Experimental characterization of the efficiency and energy consumption of various central ventilation air cleaning systems

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ABSTRACT

The present study aimed at assessing six commercially-available in-duct air cleaning devices which are designed to be mounted in the central ventilation system of offices or commercial buildings. The selected devices use different air cleaning technologies: mechanical filtration, electrostatic precipitation, gas filtration, ionisation / cold plasma, photocatalytic oxidation (PCO) and catalysis under UV light. They were tested against particles, a mixture of volatile organic compounds containing acetone, acetaldehyde, toluene, heptane and formaldehyde, and two bio-contaminants: *Aspergillus brasiliensis* (fungus) and *Staphylococcus epidermidis* (bacteria).

Two different test rigs were used for the tests. The single pass efficiency of each device was determined for 3 airflow rates, ranging from 1200 m^3/h to 3600 m^3/h, and two sets of temperature and humidity that are representative of wintertime and summertime indoor air conditions. The concentrations of the challenge VOC were also varied in the range from 30 to 100 $\mu g/m^3$ as a way to characterize their influence upon efficiency at realistic concentration levels for non-industrial buildings. Ozone and formaldehyde concentration measurements downstream of the air cleaners were achieved to determine the rate of harmful by-products that are released. Finally, the energy issue was addressed by measuring the electric consumption (if any) and pressure loss of the devices.

The results show that single pass efficiencies can vary in a wide range from one system to another. For a same device, it can also vary a lot from one challenge contaminant to another, which is somewhat a more intuitive conclusion. Two systems have no efficiency at all, or negligible impact on the concentrations of the challenge pollutants. The air handling unit containing a F8 class mechanical filter, a PCO reactor and a gas filter proves to be quite efficient in removing pollutants. However, photocatalytic oxidation isn't effective while tremendously adding to the energy consumption. Finally, two devices show from moderate to high efficiency for a wide range of contaminants and acceptable energy consumption. In a general way, the study provides a methodology to assess the benefits of using central ventilation in-duct air cleaners, and then to determine which system is most suited for a building, based on indoor air quality, cost and energy criteria.

KEYWORDS

Air cleaning, in-duct, efficiency, energy, by-products

1 INTRODUCTION

During the past decade, various indoor air cleaning solutions have come to the market, including stand-alone devices, photoactive or adsorbent materials, and in-duct devices. In-duct systems put into play different air cleaning technologies. They are intended to be mounted on the recycled air as a way to promote efficiency by multiple passes of the indoor air through the device. So far, this type of systems has mainly been assessed in the context of house applications, and tested against airflow rates of few hundreds of cubic meter per hour. Experimental studies dealt with the efficiency of either commercially-available devices (Sidheswaran et al, 2012) or prototypes (Hodgson et al, 2007; Destaillats et al, 2012). Others aimed at characterizing the possible adverse health effects resulting from the emission of ozone or by-products (Gunther et al, 2011; Saughnessy et al, 2014). Very few researches nevertheless investigated the relevance of in-duct air cleaning in the context of office or commercial buildings where air handling units are designed to circulate and condition large airflow rates. Moreover, all available studies focussed on the capacity of adsorbent filters to remove volatile organic compounds (VOC) or ozone (Haghighat et al, 2008; Bastani et al, 2010; Stanley et al, 2011), while many other technologies are now available on the market. The present study aimed at filling the gap in the knowledge. Six commercially available in-duct air cleaners having a nominal airflow rate about 3600 m^3/h were fully assessed from laboratory experiments. For each device, the single pass efficiency was measured for a wide range of air contaminants in realistic conditions of operation. Ozone and formaldehyde production rates were also measured, when relevant. Finally, the energy consumption was evaluated by measuring both the device energy and pressure drop.

After presenting the main features of the selected devices, the paper describes the two tests rigs and associated protocols that were used to carry out the tests. Then, the devices are compared, and the potential of in-duct air cleaning for office buildings is discussed based on single-pass efficiency, yield of ozone and by-products, and energy cost.

2 MATERIAL AND METHODS

2.1 Selected devices

Six in-duct air cleaning devices that are commercially available in Europe were selected to undergo the tests. All of them have a nominal airflow rate around 3600 m^3/h, but use different air cleaning processes (Figure 1).

