Journal of Occupational and Environmental Hygiene
Publication details, including instructions for authors and subscription information:
http://www.informaworld.com/smpp/title~content=t713657996

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First published on: 17 August 2010

To cite this Article Raynor, Peter C. and Chae, Soo Jae(2004) 'The Long-Term Performance of Electrically Charged Filters in a Ventilation System', Journal of Occupational and Environmental Hygiene, 1: 7, 463 — 471, First published on: 17 August 2010 (iFirst)

To link to this Article: DOI: 10.1080/15459620490467783

URL: http://dx.doi.org/10.1080/15459620490467783

Journal of Occupational and Environmental Hygiene, 1: 463–471
ISSN: 1545-9624 print / 1545-9632 online

DOI: 10.1080/15459620490467783

The Long-Term Performance of Electrically Charged Filters in a Ventilation System

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The efficiency and pressure drop of filters made from polyolefin fibers carrying electrical charges were compared with efficiency and pressure drop for filters made from uncharged glass fibers to determine if the efficiency of the charged filters changed with use. Thirty glass fiber filters and 30 polyolefin fiber filters were placed in different, but nearly identical, air-handling units that supplied outside air to a large building. Using two kinds of real-time aerosol counting and sizing instruments, the efficiency of both sets of filters was measured repeatedly for more than 19 weeks while the air-handling units operated almost continuously. Pressure drop was recorded by the ventilation system's computer control. Measurements showed that the efficiency of the glass fiber filters remained almost constant with time. However, the charged polyolefin fiber filters exhibited large efficiency reductions with time before the efficiency began to increase again toward the end of the test. For particles 0.6 μm in diameter, the efficiency of the polyolefin fiber filters declined from 85% to 45% after 11 weeks before recovering to 65% at the end of the test. The pressure drops of the glass fiber filters increased by about 0.40 in. H_2O, whereas the pressure drop of the polyolefin fiber filters increased by only 0.28 in. H_2O. The results indicate that dust loading reduces the effectiveness of electrical charges on filter fibers.

Keywords air filtration, dust loading, efficiency, electrostatics, filters, ventilation

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INTRODUCTION

Filters made from fibers carrying electrical charges have been used since 1930 in applications such as respiratory protection, home air filtration, and large building ventilation.[1] Electrically charged fibers enhance filtration by attracting particles carrying an opposite charge and by establishing image forces in neutrally charged particles to accelerate their movement toward the fiber surface. These mechanisms lead to higher initial collection efficiency with no pressure drop penalty relative to a similar filter with fibers carrying no electrical charge.

Several experimental studies have indicated that the efficiency of particle collection by electrostatically enhanced filters, often called electret filters, can decrease as particles deposit within the filter. As electret filters made from large polypropylene fibers were loaded with quartz particles, Jodeit and Löffler[2] found that efficiency declined initially, reached a minimum, and then increased again with time. For small polycarbonate electret fibers, no efficiency decrease was observed. Lathrache et al.[3] found that both electrostatically spun fibers and split fiber electret materials exhibited decreases in efficiency with time as they were loaded with sodium chloride particles before reaching a maximum particle penetration and becoming more efficient. Baumgartner and Löffler[4] observed similar efficiency changes for electret filters exposed to small sodium chloride particles. However, when the same filters were exposed to large quartz particles, only increases in efficiency were observed. All three of these papers hypothesized that efficiency decreased initially upon loading with small particles because the small particles discharged the initial electrostatic charge on the fibers. They also hypothesized that once sufficient particles were collected, increases in collection by impaction, interception, and diffusion mechanisms led to an increase in efficiency. Small particles were expected to be more effective at reducing electrostatic effects because they had more intimate contact with the fiber upon collection.

