BELOK project 2011:6

Performance of Ionizer Assisted Air Filtration

Evaluation of long-term performance and influencing factors

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Förord

I lokalbyggnaders ventilationsaggregat används normalt filter av klass F7, på både tilluftssidan och frånluftssidan. Tryckfallet över ett F7 filter varierar från ca 100 Pa, då filtret är nytt, till bortåt 180 Pa, då det byts. För luftbehandlingssystemet innebär det sammanlagt för till- och frånluftssidan ett tryckfall på 200 till 360 Pa, eller ett genomsnittligt tryckfall på nära 300 Pa. Filtren svarar därmed för ca 20% av fläktarnas elbehov i nya byggnader och ca 15% av behovet i äldre byggnader. I ett äldre kontorshus med CAV system rör det sig om ca 1,5 kWh/m^2 per år.

Tidigare studier i laboratorium vid Avdelningen för Installationsteknik, Chalmers, tyder på att en jonisator före filtret skulle kunna få ett grundfilter av låg klass att uppvisa i stort samma avskiljningsgrad som ett F7 filter. Tryckfallet är emellertid 30% till 50% lägre än F7 filtrets.

Vid studierna på Chalmers användes en enkel jonisator, där joniseringen sker i direkt i spänningssatta kolborstar. Utrustningen har lång livslängd och en mycket ringa elförbrukning – hög spänning men i stort ingen ström. Ingen mätbar ökning av ozonhalt har kunnat konstateras.

Metoden är intressant dels genom att den enkelt skulle kunna ge en minskning på ca 10% av ventilationssystemets elbehov, dels innebära en minskning av filterkostnaden med 30-40%. Filtren byts åtminstone en gång per år.

För att lösningen med jonisering och filter skall kunna komma i fråga i praktiken måste den dock provas i verklig drift i verkliga anläggningar. Det i denna rapport redovisade projektet syftar till sådan provning.

Projektet, som hade arbetsnamnet ”Jonisering för effektivisering av grundfilter” har erhållit ekonomiskt stöd av BELOK tillsammans med Akademiska hus. Projektet har också stöttats med material och värdefulla arbetsinsatser av personal från Transjonic AB, Göteborg, och Vokes Air Group, Svenljunga.

Mätningar och analyser har i huvudsak utförts av Dr. Bingbing Shi, Chalmers, med stöd av undertecknad som projektledare.

2013-12-09

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CIT Energy Management AB

Sammanfattning

Under större delen av det genomförda långtidsförsöket uppvisade det joniseringsförstärkta syntetiska filtret av klass M6 högre avskiljningsgrad än ett traditionellt glasfiberfilter av klass F7.

Den testade lösningen hade mer än 20 procentenheter högre avskiljningsgrad jämfört med ett identiskt syntetiskt M6-filter utan jonisering. Under större delen försöket var avskiljningsgraden runt 40 procentenheter högre.

Efter 110 dagars drift sjönk avskiljningsgraden under 50 % (för 0.4 µm partiklar). Då växlades joniseringens elektriska polaritet från minus till plus. Då ökade avskiljningsgraden med viss tidsfördröjning till 70-75%, för att åter börja sjunka.

Under den studerade sjumånadersperioden var det genomsnittliga tryckfallet över det joniseringsförstärkta M6 filtret 25%-33% lägre än motsvarande värde för det glasfiberfilter av klass F7 som luftbehandlingsaggregatet ursprungligen var utrustat med. Resultatet visar att det joniseringsförstärkta systemet kan reducera filtreringens andel av elanvändningen för fläktdrift med åtminstone 1/4 jämfört med traditionella filter av klass F7. Om lufthastigheten genom filtret begränsas till ca 2 m/s tycks besparingen uppgå till 1/3. Normalt är lufthastigheten lägre än 2,5 m/s.

Koncentrationerna av ozon var i praktiken desamma före och efter det joniserings-förstärkta filtret. Således finns det inga indikationer på att utrustningen alstrade ozon.

Mätningarna visade att uteluftens relativa fuktighet och partikelhalt påverkade avskiljningsgraden. Lägre luftfuktighet och lägre partikelhalt leder till högre avskiljningsgrad. Under fältförsöket varierade dessa två faktorer inom breda intervall, med bibehållen acceptabel filterfunktion.

Slutligen konstateras att den studerade lösningen med joniseringsförstärkt filtrering har klara fördelar. Det finns anledning att fortsätta studera tekniken med målet att etablera vägledning för projektering och drift. Därefter skulle tekniken kunna vara redo för slutlig fullskaleprovning i fält. En fortsatt undersökning bör fokuseras på följande:

- Optimering av joniseringssystemets dimensionering och drift
    - Anpassning av frekvensen för växling av joniseringens polaritet
    - Antalet joniseringspunkter (kolborstar)
    - Elektrisk spänning till joniseringen
- Optimering av filterfibermaterialet
    - Blandningen av syntetiska fibrer (exempelvis polypropylen, polyester och modakrylfibrer)
    - Filtermaterialets struktur och täthet
- Klargörande av konsekvenser kopplade till det faktum att lösningen innefattar installation av högspänningsutrustning i luftbehandlingsaggregatet. I det

sammanhanget måste man reda ut om det skulle krävas att driftpersonalen har elbehörighet.

- Beräkning av livscykelkostnad. Den nya lösningen innebär att el för fläktdrift kommer att reduceras avsevärt. Joniseringsutrustningens elanvändning är försumbar och utrustningen består av rätt enkla komponenter. Kostnaden för filter och övrig utrustning är möjligen lägre än kostnaden för traditionella filter. Emellertid kan det hända att den nya lösningen kommer att kräva tätare filterbyten än normalt, exempelvis var 6:e månad istället för varje år. Sammantaget finns det mycket som talar för att den nya lösningen skulle innebära både lägre elanvändning och lägre livscykelkostnad.

Summary

The ionizer assisted synthetic filter of class M6 typically showed substantially higher efficiency values than a glass fiber filter of class F7.

Compared to an identical synthetic M6 filter operated without ionization, the ionization enhanced the filtration efficiency of the synthetic M6 filter by more than 20 %-units and maintained about 40 %-units increase during most of the operation time.

After about 110 days the efficiency of the ionizer assisted M6 filter dropped below 50% (for 0.4µm particles). When the polarity of the ionization was switched from positive to negative, the efficiency increased to 70-75%. The efficiency then began to degrade again.

The average pressure drop of the ionizer-assisted synthetic M6 filter operated during 7 months was about 25%-33% lower than that of the glass fiber F7 filter originally installed in the air handling unit. The results indicate that the ionizer-assisted air filtration system can save at least 1/4 of the fan electricity used for F7 class air filtration. If the filter face velocity is not higher than about 2 m/s the saving may approach 1/3. Note that typically the air velocity is found to be well below 2.5 m/s.

The ozone concentrations measured in both the field and the laboratory were about the same upstream and downstream of the ionizer assisted filtration system. Thus, there are no indications of any substantial ozone generation.

The analysis of influencing factors showed that outdoor air humidity, particle concentration and outdoor air flow rate had substantial effects on the filtration efficiency, while outdoor temperature had only a slight (negligible) effect. The efficiency of ionizer-assisted air filtration appears to be more sensitive to the studied influencing factors, compared to the efficiency without ionization.