S1 is an air filtering solution which is made of a particle filter and an activated-carbon gas filter. Therefore, there's no device energy in this case. The particle filter has a V shape and is of class F7 according to EN 13779. It is sold as a low energy consumption filter. The adsorbent (activated-carbon) filter also has a V-shape. It was designed to adsorb low-weight volatile organic compounds (VOC); therefore it is particularly well suited for indoor air applications. The two filters were tested one by one against airborne particles but as an assembly against gases and bio-contaminants.

S3 is a stand-alone and ready to use air handling unit (AHU) having external dimensions of 1.95 x 0.71 x 0.85 m. The internal cross-sectional area is 0.61 x 0.61 m. The AHU has a fan that can circulate airflow rates up to 5600 m^3/h, but it was turned off during all tests. The device was supposed to contain a F8 class filter (EN 13779), a photocatalytic oxidation (PCO) reactor, and an activated-carbon gas filter, which corresponds to the manufacturer's recommendation for office building applications. However, only the PCO reactor was tested. The efficiency and energy parameters of the whole device was computed afterwards from typical fractional efficiency and pressure loss data for F8 class filters, efficiency and pressure loss of the activated carbon filter, which was assumed to be the one implemented in S1, and finally measured efficiency and pressure loss of the PCO reactor. The PCO reactor is made of a series of 3 flat TiO_2-coated filters and 2 series of 8 UVC lamps having a unit power of 95 W between them. The tests were repeated for two geometries of the filters, honeycomb and knitted metal.

S4 is an air cleaning device which is to be inserted into a duct or an AHU. It utilizes the so-called radio catalytic ionization (RCI) to generate a plasma from a ‘UVX’ lamp that irradiates honeycomb cells. The latter are made of a rhodium, titanium, silver and copper alloy. The manufacturer claims destruction of airborne and deposit fungi and bacteria, as well as removal of airborne particles and VOC due to the production of ions, free radicals, and subsequent oxidation processes.

S5 is an electrostatic precipitator (also called electronic particle filter) and S6 a plasma ionizer which are distributed by the same company. Both have standard filter dimensions of 0.592 x 0.592 m. The two devices were tested separately but also as an assembly (S2 = S5 + S6) since the distributor claims higher efficiency of the plasma ionizer when the electrostatic precipitator operates upstream. The explanation is that the electrostatic precipitator releases ozone which promotes ion generation.