Other authors have suggested that collected particles do not discharge the fibers. Instead, they hypothesize that while the inherent charge remains on the fibers, the collected particles block the charge from being effective on additional particles. Brown et al.[5] tested the efficiency performance of electrically charged respirator filters over time against seven different industrial dusts. Having observed different amounts of efficiency degradation depending on the properties of the aerosol being collected, Brown et al. suggested that the electrical properties and size distribution of the aerosols influenced the changes in efficiency. Walsh and Stenhouse[6] observed efficiency reductions followed by rising efficiency as electret filters were loaded with stearic acid particles. They indicated that particle size, particle charge, filter face velocity, fiber charge, and humidity were important factors in determining the change in penetration through electret filters with time. Brown[7] and Moyer and Bergman[8] showed that intermittent exposures to aerosols could lead to larger increases in penetration than a constant incoming particle challenge.

Electrically charged filters have exhibited significant efficiency decreases when exposed to liquid aerosols. Schürmann and Fissan[9] and Tennal et al.[10] measured large efficiency decreases over time for electret filters exposed to oil droplets. These authors hypothesized that oils were especially effective at shielding charges on fibers because the liquid spread across the fiber surface.

Most of the studies on changes in performance over time in filters with electrically charged fibers have been conducted in laboratory settings. Lehtimäki and Heinonen[11] indicated that although many laboratory studies have shown that changes in electret filter performance will depend on aerosol properties, little information is available to determine how electret filters will perform when exposed to typical atmospheric aerosols. Wang,[12] noting that wide discrepancies exist between theory and experimental measurements, suggested that more information is needed to understand the long-term performance of electret filters.

With increasing concern about the susceptibility of large buildings to terrorist attacks, assuring adequate performance of filters used in heating, ventilating, and air-conditioning (HVAC) systems has been identified by the National Institute for Occupational Safety and Health[13] as a critical element in protecting building environments. Thus, the purpose of this research was to gather data on the long-term performance of electrically charged ventilation filters exposed to atmospheric aerosols in an operating HVAC system.

METHODS

The performances of filters made from glass fibers carrying no inherent charge, and filters made from polyolefin fibers carrying an electrostatic charge, were evaluated for more than 19 weeks in operating HVAC systems. These systems, which were virtually identical, were located in a large office and laboratory building on the University of Minnesota Twin Cities campus.

Ventilation Systems

The two air-handling units used to test the filters were each sized to deliver a maximum of about 60,000 cfm of fresh air to the building. Both systems, located in the basement of the building, supplied 100% outside air to minimize concentrations of pollutants generated within the building. The intakes to the systems were located about one story above the ground within 10 m of one another horizontally on the same side of the building. The intakes were located above a lightly traveled road. The loading dock for the building was located around the corner from the intakes.

Air was drawn through the intakes downward into the air-handling units. In each system, the air then passed through a bank of thirty 2 ft. × 2 ft. prefilters before entering the blower. Tests performed by an outside laboratory according to ASHRAE Standard 52.2-1999 indicated that the prefilters collected more than 90% of incoming particles 3 μm in diameter or larger after minimal dust loading. On exiting the blower, the air encountered a mist humidification system that was turned off throughout the test. The air next moved through the 30 primary filters tested in the units. In each unit, the 2 ft. × 2 ft. filters were arrayed in five rows and six columns. On leaving the filters, the air passed through the air-conditioning and heating systems before being distributed to the building. The airflow and temperature delivered by the systems were adjusted by computer control to meet the requirements of the building environments.

Test Filters

Examples of the test filters are shown in Figure 1. The polyolefin fiber filters were made from polyethylene and polypropylene fibers. Both the polyolefin fiber and glass fiber filters were constructed by forming the media into 15 pleats, each about 28 cm deep and 54 cm tall, that were glued into frames. When measured according to the ASHRAE 52.1-1992 dust spot efficiency test by an outside testing laboratory, both kinds of filters were nominally 90–95% efficient. Thirty polyolefin fiber filters were installed randomly into the first air-handling unit while 30 glass fiber filters were placed randomly into the second unit. The choice of air-handling unit for each type of filter was decided by a coin flip.

