Out2In: impact of filtration and air purification on the penetration of outdoor air pollutants into the indoor environment by ventilation

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ABSTRACT

Within the ventilation principle of buildings, the **outdoor air is considered as a source of fresh, "clean" air.** Outdoor air quality monitoring by environmental agencies, academic research projects and a broad range of citizen science projects show that this is not always the case. Although the outdoor air quality in our cities already improved, the concentrations of **certain pollutants**, especially **particulate matter** and peak pollutions of **ozone** (and its precursors **nitrogen oxides** and **volatile organic compounds**), **remain problematic**. Ventilation systems may play a role in the introduction of these outdoor air pollutants into the indoor air, with potential adverse effects on the indoor air quality and the health of residents. The filters that are present in certain mechanical ventilation systems are primarily present to protect the system and its components against fouling, but have the potential to improve the quality of the supplied air.

In the context of indoor air quality, the **aim of this project** is to investigate: what role do mechanical ventilation systems play in the penetration of outdoor air pollutants? | to what extent is conventional air filtration sufficient? | what is the effectiveness and added value of advanced filtration and electrostatic precipitation as an innovative technique?

These research questions will be answered from a bottom-up research approach, including in-laboratory experiments on filters as a first step. The **novelty of our research approach** lies in the fact that: the measurements are carried out with the *real-life pollutant load of the Brussels outdoor air*, *the filtration efficiency for particulate matter* is considered in a *measuring range of 10nm-10µm* and is based on *number concentrations*, the filtration efficiency is *monitored in function of time* and the collection and penetration of *chemical pollutants* (O_3, NO_X and VOC) is also considered.

This paper presents the first **results of the in-laboratory measurement part**. For this part, a **test setup** consisting of **twelve parallel test lines equipped with either one or two different air filters/ -cleaning devices in cascade** was installed in our Brussels-based laboratory. The selected filters **allow a comparison between different filter classes** (G3,G4,F7,F9,H10), **or combinations of them,** and **also of different types within the same class** (wireframe, folded panel, bag type). Furthermore, two **filters containing active carbon** and two **electrostatic precipitators** are included in the test setup. This paper shows **time resolved data** including the **filter efficiency** and **pressure drop** on the filters/devices included in the test setup. The **preliminary results** on filter efficiency indicate a **large difference in performance between different filter types within the same filter class** and point to a high performance of the electrostatic precipitators within the full measuring range.

KEYWORDS

Ventilation | Particulate matter | Filter Performance | Indoor Air Quality

1 INTRODUCTION

There is an increasing awareness about the importance of **Indoor Air Quality** in our buildings. Not least because of the realization that we spend most of our time indoors during which we can get exposed to potential harmful pollutants for a long time span. As recognized by both national and international (e.g. WHO) bodies, some of these indoor pollutants have a negative impact on our comfort, cognitive performance and health in general.

Preventing and minimizing the release of pollutants at the source (I), the removal of inevitable pollutants from the indoor air (II) and prevention of penetration of outdoor air pollutants in the indoor environment (III) are the three cornerstones to obtain a good indoor air quality. **Ventilation** plays a prominent role in this, especially in the second and third cornerstone. Within the ventilation principle, no matter the method, the polluted indoor air is replaced/diluted by **outdoor air, which is considered as a source of fresh and "clean" air**.

It goes without saying that the outdoor air cannot always be regarded as pure, especially in city environments. Although the **outdoor air quality** already improved in cities like Brussels, some pollutants, in particular **ozone** (and its precursors **NO_x & VOCs**) and **particulate matter** remain problematic. The principle sources of NO_x and particulate matter are combustions processes as in car engines (traffic) and heating systems of buildings.