Finally, the investigation shows that ionizer assisted filtration in combination with synthetic filters has clear benefits. There is reason to study this technology further, with the aim to establish design and operation guidelines. The technology should then be ready for final full scale testing, under a variety of conditions. Future investigations should address the following issues:

- Optimization of ionizer operation
    - Frequency of switching the ionization polarity
    - Number of ionization points
    - Ionization voltage
- Optimization of filter fiber material
    - Mix of synthetic fiber types (e.g. polypropylene, polyester and mod crylic fibers)
    - Packing density of the fiber structure

- Clarification of any implications from the fact that the solution comprises installation and operation of high voltage components in the air handling unit. In this context, one important issue is related to whether the solution will require special certification of the maintenance personnel.
- Calculation of the life cycle costs. The new solution means that the use of fan electricity will be substantially reduced, the energy use of the ionizer is negligible, the ionization equipment is rather simple and the cost of filters and other equipment is possibly lower compared to the traditional solution. However, the solution may require more frequent filter replacement, e.g. every 6 months instead of every 12 months. All in all, there are good prospects that the new solutions can lead to both reduced use of electricity and reduced life cycle cost.

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1. Introduction

Many studies have investigated ionization for removal of airborne particles, aero-allergens and airborne microorganisms from indoor air in various settings [1-6]. An ionizer is an electrical device to charge airborne particles through ions attaching on them. The charged particles stick to each other and become big particles and finally the “big” particles are captured by or deposit on the surrounding surfaces, e.g. ventilation ducts and filters. An ionizer operated upstream of a ventilation air filter could enhance the particle collection efficiency of the filter, without affecting the pressure drop. The increased filtration efficiency is not only due to the “growth” of the particles; electrostatic attraction between the particles and charged filter fibers may also play an important role.

A previous study investigated the enhanced filtration efficiency obtained by ionization before charged synthetic and glass fiber ventilation air filters [7, 8]. As expected, it was found that the increased filtration efficiency was higher for a charged synthetic filter than for a glass fiber filter of intermediate class. The study also indicated that an ionizer-assisted low class filter may show particle removal performance of similar magnitude as a filter of higher class alone. Since the low class filter has substantially lower air flow resistance, the technology could be used to reduce the use of fan electricity to overcome the filter pressure drop.

This study extends the previous study into field applications. The field evaluation was conducted in a demand controlled ventilation (DCV) system in an office building in Göteborg, Sweden. Besides the enhanced efficiency, the risk of by-products emission (e.g. ozone) is another important issue considered in the experiments. The filtration performance was valuated during 216 days’ operation (7 months).

Because the filtration efficiencies of charged synthetic filters may decrease quickly with filter operation time [9-10], a set of measurements were conducted in the laboratory of Building Services Engineering, Chalmers. These measurements were conducted in order to determine the efficiency of an identical synthetic M6 filter without ionization during the same period of 7 months.

The performance of an ionizer assisted air filtration system can be expected to be influenced by air humidity, outdoor air particle concentration and air flow rate through the filter. Thus, these factors were studied in the laboratory full scale filter test rig. The results indicated the degree to which the filtration efficiency is influenced by the factors mentioned above. This information is important for determining the direction of further studies of this technology, and for consideration of the best design of ionizer assisted filtration systems.

2. Test site and Methods

The DCV system has a design supply airflow rate of 4.8 m^3/s, and an exhaust airflow rate of 4.6 m^3/s. However, due to the DCV-function, it operates at substantially lower flow rates most of the time. The outdoor air intake is located at the roof of the building. Originally, the supply air was filtered by glass fiber bag-filters of class F7.

The particle number concentrations were measured by a TSI P-TRAK Ultrafine Particle Counter in the particle size interval 0.02-1.0 µm, and a CLiMET CI-500 optical particle counter in the following size ranges: 0.3-0.5, 0.5-1.0, 1.0-5.0, 5.0-10.0, 10.0-25.0 and >25 µm. Additionally, a TSI Dust-Trak photometer was used to measure the total mass concentration of particles with diameters less than 10 µm (PM_{10}).

Ozone concentrations were measured by an Environics Series 300 UV-photometry instrument, with the detection limit of 1 ppb by volume. The ion concentration in the exhaust air was measured by an ion meter, model Transjonic T-111. Additionally, outdoor air temperature and relative humidity were monitored upstream of the filters by portable loggers.

Figure 1 shows a sketch of the air handling unit, with the locations of ionization, the filters and the air sampling points marked.

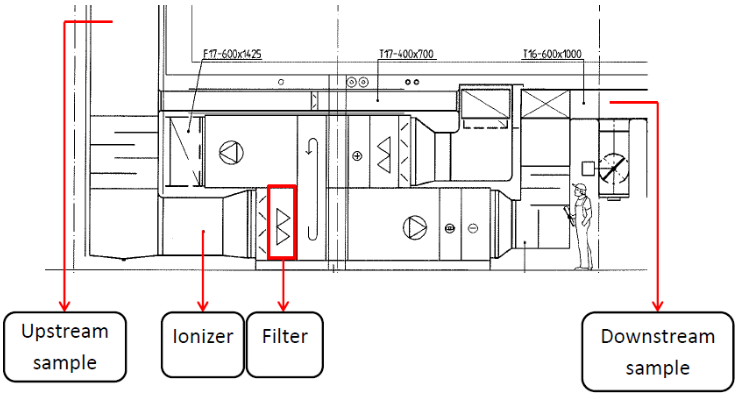

Figure 1. *Sketch of the air handling unit showing the locations of ionization, filters and air sampling. The supply air unit is located below the extract air unit.*

The ionization system has a total of 50 carbon fiber brushes which were operated at 25 kV. These factors determine the capacity of the ionization. In the main part of the experiments, a charged synthetic air filter of class M6 was tested at an ion concentration of about $5.0 \cdot 10^5$ $ions^-/cm^3$. The original glass fiber filter of class F7 was also tested to compare the two solutions. Table 1 lists a specification of the tested filters.

The air handling unit has a comparatively large cross section area at the filter bank. There is room for nine filter modules. However, this original design leads to an unusually low air velocity at the filter face. In order to increase the face velocity towards more typical values 1/3 of the total cross section was blocked. So, six filter modules were used during the experiments, whereas there is room for nine modules.

Table 1. *Specifications of the Filters Tested in the DCV system*

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

Figure 2 shows an example of the variation of the air flow rate as logged by the control system of the air handling unit. The lowest airflow rate was found to be about 5 000 m^3/h (1.4 m^3/s). This airflow rate prevailed at nighttime and during weekends. During daytime, weekdays, the airflow rate increased to a maximum of about 10 000 m^3/h (2.8 m^3/s). Obviously, the system is operating at a substantially lower capacity compared to its design maximum capacity of 17 000 m^3/h (4.8m^3/s). This is the reason for unusually low pressure drops in the system. At 5 000 m^3/h the face velocity was about 0.8 m/s and at 10000 m^3/h the velocity was about 1.6 m/s. Note that the nominal air velocity used when filters are tested according to the standard SS EN 779 is 2.7 m/s.

