BELOK project 2013:6

# Performance of Ionizer Assisted Air Filtration, Part 2

## System optimization and energy saving

Utarbetad av
Lars Ekberg, CIT Energy Management AB
Bingbing Shi, Vokes Air AB

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Gruppens målsättning är att energieffektiva system, produkter och metoder tidigare skall komma ut på marknaden. Utvecklingsprojekten syftar till att effektivisera energianvändningen samtidigt som funktion och komfort förbättras.

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## Foreword

As a continuation of the project BELOK 2011:6 “Performance of Ionizer Assisted Air Filtration - Evaluation of long-term performance and influencing factors”, this project is aimed to answer how to design an efficient, safe and reliable ionizer-assisted air filtration system. Two major issues are in focus:

1. Optimum settings of the ionizer-assisted air filtration system for high air cleaning efficiency and low generation of ozone.
2. Long-term performance of an optimized system tested in the field regarding air filtration efficiency and saving of electrical energy for fan operation.

The project provides important knowledge to establish design and operation guidelines for the technology studied. The solution has been optimized with respect to selection of filter medium, ionizer distribution, distance between ionizer and filters and ionizer voltage.

The project has received financial support from BELOK and Akademiska Hus AB. The project has also been supported with materials and valuable efforts of personnel from Transjonic AB, Gothenburg, and Vokes Air Group, Svenljunga. Measurements and analysis has been done mainly by Dr. Bingbing Shi, supported by Alf Schagerholm, Transjonic AB.

Gothenburg, 2015-12-11

Lars Ekberg, CIT Energy Management AB

Bingbing Shi, Vokes Air AB

## Summary

The previous report from BELOK-project 2011:6 shows that an ionizer-assisted M6 filter can reach the same level of air cleaning for small particles as a traditional F7 filter, during 6 months of operation. The aim of the present project is to further investigate the design criteria of this technology (including ionizer systems and filters) and the saving of electricity for fan operation compared to traditional filtration.

A series of tests were conducted in the laboratory in order to reveal any possibilities to improve the performance further. The by-product generation of the ionizers (i.e. ozone) was measured in a closed chamber at different experimental settings. Finally, an ionizer-assisted bank of filters with optimized settings was applied in the ventilation system of an office building. Thus, the long-term filtration efficiency and the electricity saving were investigated in the field for six months.

The tests carried out in the laboratory comprised testing of various alternative filter media, ionizer distribution, supply electricity voltage, the distance between ionizers and filters.

- Among eleven tested filter media, an M6 class synthetic filter (consisting of polypropylene, modacrylic and polyester fibers) and a G4 class synthetic filter (consisting of polyester and conductive fibers) showed higher filtration efficiencies for small particles than an F7 class filter. Moreover, the pressure drop of the M6 class filter and the G4 class filter were lower than the pressure drop of a traditional F7 filter (35% and 50% respectively).
- A higher number of ionizers does not automatically increase the performance. The optimum number of ionizer brushes was found to be 2~3 brushes per $m^2$ of duct cross section area.
- The optimum distance between ionizer and filter is about 1.8 m for the M6 class filter and 0.8 m for the G4 class filter.
- The test of optimum ionization voltage shows that the filtration efficiency does not increase further when the supply voltage is increased above 10kV for the M6 class filter. However, for the G4 class filter, the filtration efficiency linearly increases with the observed supply electricity voltage from 2kV to 20kV.

The testing of by-product (ozone) generation shows that the ozone generation increases with the decrease of the distance between ionizer and duct. The ozone generation was very low as long as the distance between any ionizer and the interior surface of the air handling unit (AHU) or duct was at least 20 cm.

The laboratory tests showed very good results both for the G4 and the M6 filter, when small-scale samples of the filters were tested in the laboratory. Unfortunately, it turned out not the be possible to reach the same good results when testing the G4 filter in full-scale. However the M6 filter performed well both in small scale laboratory tests and full

scale field tests. Thus, the M6 class filter was installed for field test in the ventilation system of an office building.

During the field tests with optimized settings the ionizer-assisted M6 filter showed filtration efficiency values of 80%±15% for $PM_{0.3-0.5}$ during 6 months of operation. According to the criteria for filter "P-marking" by SP Swedish Technical Research Institute, an F7 filter, operated under real-life conditions, should show at least 50% efficiency for 0.4 µm sized particles (12). The result indicates that the ionizer-assisted M6 filter could provide the same level of air cleaning for small particles as a traditional F7 filter. The results indicated that the "P-marking" requirement also for 0.85 µm particles was met most of the 6 month period.

The optimized settings increased the ionizer-assisted filtration efficiency 15%-units further, compared to the level reported in the previous BELOK-report (8).

The measurement of fan electricity indicated that an ionizer-assisted M6 filter replacing a traditional F7 filter can save about 35% of the fan power needed to overcome the flow resistance of the filters.

Life cycle costs were calculated using the BELOK LCC calculator. The results indicated that changing from traditional F7 filtration to ionizer assisted filtration is profitable under the prerequisites of the calculations made, when all filters are replaced semi-annually. The calculations also indicate that the ionizer assisted M6 filter solution would have slightly higher LCC (~5%) if the M6 filters are replaced semi-annually and the traditional F7 filters are replaced annually.

The technique is quite uncomplicated and is judged to require a minimum of service. After installation the equipment can most likely be handled by the regular service personnel. The ionization brushes should be inspected regularly. There were no signs of dust accumulation or deterioration during the six months of operation in the present study. It is suggested that it is sufficient to check the ionisers simultaneously with filter replacements. The brushes may need cleaning or replacement.

The studied technology showed good performance regarding filtration efficiency, safety, reliability and energy saving. However, there is a potential for further improvements of the energy efficiency. Further studies may be needed before the technology will be widely accepted in the market. Future investigations should address the following issues:

- Further development of the G4 filter medium in order to reach even higher energy savings with maintained filtration efficiency.
- Life-time estimation of this technology with the G4 class and M6 class filters operated with outdoor air of various quality (pure air, dusty air and very high concentrations of dust or gases).
- The system settings for the applications in premises with higher indoor air quality requirements, e.g. hospitals and cleanrooms.

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## 1. Introduction

The BELOK project 2011:6 (8) showed that an ionizer-assisted M6 filter had even higher efficiency values than an F7 class filter during the first 6 months of operation (1). This indicates that the ionizer-assisted M6 synthetic filter could perform equally well or better than a traditional F7 class filter. Furthermore, the pressure drop of the ionizer-assisted M6 filter was 25-30% lower than that of a filter of class F7. It is meaningful to optimize this ionizer-assisted air filtration system (both ionizer system and filters) and to evaluate the fan electricity saving for this technology application.

Previous research found that the enhanced filtration efficiency obtained by ionization is influenced by filter media, supply electricity voltage of ionizers and the distance between ionizers and filters. Results from Agranovski et al. (2006) and Park et al. (2011 and 2009) demonstrated that ionizers can increase the efficiency of filters made of both synthetic fibers and glass fibers, but the increased efficiency of synthetic fiber filters was significantly higher than that of glass fiber filters (2-4). Similar findings were also presented by Shi et al. (2012 and 2013), with special focus on the influence of filter material on the enhanced efficiency for collecting ultrafine and submicron particles (5-6). In this project, 11 types of synthetic filter media were tested in order to find the optimum filter media used in this technology .

Agranovski et al. (2006) observed the influence of the distance from the ion emitter to the filter surface on the filtration efficiency (2). In his study, the optimum distance was not the longest distance in the measurements. Thus, in this project, the system performance was observed when varying the distance from 30 cm to 205 cm.

The voltage connected to the ionizers influence the efficiency increase (7). Usually, a high voltage leads to higher output of ions, which further results in increased filtration efficiency. However, a high supply voltage could also possibly result in a high generation of ozone. It is important to find out a supply voltage which works good on these two aspects. Additionally, the ionizer distribution in the duct before the filter is also related with ozone generation and efficiency improvement. Thus, the optimum distribution of ionizers was also investigated.

Finally, electricity saving of the fan input power due to the ionizer-assisted air filtration replacing the traditional F7 class air filtration is very important. The BELOK project 2011:6 measured filter pressure drop, but did not record the fan input power during the long-term measurement (8). Thus, an ionizer-assisted air filtration system with optimized settings was applied at a ventilation system in an office building. The electricity saving on the fan input power and long-term performance at the optimum setting was analyzed.

## 2. Research

This chapter presents the experimental procedures and the results. The presentation is divided into the following sub-sections:

- Optimum settings
- Lab tests of full-scale filters
- Chamber test of ozone emission
- Field long-term measurements

## 2.1 Optimum settings

### *2.1.1 Optimum filter media*

The filter media test was conducted at Vokes Air AB. The experimental setting is as follows:

- Air velocity through filter media: 0.2 m/s;
- Upstream DEHS aerosol at 0.3-0.5 µm: 15,000,000 pc/ft$^{3}$;
- Relative humidity: 15%-40% and Temperature: 20ºC-25ºC;
- Ionizer voltage: -24kV;
- Distance between ionizer and the filter: 35 cm;
- The filter was earthed;
- Ion concentration 240,000 ions$^{-}$/cm$^{3}$.

**Measurement equipment**

The particle number concentrations were measured by an optical particle counter **(LAP 340, TOPAS)** in the following size fractions: 0.2-0.3, 0.3-0.5, 0.5-0.7, 0.7-1.0, 1.0-1.5, 1.5-2.5, 2.5-5.0, 5.0-10.0 and >10 µm.