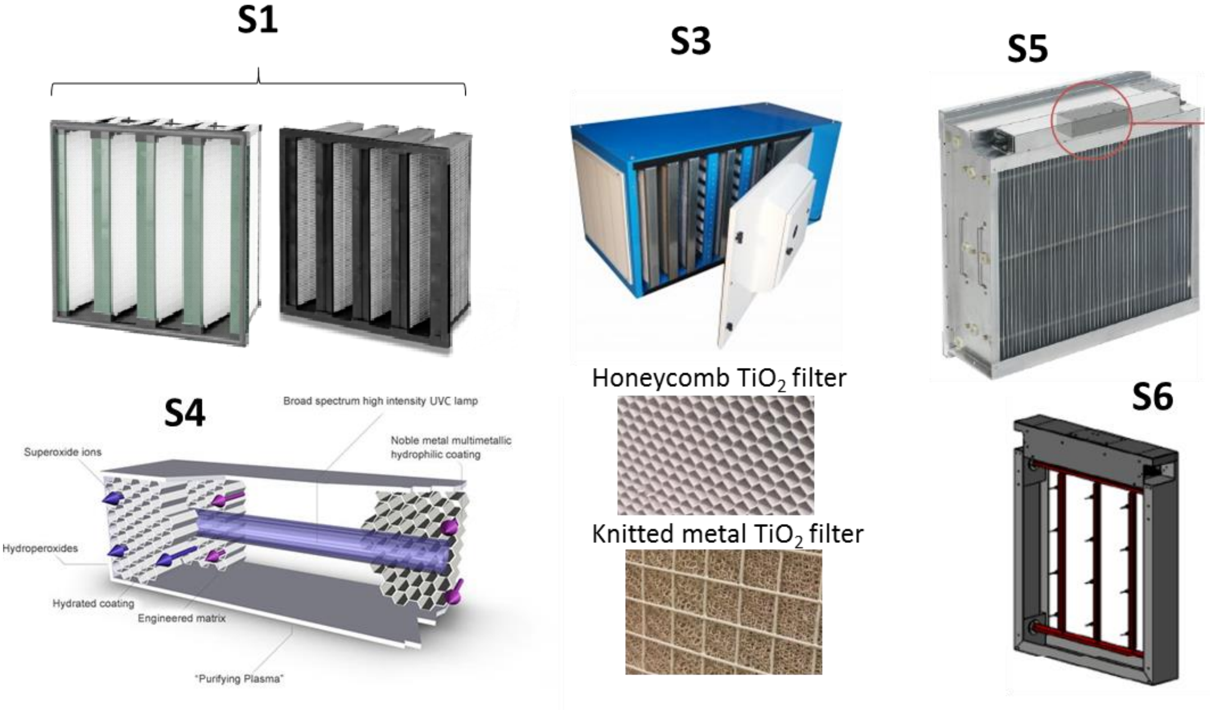

Figure 1: Air cleaning devices tested (NB: S_2 is the combination of S_5 and S_6)

2.2 Challenge contaminants and energy parameters

The selected systems were first assessed based on their efficiency against three groups of indoor air contaminants:

- VOCs, including acetaldehyde (C_2H_4O), acetone (C_3H_6O), heptane (C_7H_{16}), toluene (C_7H_8), and formaldehyde (CH_2O). These are the challenge contaminants that were selected to determine the efficiency of photocatalytic devices in the frame of the European standard project prEN 16846-1;

- Airborne particles. The fractional efficiency of the air cleaners was determined using either latex or DEHS particles. Latex particles exhibit a wider range of particle sizes (0.2 – 5.0 µm) than DEHS particles;

- Bio-contaminants. *Staphylococcus epidermidis* and *Aspergillus brasiliensis* (previously called *Aspergillus niger*) are representative of indoor air bio-contaminants. *Staphylococcus epidermidis* is a Gram-positive bacterium. It is part of the normal human flora, typically the skin flora, and less commonly the mucosal flora. *Staphylococcus epidermidis* has a spherical shape (cocci) of about 1 µm diameter. *Aspergillus brasiliensis* is a fungus and one of the most common species of the genus *Aspergillus*. Its spores have a spherical shape of diameter lying in the range from 3.5 to 5.0 µm.

Possible adverse health effects resulting from the yield of ozone when the devices use either UV lamps or electric fields (S2, S4, S5, S6), and/or production of by-products when the air cleaning process is based on the principle of VOC mineralization (S2, S3, S4, S5, S6), were assessed by measuring ozone and formladehyde concentrations upstream and downstream of the tested devices (C_{up} and C_{down} in µg/m^3, respectively). Then, this data was converted into ozone or formaldehyde production rate, τ (µg/h), from the equation:

$$\tau = Q\left(C_{up} - C_{down}\right), \qquad (1)$$

Where Q (m^3/h) is the air flow rate.

Finally, the energy consumption related to the implementation of the air cleaning devices in the HVAC system of a building was assessed by measuring the electric power and pressure loss.

2.3 Test conditions

When mounted on the recycled air of the HVAC system of buildings, air cleaning devices operate under time varying contaminant concentrations, air flow rate, temperature and humidity. Therefore, for a full characterization of the selected devices, these parameters were varied in a range which corresponds to realistic values for office-like buildings. The maximum concentration to be tested was set to 100 µg/m^3 for each single VOC. Then the tests were repeated for set point concentrations of 50 and 20 µg/m^3 (concentration was assumed to have negligible influence upon efficiency for airborne particles and bio-contaminants). Similarly, the devices were tested at a maximum and minimum airflow rate of 3600 m^3/h and 1200 m^3/h (particles) or 1600 m^3/h (gas and bio-contaminants), respectively. When the measured efficiencies were significantly different, the tests were repeated for an intermediate airflow rate of 2400 m^3/h for particle measurements, and 2600 m^3/h for gas and bio-contaminant measurements. Finally, two sets of temperature and relative humidity were considered: 19°C / 45% RH and 24°C / 70% RH. These are commonly used set points for wintertime and summertime, respectively, in the air conditioned buildings of European countries.