Particulate matter is defined as a complex mixture of extremely small particles and liquid droplets present in the air. According to their aerodynamic diameter they are classified into coarse [PM_{10} (< 10μm)], fine [$PM_{2.5}$ (<2.5μm)] and ultrafine particles [$PM_{0.1}$ (<0.1μm) = UFP]. Black carbon, which consists of pure carbon in several linked forms (≈ soot), are in general particles with a size comprised between 20-150nm and are directly linked to combustion processes. The mass concentration of PM_{10} and $PM_{2.5}$ in the outdoor is regulated on an EU-level and more severe guide values from the WHO are available. By contrast, UFP and black carbon concentrations are not regulated, neither are there guide values available. However, the smaller particles are, the deeper they can penetrate our respiratory system and the greater the potential health risks are.

From a **health** point of view, a poor outdoor air quality is worldwide responsible for over 6 million deaths a year (± 8000 for Belgium). It largely contributes to death as a result of stroke, lung cancer, cardiovascular - and chronic pulmonary disease. The total social cost for Belgium amounts to 8 million euros a year.

Given the magnitude and the impact of outdoor air quality problems in our cities and the fact that our buildings are becoming more airtight (meaning less uncontrolled infiltration), the following **research questions** arise: *what role do mechanical ventilation systems play in the penetration of outdoor air pollutants into the indoor environment? | to what extent is conventional air filtration sufficient? | what is the effectiveness and added value of advanced filtration and electrostatic precipitation as an innovative technique?*

2 MATERIALS AND METHODS

2.1 Test setup

To answer the above questions, a test setup was constructed in our Brussels-based laboratory. As illustrated by Figure 1 A, this test setup consist of 12 parallel test lines which are all connected to a distribution box. Inside this distribution box (see C & D) a partition plate with four square openings is foreseen to evenly distribute the air to the different test lines. At his turn the distribution box is connected to the outdoor air by two supply boxes (see C) **allowing the measurements to be conducted with the real-life pollutant load of the Brussels outdoor air.** The exhaust air (red) of each line is collected and evacuated to the outdoor air at the other side of the laboratory.

Each test line is composed of one or two **filter boxes/devices** (inter)connected to the other parts by **round metal ductwork (ø160 mm)** (see § 2.2 for the selected filters/devices), a **constant flow fan** set at 150 m³/h and a **diaphragm** allowing to measure the air flow rate on the basis of a differential pressure measurement.