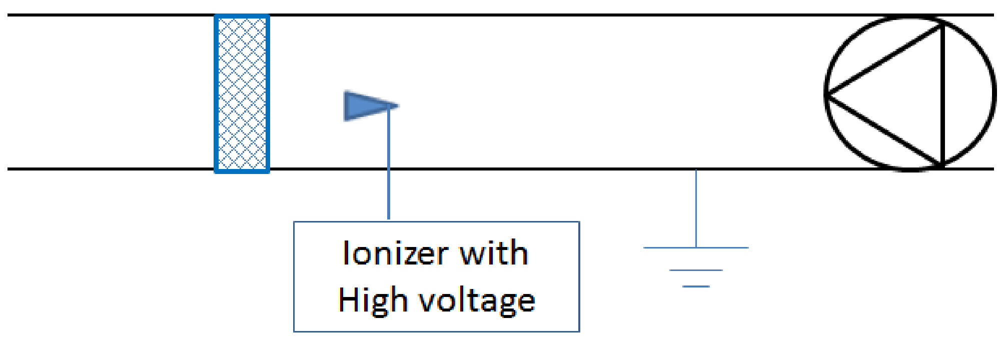


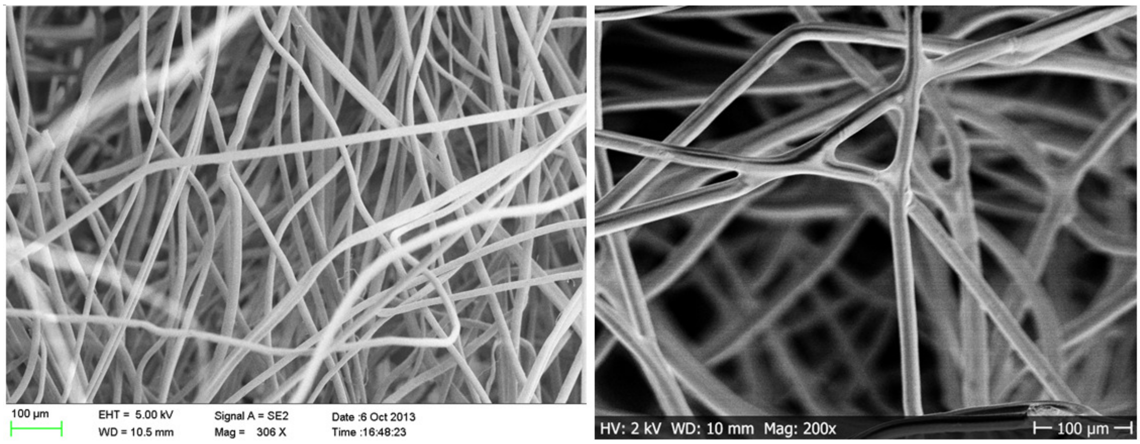

**Figure 1.** Experimental setup in the filter media tests

Figure 1 shows the experimental setup in the filter media tests. Eleven filter media were tested. Two filter media were selected according to their high efficiencies with ionizer and low pressure drops. One is an M6 class synthetic filter consisting of polyester and conductive fibers. The other is a G4 class synthetic filter consisting of polypropylene, modacrylic and polyester fibers. The properties of the two filter media are shown in Table 1. Scanning electronic microscope (SEM) images of the two filter media in Table 1 are presented in Figure 2 (a-b). A photo of one ionizer brush mounted in an air handling unit is shown in Figure 3.

**Table 1**. Specifications of the Filter Media Tested in the filter media tests. The filter classes are according to the standard SS EN 779 (10).

| Tested filters | Filter class | Fiber diameter (µm) | Thickness (mm) | Packing density | Pressure drop (Pa)* |
|---|---|---|---|---|---|
| P1 | G4 | 15-25 | 2.44 | 0.045-0.068 | 13 |
| P4 | M6 | 10-25 | 11 | 0.041 | 26 |

*The data were collected when the air velocity was 0.2 m/s.




**(a)** **(b)**

**Figure 2.** Scanning Electron Microscopy (SEM) images of the filter media of (a) M6 class filter; (b) G4 class filter.

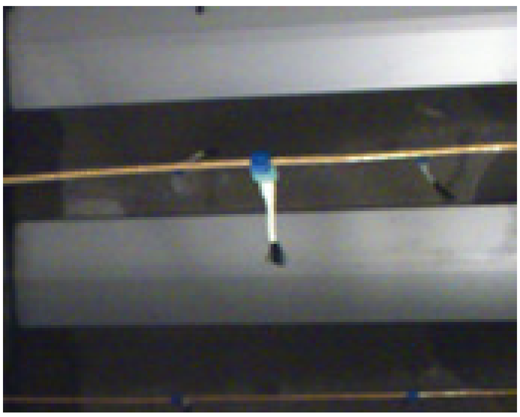


**Figure 3.** Photo of one ionizer brush mounted in an air handling unit..

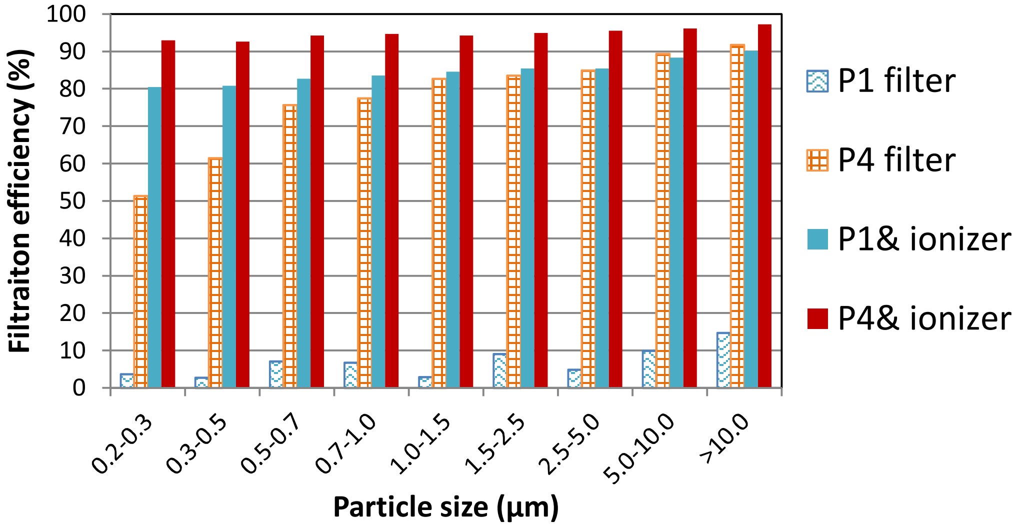



**Figure 4.** Filtration efficiency measured for the P1 (G4 class) and P4 (M6 class) filters tested with and without ionizer. Small scale testing of flat sheets of filter material.

The filtration efficiencies for the two selected filter samples, measured with and without ionizers, are presented in Figure 4. In the figure, the ionizer-assisted efficiencies of these G4 class and M6 class filters are above 80% on $PM_{0.3\text{-}0.5}$. These efficiencies are not lower than the efficiency level of F7 glass fiber filters. The results of other filter media tested are presented in Appendix A. In addition, we also tested used sheets of the eleven filter media after running them for 5 weeks at an air velocity of 1 m/s. The total air volume is equal to the volume of air filtered during 25 weeks in the following field tests an air velocity of 0.2 m/s.
The results shows that the ionizer-assisted efficiency of the used G4 class filter is higher than that of the new G4 class filter. This means that the efficiency of the ionizer-assisted G4 class filter is at the minimum value when the filter is new. This phenomena is opposite to the rather common observation that the collection efficiency of such electrically charged synthetic filters (electret filters) falls down during the dust loading process.

The following test of optimum settings were made on pocket bag filters made by the two filter media with the properties shown in Table 2.

***Table 2.*** *Specifications of the full-scale filters tested in the laboratory at Chalmers.* The filter classes are according to the standard SS EN 779 (10).

| Tested filters | Filter class | Filter size (mm) | Number of bags per module |
|---|---|---|---|
| P1 | G4 | 592×592×200 | 4 |
| P4 | M6 | 592×592×592 | 4 |

### 2.1.2 Optimum distance between ionizer and filter

The optimum distance between ionizer and the filter was tested on the filters with properties in Table 2 using an experimental set-up as indicated in Figure 5. The test distance was varied from 30 cm to 205 cm. The prevailing outdoor aerosol was used as the upstream aerosol. The particle number concentrations were measured by an optical particle counter (CI-500, CLiMET) in the following size fractions: 0.3-0.5, 0.5-1.0, 1.0-5.0, 5.0-10.0, 10.0-25.0 and >25 µm.

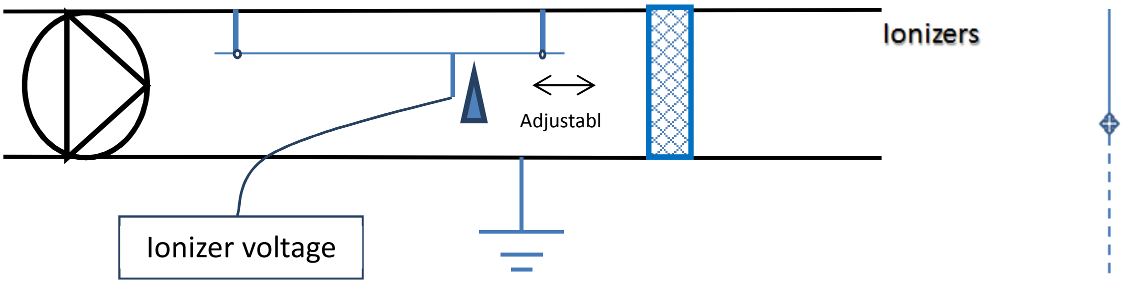



**Figure 5** Experimental set-up of optimum distance test carried out in the full-scale test rig (duct cross section area 0,36 m$^2$).

Figure 6 shows that the observed optimum distance varied both with the upstream particle concentration and the air velocity. Figure 5 also shows that the optimum distance between the ionizer and the M6 filter is about 160-200 cm. According to Figure 7, the optimum distance of the G4 class filter to the ionizer is 80 cm, which is much shorter than the optimum distance for the M6 class filter.