2.4 Test rigs and measurement methods

Two different test rigs were used to carry out the tests: rig 1 was used for particle efficiency and pressure loss measurements, while rig 2 was used for gas, bio-contaminants and device energy measurements.

Test rig 1 is made of horizontal square ducts with a cross sectional area of 0.61 m x 0.61 m. Any filter having standard dimensions can be inserted in the open-loop and tested according to the EN 13779:2012 standard. Starting from the air inlet, the test apparatus includes a diaphragm to monitor the circulating airflow rate, a heating coil to prevent from excessive moisture content of the air in wintertime, and a speed-regulated fan. A high efficiency filter (HEPA type) is mounted downstream of the fan to remove as many particles as possible from the air. The pressure loss of filters, or any other air cleaning device, is measured from four pipes which are connected to each of the four sides of the duct upstream and downstream of the device on the one hand, and to a differential pressure sensor (Rosemount) on the other hand.

Particles were generated and injected upstream of the tested device using a Collison-type (latex) or a Laskin-type (DEHS) generator. Air samples were then collected in an isokinetic way upstream and downstream of the device, and analysed by an optical particle counter (Lasair PMS 210). The fractional efficiency was determined as the average of 13 alternate particle counts upstream and downstream of the device. Each count lasted for one minute. The sampling line was purged with clean air for one minute each time the system was changing sampling port.

Test rig 2 was designed to test different sizes and types of air cleaning devices in a once-through (open-loop) mode (Figure 2). It is made of insulated galvanized steel round or rectangular ducts. Airflow rates ranging from 1200 to 3600 m^3/h can be circulated through the apparatus by a centrifugal fan having a speed control which is mounted prior to exhausting. The outdoor air is introduced to the system through an inlet damper and then passes through an AHU containing a G4 filter and a F7 filter, heating coils, a humidifier, a cooling coil and finally a high efficiency particle filter (H10). The components were designed to achieve setup air temperature between 19°C and 25°C, and relative humidity between 45% and 75%, whatever the outdoor air conditions. These parameters were monitored upstream of the tested device using a unique probe (HOBO U14 LCD data Logger, point 4 in Figure 2a). The airflow rate was also monitored using a hot-wire air speed probe (960 Probe, TSI, point 3 in Figure 2a).

The test apparatus had two parallel lines: Line 1 is made of square ducts and was designed to test devices with nominal cross sectional area of 0.61 m x 0. 61 m; the devices are mounted inside an AHU which is part of the rig (see between points 5 and 6 in Figure 2a). Line 2 allows to test air cleaning devices of any size and shape by connecting flexible ducts to the device on one side, and the test rig on the other side. This line was used to test device S3 (Figure 2b). Low leakage dampers were mounted in each end of the two lines to avoid air leakage through the unused line.

The challenge contaminants were injected far enough upstream of the air cleaning device, and upstream the duct bend (point 2 in Figure 2), as a way to promote mixing of the contaminants with the air. VOCs were injected from two programmable syringe pumps (Harvard apparatus 70-4500): one contained toluene, heptane, acetone and acetaldehyde while the other one contained formaldehyde as an water solution. *A. brasiliensis* and *S. epidermidis* were generated from a liquid suspension using a Collison CN25 particle generator and a stainless steel pipe going through the duct wall. This pipe was bended inside the duct so that the contaminants are injected in the direction of the airflow. The suspensions were calibrated to concentrations of 10^6 ufc/ml of *A. brasiliensis*, and 5.10^6 ufc/ml of *S. epidermidis*. The generator was cleaned with water and a biocide solution after each test, and the pipe was disinfected using alcohol 70%.

