Real-life ventilation filter performance: final results of an in-depth study

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ABSTRACT

Within the ventilation principle of buildings, the **outdoor air is considered as a source of fresh, "clean" air.** However, as we all know, 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 our study** was 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 were answered in a bottom-up research approach, including in-laboratory experiments on filters, *in situ* measurements on the ventilation system level and computer simulations on the building level. 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* (PM_{10}, $PM_{2.5}$, PM_1 & $PM_{0.1}$) and the filtration efficiency is *monitored in function of time*.

This paper presents the **final results of the in-laboratory measurements for particulate matter**. 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** (Coarse, ePM_1, $ePM_{2.5}$ and EPA), **or combinations of them,** and **also of different types within the same class** (wireframe, folded panel, bag type). Furthermore, two **electrostatic precipitators** were included in the test setup. This paper shows **time resolved data** including the **filter efficiency** and **pressure drop** of the filters/devices included in the test setup. The **results** indicate a **large difference in performance between different filter types within the same coarse filter class,** the **potential of fine filters to improve supplied air quality** and point to a high performance of the electrostatic precipitators within the full measuring range. They also reveal important points of attention.

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)], very fine [$PM_{1.0}$ (<1µm)] 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, $PM_{1.0}$, 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 indoor air quality is worldwide responsible for over 3.8 million deaths a year (WHO, 2021). It largely contributes to death as a result of stroke, lung cancer, cardiovascular - and chronic pulmonary disease.

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.

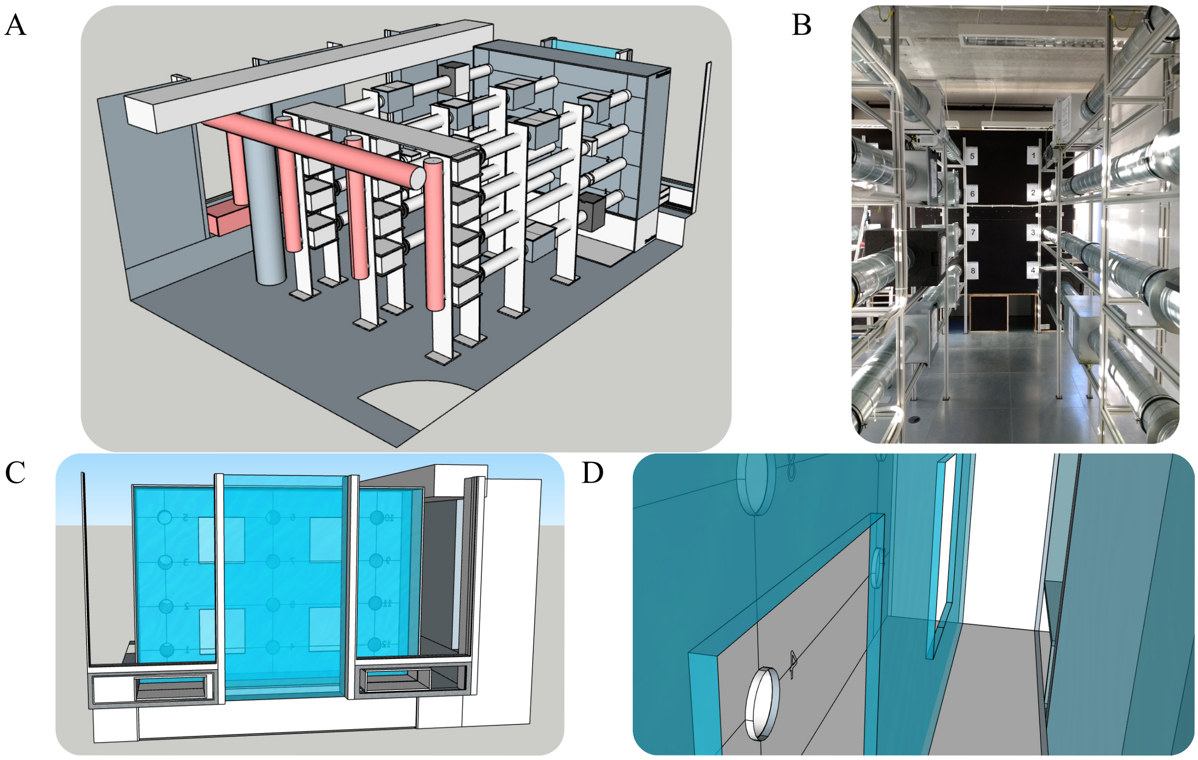

Figure 1 Computer-based design model and picture of the test setup as built: A) general view B) picture of a part of the test setup C) detailed view of the distribution box and the supply boxes integrated under the windows D) interior view of the distribution box