Efficiency Measurements

After the filters were installed, efficiency measurements were made immediately and then 25 more times during the next 19 weeks and 1 day. For each set of tests, the efficiency of the filters was measured by taking air samples at four locations immediately upstream and four locations immediately downstream from the test filters in each air-handling unit. The samples were drawn through 3.66 m long, sharp-edged probes

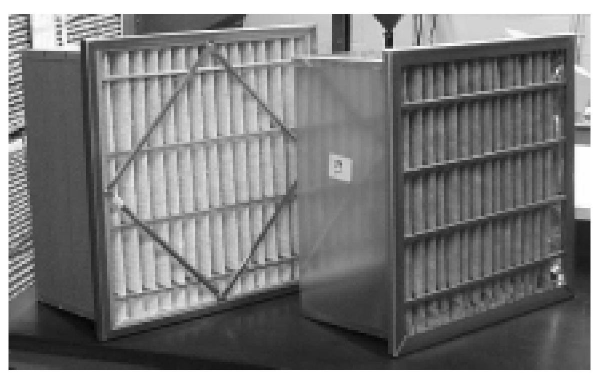

FIGURE 1. Glass fiber (left) and polyolefin fiber filters used for testing

oriented perpendicular to the flow and to gravity. A perpendicular orientation was required to facilitate easy realignment of probes during tests and removal of the probes between sets of tests. The probes were 0.95 cm in diameter. The four samples upstream from the test filters were drawn from the same positions across the face of the filter bank as the four downstream samples. These sampling locations were chosen by bisecting the cross section of the filter bank vertically and horizontally to form four equal rectangles and then centering a sampling point on each of these rectangles. The probes were positioned within 30 cm of the filter surfaces. Two probes were used; at any time during the tests, one probe was located upstream and the other downstream from the same point on the filter bank. Each probe was connected to particle sizing instruments using a 1.52 m length of plastic tubing having an inner diameter of 1.27 cm.

Two instruments were used to measure particle sizes and concentrations upstream and downstream from the filters. For larger particles ranging from 0.504 to 3.05 μm in aerodynamic diameter, an aerodynamic particle sizer (APS) model 3310 (TSI Inc., St. Paul, Minn.) time-of-flight instrument was used to sample the airstream at 5 L/min. Although isokinetic sampling was not possible due to the requirements of realigning and moving the sampling probes, the aspiration efficiency for particles into the probe and transmission efficiency through the probe were calculated.[14] Aspiration efficiency was determined to be at least 90% for all particles of interest when the APS was used. Transmission efficiency was also calculated as more than 90%. For particles between 0.117 and 0.457 μm in diameter, a differential mobility particle sizer (DMPS) electrical mobility instrument (Model 3932; TSI Inc.) was used. This instrument sampled air from the ventilation system at 1 L/min. For the DMPS, the aspiration efficiency of particles of interest was at least 75%, and the transmission efficiency was calculated to be greater than 90%.[14] Although the aspiration and transmission efficiencies were less than 100%, the losses were relatively small. In addition, the sampling probes and sampling lines were identical. Therefore, losses should not have biased the filtration efficiency measurements because they presumably occurred in approximately the same proportions upstream and downstream from the test filters.

For one test, a single sample was taken with each instrument at each of the four locations upstream and downstream from the filters. The APS was allowed to count and size particles for 5 min at each location. The duration of the DMPS samples depended on the amount of time needed for the instrument to stabilize at each voltage employed by the instrument.

In the APS model 3310, counts of particles larger than about 2 μm in aerodynamic diameter were subject to errors due to "phantom particles" created by instrument sizing deficiencies. In the efficiency measurements, the phantom particles manifested themselves as an unlikely decrease in efficiency as particle diameter increased for particles larger than 2 μm. Heitbrink and Baron[15] developed a procedure to correct for the influence of phantom particles by considering information from both the large and small particle signal processors that operate in the APS. Sreenath et al.[16] developed a correction by comparing APS measurements of sampling efficiency to well-developed theory. Unfortunately, neither of these methods corrected counts in a way that seemed to make the efficiency results more accurate. Therefore, no correction was applied to the APS data.