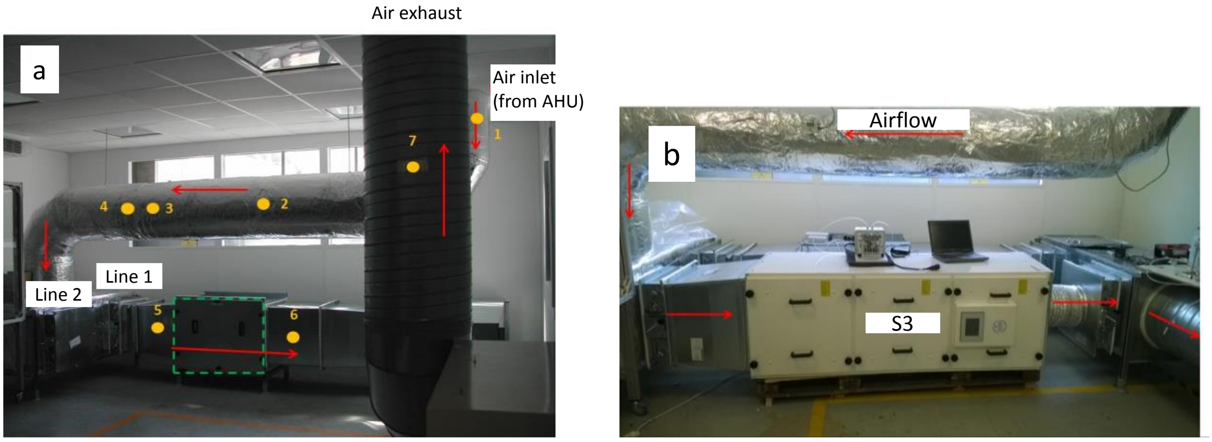

Figure 2: General view of test rig 2, used for gas and bio-contaminant measurements

The position of sampling ports upstream and downstream of the air cleaning device is represented by points 5 and 6 in Figure 2. Preliminary tests showed that challenge contaminant concentrations were uniform throughout the whole cross section of the duct in the upstream and downstream zones of the tested device, thus allowing a single point sampling procedure from each zone.

Bio-contaminant concentrations were determined using a single-stage Andersen impactor. Isokinetic air sampling was achieved at a rate of 28.3 l/min for 4 to 8 minutes. Samples upstream and downstream of the tested device were taken at the same time, each with 3 replicates. Trypticase soy broth incubated at 37°C for 48 h, and malt agar incubated at 27°C for 72 h were used as culture media for *S. epidermidis* and *A. brasiliensis*, respectively. The count uncertainty was estimated to be of ±10% for *S. epidermidis* and ±15% for *A. brasiliensis*. It can be noted that for all tests, sample blanks were achieved by measuring the bacteria and fungus concentrations upstream and downstream of the device before they were generated. Additional measurements also included situations when the device is turned off. Finally, S3 was tested with only the UVC lamps operating (TiO_2 filters were removed from the AHU), and then with the filters but the UVC lights turned off, as a way to isolate the effects of mechanical filtration and direct germicidal irradiation from the global efficiency of the PCO reactor.

Toluene, heptane, acetone and acetaldehyde concentrations were measured online using a Ion Molecule Reaction Mass Spectrometry (IMR-MS) analyzer (Airsense, V and F). The limit of quantification for acetaldehyde, acetone, heptane and toluene are 13, 17, 25 and 25 $\mu g/m^3$, respectively. Formaldehyde concentrations were measured according to ASTM Method D5197 which consists of trapping of the analytes on a silica gel adsorbent coated with 2,4-dinitrophenylhydrazine (DNPH), followed by analysis by HPLC/UV. The limit of quantification is 5 $\mu g/m^3$. Finally, ozone concentrations were measured downstream of the tested devices using an online analyzer (03 41M, Environnement SA). Continuous measurements were made over a period of 10 to 30 minutes, with a time resolution of 1 measurement per minute. The ozone concentration that was measured with the device turned off was taken as the concentration upstream of the device to compute the ozone production rate from Eq. 1.

3 RESULTS AND DISCUSSION

3.1 Efficiency

Figure 3 provides an overview of the efficiency of the selected air cleaning devices. S2, S4 and S6 are not displayed because all efficiencies were close to zero for S4 and S6, and any significant increase in efficiency could be observed when comparing S2 with S5 (which means that there's actually very few influence of ozone generated by S5 upon efficiency of S6). These devices are no longer considered hereafter.