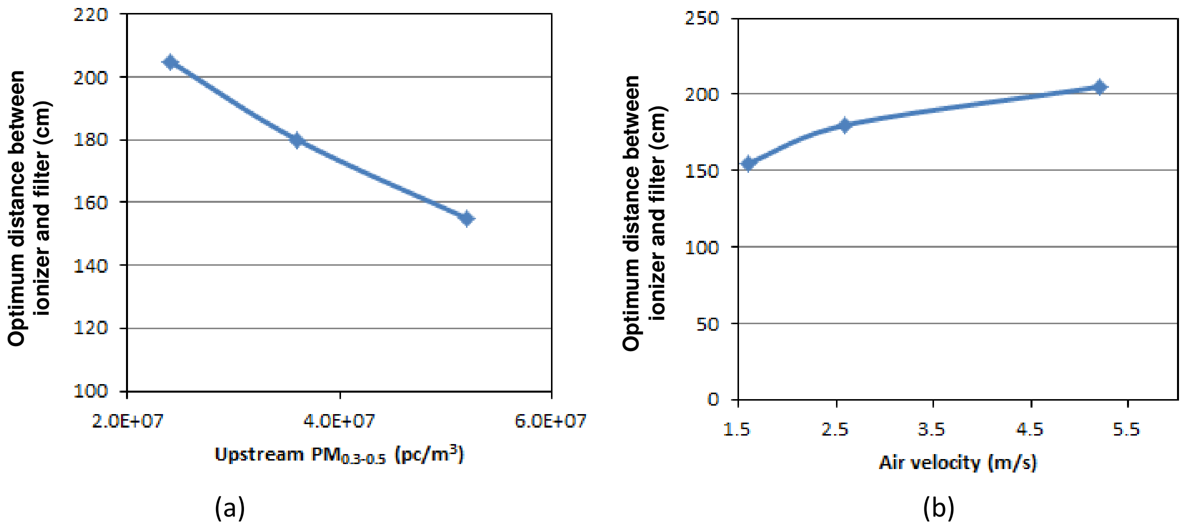



**Figure 6** Optimum distance of the M6 class filters with (a) varied upstream particle concentration at an air velocity of 1.6 m/s (0.2 m/s through the filter medium); and (b) varied air velocity at particle concentration of $5.8 \cdot 10^7$ particles per m$^3$ (pc/m$^3$).

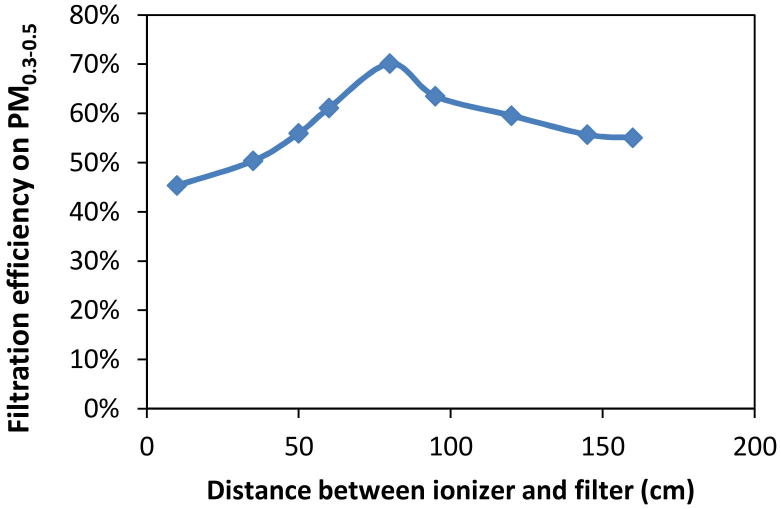



**Figure 7** Optimum distance of the G4 class filters at the upstream particle concentration of $1 \cdot 10^7$ pc/m$^3$ and the air velocity of 0.24 m/s through filter media.

### *2.1.3 Optimum voltage on ionizer*

The filtration efficiencies under different supply voltages of ionizer were tested for the G4 class and the M6 class filters with properties shown in Table 2. Figure 8 indicates the set-up of the experiments. Outdoor aerosol was used as the upstream aerosol. The particle number concentrations were measured by an optical particle counter (CI-500, CLiMET) in the following size fractions: 0.3-0.5, 0.5-1.0, 1.0-5.0, 5.0-10.0, 10.0-25.0 and >25 µm. The results are shown in Figure 9 and 10.

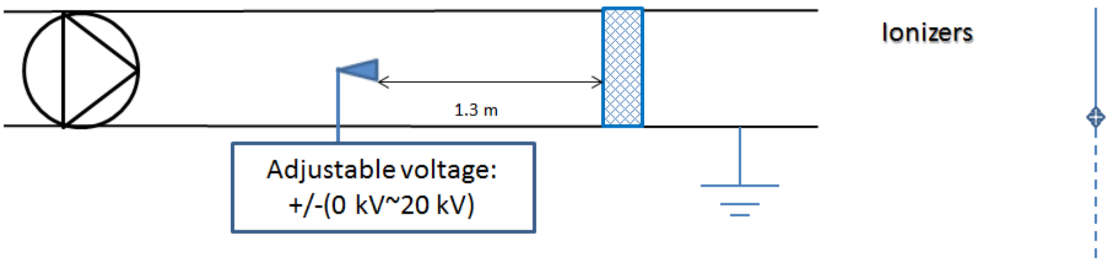



**Figure 8** Experimental set-up of optimum voltage test.

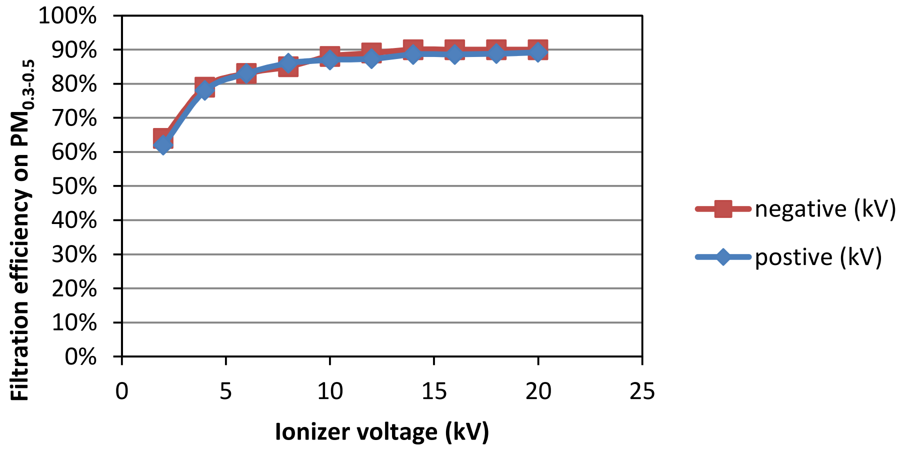



**Figure 9** Filtration efficiency of the M6 class filter when the ionizer voltage was varied from +/-2 kV to +/-20 kV.

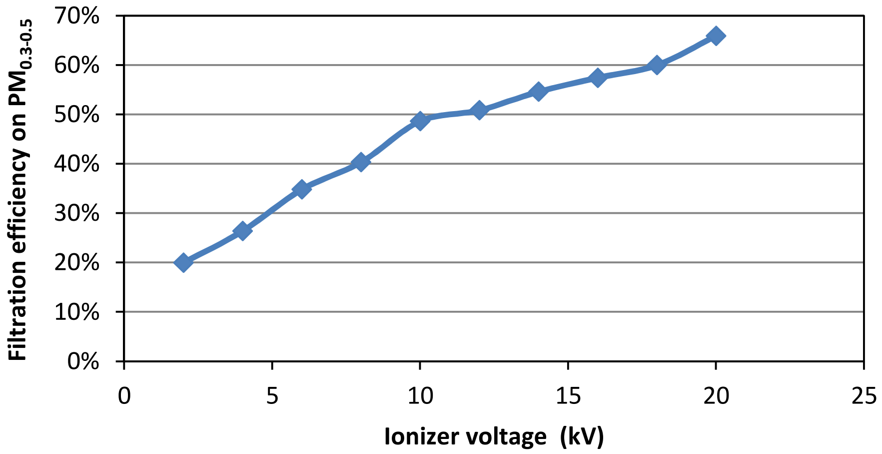



**Figure 10** Filtration efficiency of the G4 class filter when ionizer voltage was varied in the range 2 ~20 kV.

The figures show that the M6 class filter achieved a stable efficiency when the supply voltage of ionizer was higher than 10 kV. However, the efficiency of the G4 class filter was almost linearly increased with the supply voltage of 2 ~20 kV.

### *2.1.4 Optimum ionizers number and distribution*

The optimum ionizer number and distribution was investigated for the filters with properties in Table 2 at the experimental set-up indicated in Figure 11. Outdoor aerosol was used as the upstream aerosol. The particle number concentrations were measured by an optical particle counter (CI-500, CLiMET) in the following size fractions: 0.3-0.5, 0.5-1.0, 1.0-5.0, 5.0-10.0, 10.0-25.0 and >25 µm.

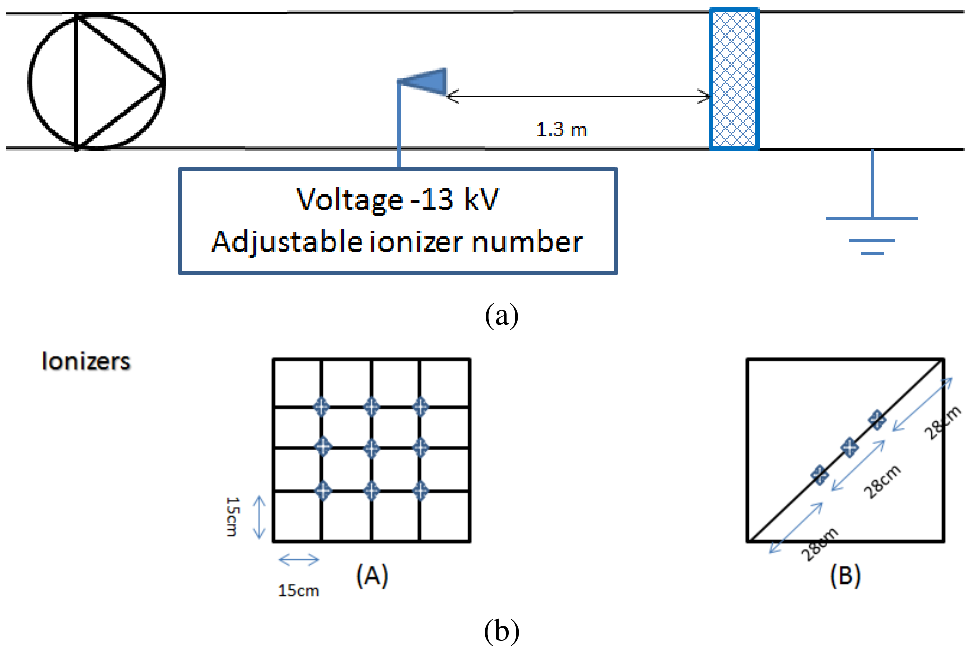



**Figure 11** Experimental set-up of optimum ionizer number and distribution. (a) test rig; (b) ionizer design A and B.

The ionizer distribution was designed in nine cases, see Figure 12. Their corresponding performance on $PM_{0.3\text{-}0.5}$ are showed in Figure 13.