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-coarse 60/65% class filters according to EN 779[a] [1] – EN ISO 16890 [2] and a fine filter (F7-ePM1 50/50% class). From the same classes also different types of filters were included like duct type, wireframe, folded panel and bag type filters.

Intensive filtration – four test lines are equipped with filters which are nowadays rather exceptionally in use in domestic ventilation systems including an F9-ePM1 80% (EN 779 – EN ISO 16890) and E10 filter (Efficiency Particulate Air filter, EN1822:2009 [3]). 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 the 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 filter efficiency and pressure drop was followed up based on monthly measurements during a total runtime of 9 to 13 months.

Ozone production was verified using a Teledyne T204 gas analyser.

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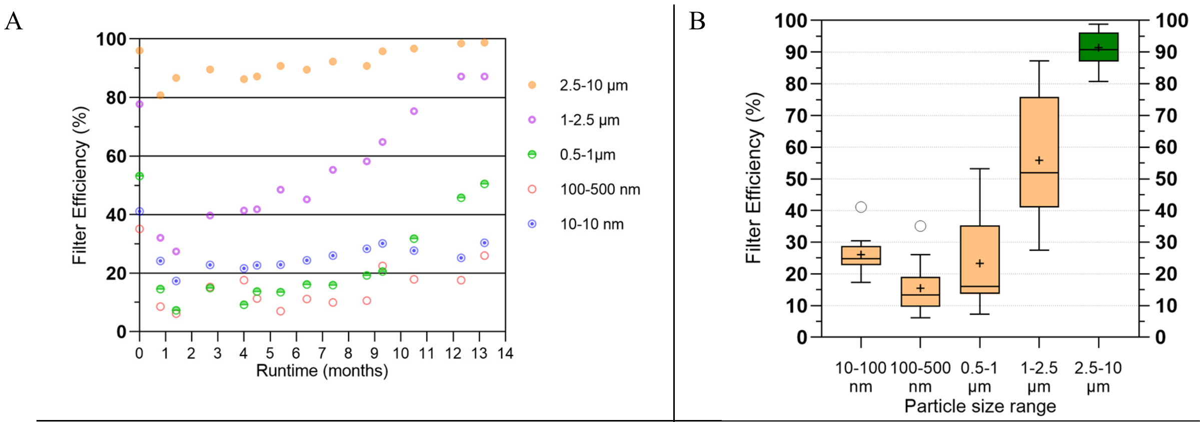
[a] Although the filter classification standard EN779:2012 and classification (G, M, F) has been replaced in 2017 by the EN ISO 16890 standard and its new classification (coarse, ePM1,ePM2.5 or ePM10), both class indications can nowadays still be found on datasheets of general air filters.

3 RESULTS

3.1 Coarse filters

3.1.1 G4-coarse 60% folded panel

From a market study, the G4-coarse 60% filter in folded panel form (see picture in Figure 2 C) appears to be the most commonly included coarse filter class and form in residential ventilation systems. The graphs below show the results over a runtime of 13 months for such a filter that can be installed in a filterbox coupled to a ventilation system. As can be seen from graph B, this filter has a high capture efficiency for particles larger than 2.5µm. For smaller particles this filter is much less efficient and there is more variability on the efficiency. The time resolved efficiency profile (see graph A) reveals that an initial high efficiency for some particle size ranges is followed by a steep decrease within the two first months in use. This especially holds true for the particle size ranges 1-2.5µm and 0.5-1µm. This phenomenon is most likely due to a static electrostatic charge given to the filter medium during production (Electret Filter medium). As a result, the filter has electrostatic interaction as an additional retention mechanism, besides the mechanical retention mechanisms, resulting in an increased efficiency at new state. However, during use this charge gets lost explaining the decrease in efficiency. Graph A further reveals that the efficiency for these affected particle size ranges again increases in function of time. This is due to the gradual build-up of a filter cake on the filter surface. As a results also the pressure drop across the filter increases after 6 months in use. The pressure drop exceeds the proposed limit of 150 Pa for this class of filters according to standard EN 13053:2011 after approximately 1 year, indication the need for filter cleaning or replacement. A G4-Coarse 60% system filter, which can be directly installed into a ventilation system, was found at new state to be less efficient, but has over the complete runtime a similar median efficiency for the larger particles (2.5-10µm) as the filterbox equivalent, however with a faster increase in pressure drop exceeding 150 Pa after 9 months in use (data not shown).