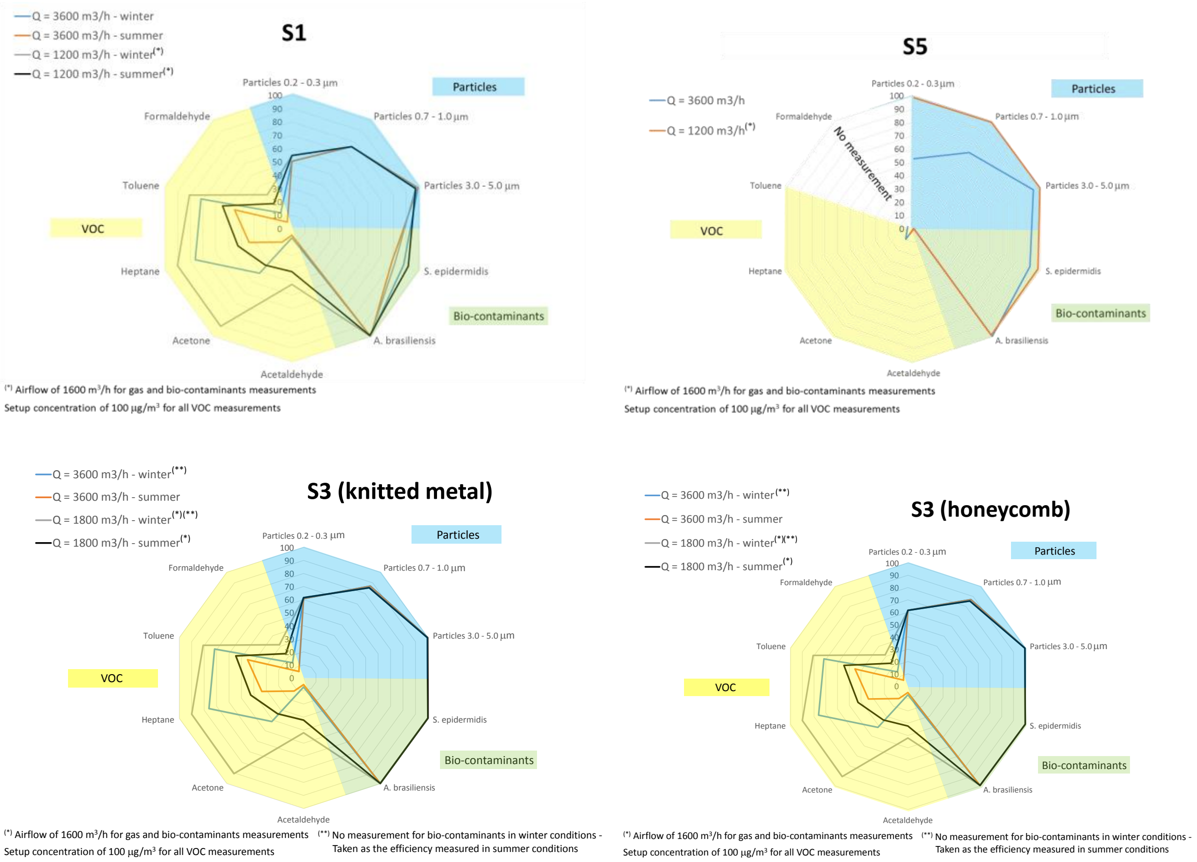

Figure 3: Overview of measured efficiencies for devices S1, S3 and S5 – Summer = 24°C/70% RH, Winter = 19°C/25% RH

At first, it can be noted from Fig. 3 that the electrostatic filter S5 exhibits high efficiencies for all kind of particles, including bacteria and fungus, but it is inefficient against VOC, which was expected. The measured efficiency is close to 100% for all particle sizes at the lowest air flow rate tested (1200 m^3/h), but it falls to 55% for the smallest particles when the air flow rate is increased to 3600 m^3/h. This observation is consistent with the principles of electrostatic precipitation. S1 and S3 are a bit less efficient in removing particles and bio-contaminants from the air than S5, especially when the air flow rate is high. On the other hand, Fig. 3 shows that these devices have from moderate to pretty high efficiencies for VOCs depending on species and airflow rate. The fact that S1 and S3 efficiency profiles are very similar whatever the type of photocatalytic filter implemented demonstrates that the PCO reactor doesn't really add to the air cleaning performance of S3. Actually, the tests which were performed with this reactor showed 100% efficiency for *S. epidermidis*, and a very low efficiency, or no efficiency at all, for all other challenge contaminants. By comparing the results when the lights were turned on and off, and when TiO_2 filters were inside or taken out of the AHU, it could also be clearly demonstrated that bacteria were killed as a result of the germicidal effect of UVC lamps rather than photocatalytic oxidation processes. In the end, the particle and bio-contaminant efficiencies of device S3 are mainly contributed by the mechanical filter (F8 class) while the VOC efficiency is only contributed by the adsorbent filter.