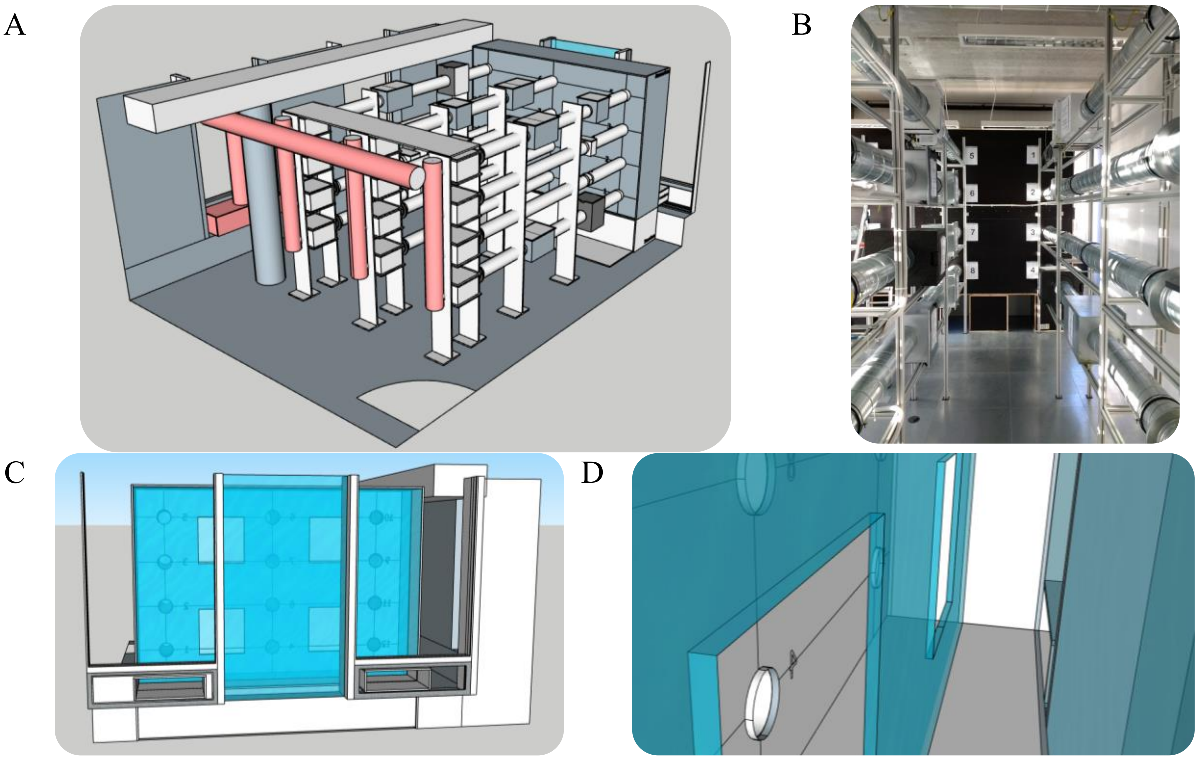

Figure 1 Computer-based design model and picture of the test setup as built: A) general view B) picture of a part of the test setup C) detailed view of the distribution box and the supply boxes integrated under the windows D) interior view of the distribution box

2.2 Selected filters and devices

Classic filters – six test lines are equipped with filters or combinations of them which are nowadays already used in ventilation systems. This includes coarse filters (G3 and G4 class filters according to EN779[1][1]) and a fine filter (F7 class). From the same classes also different types of filters were included like duct type, wireframe, folded panel and bag type filters (see *Figure 2*).

A **B** **C** **D**

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[1] By the time the filters were purchased, the EN779:2012 standard was still in use. In the meanwhile, is has been replaced by the EN ISO-16890:2016 standard [3] which makes use of a different method and classification of filters. As an indication, the G3 and G4 classes would now correspond to ISO-coarse >80% and >90% (dust arrestance), F7 to ePM1 50-65% or ePM2.5 65-95% and F9 to ePM1> 80% or ePM2.5>95% (efficiency).

Figure 2 Pictures of the different tested filter types:
A) G3 duct type, B) G4 wireframe, C) G4 folded panel, D) G4 bag type

Intensive filtration – four test lines are equipped with filters which are nowadays rather exceptionally in use in domestic ventilation systems including an F9 and H10 filter (= E10, Efficiency Particulate Air filter, EN1822:2009 [2]). These filters are all of the folded panel type.

Innovative devices – two test lines are equipped with electrostatic precipitators (ESPs). Although, the principle of electrostatic precipitation is known for decades and already used in industrial applications, only recently devices connectable to domestic ventilation systems became available on the market. An electrostatic precipitator in general consists of two parts: the ioniser and the collector. Within the ioniser, the air and its particulate load will get charged (in this case positively) due to the corona discharge principle (high voltage on a small electrode). Within the second part, the ionised particles are then collected on collector plates with an opposite or neutral charge. In one of the systems included in the test setup, the ioniser (thin horizontal wires between the collector plates) and collector (multiple horizontal aluminium plates) are integrated into one piece which must be cleaned using a soap solution after a certain while in use. In the second system, the ioniser and collector are two separate parts, which might even be installed with a certain distance in between. Within this system the collector part consists of two consecutive polypropylene plates with a honeycomb structure and are considered as consumables (needs to be replaced after a while in use).

2.3 Measurements

Differential pressure over each filter box or device is measured on a monthly basis using a TSI PVM-620 manometer. To enable these measurements an airtightly sealed nipple was integrated in the duct, before and after each filterbox/device, to which the manometer can be connected for measurement. The reported value is an average value of three consecutive measurements of 10s each.