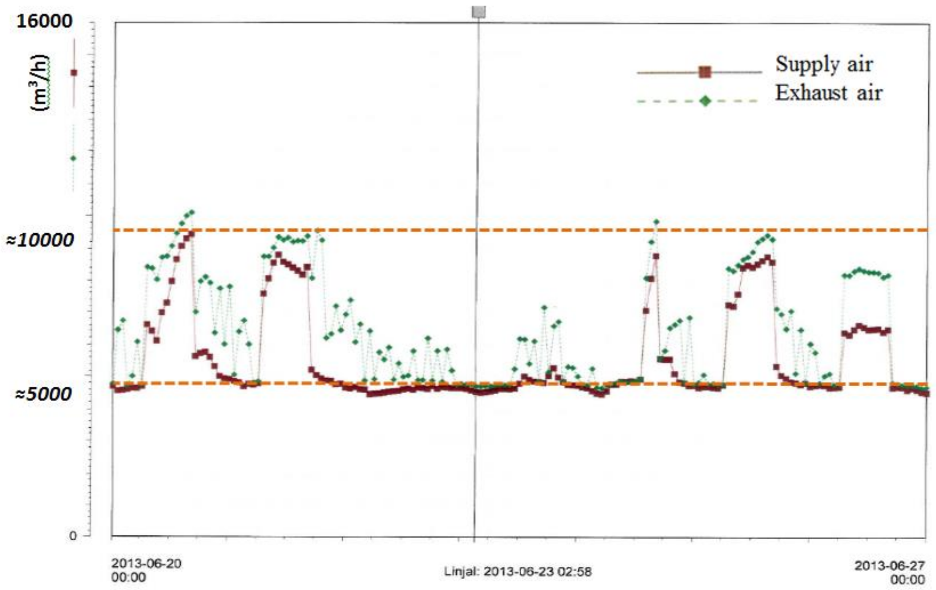

Figure 2. *Air flow rate in the ventilation system during one week.*

In addition to the field measurements in the air handling unit described above, a set of measurements were also carried out in a laboratory full-scale filter test rig at Chalmers. The test-rig is designed in accordance with the standard SS EN 779. The basic principle of the test-rig is indicated in Figure 3. The main objective of the laboratory tests was to evaluate a filter of the same model and class (M6) as tested in the field, but without ionization. The full scale test rig was used to test three filter types; a synthetic M6 filter identical to the one tested in the field setting, and two glass fiber filters of class M6 and F7, respectively. All three filters had a cross-section of the dimensions 0.6 m · 0.6 m.

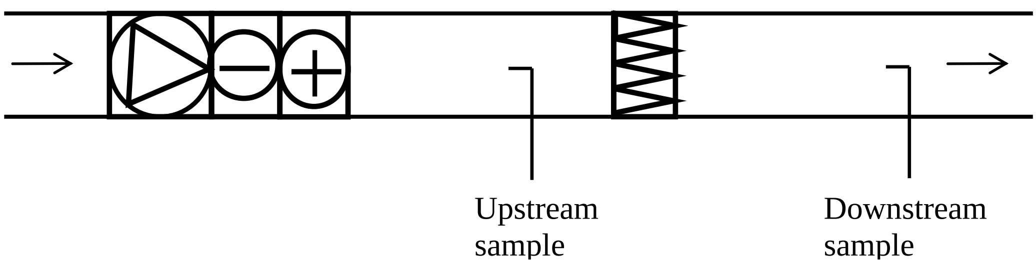

Figure 3. *Sketch of the laboratory filter test rig. The test rig has room for one filter module of the dimensions 0.6 m · 0.6 m.*

The filtration efficiency (EF) is defined according to Equation 1. The marginal effect of the ionizer on the filtration efficiency is described by the “enhanced efficiency” with the definition given in Equation 2.

$$EF = (1 - \text{Concentration downstream}/\text{Concentration upstream}) \cdot 100\ [\%] \quad (1)$$

$$\text{Enhanced efficiency} = \text{EF with ionizer} - \text{EF without ionizer}\ [\%\text{-units}] \quad (2)$$

The measurements were repeated with a frequency of 1-3 weeks over the entire 7 month test period. The field experiments comprised measurements both with the ionization on and with the ionization temporarily switched off. Between the measurement occasions the ionization was turned on. The laboratory experiments only comprised measurements without ionization. Below, all efficiency values refer to particles with diameters between 0.3 µm and 0.5µm. For the cause of simplicity, this size-interval is referred to as “0.4 µm”. Data for other particle sizes are presented in Appendix A.

3. Results

4.1 Field measurements

Figure 4 and 5 shows a summary of the filtration efficiency measured repeatedly over a period of 220 days (7 months). It is clear that the filtration efficiency continues to drop from an original value of 90% or more. The efficiency measured with the ionization active (“ionizer on”) is substantially higher than the efficiency measured when the ionizer temporarily was switched off (“ionizer off”). In the latter case the filtration efficiency dropped and stayed below 50% already after 100 days of operation. The measurements with the ionizer switched on showed that the efficiency typically stayed clearly above 50% during the first 190 days.

Comparison of the data in Figure 4 and 5 shows that the efficiency values were somewhat higher at low airflow rate than at high airflow rate. The influence of air flow rate is analyzed in more detail in a separate section below, where also the influence of relative humidity and particle concentration are also analyzed.

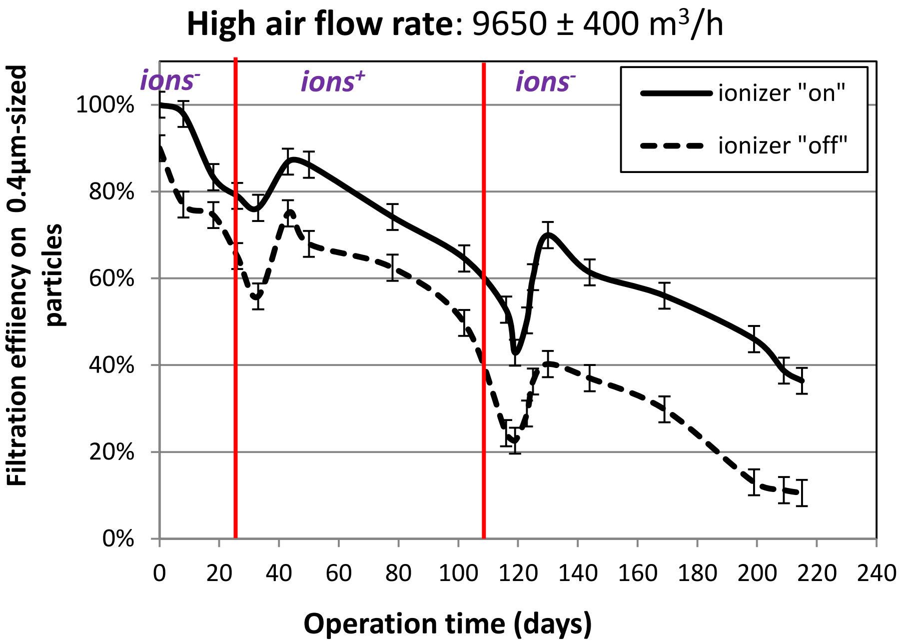

Figure 4. *Summary of the results from the field measurements. The data were collected when the air handling unit was operating at a high airflow rate.*