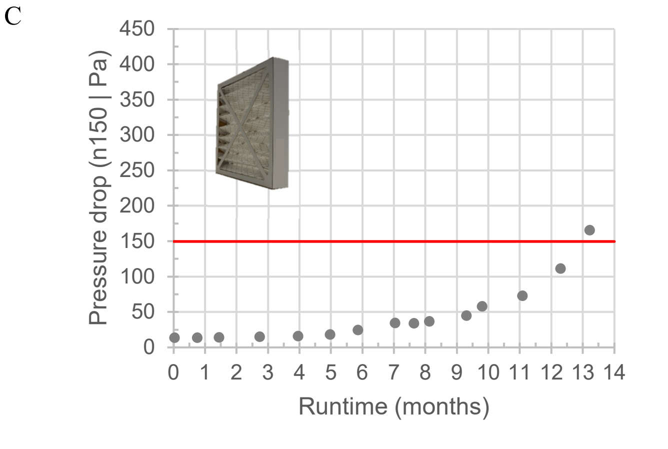


Figure 2 ***G4-Coarse 60% filterbox filter***
A) Filter efficiency profile for different particle size ranges in function of the runtime
B) Summarizing box plot representation of the filter efficiency for different particle size ranges over a 13 months runtime
C) Pressure drop profile in function of the runtime with indication of the maximal final pressure for a coarse filter according to EN 13053 :2011 Insert: picture of the tested filter