For each pair of readings taken at the same horizontal and vertical location upstream and downstream from the filters, the efficiency, η, was calculated for each particle size according to the equation

$$\eta = 1 - \frac{C_{down}}{C_{up}} \tag{1}$$

where C_{down} is the downstream particle count and C_{up} is the upstream particle count. For each filter bank, this resulted in a set of four efficiency readings for each size interval for each test.

Pressure Drop Measurements

Pressure drop (ΔP) across the filters was recorded once per hour by the computer control system. The pressure drop can be divided by the fan rotational speed to normalize for the flow through the system. This normalized pressure drop (ΔP_{norm}) can be related to ΔP by

$$\Delta P_{norm} = \Delta P\left(\frac{100\%}{V}\right) \tag{2}$$

where V is the fan rotational speed as a percentage of the maximum fan rotational speed. The fan speed was recorded by the computer control system once per hour at the same time as the pressure drop.

Velocity Measurements

At the conclusion of the test period, the velocity in the air-handling units was measured using a thermal anemometer (model 8330 VelociCheck; TSI Inc.). The velocity was measured about 50 cm downstream from the center of each of the 30 filters in each air-handling unit at fan rotational speeds of 80, 85, 90, 95, and 100% of the maximum rotational speed. The anemometer was calibrated to ensure its velocity readings were accurate.

Filter Mass Measurements

The four filters in each air-handling unit that were directly in line with the sampling probe inlets were weighed just before installation in the filter bank. The precision of weighing was the nearest 56.8 g (0.125 lb). After completion of all efficiency testing and removal of the filters, the same eight filters were weighed again. The initial mass was subtracted from the mass of the filter at the completion of the test to determine the amount of mass gained by each of the filters. This mass increase was then divided by the area of the filter media, 4.65 m^2, to calculate the mass loading on the filters.

RESULTS AND DISCUSSION

Over the test period, the four glass fiber filters weighed to determine mass loading gained an average of 341 g (0.75 lb) while the four polyolefin fiber filters gained an average of 227 g (0.50 lb). These loadings are equivalent to 73 g/m^2 for the glass fiber filters and 49 g/m^2 for the polyolefin fiber filters. Although these loading differences were not highly significant ($p = 0.064$), they suggest that the two filter banks might have been exposed to two different quantities of particulates and/or that the glass fiber filters might have been more efficient on average during the entire test period. Because the air-handling units were so similar and the prefilters collected almost all particles large enough to be transported into and within the units differently, the test filters were probably exposed to similar concentrations of particles. Thus, the mass loading differences were most likely caused by differences in efficiency between the two kinds of filters over the test period.

Figure 2 shows data for filtration efficiency versus particle diameter for the glass fiber filters immediately after they were installed (Day 0) and after 134 days of use in the HVAC system. Particles smaller than 0.5 μm in diameter are collected primarily due to Brownian diffusion whereas particles larger than 1 μm in diameter are collected due to interception, impaction, and electrostatic attraction.[7] The efficiency of particle collection by the diffusion mechanism has been shown to vary with particle diameter to the $^{-2}/_{3}$ power for single fibers. On the other hand, filtration by the other mechanisms increases with particle diameter for single fibers. Thus, single fiber efficiency, η_f, can be approximated by the function