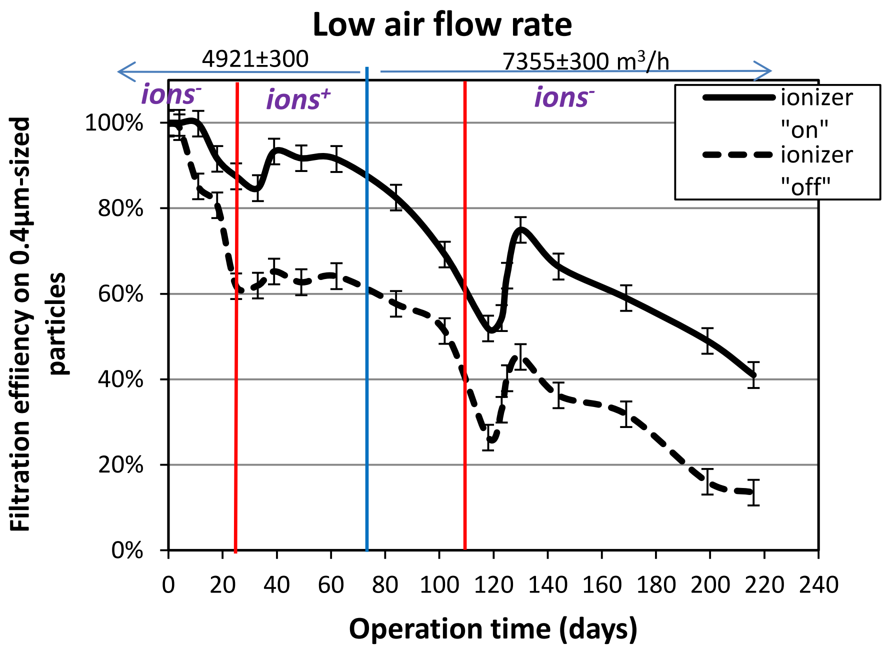

Figure 5. *Summary of the results from the field measurements. The data were collected when the air handling unit was operating at low airflow rates.*

4.2 Comparison of laboratory and field measurements

In Figure 6 and 7 the filtration efficiency of the M6 synthetic filter and the M6 glass fiber filter, tested without ionizer in the full scale test rig, are compared with the efficiency of the ionizer assisted M6 filter tested in the field. The efficiency of the M6 synthetic filter without ionizer rapidly decreased with its operation time from above 90% to about 20%. However, the efficiency of the synthetic M6 filter with ionizer was substantially enhanced during the whole operation time. The efficiency values of the M6 glass fiber filter were almost constant at 15%-20%, although the air velocity varied substantially. At the end of the test period, the two M6 filters tested in the laboratory without ionization reached down to about the same low filtration efficiency. Moreover, the efficiency of the glass fiber filter of class F7 in Figure 7 was lower than that of the ionizer assisted synthetic M6 filter during most of the measurement period.

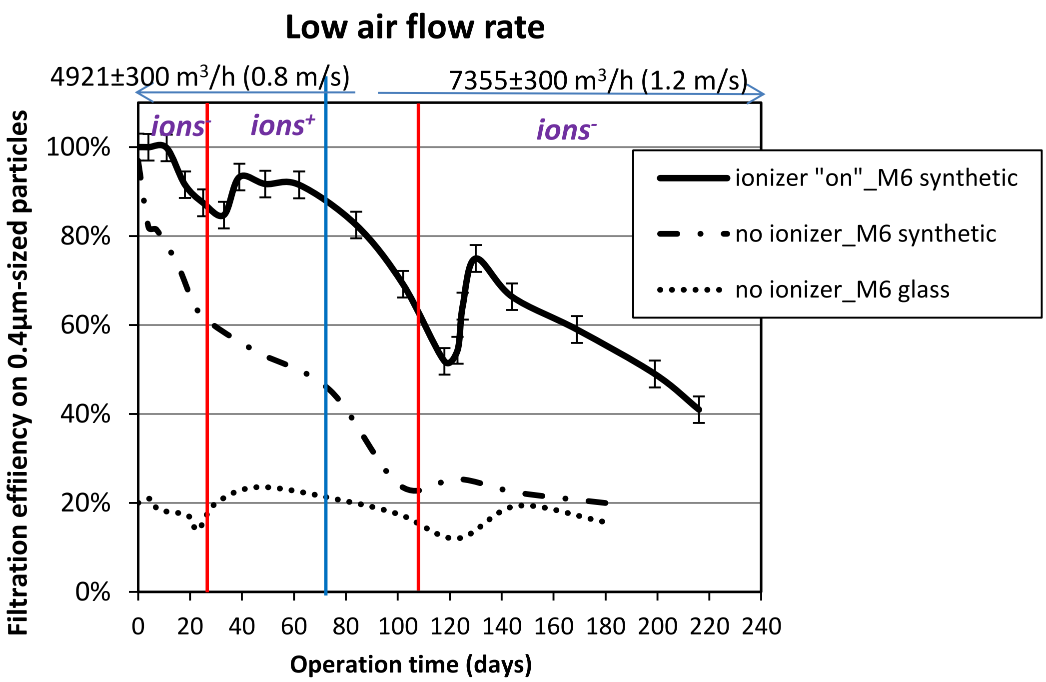

Figure 6. *Filtration efficiency values measured for the synthetic M6 filter tested in the field with ionization, together with values measured for an identical synthetic M6 filter and a glass fiber filter of class M6 tested in the laboratory without ionization. The data were collected at relatively low air flow rates. The laboratory tests were conducted at an air velocity of 1 m/s, while the field measurements were made at velocities between 0.8 and 1.2 m/s (4920 – 7350 m³/h).*

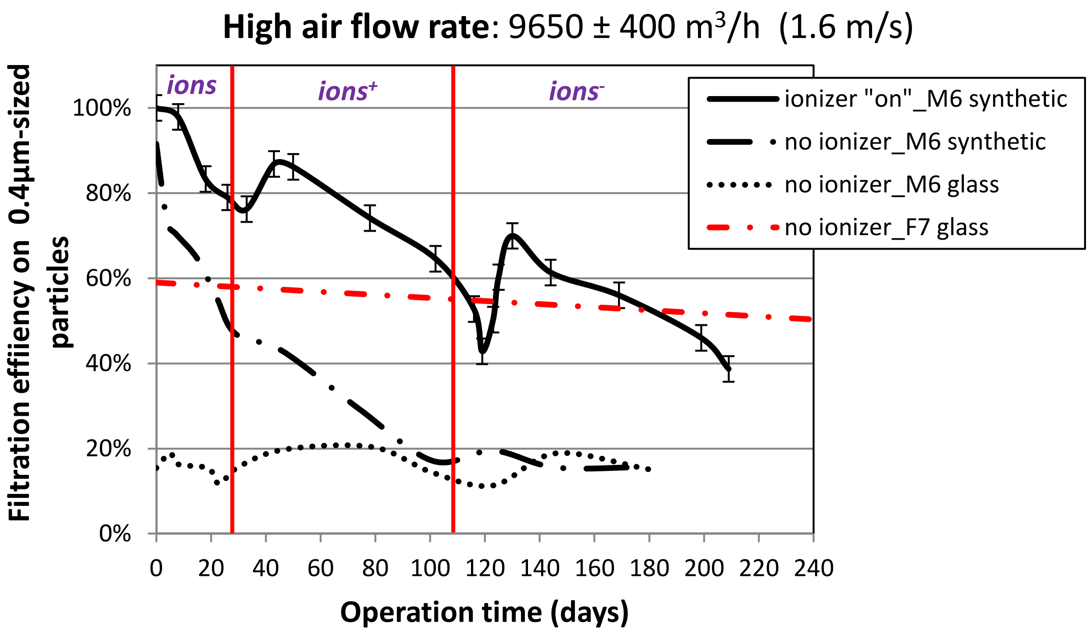

Figure 7. *Filtration efficiency values measured for the same filters as in Figure 6. The diagram also shows data for a glass fiber filter of class F7, tested in the laboratory without ionization. The data were collected at relatively high airflow rates. Both the laboratory tests and the field measurements were conducted at an air velocity of 1.6 m/s, corresponding to an airflow rate of about 9650 m³/h in the field air handling unit .*

The data for the F7 glass fiber filter shown in figure 7 were obtained by field measurements in the air handling unit at two occasions. One measurement was made when the filter bank was equipped with new filters, and one measurement was made with a set of filters that previously had been in operation for seven months. The straight dotted line in the diagram is estimated when the long-term filtration efficiency is assumed to vary linearly with operation time, from the initial efficiency to the final efficiency.