Particulate matter load of air samples is measured in number-based concentrations within the range of 10nm up to 10µm using two different devices. Particles within the size range of 10-420nm are quantified using a Scanning Mobility Particle Sizer (TSI, Nanoscan 3910 SMPS), while those between 0.3-10µm using an Optical Particle Sizer (TSI, OPS 3330). The measurements are conducted according to a procedure based on the Eurovent 4.10 guideline [4]. This guideline describes a method for in situ determination of fractional efficiency of general ventilation filters. Briefly outlined, the particle load is consecutively measured before and after each filter, by inserting an isokinetic sampling probe into the duct, for in total respectively 7 and 6 measurements of one minute each. Fractional efficiencies are calculated six times using each time two measurements in front and one measurement after the filter. The reported values are mean efficiency values with indication of the 95%

confidence interval. Whenever absolute values are reported they are expressed in the number of particles/L in dN/dlogDp format allowing inter-instrumental comparison of the results.

Ozone production was verified using a Teledyne T204 gas analyser.

3 RESULTS AND DISCUSSION

3.1 Typical profile for the particulate load of the outdoor air in Brussels

As stated before, the efficiency of the filters in the test setup is determined using the real-life particulate load of the Brussels outdoor air. The graph below shows a typical number-based profile of the particulate load in the Brussels outdoor air. This profile indicates that mainly particles belonging to the smaller particle classes ($PM_{0.01\text{-}0.1}$ & $PM_{0.1\text{-}0.5}$) are dominating the particle load. They respectively represent 81 and 19% of the total particulate load. Particles with a size above 0.5µm only represent 0.044% of the total particulate load.

These results also indicate that it is for most of the particle sizes feasible to determine the fractional efficiency according to Eurovent 4.10 (number/L in front of filter > 37/L). Only for the largest particles the numbers (> 6µm) are in general too low, resulting in larger uncertainty on the obtained results.

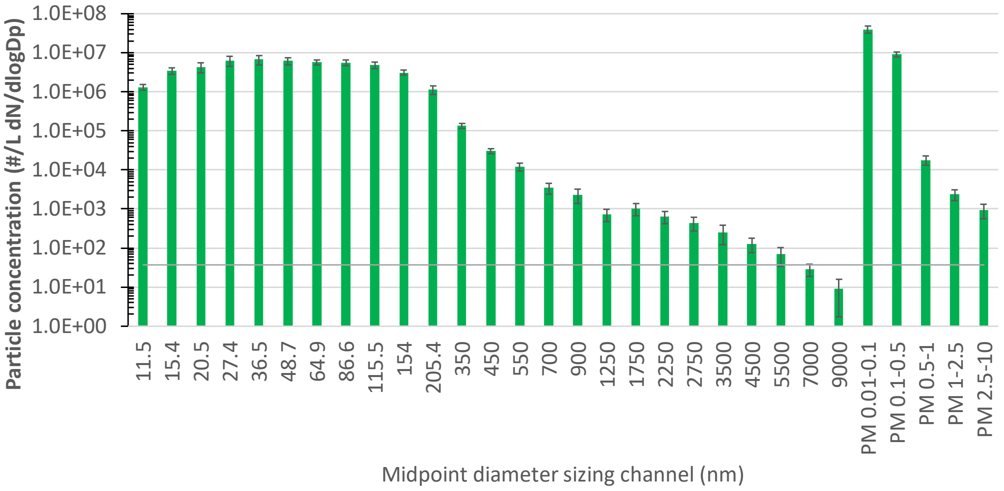

Figure 3 Typical profile of the particulate load of the Brussels outdoor air expressed in number of particles/liter within the measurements range of 10nm-10µm. In the left part of the graph, the number of particles for each sizing channel within the measurement range are indicated (size indications in nm). In the right part of the graph, the measured number of particles are aggregated into particle classes (size indications in µm). The grey line indicates the minimal number of particles (37 particles/L) upstream of the filter for efficiency determination according to Eurovent 4.10.