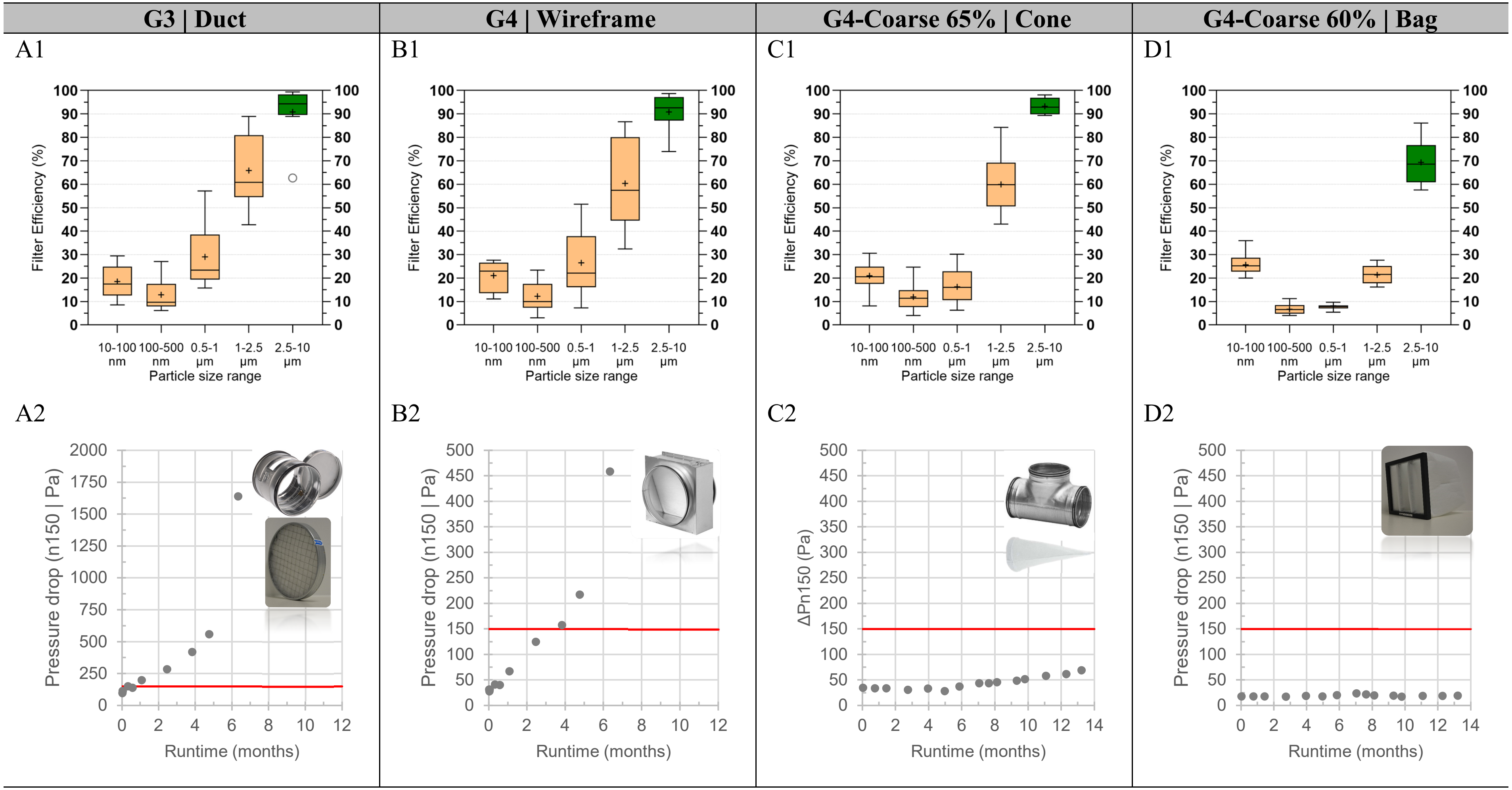


Figure 3 ***Coarse filters – different filter forms*** *Series A1-D1 Summarizing box plot representation of the filter efficiency for different particle size ranges over the runtime Series A2-D2 Pressure drop profile in function of the runtime with indication of the maximal final pressure for a coarse filter according to EN 13053 :2011 Insert: picture of the tested filter*

3.1.2 Other forms of coarse filters

Besides the folded panel form, coarse filters also exist in other filter forms like a duct, wireframe, cone and bag type. Except the bag filter, the other types seem an easy add-on for a ventilation system as a prefilter given the limited space their installation requires. As can be seen in the graphs in Figure 3 their efficiency for the different particle sizes is similar to that of the G4-Coarse 60% folded panel filter. Only the efficiency for the larger particles (2.5-10µm) of the coarse bag type filter is much lower, although it belongs to the same filter class as the folded panel filter type (see § 3.1.1). The G4-coarse 60% bag filter is in contrast characterized by a lower pressure drop (build-up). The G3-duct and G4-wireframe filter types on the other hand exhibit a relatively high initial pressure drop and a strong increase in function of time compared to the other coarse filters (see series A2-B2 in Figure 3 versus C in Figure 2). The reason for this lies in the limited filter surface of this type of filters and the associated rapid build-up of a filter cake. Only the cone filter type seems an interesting space saving alternative, due to its rather limited increase in pressure drop, but nevertheless higher initial pressure drop in comparison to the G4-Coarse 60% folded panel filter.