The strong influence of air flow rate (air speed) upon VOC efficiency of S1 is consistent with the fundamentals of adsorption dynamics. The results are also consistent with theory regarding 1) the observed correlation between boiling point of VOCs and sorption efficiency (Figures 3 and 4): for a same airflow rate, the gas filter efficiency is the highest for toluene (T_b = 110.6 °C) and then heptane (T_b = 98.4 °C), acetone (T_b = 56.1 °C), acetaldehyde (T_b = 20.2 °C) and formaldehyde (T_b = -19.3 °C). Such correlation had previously been emphasized by Haghighat and al (2008), Bastani and al (2010) and Popescu and al (2013); 2) the influence of temperature and relative humidity upon sorption efficiency: for a same airflow rate and a same VOC concentration upstream of the filter, the measured efficiency is significantly higher at a lower temperature and a lower relative humidity. Only formaldehyde shows similar efficiency at 24°C/70% RH and 19°C/45% RH, which can be explained by a very high solubility in water. In this case, higher amounts of condensed water in the pores of the activated carbon when relative humidity is increased contribute to promote formaldehyde absorption. It can balance and even overtake the decrease of formaldehyde adsorption at the pore surfaces due to higher temperature and competition with water vapour; 3) the influence of concentration: except in the case of toluene, for which the efficiency is close to 100% whatever the concentration in the conditions presented on Figure 4, higher efficiencies are observed at higher concentrations upstream of the filter. The increase in efficiency is most particularly visible when the setup concentration is increased from 33 to 66 µg/m^3.

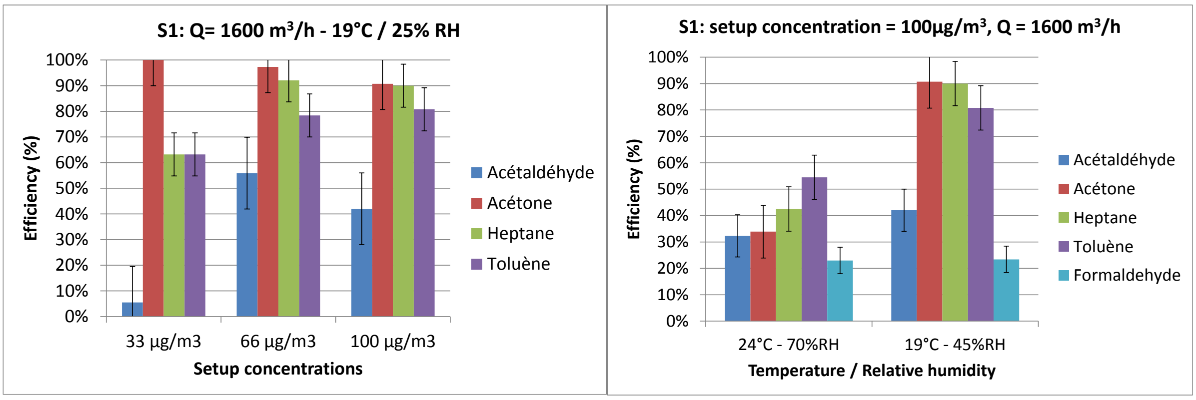

Figure 4: Efficiency of S1 as a function of VOC, concentration and temperature / humidity air conditions

3.2 Production of ozone and by-products

No formaldehyde could be detected downstream of devices S2, S3, S4, S5 and S6 when they were tested against the mixture of toluene, heptane, acetone and hexaldehyde. This was expected since no significant removal efficiency, and therefore no significant oxidation of any of the challenge VOCs, could be observed. S3 and S4, which use UV lamps, were found to emit no ozone in the circulating air. On the other hand, measurements of ozone concentrations downstream of S5 and S2 led to surprising results. Figure 5 shows that the ozone emission rate is both influenced by the air flow rate and the hygrothermal conditions of the air upstream of the device. In indoor air summertime conditions, the ozone production rate at 3600 m^3/h is twice the one measured at 1600 m^3/h. No linearity with airflow rate can be observed from Fig. 4 but the production rates at 2400 m^3/h are most probably underestimated due to technical problems that led to achieve a relative humidity of the air which was far below the set point (41% vs 70%). Relative humidity obviously has a strong influence upon ozone production since for the maximum airflow rate, the production rates of S5 and S2 in summertime air conditions are about 3 times higher than in wintertime air conditions.

