity. The air humidity (in large quantity as tested in this study) may significantly increase the particulate cake resistance to airflow, because of the water capillary condensation leading to the formation of compact particulate cake. Bag cleaning system by pulse-jet is less efficient in the presence of water vapor in gas than with dry gas. For a given number of collected particles, the collection efficiency at 150 °C increases with humidity for particle sizes higher than 110 nm in diameter; the explanation proposed in the study would be the direct consequence of humidity on particle density leading to improve particle collection by inertial impaction mechanism. At the same time, no effect of humidity was observed for nanoparticle collection efficiency (below 100 nm).

To conclude, air humidity increases the efficiency of bag filter particle collection but accelerates the increase of filter pressure drop and reduces the unclogging efficiency leading to an increase of the residual cake which is the major parameter that reduces the lifetime of the bag filter.

References

Boudhan, R., Joubert, A., Gueraoui, K., Durécu, S., Venditti, D., Tran, D. T., & Le Coq, L. (2017). Pulse-jet bag filter performances for treatment of submicronic and nanosized particles from waste incineration. *Waste and Biomass Valorization, 9*, 731–737.

Butt, H. J., & Kappl, M. (2009). Normal capillary forces. *Advances in Colloid and Interface Science, 146*, 48–60.

Cheng, Y.-H., & Tsai, C. J. (1998). Factors influencing pressure drop through a dust cake during filtration. *Aerosol Science and Technology, 29*, 315–328.

Feng, C. L., & Yu, A. D. (1998). Effect of liquid addition on the packing of mono-sized coarse spheres. *Powder Technology, 99*, 22–28.

Gupta, A., Novick, V. J., Biswas, P., & Monson, P. R. (1993). Effect of humidity and particle hygroscopicity on the mass loading capacity of high efficiency particulate air (HEPA) filter. *Aerosol Science and Technology, 19*, 94–107.

Joubert, A., Laborde, J. C., Bouilloux, L., Callé-Chazelet, S., & Thomas, D. (2010). Influence of humidity on clogging of flat and pleated HEPA filters. *Aerosol Science and Technology, 44*, 1065–1076.

Joubert, A., Laborde, J. C., Bouilloux, L., Chazelet, S., & Thomas, D. (2011). Modelling the pressure drop across HEPA filters during cake filtration in the presence of humidity. *Chemical Engineering Journal, 166*, 616–623.

Kim, C., Bao, L., Okuyama, K., Shimada, M., & Niinuma, H. (2006). Filtration efficiency of a fibrous filter for nanoparticles. *Journal of Nanoparticle Research, 8*, 215–221.

Le Bihan, O., Joubert, A., Venditti, D., Tran, T., Ounoughene, G., Debray, B., ... Le Coq, L. (2014). *Characterization and reduction of particulate emissions from the incineration of wastes containing engineered nanomaterials*144 (Final report of the NanoFlueGas ADEME Project. Convention n° 1181C0088).

Miguel, A. F. (2003). Effect of air humidity on the evolution of permeability and performance of a fibrous filter during loading with hygroscopic and non-hygroscopic particles. *Journal of Aerosol Science, 34*, 783–799.

Montgomery, J. F., Green, S. I., & Rogak, S. N. (2015). Impact of relative humidity on HVAC filters loaded with hygroscopic and non-hygroscopic particles. *Aerosol Science and Technology, 49*, 322–331.

Novick, V. J., Monson, P. R., & Ellison, P. E. (1992). The effect of solid particle mass loading on the pressure drop of HEPA filters. *Journal of Aerosol Science, 23*, 657–665.

Ribeyre, Q., Charvet, A., Vallières, C., & Thomas, D. (2017). Impact of relative humidity on a nanostructured filter cake – experimental and modelling approaches. *Chemical Engineering Science, 161*, 109–116.

Ramskill, E., & Anderson, W. L. (1951). The inertial mechanism in the mechanical filtration of aerosols. *Journal of Colloid Science, 6*, 416–428.

Saleem, M., & Krammer, G. (2007). Effect of filtration velocity and dust concentration on cake formation and filter operation in a pilot scale jet pulsed bag filter. *Journal of Hazardous Materials, 144*, 677–681.

Thomas, D., Pénicot, P., Contal, P., Leclerc, D., & Vendel, J. (2001). Clogging of fibrous filters by solid aerosol particles Experimental and modelling study. *Chemical Engineering Science, 56*, 49–61.