3.2 Fine filters

3.2.1 Different fine filter classes protected with a G4-Coarse 60% prefilter

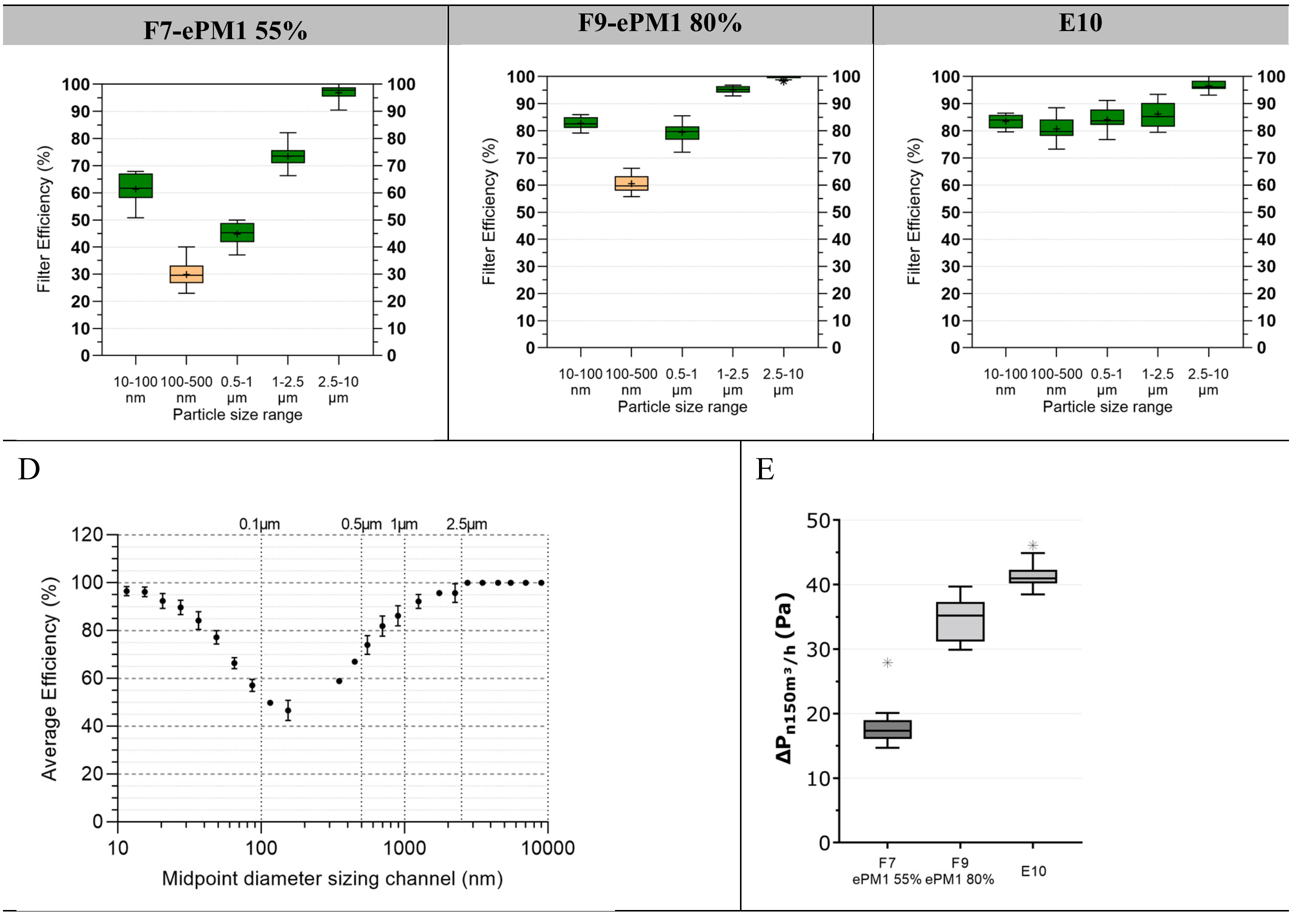


Figure 4 ***Fine filterbox filters in folded panel form installed <u>after a G4-Coarse 60% prefilter</u>*** *Top) Summarizing box plot of the efficiency profile for different fine filter classes over a 13 months runtime D) Fractional efficiency profile of the F9-ePM1 80% filter after 6 months in use E) Summarizing box plot of the pressure drop over the different fine filters over a runtime of 13 months*

As can be expected, fine filters are in general more efficient than coarse filters (see Figure 2 and 3 versus Figure 4). Upon comparison of the tested F7-ePM1 55% and F9-ePM1 80% filter, the results indicate a significant higher efficiency for the F9-ePM1 80% filter throughout the complete measurement range. Both filters however show a dip in their efficiency for the particle sizes 0.1-0.5µm and 0.5-1µm. As shown by the fractional efficiency profile for the F9-ePM1 80% filter (Figure 4 C) the lowest point of this dip is around a particle diameter of 200nm. These particles are known as the most penetrating particle size (MPPS), being the particles the hardest to capture by a classic air filter. The tested E10 filter, lowest class of the HEPA-filters, on the other hand shows a high efficiency within the full measuring range (see Figure 4). These kind of filters are specially designed to capture MPPS particles. The higher efficiency for the F9-ePM1 80% and E10 filter also result in a higher pressure drop over the filter as can be seen in graph E. Based on the efficiency results, a cascade of a G4-Coarse 60% + F7-ePM1 55% allows the reduction of the $PM_{2.5}$ fraction in the supplied air with on average 58±9%[a] and the cascade of the same coarse filter with an F9-ePM1 80% filter with on average 80±4%[a]. An F7-ePM1 50% system filter, which can be directly installed into a ventilation system, was found the be significantly less efficient (data not shown).