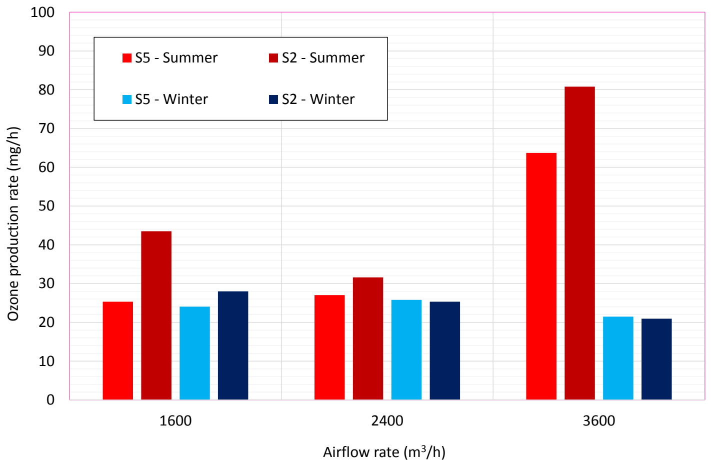

Figure 5: Ozone production rate of devices S5 and S2 - Summer = 24°C/70% RH, Winter = 19°C/25% RH

3.3 Energy consumption

The fan energy resulting from the implementation of any device in the HVAC system of a building, P_v (W), can be computed from the equation:

$$P_v = \frac{Q\Delta P}{\eta_v}, \tag{2}$$

Where ΔP (Pa) is the pressure loss of the device, and η_v is the fan efficiency. The latter was here assumed to be 50% as a way to compare P_v with the device energy, P_a (W), on one hand, and to compare the selected air cleaning devices based on their total energy consumption, on the other hand. The results presented in Table 1 show that for all systems except S3, the device energy is pretty low, and far less than the fan energy when the air flow rate is greater than 2400 m^3/h. For S3, the fan energy is also quite important at high air flow rates when knitted metal filters are used (3 filters are connected in series). The device energy is overall so high here that it can hardly fit the standards of low energy buildings.

Table 1: Device energy and fan energy of the selected air cleaning devices

Energy (W)	**S1**	**S2**	**S3** Honeyc.	**S3** M. stitch	**S4**	**S5**	**S6**
Device energy	0	24	1520	1520	20	15	9
Fan energy, $\eta_v = 0.5$							
Q = 1200 m^3/h	17	5	1	12	negligible	5	negligible
Q = 1800 m^3/h	49	15	5	40		15	
Q = 2400 m^3/h	142	46	13	131		46	
Q = 3600 m^3/h	310	104	29	272		104	

4 CONCLUSIONS

The results presented in this paper are a first insight into the potential of in-duct air cleaners to improve indoor air quality while preserving energy in office-like or commercial buildings. Six devices that are available on the market were tested against a set of challenge contaminants, in realistic operating conditions. In the end, only two of the six devices proved to be relevant. Two of them showed no efficiency, or a very low efficiency, for all challenge contaminants. One has significant efficiency for a wide range of contaminant but it was demonstrated from additional tests that the main cleaning process is partly inefficient in removing contaminants while tremendously adding to the energy consumption of the building. Finally, the association between the electrostatic precipitator and the plasma ionizer wasn't found to be relevant though it was recommended by the seller. The reader's attention is drawn to the fact that the selected devices utilize different air cleaning techniques, but in no way the conclusions of this study should be extrapolated to all devices that utilize one of the tested technologies. It's also worth mentioning that all devices were assessed as brand new devices. Consequently, the efficiency and pressure loss of devices that contain filters are the initial efficiency and pressure loss. Although considering the mean efficiency and pressure loss over a given period of time would probably be more suitable, the methodology presented here may serve as a basis to develop a new standard to assess in-duct air cleaners.

5 ACKNOWLEDGEMENTS

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