4.3 Pressure drop

Figure 8 shows the pressure drops of the synthetic M6 filter and the glass fiber F7 filter measured in the full scale laboratory test rig. Data are shown both for new filters and for filters that had been in operation during about 7 months. The average pressure drop was calculated as the arithmetic average of the value observed for the new filter and the value for the used filter. The pressure drop of the synthetic M6 filter is about 25%-33% lower than that of the glass fiber F7 filter. Assuming that the fan efficiency is constant, this means that the ionizer-assisted synthetic M6 filter consumes 25%-33% less fan electricity than the glass fiber F7 filter does. The pressure drop reduction percentage is calculated according to Equation 3. Pressure drops observed during the field measurements have also been added to Figure 8. These data are distributed on the curves of the laboratory filter test rig measurements. The diagram shows results for face velocities up above 4 m/s, which is substantially above normal values. Typically the face velocity is well below 3 m/s.

$$Pressure\ drop\ reduction\ = 1 - \frac{average\ \ pressure\ \ drop\ \ of\ M6}{average\ \ pressure\ \ drop\ \ of\ F7} = 1 - \frac{dP_{M6}}{dP_{F7}} \qquad [3]$$

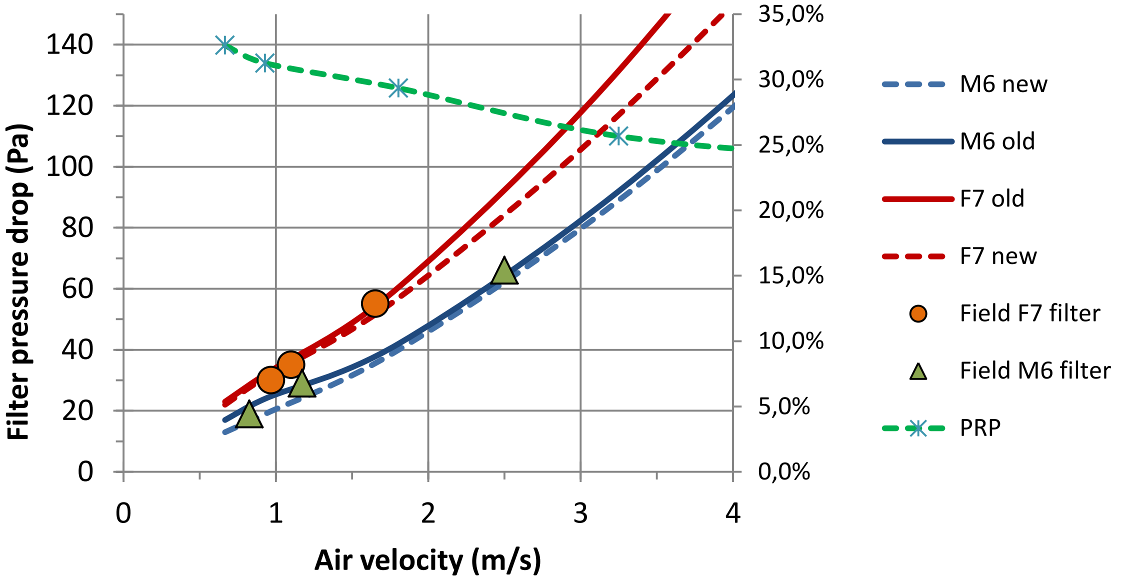

Figure 8. *Pressure drops measured for the glass fiber filter of class F7 and the synthetic M6 filter together with the pressure drop reduction percentage. The reported pressure drops are the values measured when the filters were new and the values measured after about 7 months of operation. Data from the field test of the glass fiber F7 filter and the ionizer assisted synthetic M6 filter are also presented.*

4.4 Ozone generation

The ozone concentrations were measured upstream and downstream of the ionizer assisted M6 filtration in the field, see Figure 9. The results showed that ozone concentrations were almost the same on the upstream and downstream sides. This clearly indicates that the ionization did not generate ozone at any rate of concern.

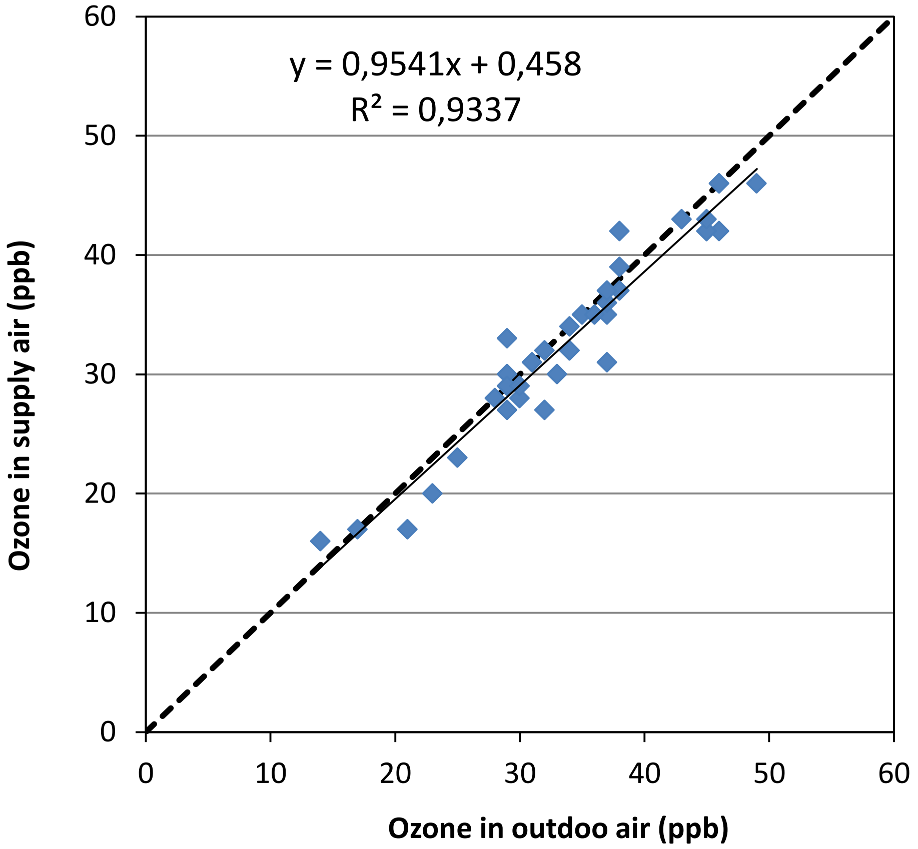

Figure 9. *Ozone concentrations measured before (outdoor) and after (supply) the ionizer assisted M6 filter tested in the field. The data were collected repeatedly over the entire test period of about 7 months.*

4.5 Influencing factors

The outdoor relative humidity (RH), temperature (t) and particle concentration as well as air flow rate ($\dot{V}$) in the air handing unit may influence the air filtration efficiency. Therefore, when the synthetic M6 filter had been in operation for 6 months without ionization in the laboratory, an ionizer system was installed in the laboratory filter test rig to test the influence of these factors on the filtration efficiency.