3.2.2 Added value of coarse prefiltration for different F7 filter forms?

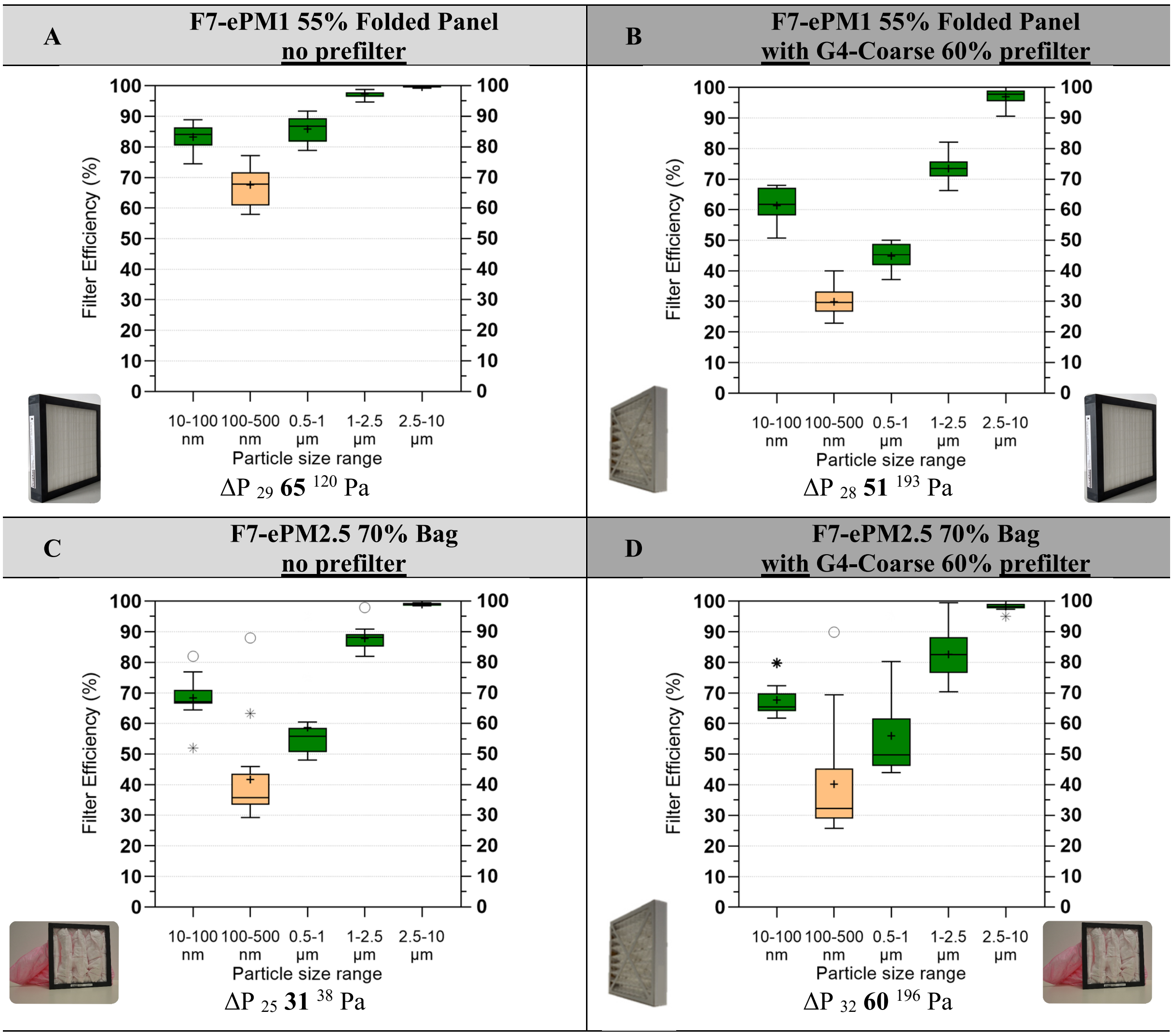


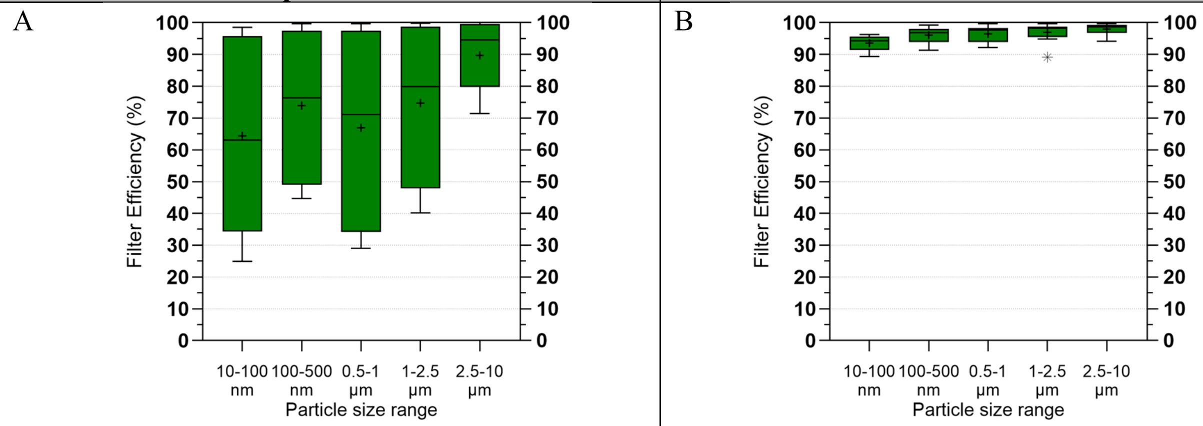
Figure 5 Summarizing box plot representation of the filter efficiency of two different F7 filter forms (ePM1 55% Folded Panel vs ePM2.5 70% bag) without (left) and with (right) G4-Coarse prefiltration over a runtime of 13 months. Indication of the pressure drop as ΔP_{min} median ^{max} in Pa over the 13 months runtime.

[a] *This efficiency value cannot be compared to the efficiency values attributed to a filter for filter classification purposes (e.g. ePM2.5 70%) since the in laboratory measurements conducted for this work do not allow the calculation of these classification efficiencies strictly according to the filter classification standard EN ISO 16890:2017*

The above graphs demonstrate the influence of a G4-Coarse 60% prefilter placed in front of an F7-ePM1 55% folded panel as well as an F7-ePM2.5 bag fine filter. For the **F7-ePM1 55% folded panel filter** the absence of the prefilter (A versus B in Figure 5*)* results in a significantly higher filter efficiency for all particle size ranges. This is the result of a faster filter cake build-up on this fine filter when it is not protected by a coarse filter. This also results in a higher median pressure drop over the run time across this F7-ePM1 55% filter alone, compared to the median pressure drop across the cascade of the G4-Coarse 60% and F7-ePM1 55% fine filter. For the **F7-ePM2.5 70% bag filter** the presence of a G4-Coarse 60% prefilter has no marked effect on the filter efficiency (C versus D in Figure 5). The filter efficiency profile remains more or less the same, expect for the fact that the absence of a prefilter results in less variability on the efficiency. Furthermore, the median pressure drop across this F7-ePM2.5 70% filter alone is much lower than across its cascade with a G4-Coarse 60% prefilter. Based on the efficiency results an F7-ePM2.5 70% bag filter without prefilter allows the reduction of the $PM_{2.5}$ fraction in the supplied air with on average 59±11%.