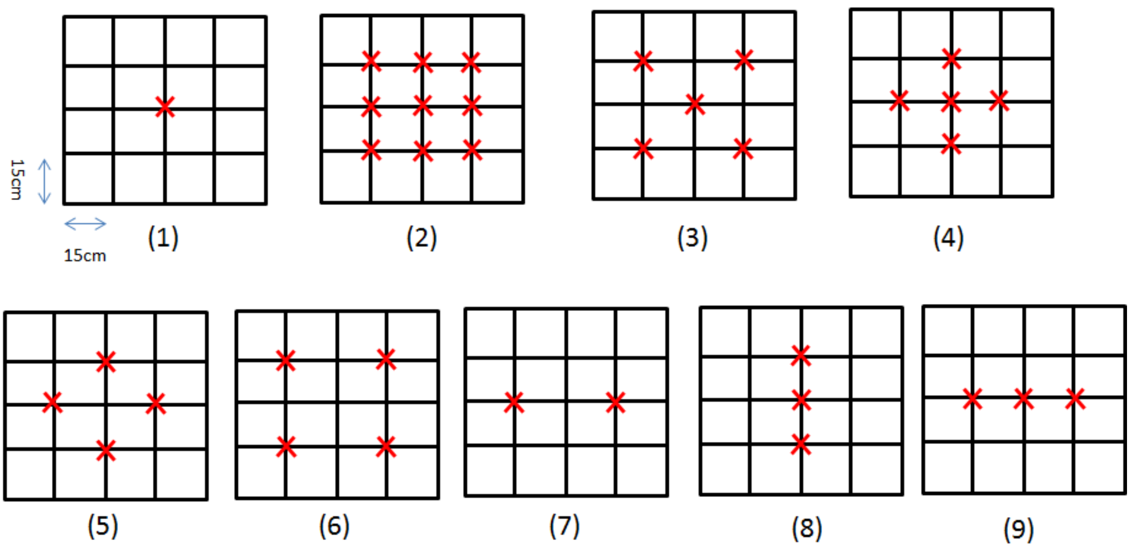



**Figure 12** The tested cases in ionizer design A

Figure 13 shows the tested cases sorted in increasing order of the efficiency, from high to low.

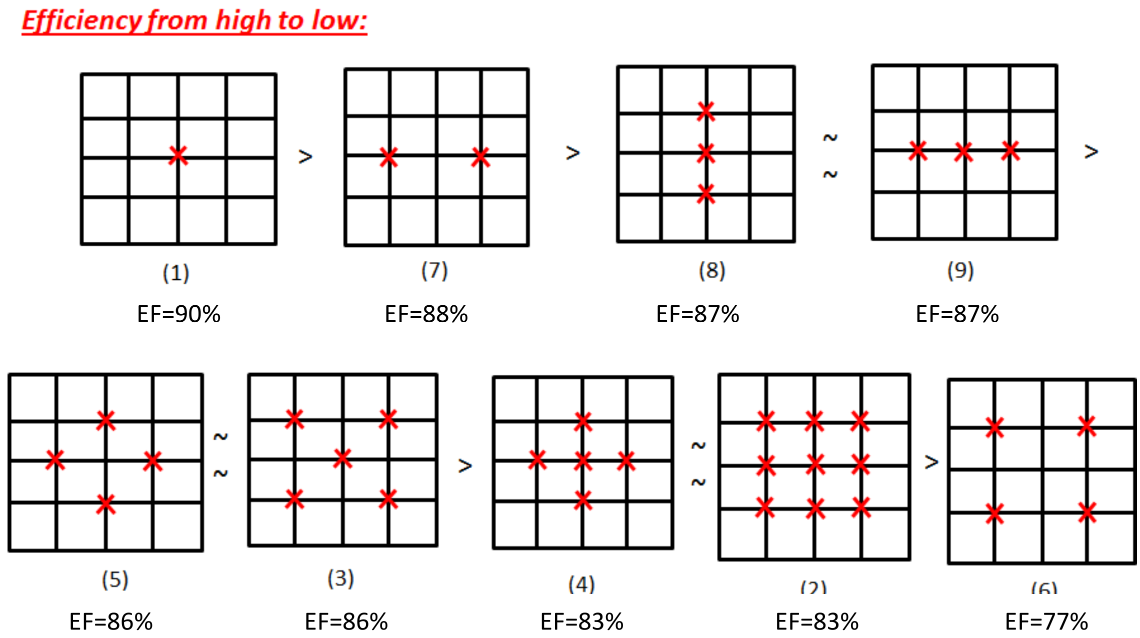



**Figure 13** Ionizer design A. Cases sorted from high to low filtration efficiency for $PM_{0.3\text{-}0.5}$.

The tests indicate that the distance between the ionizers influences the filtration efficiency. Thus, also an alternative ionizer design with a longer distance between the ionizers was tested (design B). Figure 14 shows the ionizer design B with the cases sorted in increasing order of efficiency, from high to low.

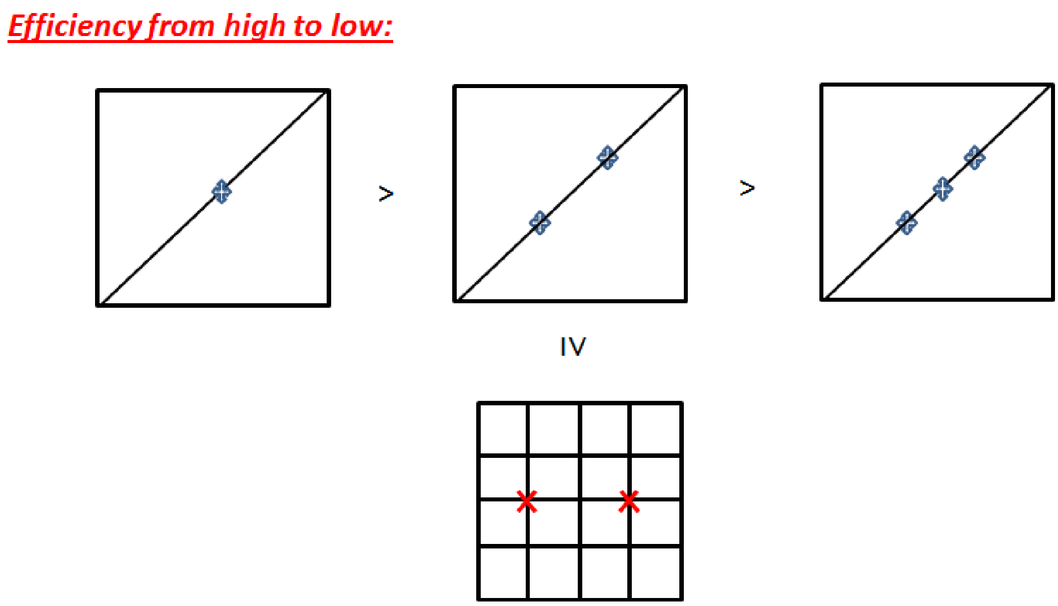



**Figure 14** Ionizer design B cases sorted from high to low filtration efficiency.

According to the results in Figure 13 and 14, a higher number of ionizers does not necessarily mean a higher efficiency. The optimum distance between ionizers is judged to be 20 ~ 30 cm in the tested duct, which has the dimensions 600·600 mm.

The investigations carried out in the 600·600 mm test-rig lead to the following conclusions:

- Optimum distance between ionizer and filter: 160-200 cm for the M6 class filter and 80 cm for the G4 class filter
- Optimum voltage: ≥ 10 kV for the M6 class filter and ≥ 20 kV for G4 class filter
- Optimum ionizer number: not the more the better
- Optimum distance between ionizers or between ionizer and duct: 20-30 cm. In the 600·600 mm duct this leads to one brush per 0.36 $m^2$, indicating that 2.8 brushes per $m^2$ would be appropriate.

During the tests, we also found that electrical earthing of the filters and oppositely charging of the filters could further increase the filtration efficiency up to 10%-unit. However, due to practical application difficulties, these two operations were not applied in the field long-term measurements.

## 2.2 Lab test on full-scale filters

The full-scale M6 class filter and half full-scale G4 class filters with the properties shown in Table 2 were tested at Chalmers laboratory. This half full-scale G4 class filter and the previously tested G4 filter medium was produced in the laboratory at Vokes Air. Figure 15 shows the experimental set-up of the test. The distance between ionizer and filter was 0.8 m for the G4 class filter and 2 m for the M6 class filter. The air velocity through the filter media was 0.24 m/s for both tests. Outdoor aerosol was used as the upstream aerosol. The particle number concentrations were measured by an optical particle counter (CI-500, CLiMET) in the following size fractions: 0.3-0.5, 0.5-1.0, 1.0-5.0, 5.0-10.0, 10.0-25.0 and >25 µm.