3.2 Coarse filters (G3 and G4)

As the graphs below indicate, the **filter efficiency** for particles < 1µm is rather low for coarse filters. The only exception to this is the G4 folded panel filter at new state (*Figure 4* A). This is most likely due to a static electrostatic charge given to the filter medium during production (Electret Filter medium). As a result, these types of filters have electrostatic interaction as an additional retention principle besides the mechanical retention principles, resulting in an increased efficiency at new state. However, during use this charge gets lost explaining the lower efficiency of this filter after 2.5 months in use (*Figure 4* B). The decrease in efficiency manifested itself already after 238 hours (1/3th of a month) in continuous use (data not shown).

For the folded panel filter type, a much higher efficiency can be observed for the G4 filter in comparison to the G3 filter. Within the same filter class, large differences in efficiency can be observed between the different filter types (e.g. G3: duct vs. folded panel | G4: wire frame vs. folded panel vs. bag type). In function of time the efficiency of the folded panel filter types tends to decrease, while the efficiency for the duct, wireframe and bag type filters increases. Especially for the duct and wireframe filter types, which are characterized by a small filter surface, this might be explained by the influence of the filter cake that gradually builds up on the filter surface.

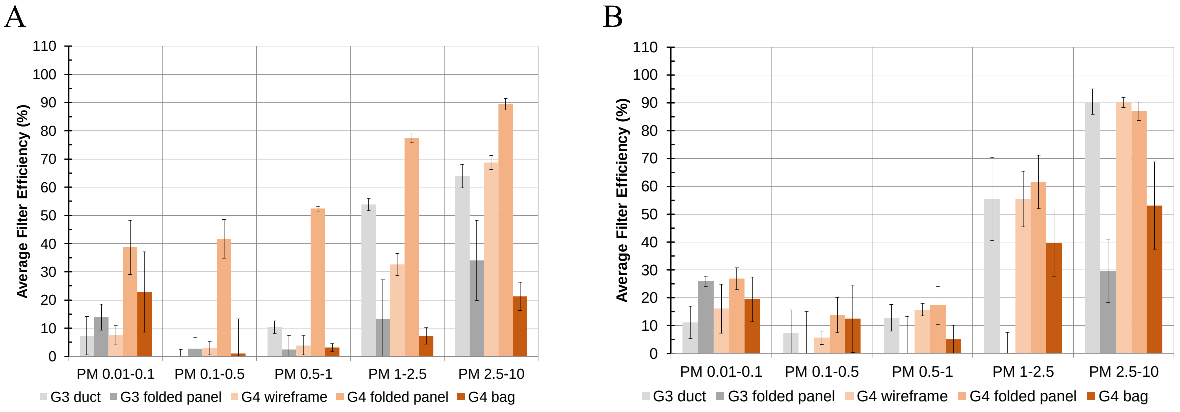

Figure 4 Average filter efficiency of coarse filter types with indication of the 95% confidence interval at new state (A) and after 2.5 months of continuous use (B). Results for the filters of the G3 class are given in grey, those for the filters of the G4 class in orange.

The G3-duct and G4-wireframe filter types exhibit a relatively high initial **pressure drop** (see *Table 1*) and a strong increase in function of time compared to the other coarse filters. The reason for this lies in the limited filter surface of this type of filters.

*Table 1 Pressure drop (Pa) as a function of time for the coarse and fine filters and the electrostatic precipitators (ESP), cc: cleanable collector, taw-c: throw away collector, FP= folded panel, B=bag, * protected by a G4 FP coarse filter*

→ filter class and type	G3		G4			F7*	F9*	H10*	ESP	
↓time elapsed	duct	FP	wireframe	FP	B	FP			cc	taw-c
Initial	88.4	8.6	36.9	11.4	7.1	23.2	24.5	28.3	8.3	16.3
1 month	136.4	11.7	71.7	19.0	9.3	25.9	24.5	29.7	9.5	17.1
3.5 months	198.1	12.8	115.4	47.0	9.9	28.2	26.2	29.0	12.8	19.1