Relative Humidity

Figure 10 shows that the ionizer-assisted air filtration efficiency decreases with increasing RH, while the efficiency values measured without ionizer increases a bit with RH. Furthermore, the former efficiency is more sensitive than the latter efficiency to the variation of outdoor RH. The solid lined represent RH-values observed during the field measurements. Lower RH-values, down towards 40% RH, were observed in the laboratory only. The data were collected at about constant values of temperature and upstream particle concentration (t=20 ºC, conc. of 0.4µm particles= $1*10^7$ #/m^3)

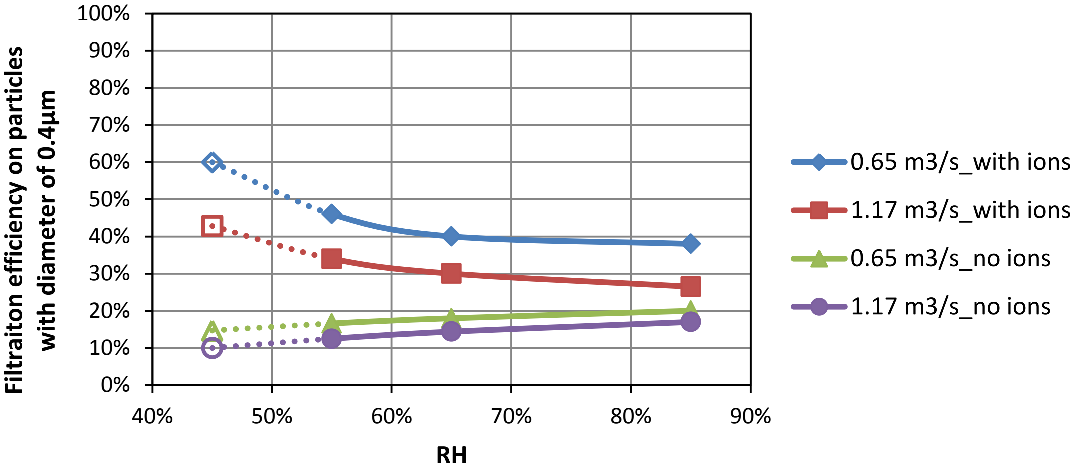

Figure 10. *Filtration efficiency (0.4µm) of the synthetic M6 filter, both with and without ionization, plotted against the upstream relative humidity. All data were collected when the filter had been in operation for 6 months.*

Temperature

Figure 11 indicates that the air filtration efficiencies, both with and without ionizer, vary slightly with temperature. However, the influence of temperature on the filtration efficiency is much smaller than the influence of RH is. Note that the observed temperature interval is quite small, and that there is no apparent reason why the temperature should influence the efficiency. The result may be due to experimental uncertainties. The data were collected at about constant values of relative humidity and upstream particle concentration (RH=45%, conc. of 0.4µm particles= $1.2*10^7$ #/m^3)

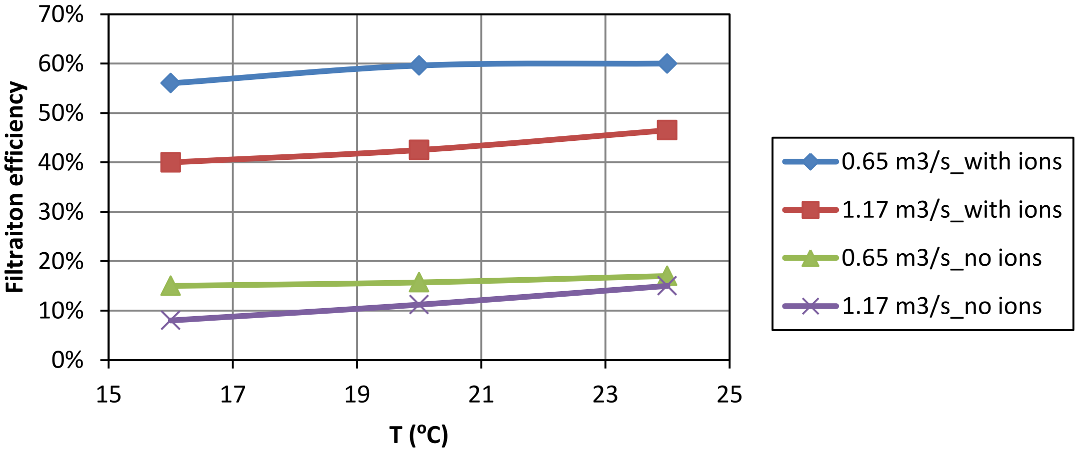

Figure 11. *Filtration efficiency (0.4µm) of the synthetic M6 filter, both with and without ionization, plotted against the upstream air temperature. All data were collected when the filter had been in operation for 6 months.*

Outdoor PM

Figure 12 shows that the air filtration efficiencies, both with and without ionizer, decrease with increasing outdoor particle concentration. However, the variation appear to decrease as the outdoor particle concentration increases. The data were collected at about constant values of temperature and relative humidity (t=20 ºC, RH=65%).

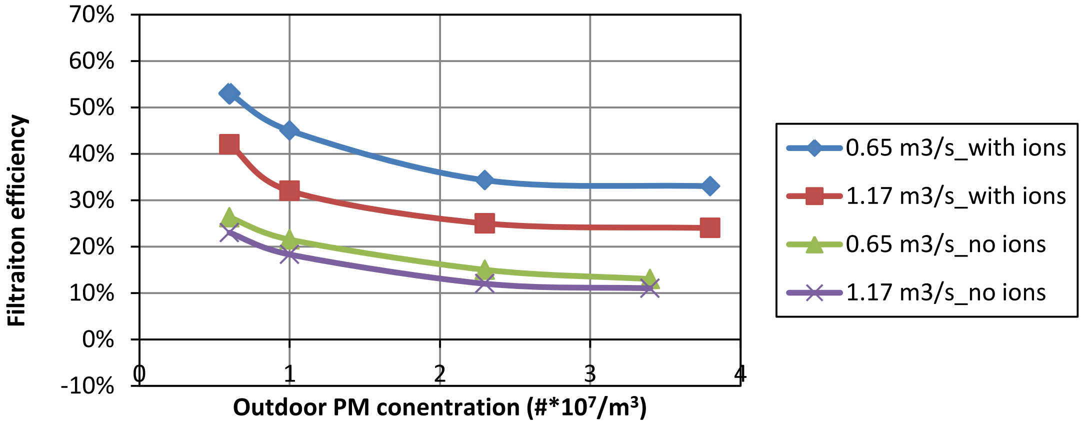

Figure 12. *Filtration efficiency (0.4µm) of the synthetic M6 filter, both with and without ionization, plotted against the upstream concentration of 0.4µm particles. All data were collected when the filter had been in operation for 6 months.*