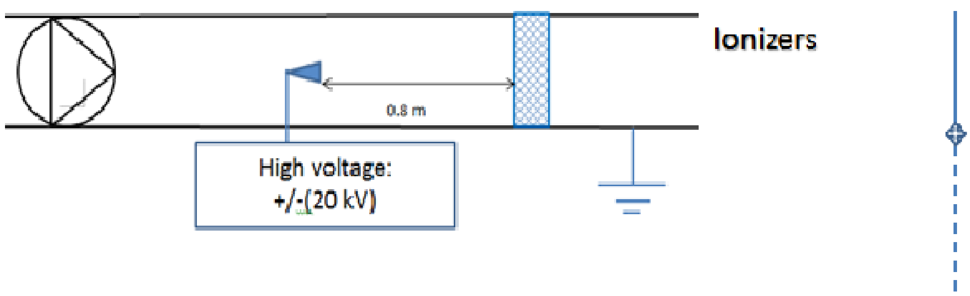
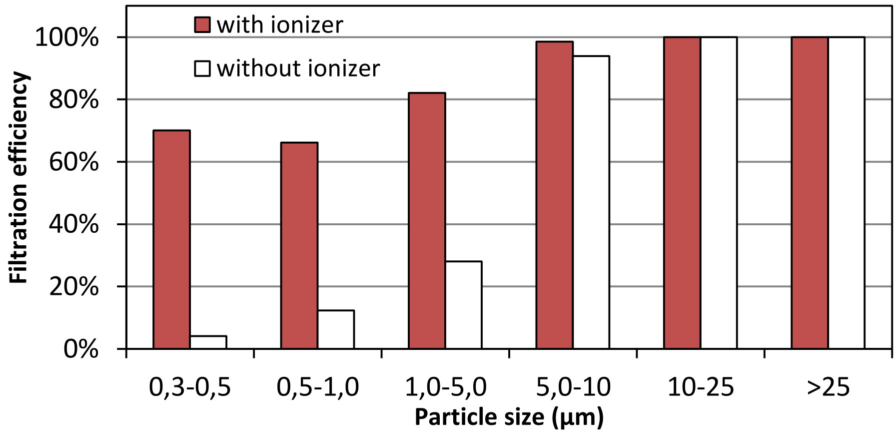
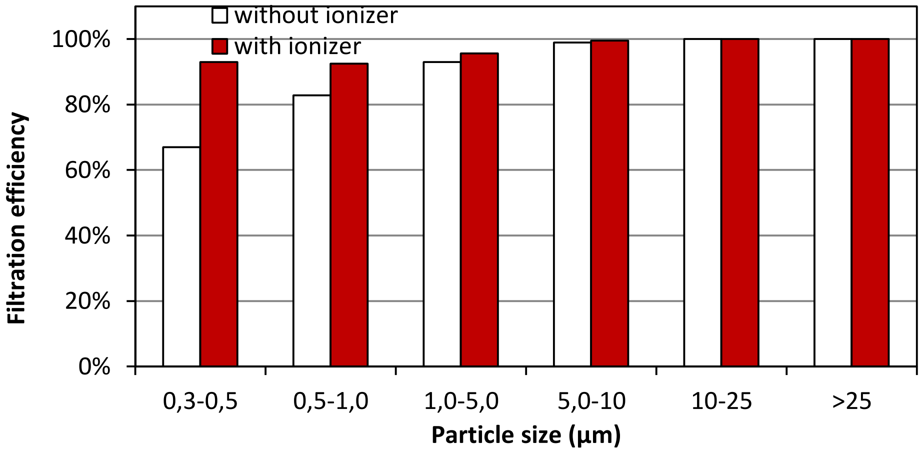



**Figure 15** Experimental set-up of full scale filter test on the G4 class and M6 class filters. The distance between ionizer and filter was 0.8 m for the G4 filter (marked in the figure) and 2 m for the M6 filter.

The filtration efficiencies of the two filters at optimum settings are shown in Figure 16. The efficiencies of both filters on $PM_{0.3\text{-}0.5}$ are above 50%. This means that the ionizer-assisted G4 class and M6 class filters perform equal to, or better than, a traditional F7 class filter. Additionally, the pressure drop of the G4 class and the M6 class filter is about 50% and 30% respectively less than that of a traditional F7 class filter.




(a)




(b)

**Figure 16** Filtration efficiency at an air velocity of 0.24 m/s through the filter media (a) G4 class filter; (b) M6 class filter.

Moreover, a full-scale G4 class filter in the size of 592×592×592 mm with 5 bags were tested later with the same experimental settings. This filter was produced in the factory at Vokes Air. Additionally, the same type of G4 filter that had been running for half a year at Vokes Air was also tested. Figure 17 presents the efficiency results of the two filters assisted with ionizer. Unfortunately, the figure shows that the G4 class filter produced in the factory did not reach the same good efficiency as shown in Figure 16 for the filter produced by the laboratory machine. Additionally, the used G4 class filter performed slightly better than the new filter for small particles.

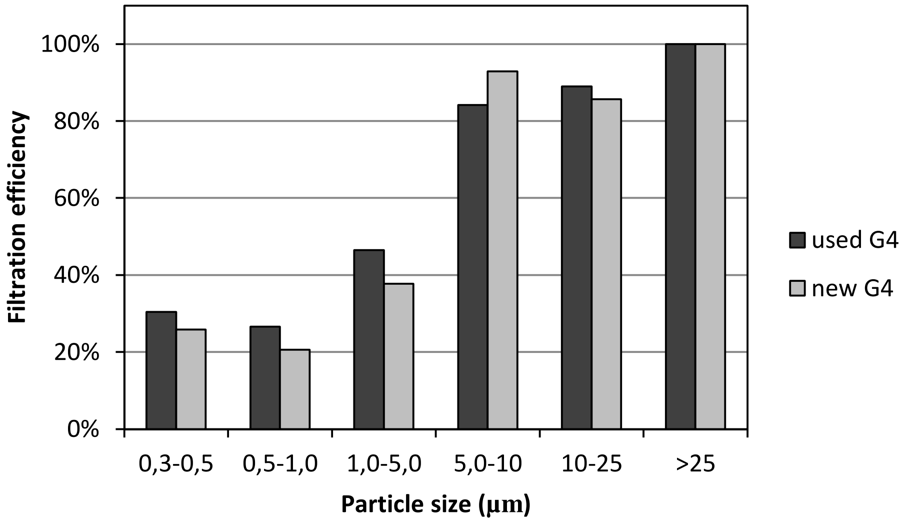



Figure 17 Filtration efficiency of ionizer-assisted full-scale G4 filter produced in the factory. The air velocity through filter media of 0.24 m/s.

The M6 filter performed well both in small scale laboratory tests and full scale field tests, thus the M6 class filter was installed for field test in the ventilation system of an office building.

### 2.3 Chamber test on ozone emission

The ionizers were tested with respect to ozone generation in a full-scale test chamber. The chamber was sealed (less than 0.1 air changes per hour) during the tests. A small table-fan was used to mix the air in the chamber. Figure 18 shows experimental set-up of the chamber test.

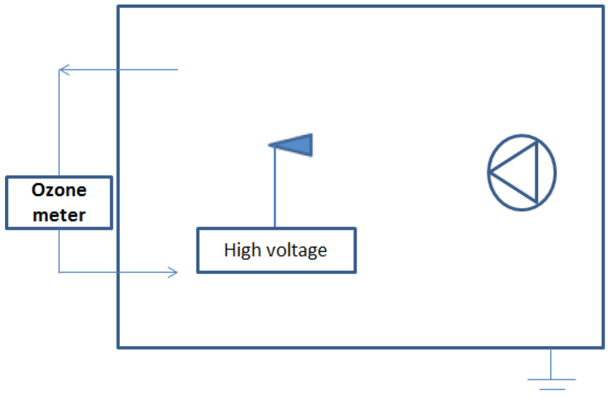
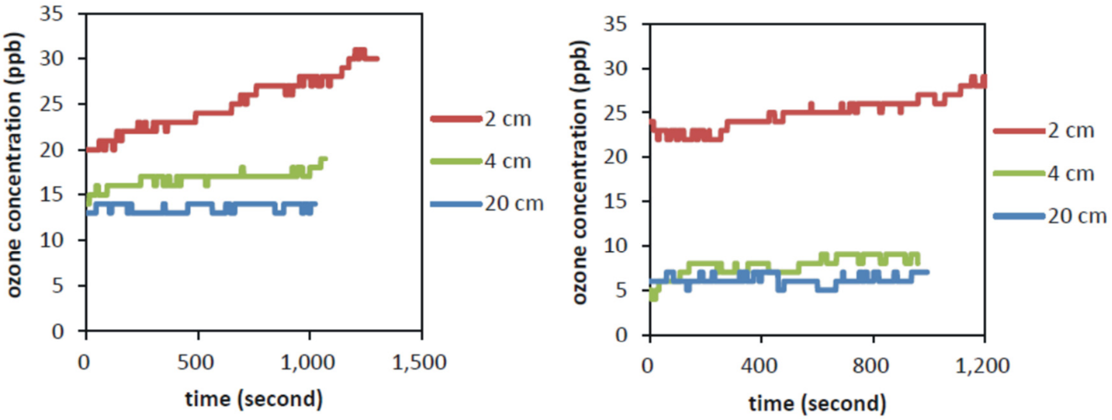



**Figure 18** Experimental set-up of the ozone generation test in the test chamber.




(a) (b)

**Figure 19** Ozone concentration in the laboratory test chamber when the distance between the ionizer and chamber wall was 2 cm, 4 cm and 20 cm. (a) negative ionizer; (b) positive ionizer. The ionization voltage was 24 kV.

The test results at varied distance between the ionizer and chamber wall are presented in Figure 19. It shows that the ozone concentration did not change with time when the distance between the ionizer brush and the test chamber wall was 20 cm or longer. However, when the distance between the brush and the wall was decreased to 4 cm, there was a tendency of ozone concentration increasing towards 7-8 ppb, when using positive ionization. At 2 cm distance the concentration increased dramatically towards 24 ppb. Since the shortest distance between an ionizer and AHU duct surface is about 20 cm in the field experiment, the ozone generation from an ionizer should be very low. Additionally, the increase of the chamber ozone concentration from the negative ionizer was larger than that from the positive ionizer, which is in agreement with the finding from Chen and Davidson (2003) (9).

From the data obtained in the chamber experiments the ozone generation rate can be calculated to 0.24 mg/m$^3$. When diluted by the air flow rate prevailing the air handling unit where the field test were made this generation rate leads to an increase om the ozone concentration by less than 0.6 ppb. This observation is supported by field measurements of ozone reported in the previous project (8).

### 2.4 Field long-term measurement

The field measurements were carried out at the air handling unit of an office building in Gothenburg. Figure 20(a) shows a sketch of the air handling unit. The air handling unit has a comparatively large cross section area at the filter bank, which comprises nine filter units. The nominal supply airflow rate is 5.8 m$^3$/s. However, the system has a variable airflow rate with demand control with respect to room temperature and carbon dioxide concentration. Thus, during most of the time the system was operating at an airflow rate substantially lower than the nominal value.