$$\eta_f = A' d_p^B + C' d_p^{-2/3} \quad (3)$$

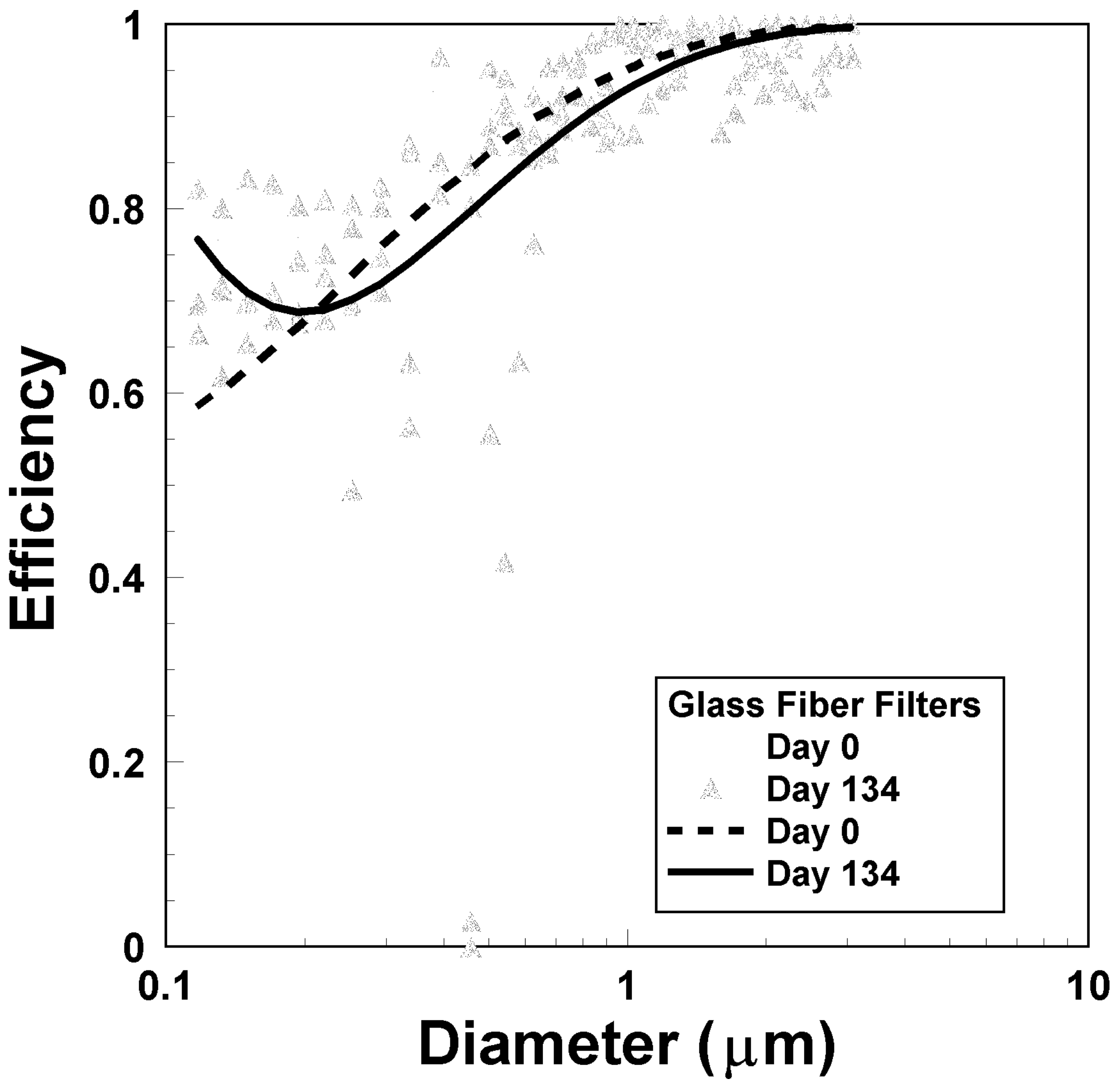

FIGURE 2. Efficiency as a function of particle diameter for the glass fiber filters on the first day of testing (Day 0) and the last day of testing (Day 134). Curves fit through the data according to Eq. 3 are displayed for both days.

where d_p is particle diameter and A′, B, and C′ are parameters to be evaluated empirically from experimental data. Single fiber efficiency is related to total filter efficiency using the expression

$$\eta = 1 - \exp\left(-G\eta_f\right) \quad \textbf{(4)}$$

where G is another parameter.[7] Substituting Eq. 3 into Eq. 4 yields

$$\eta = 1 - \exp\left(-Ad_p^B - Cd_p^{-2/3}\right) \quad \textbf{(5)}$$

where A = G × A′ and C = G × C′.