Air flow rate

Figure 13 shows that the air filtration efficiencies, both with and without ionizer, decrease with air flow rate through filters. The efficiency with ionizer is more sensitive than the efficiency without ionizer to the variation of air flow rate. The data were collected at about constant values of temperature, relative humidity and upstream particle concentration (t=20 ºC, RH=45%, conc. of 0.4 µm particles=$1.2*10^7$ #/m^3)

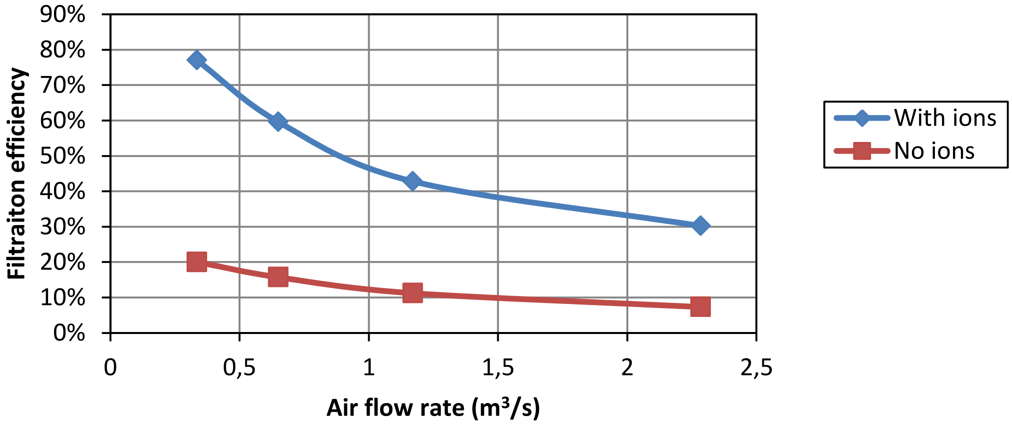

Figure 13. *Filtration efficiency (0.4µm) of the synthetic M6 filter, both with and without ionization, plotted against the supply airflow rate through the filter. All data were collected when the filter had been in operation for 6 months.*

4. Summary and Conclusions

Compared to an identical filter operated without ionization, the ionization enhanced the filtration efficiency of the synthetic M6 filter by more than 20 %-units and maintained about 40 %-units increase during most of the operation time.

The glass fiber filter of class M6 tested without ionization showed efficiency values in the range 15-20% throughout the test. The corresponding values for the glass fiber filter of class F7 were 50-60%. The ionizer assisted synthetic filter of class M6 typically showed substantially higher efficiency values than both the glass fiber filters.

The filtration efficiency of the ionizer assisted synthetic M6 filter dropped from an initial value close to 100% to about 40% at the end of the 7 month test period. The efficiency was found to be substantially above 50% during most of the measurements made during the first 190 days of operation. However, after about 110 days the efficiency dropped below 50%. When the polarity of the ionization was switched from positive to negative, the efficiency increased to 70-75%. The efficiency then began to degrade again.

The pressure drop measurements indicated that the average pressure drop of the ionizer-assisted synthetic M6 filter operated during 7 months was about 25%-33% lower than that of the glass fiber F7 filter originally installed in the air handling unit. The pressure drop reduction appeared to decrease with increasing filter face velocity. The results indicate that the ionizer-assisted air filtration system can save at least 1/4 of the fan electricity used for F7 class air filtration. If the filter face velocity is not higher than about 2 m/s the saving may approach 1/3. Note that typically the air velocity is found to be well below 2.5 m/s.

The ozone concentrations measured in both the field and the laboratory were about the same upstream and downstream of the ionizer assisted filtration system. Thus, there are no indications of any substantial ozone generation.

The analysis of influencing factors showed that outdoor air humidity, particle concentration and outdoor air flow rate had substantial effects on the filtration efficiency, while outdoor temperature had only a slight (negligible) effect. The efficiency of ionizer-assisted air filtration appears to be more sensitive to the studied influencing factors, compared to the efficiency without ionization.

The filtration efficiencies observed with and without ionization showed opposing variation trends, with respect to relative humidity. The filtration efficiency with ionization decreased with increasing relative humidity, while the efficiency without ionization slowly increased with relative humidity. Both increasing outdoor particle concentration and increasing air flow rate through the filters showed negative effects on the filtration efficiencies, both with and without ionization.

Finally, the investigation shows that ionizer assisted filtration in combination with synthetic filters has clear benefits. There is reason to study this technology further, with the aim to establish design and operation guidelines. The technology should then be ready for final full scale testing, in under a variety of conditions. Future investigations should address the following issues:

- Optimization of ioniozer operation
    - Frequency of switching the ionization polarity
    - Number of ionization points
    - Ionization voltage
- Optimization of filter fiber material
    - Mix of synthentic fiber types (e.g. polypropylene, polyester and modacrylic fibers)
    - Packing density of the fiber structure

5. References

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Appendix A

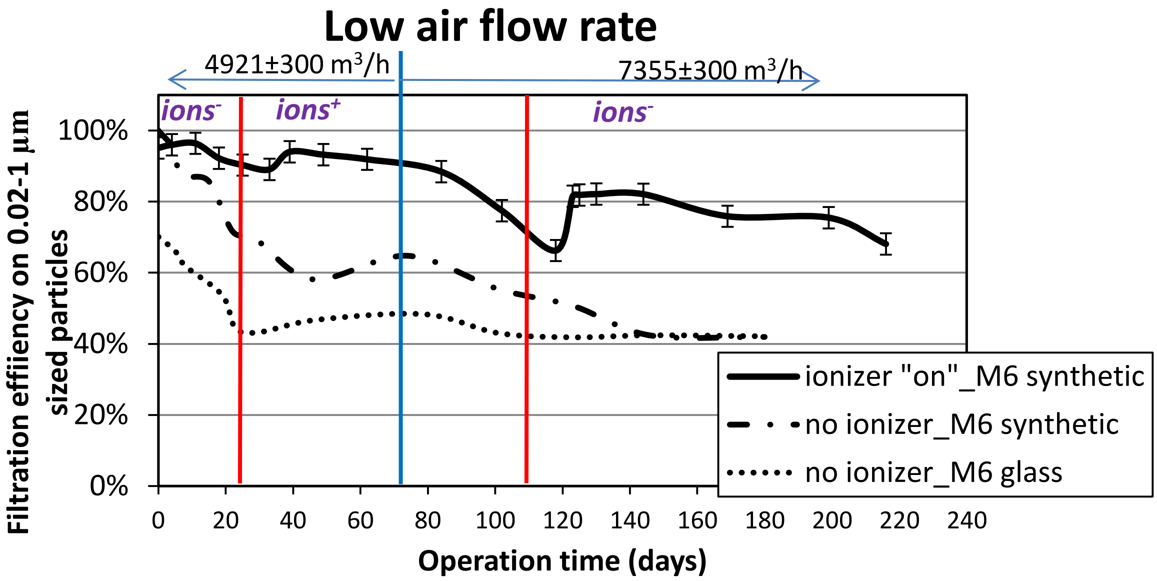

Figure A1. *Filtration efficiency values (0.01-1µm) measured for the synthetic M6 filter tested in the field with ionization, together with values measured for an identical synthetic M6 filter and a glass fiber filter of class M6 tested in the laboratory without ionization. The data were collected at relatively low air flow rates. The laboratory tests were conducted at an air velocity of 1 m/s, while the field measurements were made at velocities between 0.8 and 1.2 m/s.*