3.3 Fine filters (F7, F9, H10)

As can be expected, fine filters are in general more efficient than coarse filters (see *Figure 4* & *Figure 5*). Upon comparison of the tested F7 and F9 filter, the results indicate a slightly, but non-significant, higher efficiency for the F9 filter throughout the complete measurement range. Both filters however show a dip in their efficiency for the particle classes $PM_{0.1\text{-}0.5\ \mu m}$ and $PM_{0.5\text{-}1 \mu m}$. As shown by the fractional efficiency profile for the F7 filter (*Figure 5 C*) this dip in efficiency (< 80%) extends from particles with an aerodynamic diameter of 56nm to 800nm. The tested H10 filter at new state on the other hand, shows a very high efficiency within the full measuring range (see *Figure 5 A & D*). After two and half months in continuous use, the F7 and F9 filters do not show an obvious difference in efficiency, while for the H10 a decrease for the classes $PM_{0.1\text{-}0.5}$ and $PM_{0.5\text{-}1 \mu m}$ can be observed.

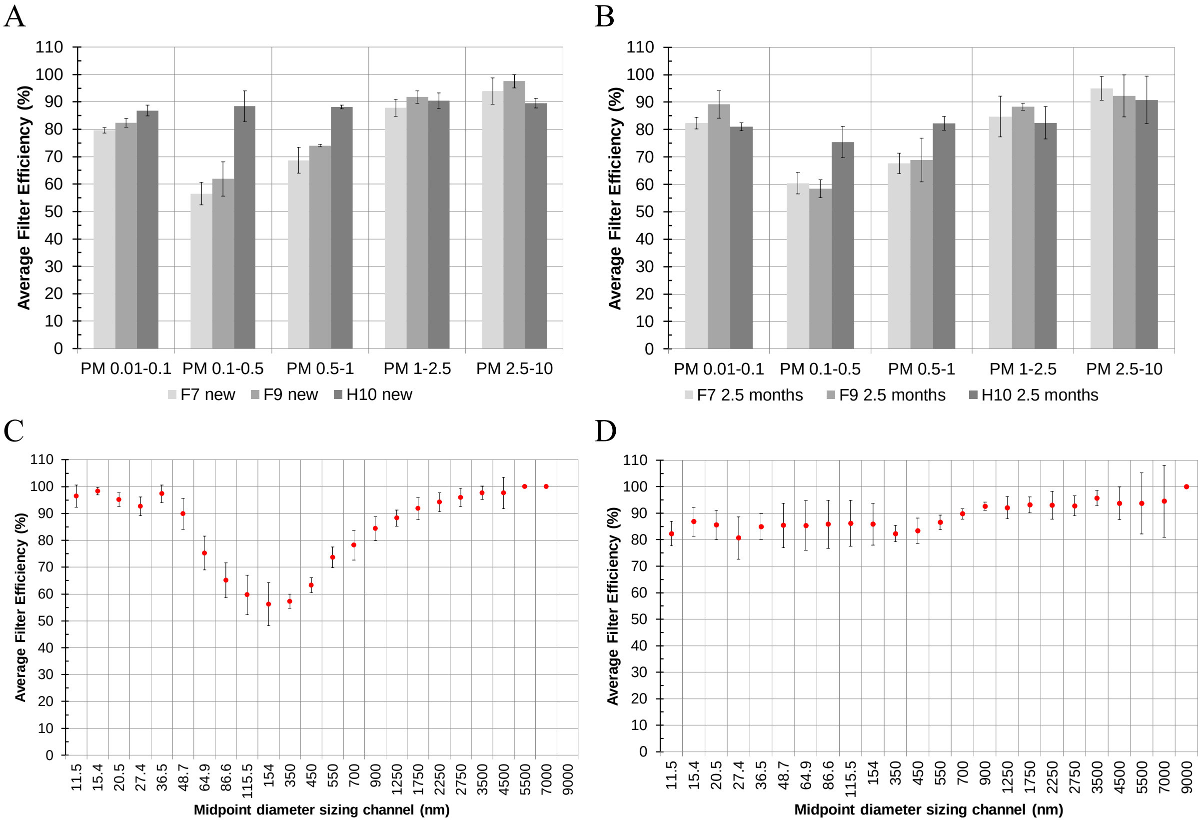

Figure 5 Average filter efficiency of fine filter types with indication of the 95% confidence interval at new state (A) and after 2.5 months of continuous use (B). Fractional efficiency profile within the complete measurement range (10nm-10µm) for an F7 filter (C) and an H10 (D) after 1 month in continuous use.