3.3 Electrostatic precipitators

ESP – Disposable Collector	ESP – Cleanable collector



ΔP_{15} **18** ^{21} Pa | ΔP_{8} **10** ^{16} Pa

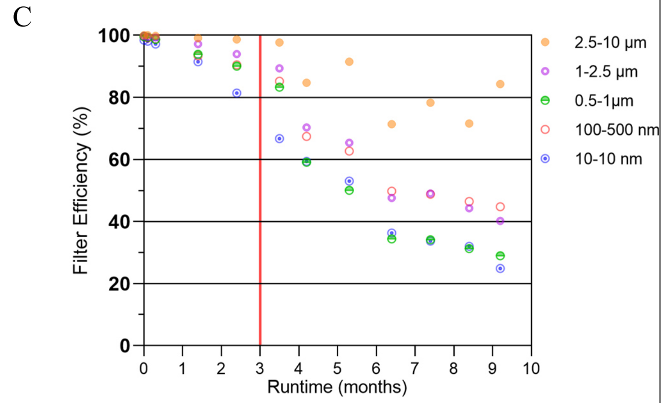


Figure 6 Summarizing box plot representation of the filter efficiency of two electrostatic precipitators (ESPs) each with a different collector type [A) disposable collector, without replacement!, B) cleanable collector] over a runtime of 13 months. C) Filter efficiency profile for different particle size ranges in function of the runtime for the ESP with the disposable collector. Red line: indicative collector replacement interval as suggested by the manufacturer. Indication of the pressure drop as ΔP_{min} *median* ^{max} *in Pa over the runtime.*

Both precipitators exhibit a very high efficiency (>90%) within the full measuring range at new state. For the version with the cleanable collector (see graph B in Figure 6) this very high efficiency remains stable during the whole runtime of 13 months. For the version with the disposable collector, the efficiency decreases in function of time, resulting in a large variability on the overall efficiency. According to the manufacturers guidelines the collector plates should be replaced after 3 months in use (see red line in graph C), which was from a scientific interest not done during the 13 months runtime. Upon replacement at the end of the runtime (data not shown), the efficiency increases again above 90%. 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. During an additional run an increase in pressure drop was observed for the ESP with the disposable collector due to dust accumulation on a grill in the ioniser part in front of the collector plates. This indicates the need for prefiltration in front of electrostatic precipitators. The ozone production, commonly seen as risk of this technology, was found to be limited for both systems (cleanable: 29±4 and disposable:16±4 µg/m³).

4 CONCLUSIONS AND DISCUSSION

Coarse filters are mainly installed in balance ventilation systems to protect the system (including heat exchanger, fans,..) and the ductwork against rapid fouling. The observed high efficiency for larger particles (2.5-10µm) and lower and variable efficiency for smaller particles is in line with this function. Therefore, coarse filters cannot be considered as contributing to an improved air quality in terms of particulate load. One exception are pollen, since they are generally larger than 10µm a coarse filter will already drastically reduce their number in the supplied airstream. Although different filter forms belong to the same filter class, our findings indicate some differences in efficiency (coarse 60% folded panel versus bag type). 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. Based on its efficiency for $PM_{2.5}$ particles (see § 3.2.1 & 3.2.2), an F7-ePM1 55% folded panel or ePM2.5 70% already allows to reduce the $PM_{2.5}$ fraction in the supply air below the WHO guideline value of 5µg/m³ (annual mean) given the outdoor concentration for a city environment as Brussels. Although an F9-ePM1 80% filter has some limited potential (due to the dip in its efficiency profile) and an E10 filter a significant potential to also improve the particulate load for de PM_1 fraction, their higher pressure drop is not in favor. Further our findings indicate that an F7-ePM1 55% folded panel filter is preferably protected by a G4-coarse 60% filter, while an F7-ePM 2.5 70% bag filter can be used without prefiltration. As such this bag filter can be installed in front of a ventilation group, protecting it against fouling and improving the supplied air quality at the same time. Due to its low pressure drop and filter cost, the necessary extra investment can be rapidly recovered (< 3 years).

Electrostatic precipitation is an interesting alternative to filters due its the high efficiency of particle capture within the full range (10nm-10µm) and the associated low pressure drop in comparison to fine filters. In fact electrostatic precipitation also improves the particle load of the supplied air not only for the $PM_{2.5}$ fraction, but also for the PM_1 and $PM_{0.1}$ fraction. Although no specific WHO guidelines are available for these fractions, for some people their reduction in the supplied air can be important in view of health problems. Maintenance is an important aspect to maintain the high efficiency of systems, especially for the one with a disposable collector, and prefiltration is of importance to maintain the low pressure drop across the system.

5 ACKNOWLEDGEMENTS

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6 REFERENCES

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