The air flow rate was logged by the control system of the air handling unit. The lowest airflow rate was found to be about 0.83 $m^3/s$. This airflow rate prevailed at night-time and during weekends. During daytime on weekdays, the airflow rate increased to a maximum of about 4.7 $m^3/s$. The air velocity at the cross section of the filters (face velocity) was about 0.38 m/s at 0.83 $m^3/s$ and about 2.16 m/s at 4.7 $m^3/s$.

The outdoor air intake is located on the roof of the building. The air flow rate was determined by measurement of the pressure differential over a calibrated flow measurement device located at the inlet to the supply air fan. The air flow rate values were logged by the control system of the air handling unit. The outdoor air temperature and relative humidity were monitored upstream of the filters by portable loggers. Upstream and downstream air samples for measurement of particles were taken at the locations indicated in Figure 20(a). The pressure differential over the fan and the filters was measured at points located immediately upstream and downstream of the fan and the filter bank.

The ionization system had a total number of 5 carbon fiber brushes (graphite) powered by a high voltage transformer (24kV). Figure 20(b) indicates the location of the ionization brushes. Five brushes were distributed over the duct cross section about 1.8 m upstream of the filter bank. The number of brushes to use was determined by a set of trials, varying the number until a maximum filtration efficiency value was observed. The area of the cross section was 2.2 $m^2$, which means that there were about 2.3 ionization brushes per $m^2$. This corresponds fairly well to the observation made in the laboratory (2.8 brushes per $m^2$), see previous section.

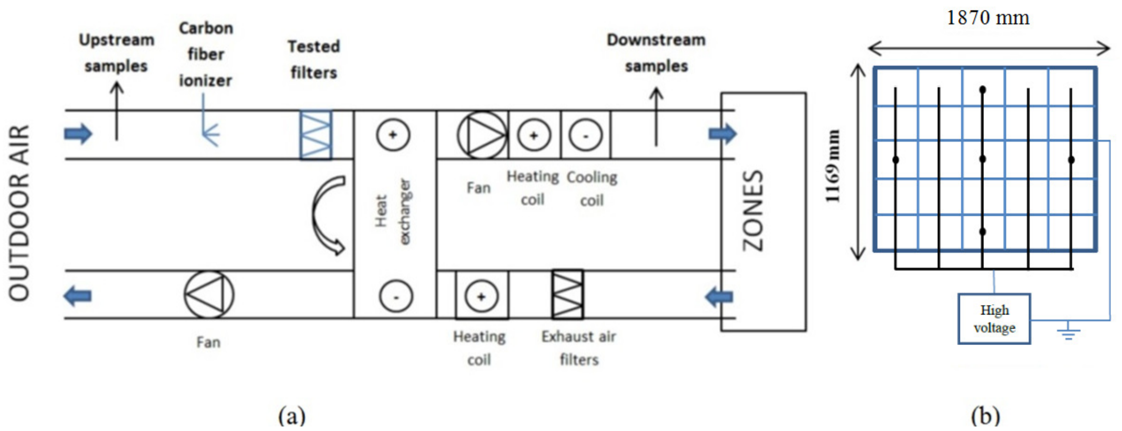



**Figure 20** Sketch of the air handling unit showing the locations of ionization, filters and air sampling. The supply air unit is located below the extract air unit.

The M6 class filters were operated in the field ventilation system from October 3, 2014 to March 30, 2015. After the M6 class filter measurements, F7 glass fiber filters were installed in the same ventilation system from March 30, 2015 to May 21, 2015. The properties of the tested filter media are shown in Table 3.

**Table 3.** Specifications of the Filters Tested in the DCV system.

| Tested filters | Filter class EN 779 | Filter class ASHRAE 52.2[11] | Filter media type | Electrostatic charged state | Filter size (mm) | Number of bags per module | Number of modules |
|---|---|---|---|---|---|---|---|
| #1 | F7 | MERV 13 | Glass fiber | Not charged | 592×592<br>592×287<br>592×490 | 10 | 3<br>3<br>3 |
| #2 | M6 | MERV 11-12 | A mix of three synthetic fiber types | Charged | 592×592<br>592×287<br>592×490 | 5 | 3<br>3<br>3 |

**Measurement equipment**

In all experiments described above, the particle number concentrations were measured by an optical particle counter (CI-500, CLiMET) in the following size fractions: 0.3-0.5, 0.5-1.0, 1.0-5.0, 5.0-10.0, 10.0-25.0 and >25 µm.

The air velocity and pressure drop were measured by a multi-function instrument of model Swema air 300 with two sensors of models SWA 31 and SWA 10. The pressure differential sensor, SWA 10, can measure from -300 Pa to 1500 Pa with an accuracy of ±0.3 Pa plus ±1% of the reading. The air velocity sensor, SWA 31, can measure from 0.1 m/s to 10 m/s, with an accuracy of ±0.04 m/s at 0.1-1.33 m/s and ±3% at 1.33-30 m/s. Additionally, outdoor air temperature and relative humidity were monitored upstream of the filters by portable loggers.

### *2.4.1 Filtration Efficiency*

The filtration efficiency with ions and without ions were measured during the long-term measurements. Figure 21 provides a summary of the filtration efficiencies observed for the synthetic filter of class M6 during the long-term measurement in the field. The columns represent the average efficiency. The error bars represent the initial and final efficiencies.

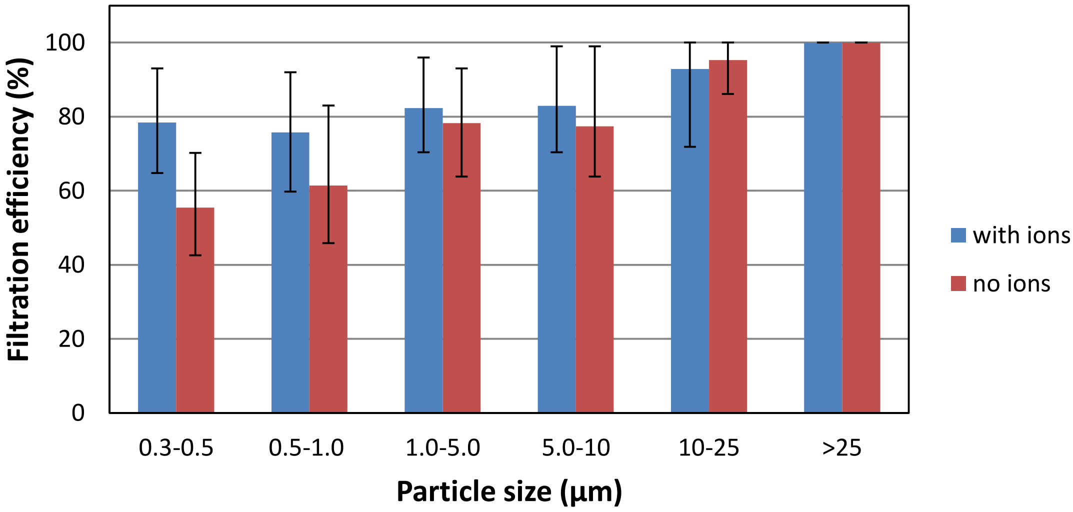



**Figure 21** Average filtration efficiency of M6 class filter during 6 months. The error bars represent the initial (highest) and final (lowest) efficiency within this period. The air flow rate was about 2.2 $m^3/s$ and the filter cross section area was 2.2 $m^2$.

In Figure 21, the ionizer-assisted efficiency for particles with the size of 0.3-0.5 µm is about 80%±15% during the 6 months. The corresponding value for 0.5-1.0 µm particles is 76%±15% The average value with ions is higher than the average efficiency without ions by about 20%-units for $PM_{0.3\text{-}0.5}$ and $PM_{0.5\text{-}1.0}$. Additionally, the filtration efficiency of the M6 class filters decayed with operation time. The lowest efficiency appeared at the end of 6 months' operation which was about 65% for particles in the interval 0.3-0.5 µm, and 60% for particles in the interval 0.5-1-0 µm.

An efficiency of 50% for 0.4 micron sized particles is the required minimum efficiency for F7 filters during 6 months operation, according to the "P-marking" requirements by SP Technical Research Institute of Sweden. The corresponding value for 0.85 µm particles is 70%. During the 6 months of operation, the ionizer-assisted M6 synthetic filter clearly showed higher efficiency values than this "P-marking" requirement for 0.4 micron sized particles. The requirement was probably also met for 0.85 µm particles most of the time, but not towards the end of the 6 months.

Moreover, at the optimum system settings, the ionizer-assisted air filtration efficiency is higher than the efficiency reported in BELOK 2011. For example, the minimum efficiency during the 6 months' operation is about 15%-units higher for $PM_{0.3\text{-}0.5}$.

### *2.4.2 Electricity saving*

The supply air system at the field site has airflow control through a frequency drive, which in turn is controlled to maintain a specified static pressure in the supply air duct. Thus a reduction of the pressure drop of the filters will reduce the total need for electricity for fan operation, maintaining the supply airflow rate constant. The total efficiency of the fan will be influenced as the pressure drop changes. However, this influence is judged to be small in this case.

Figure 22 shows the pressure drop of the M6 and the F7 filters measured at a range of airflow rates. The data were collected at the field test-site, and the measurement values spread somewhat unexpectedly. Nevertheless, linear regression curves for the two filters are shown. The relation between the regression curves indicates that the pressure drop of the M6 filter was about 37% lower than the pressure drop of the F7 filter.