Curves in the form of Eq. 5 have been drawn through each set of data in Figure 2 to show the trend in efficiency as a function of d_p. The parameters A, B, and C were fit to the data using SAS statistical software.[17] For Day 0, the parameters A = 3.01 and B = 0.617 were significantly different from zero at a 95% confidence level whereas the parameter C = 0.00333 was not. For Day 134, the parameters A = 2.64, B = 0.688, and C = 0.0350 were all significantly different from zero with 95% confidence.

For the polyolefin fiber filters, Figure 3 shows data for efficiency as a function of particle diameter immediately after the filters were installed and after 134 days of use. Curves fit to these data according to Eq. 5 have been plotted as well. The parameters A = 2.83, B = 0.570, and C = 0.00968 for the Day 0 data and A = 1.59, B = 0.874, and C = 0.0195 for Day 134 were all significantly different from zero at a 95% confidence level.

The results in Figures 2 and 3 show that the polyolefin fiber filters had a much larger decrease in efficiency over the test period than the glass fiber filters. The glass fiber filters had

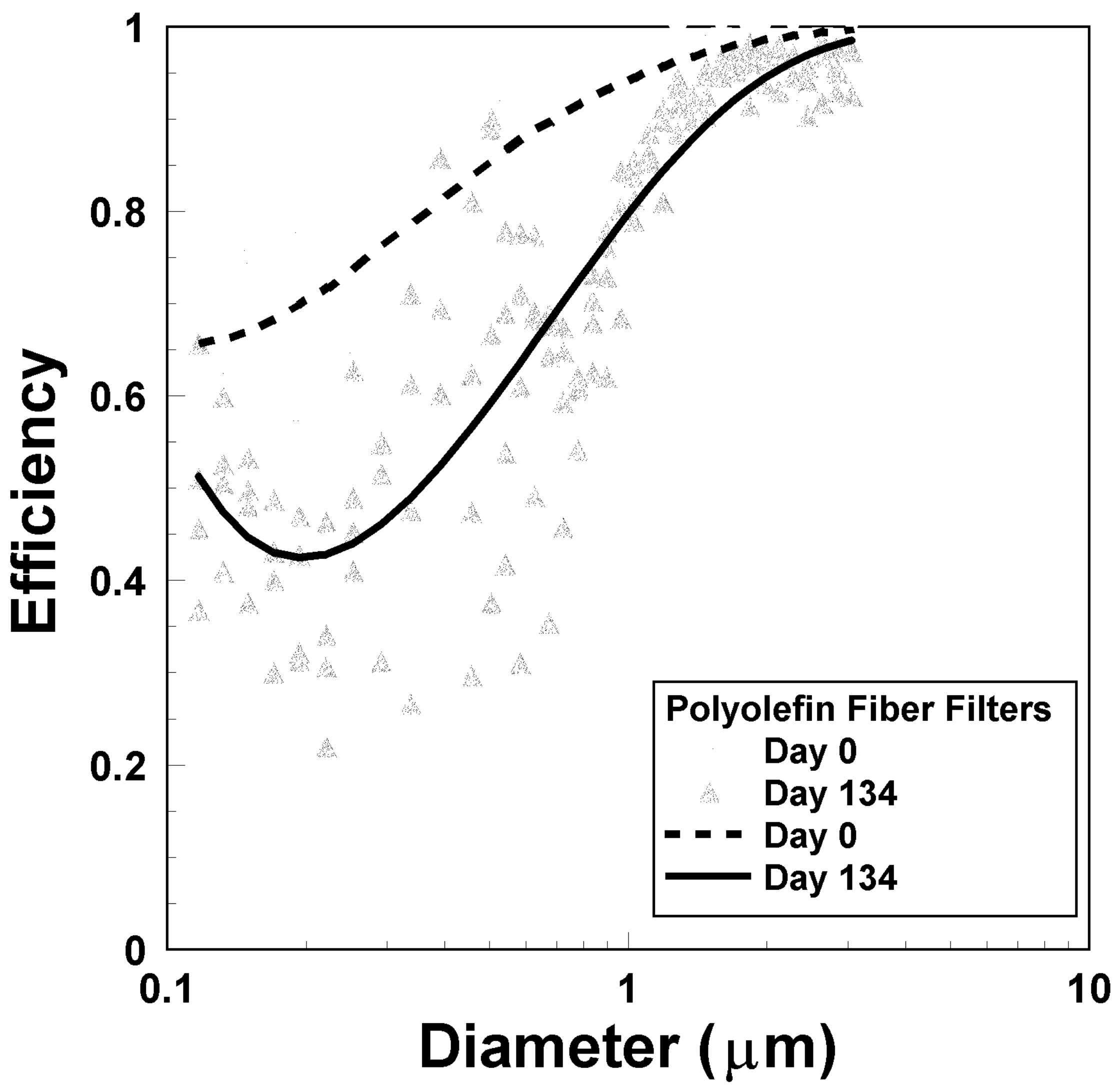

FIGURE 3. Efficiency as a function of particle diameter for the polyolefin fiber filters on the first day of testing (Day 0) and the last day of testing (Day 134). Curves fit through the data according to Eq. 3 are displayed for both days.

no statistically significant efficiency changes during the test except for a small increase in efficiency for particles with diameters smaller than 0.2 μm. However, the polyolefin fiber filters exhibited significant efficiency reductions for all particles with diameters smaller than 2 μm. These efficiency reductions are consistent with experimental findings of other authors.[2–8] The effectiveness of the electrostatic charge is reduced over time. This relatively low efficiency for the polyolefin fiber filters may explain why the mass loading is less for these filters than for the glass fiber filters.

Figure 4 presents efficiency measurements versus time for both the glass and polyolefin fiber filters. Each graph in the figure represents the efficiency for a particular particle diameter ranging from 0.15 μm to about 3 μm. In each graph, second-order polynomials are drawn through both the glass and polyolefin fiber filter data. For all particle diameters, the glass fiber filters exhibit little change or small efficiency increases. However, the polyolefin fiber filters show large efficiency decreases followed by efficiency increases for particles 0.291 μm in aerodynamic diameter and larger. The efficiency improvements