At new state the pressure drop caused by the fine filters is larger than the ones observed for most coarse filter types (except for the wireframe and duct type filter) (see *Table 1*). The differences in pressure drop between the fine filter classes are rather small, even after 3.5 months in use. It must be mentioned that each of the fine filter classes is installed in a test line with the same G4 folded panel filter as a prefilter.

3.4 Electrostatic precipitators

Both precipitators exhibit a very high efficiency (>96%) within the full measuring range at new state. After 2.5 months in use, the version with the cleanable collector still shows a high efficiency throughout the measuring range, while for the version with throw away collectors the efficiency for some particle classes, more precisely $PM_{0.01\text{-}0.1}$ and $PM_{0.5\text{-}1}$ dropped. Visual inspection of the collector plates indicates that a black coloration can be observed at the back of the collector plates, indication that the collector gradually becomes saturated.

In absolute numbers, the large initial efficiency results for the particle classes $PM_{1\text{-}2.5}$ and $PM_{2.5\text{-}10}$ in a small number of particles in the air (< ± 10 particles/L) after the ESP unit (*see Figure 6 C*). For the $PM_{0.5\text{-}1}$ class, the ESP causes a considerable reduction from 100.000 to < 1000 particles/L. However, despite the very high observed efficiencies at new state (> 99%) for the smallest particle classes, a very large number of particles remain in the air (1.000.000 for $PM_{0.01\text{-}0.1}$ | > 100.000 for $PM_{0.1\text{-}0.5}$) after de ESP unit.