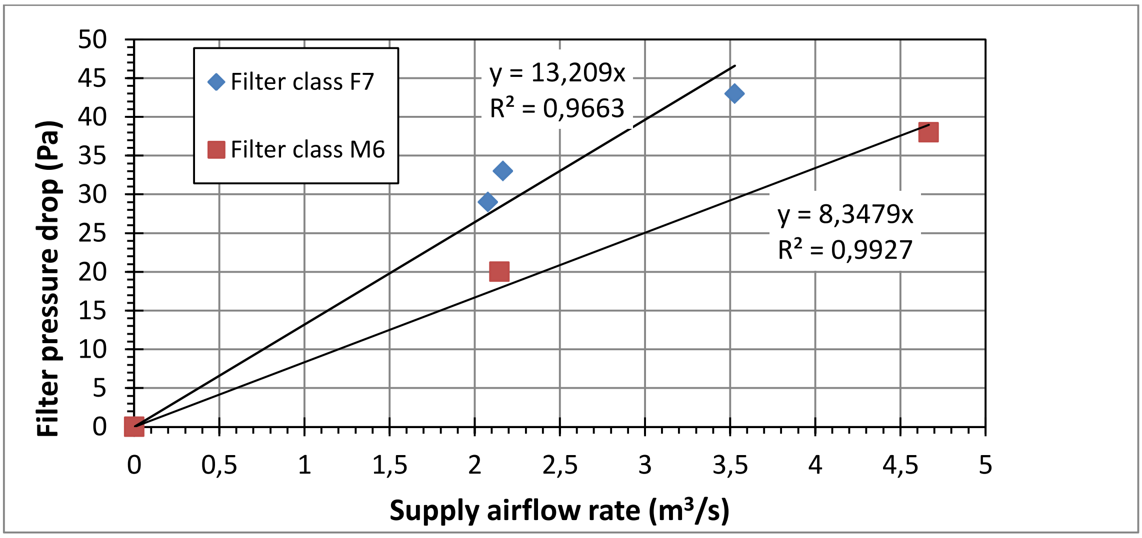



**Figure 22** Filter pressure drop plotted against the supply airflow rate. Data from the field measurements. The pressure increase over the supply air fan with F7 filters installed were: 180 Pa at 0 $m^2/s$, 308 Pa at 2,1 $m^3/s$ and 430 Pa at 3,5 $m^3/s$.

Measurements of the pressure drops were also made in the laboratory at Chalmers. These measurements showed values according to Table 4. According to the table, the average pressure drop of the M6 filter is 35% lower than the pressure drop of the F7 filter. This corresponds quite well with the results presented in Figure 22, which were obtained in the field.

**Table 4.** Filter pressure drops measured in the laboratory at an airflow rate of 0.944 $m^3/s$ through one full filter module (600·600 mm).

| Status | Filter class M6 | Filter class F7 |
|---|---|---|
| New | 52 Pa | 82 Pa |
| ~6 months | 62 Pa | 93 Pa |
| Average | 57 Pa | 87 Pa |

The measurements indicate that the filter pressure drops can be reduced by about 35% by changing from traditional F7 filters to ionizer assisted M6 filtration. The reduction of the electrical energy used to overcome the flow resistance of the filters can roughly be assumed to be of the same magnitude.

Additionally, the electrical energy used by the ionizer system was only 2 kWh during the 6 months because of the extremely low current in the ionizer system.

### *2.4.3 Lifecycle cost analysis*

The lifecycle costs (LCC) of the M6 class filter, the G4 class filter and a traditional F7 class filter were analysed by the BELOK LCC calculator, see Appendix B. The analysis is made for a ten year period. Two sets of calculations were made. One with all filters having the same replacement interval –two times per year; the other with the G4 and M6 filters being replaced two times per year and the F7 filter once per year. Note that the initial cost of the ionization equipment is not included in the LCC calculation. Any costs for visual inspection of the ionizer brushes is neglected.

The initial and final pressure drops of the M6 class filter and the F7 class filter were measured at an air flow rate of 0.944 $m^3/s$ in a full-scale filter test rig at Chalmers. The data for the G4 filter come from long-term measurements at Vokes Air.

The results of the first set of calculations show that when all filters are replaced twice per year, the LCC (10 years) for the G4 and M6 filters are respectively 5.1 kSEK and 3.3 kSEK lower than the LCC of the traditional F7 class filter. This difference is judged to clearly cover the cost of ionization equipment, thus are the ionization solutions profitable with the semi-annual filter replacement interval.

The results of the second set of calculations show that when the G4 and the M6 filters are replaced twice per year, while the F7 filter is replaced once per year, the LCC (10 years) for the G4 filter is 1.5 kSEK lower than the LCC of the traditional F7 class filter. The LCC of the M6 filter is 0.4 kSEK higher than the LCC of the traditional F7 filter.

The reader is reminded that the ionizer assisted filter of class M6 was judged to show sufficient performance for supply air filtration, while the ionizer assisted G4 filter did not.

## 3. Summary and Conclusions

The project provides important information on how to design an efficient, safe, reliable and low energy consuming system of ionizer-assisted air filtration. A series tests on the optimum system settings were conducted in a laboratory to further increase the filtration efficiency. The ozone generation of the ionizer at different experimental settings, was measured in a closed chamber to confirm the safety issue (by-products generation). Finally, an ionizer-assisted air filtration system with optimized settings was tested in an air handling unit in an office building to test the long-term performance and the energy saving under real-life conditions.

The tests for optimum settings comprised tests of various filter media, ionizer distribution, ionizer supply voltage, distance between ionizers and filters. Among eleven filter media, the filter medium of an M6 class synthetic filter (consisting polypropylene, modacrylic and polyester fibers) and a G4 class synthetic filter (consisting polyester and conductive fibers) could perform equally well or better than a traditional F7 class filter. The optimum number of ionizers was found to be 2~3 brushes per $m^2$ of duct cross section area. Additionally, the optimum distance between ionizer and filter was about 1.8 m for the M6 class filter and 0.8 m for the G4 class filter. Additionally, the tests for optimum ionizer supply voltage showed that the filtration efficiency is stable when the supply voltage is ≥ 10 kV for the M6 class filter. However, for the G4 class filter, the filtration efficiency linearly increases with the observed supply electricity voltage from 2kV to 20kV.

The by-products measurements showed that the ozone generation increases with the decrease of the distance between ionizer and duct. The ozone generation was very low as long as the distance between any ionizer and the interior surface of the air handling unit (AHU) or duct was at least 20 cm.

The laboratory tests showed very good results both for the G4 and the M6 filter, when small-scale samples of the filters were tested in the laboratory. Unfortunately, it turned out not the be possible to reach the same good results when testing the G4 filter in full-scale. However the M6 filter performed well both in small scale laboratory tests and full scale field tests. Thus, the M6 class filter was installed for field test in the ventilation system of an office building.

The long-term field measurements showed that the ionizer-assisted M6 filter at optimized settings achieved a filtration efficiency of 80%±15% on $PM_{0.3\text{-}0.5}$ during 6 months of operation. This efficiency is higher than the required minimum efficiency of 50% for 0.4 µm sized particles in the "P-marking" test by SP Swedish Technical Research Institute on an F7 filter operated under real-life conditions (12). The tests indicated that the "P-marking" requirement also for 0.85 µm particles was met most of the 6 month period.

The optimized settings increased the ionizer-assisted filtration efficiency 15%-units further, compared to the level reported in the previous BELOK-report (8).

The results indicated that an ionizer-assisted M6 filter replacing a traditional F7 filter can save about 35% of the fan power needed to overcome the flow resistance of hew filters. Additionally, the life cycle cost analysis made, using the BELOK LCC calculator, indicated that changing from traditional F7 filtration to ionizer assisted filtration is profitable under the prerequisites of the calculations made, when all filters are replaced semi-annually. The calculations also indicate that the ionizer assisted M6 filter solution would be slightly (~5%) more expensive if the M6 filters are replaced semi-annually and the traditional F7 filters are replaced annually.

The technique is quite uncomplicated and is judged to require a minimum of service. After installation the equipment can most likely be handled by the regular service personnel. The ionization brushes should be inspected regularly. There were no signs of dust accumulation or deterioration during the six months of operation in the present study. It is suggested that it is sufficient to check the ionisers simultaneously with filter replacements. The brushes may need cleaning or replacement.

The studied technology showed good performance regarding filtration efficiency, safety, reliability and energy saving. However, there is a potential for further improvements of the energy efficiency. Further studies may be needed before the technology will be widely accepted in the market. Future investigations should address the following issues:

- Further development of the G4 filter medium in order to reach even higher energy savings with maintained filtration efficiency.
- Life-time estimation of this technology with the G4 class and M6 class filters operated with outdoor air of various quality (pure air, dusty air and very high concentrations of dust or gases).
- The system settings for the applications in premises with higher indoor air quality requirements, e.g. hospitals and cleanrooms.

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## Appendix A: Supplementary information about filter effeiciency measurements

Eleven filter media were tested in a small filter test rig with the experimental settings in indicated in Figure 1. The filter media were electrically earthed in the test rig. The filter media were composed by different types of fibers, see Table A1.

Table A1 Specifications of the filter media.

| Filter media | Fiber type | Filter class | Pressure drop* |
|---|---|---|---|
| P1 | polyester fiber and 1% conductive fiber | G4 | 15 |
| P2 | polyester fiber and 5% conductive fiber | G4 | 19 |
| P3 | polyester fiber and 10% conductive fiber | G4 | 17 |
| P4 | polypropylene, modacrylic and polyester fibers | M6 | 36 |
| P5 | polypropylene, modacrylic and polyester fibers | M5 | 26 |
| P6 | conductive fiber + pure polyester + conductive fiber | M5 | 20 |
| P7 | polypropylene+ meltblown polypropylene + polypropylene | G4 | 22 |
| P8 | meltblown polypropylene+ corona treatment | M5 | 35 |
| P9 | Polypropylene fiber and modacrylic fiber | M5 | 33 |
| P10 | polyester fiber and 3% conductive fiber | G4 | 17 |
| P11 | polyester fiber and 0.5% conductive fiber | G4 | 12 |

*the pressure drop was measured at an air velocity of 0.2 m/s.

Besides the filtration efficiencies of P1 and P4 presented in Figure 2, the results of other filter media are shown in Figure A1-A3.