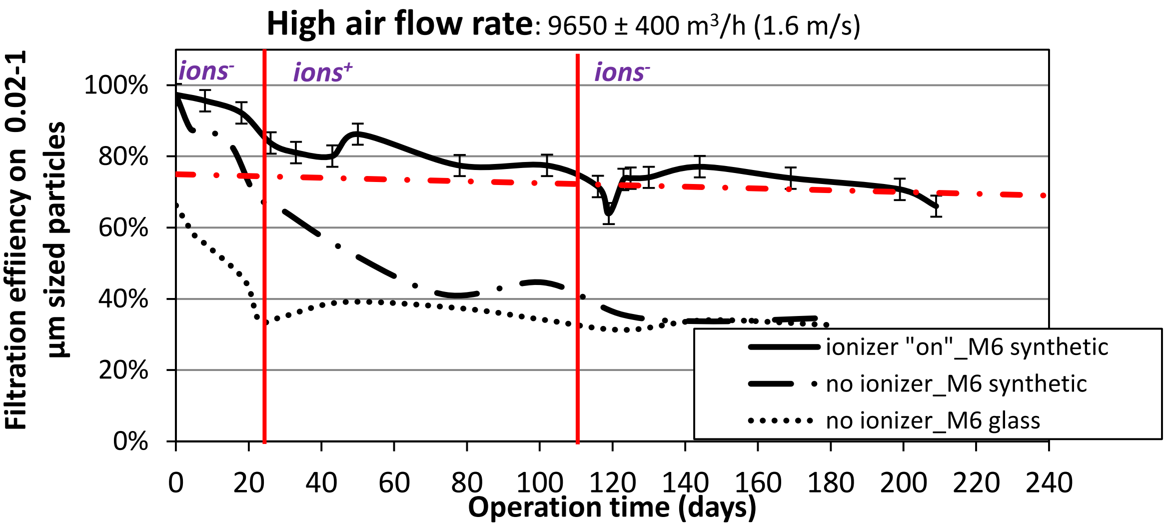

Figure A2. *Filtration efficiency values (0.02-1 µm) measured for the same filters as in Figure A1. The diagram also shows data for a glass fiber filter of class F7, tested in the laboratory without ionization. The data were collected at high airflow rates. Both the laboratory tests and the field measurements were conducted at an air velocity of 1.6 m/s.*

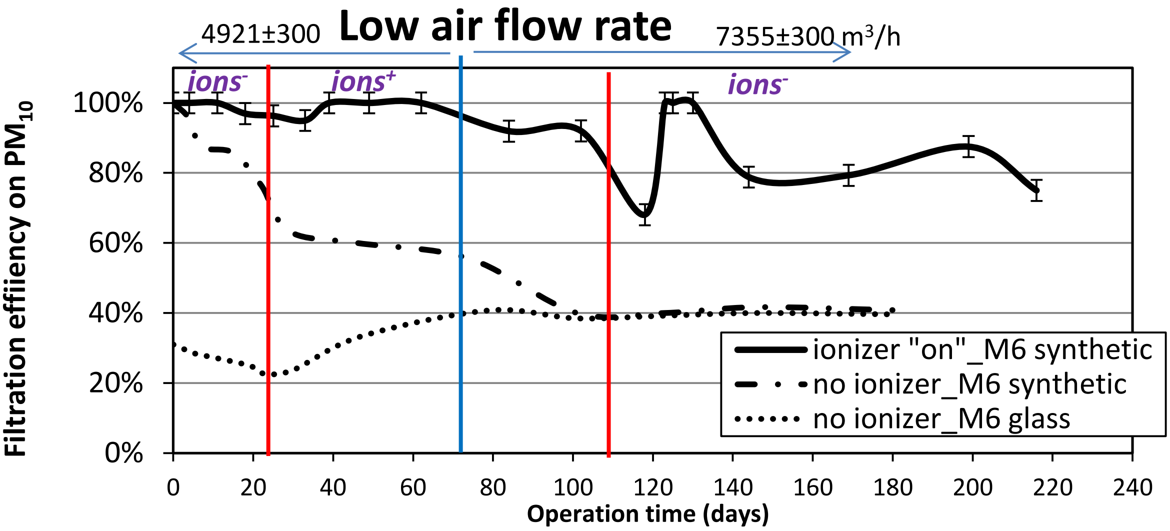

Figure A3. *Filtration efficiency values (PM10 mass concentration) measured for the synthetic M6 filter tested in the field with ionization, together with values measured for an identical synthetic M6 filter and a glass fiber filter of class M6 tested in the laboratory without ionization. The data were collected at relatively low air flow rates. The laboratory tests were conducted at an air velocity of 1 m/s, while the field measurements were made at velocities between 0.8 and 1.2 m/s.*

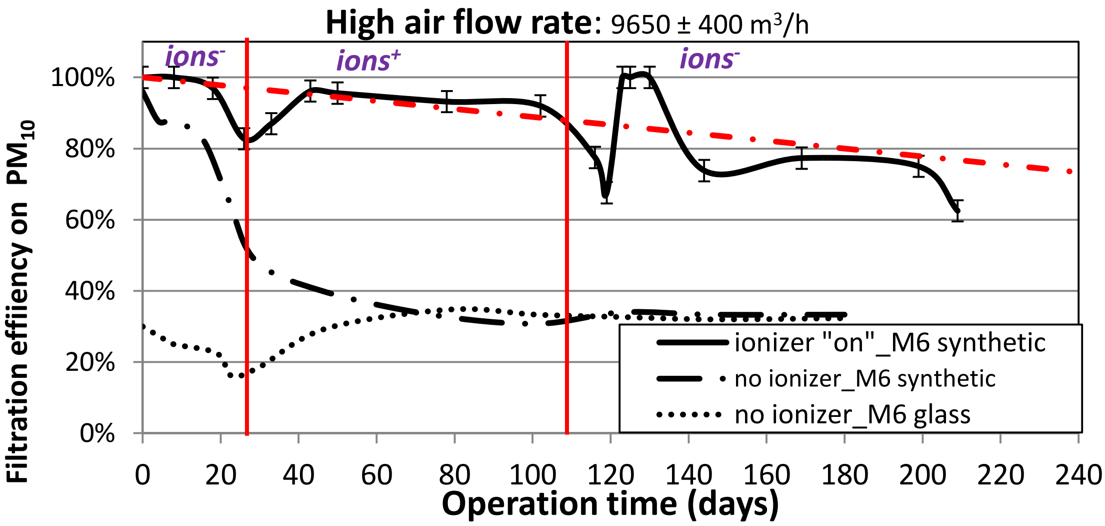

Figure A4. *Filtration efficiency values (PM10 mass concentration) measured for the same filters as in Figure A1. The diagram also shows data for a glass fiber filter of class F7, tested in the laboratory without ionization. The data were collected at high airflow rates. Both the laboratory tests and the field measurements were conducted at an air velocity of 1.6 m/s.*