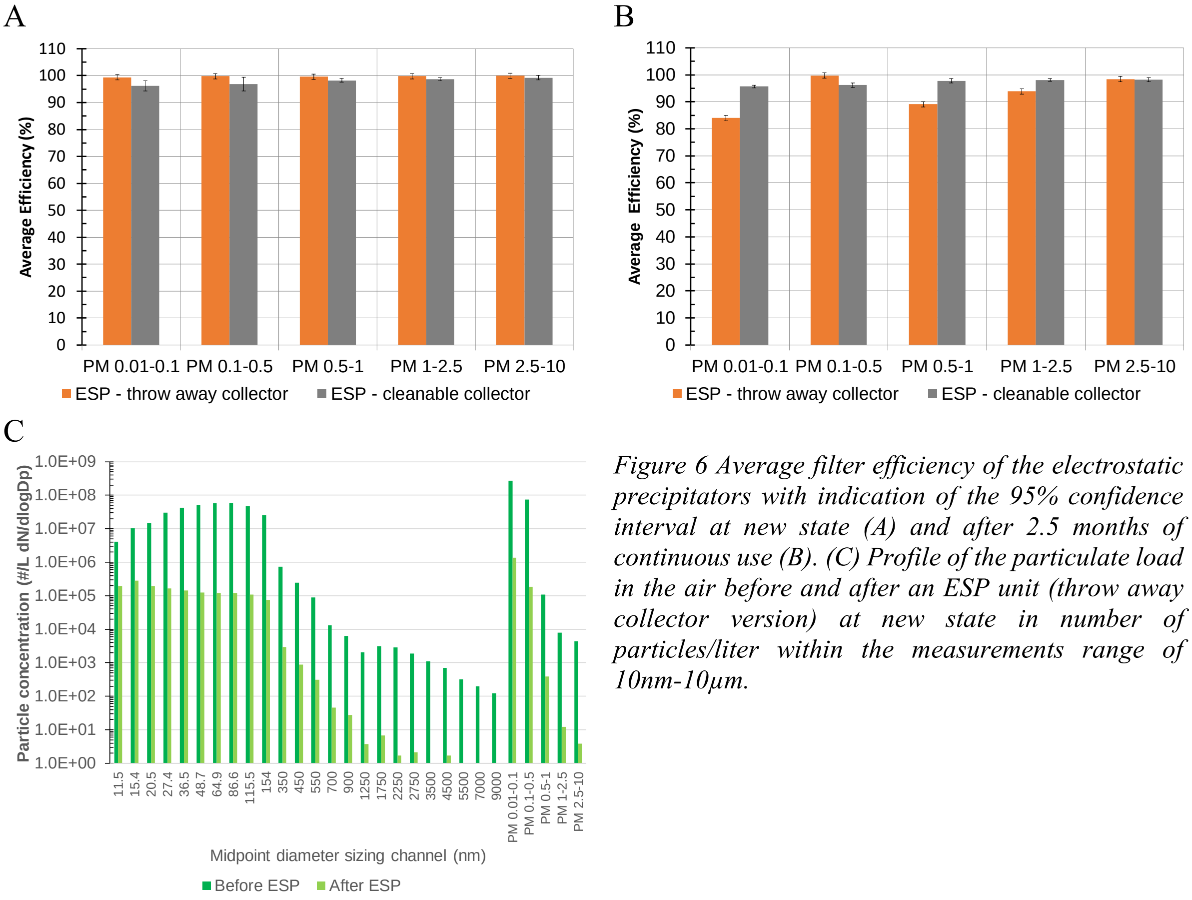

Figure 6 Average filter efficiency of the electrostatic precipitators with indication of the 95% confidence interval at new state (A) and after 2.5 months of continuous use (B). (C) Profile of the particulate load in the air before and after an ESP unit (throw away collector version) at new state in number of particles/liter within the measurements range of 10nm-10µm.

The pressure drop over the system with cleanable collector plates is lower than that of the version with throw away plates (see *Table 1*). This is a result of the more open inner structure of the cleanable system. However, for both systems their pressure drop is rather small in comparison to the pressure drop over the tested fine filters and only has a small tendency to increase in function of time. Moreover, the ESPs are not protected by a prefilter as is the case for the fine filters. The ozone production was found to be limited for both systems (cleanable: 9.1±1.5 and throw away:5.9±1.8 ppb).

4 CONCLUSIONS

Throughout our measurement we observed that, based on number concentrations, the outdoor air particulate load in Brussels is mainly dominated by **very small particles.** Especially ultrafine particles (< 0.1 µm) are gaining research attention because they can penetrate deeper into our respiratory system an even our bloodstream leading potentially to greater health risks.

Coarse filters are mainly installed in balance ventilation systems to protect the system (including heat exchanger, fans,..) and the ductwork against rapid fouling. Their efficiency, especially for particles smaller than 1µm, was found to be rather limited. Moreover, a large variability in efficiency was observed for different filter types within a same coarse filter class (G3 or G4). Therefore, coarse filters cannot be considered as contributing to an improved air quality in terms of particulate load. The use of coarse filters with a small filter surface should be avoided because of their typical very high initial and sharply increasing pressure drop.

Fine filters, have the potential to improve the quality of the supplied air by a ventilation system in terms of particulate load. However, F7 and F9 filters show a dip in their efficiency profile for particles between 56-800nm, including part of the ultrafine particles. This dip is not observed for the tested H10 (efficiency particulate filter) at least at new state. Further follow-up is necessary to get a better picture of the evolution of the efficiency of these filters and their pressure drop.

Electrostatic precipitation seems a promising technique due to the high efficiency of particle capture within the full range (10nm-10µm) and the associated low pressure drop in comparison to fine filter.

Further research will be necessary to understand the impact of the remaining load of very small particles in the air after fine filters and electrostatic precipitators. For the electrostatic precipitators also the potential effect that ionized air might have on human health should be looked at.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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