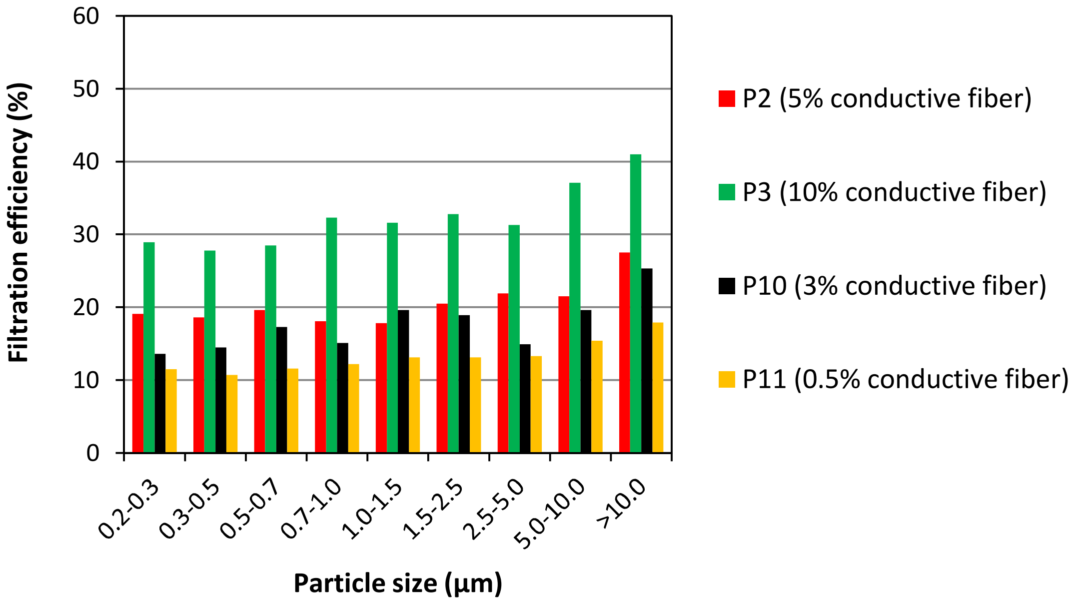


**Figure A1** Filtration efficiency of the filter media assisted with ionizers. These filters consisted polyester fiber and X% conductive fiber.

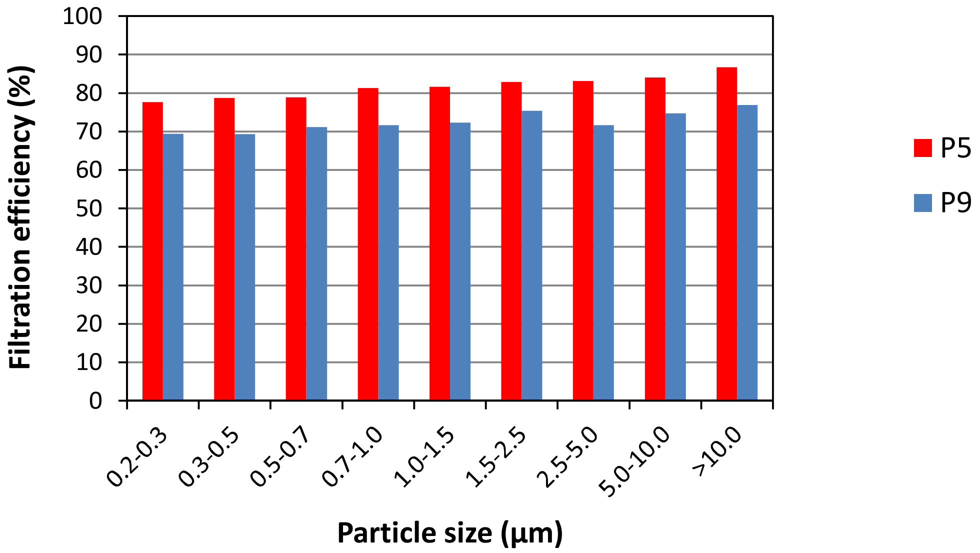


**Figure A2** Filtration efficiency with ionizer assisted on new filter media of P5 and P9.

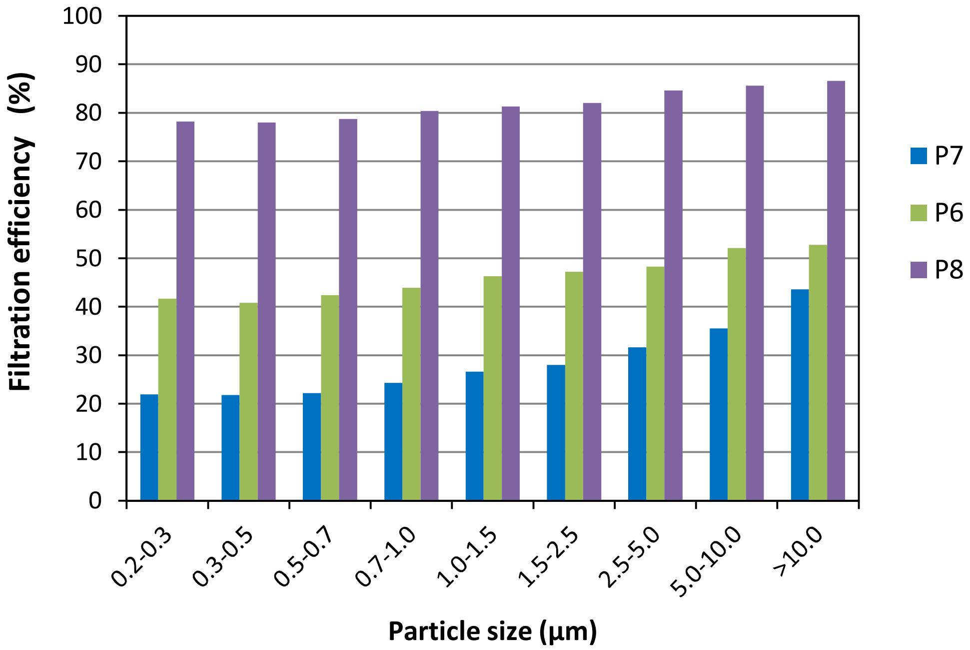


**Figure A3** Filtration efficiency with ionizer assisted on new filter media of P6-P8.

## Appendix B: LCC calculations

**Table B1** Calculation number 1. All filters replaced 2 times per year. Input parameters of the LCC analysis by the BELOK calculator. Ionizer assisted G4 = Filter 1, Ionizer assisted M6 = Filter 2, traditional F7 = Filter 3.

2015-11-19

BELOK LCC<sub>luftfilter</sub>

### Joniseringsförstärkta filter

**Filter 1 - Joniseringsförstärkt G4 Filter 2 - Joniseringsförstärkt M6 Filter 3 - Traditionellt glasfiberfilter klass F7**

### Inparametrar

#### Förutsättningar

| | |
|---|---|
| Kalkylperiod | 10 år |
| Real kalkylränta | 5 % |
| Dagens energipris | 1 kr/kWh |
| Real årlig energiprisökning | 2 % |
| Filterklass | F7 |
| Rensningskostnad/år | 0 kr |
| Arbetskostnad filterbyte | 85 kr/filter |
| Filterprisökning/år | 1 % |
| Tvärsnittsarea | 0,36 m² |
| Verkningsgrad | 60 % |
| Årlig drifttid | 4000 h |

#### Kapitalkostnader

| | Filter 1 | Filter 2 | Filter 3 | |
|---|---|---|---|---|
| Filterpris | 250 | 300 | 400 | [kr] |

#### Övriga kostnader

| | Filter 1 | Filter 2 | Filter 3 | |
|---|---|---|---|---|
| Livslängd | 0,5 | 0,5 | 0,5 | [år] |
| Begynnelsetryckfall | 35 | 52 | 82 | [Pa] |
| Sluttryckfall | 40 | 62 | 93 | [Pa] |
| Luftflöde | 0,944 | 0,944 | 0,944 | [m³/s] |

**Table B2** Results of the LCC analysis. Ionizer assisted G4 = Filter 1, Ionizer assisted M6 = Filter 2, traditional F7 = Filter 3.

### Resultat

| | Filter 1 | Filter 2 | Filter 3 | |
|---|---|---|---|---|
| $LCC_{Energi}$ | 2019 | 3069 | 4711 | [kr] |
| $LCC_{Underhåll}$ | 5445 | 6258 | 7883 | [kr] |
| **$LCC_{Total}$** | **7464** | **9327** | **12595** | **[kr]** |

**Table B3** Calculation number 2. G4 and M6 filters replaced 2 times per year. F7 filter replaced once per year. Input parameters of the LCC analysis by the BELOK calculator. Ionizer assisted G4 = Filter 1, Ionizer assisted M6 = Filter 2, traditional F7 = Filter 3.

2015-11-19

## BELOK $LCC_{luftfilter}$

## Joniseringsförstärkta filter

**Filter 1 - Joniseringsförstärkt G4 Filter 2 - Joniseringsförstärkt M6 Filter 3 - Traditionellt glasfiberfilter klass F7**

### Inparametrar

#### Förutsättningar

| | |
|---|---|
| Kalkylperiod | 10 år |
| Real kalkylränta | 5 % |
| Dagens energipris | 1 kr/kWh |
| Real årlig energiprisökning | 2 % |
| Filterklass | F7 |
| Rensningskostnad/år | 0 kr |
| Arbetskostnad filterbyte | 85 kr/filter |
| Filterprisökning/år | 1 % |
| Tvärsnittsarea | 0,36 m² |
| Verkningsgrad | 60 % |
| Årlig drifttid | 4000 h |

#### Kapitalkostnader

| | Filter 1 | Filter 2 | Filter 3 | |
|---|---|---|---|---|
| Filterpris | 250 | 300 | 400 | [kr] |

#### Övriga kostnader

| | Filter 1 | Filter 2 | Filter 3 | |
|---|---|---|---|---|
| Livslängd | 0,5 | 0,5 | 1 | [år] |
| Begynnelsetryckfall | 35 | 52 | 82 | [Pa] |
| Sluttryckfall | 40 | 62 | 103 | [Pa] |
| Luftflöde | 0,944 | 0,944 | 0,944 | [m³/s] |

**Table B4** Results of the LCC analysis. Ionizer assisted G4 = Filter 1, Ionizer assisted M6 = Filter 2, traditional F7 = Filter 3.

## Resultat

| | Filter 1 | Filter 2 | Filter 3 | |
|---|---|---|---|---|
| $LCC_{Energi}$ | 2019 | 3069 | 4981 | [kr] |
| $LCC_{Underhåll}$ | 5445 | 6258 | 3942 | [kr] |
| **$LCC_{Total}$** | **7464** | **9327** | **8922** | **[kr]** |