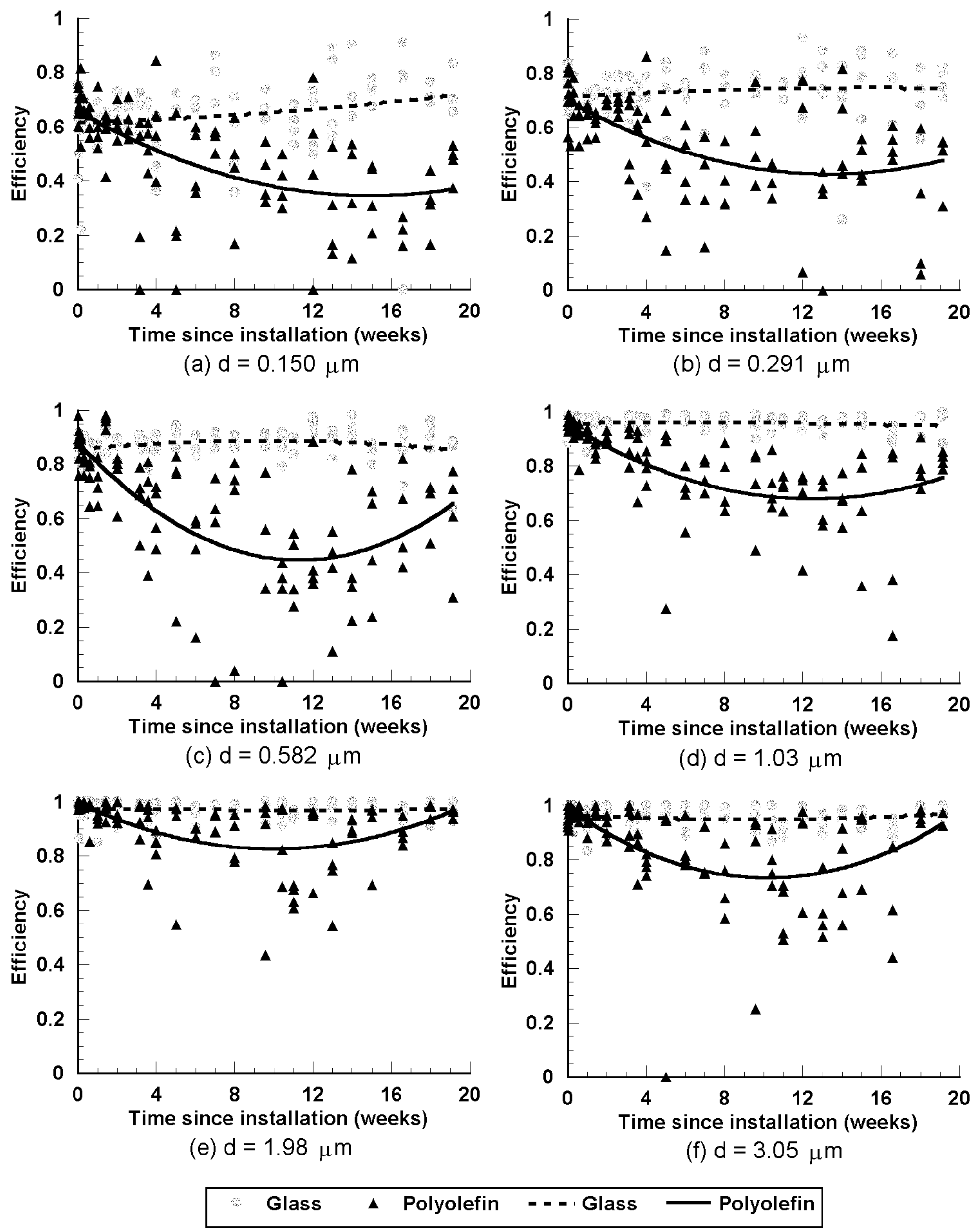

FIGURE 4. Efficiency as a function of time for particles with diameters (a) 0.150 μm, (b) 0.291 μm, (c) 0.582 μm, (d) 1.03 μm, (e) 1.98 μm, and (f) 3.05 μm. Data and second-order polynomial regressions are shown for both the glass and polyolefin fiber filters.

toward the end of the test are probably due to better particle capture by impaction and interception mechanisms as the filters become loaded with particles. For particles 0.150, 0.291, 0.582, and 1.03 μm in diameter, the efficiency differences between the two fiber types are significant statistically after about 2 weeks of use. For particles 1.98 and 3.05 μm in diameter, the efficiency is significantly different between fiber types from 2 weeks into the test until the 2 kinds of filters have almost the same efficiency again at the end of the test period.

With the polyolefin fiber filters, the minimum efficiency for particles 0.582 μm in diameter and larger occurred 10–12 weeks into the test. For 0.291-μm particles, the minimum occurred at about 13 weeks. The minimum efficiency occurred after about 15 weeks for the 0.150-μm particles. These differences with particle size indicate that the interactions among electrostatic and mechanical filtration mechanisms are complex and that efficiency reductions continue to mount for a long time.

The efficiency data in Figures 2–4 exhibit more variability than usually found in a controlled laboratory experiment. This variability is not surprising because many important factors cannot be controlled during field tests like this. For example, the ambient particle size distribution changed from day to day. In particular, the breadth of the distribution and the overall numbers of particles varied widely. In addition, changes in particle concentration occurred within a test. In several instances the data suggested that incoming particle concentrations fluctuated within the pair of size distribution measurements that comprised one efficiency measurement. Thus, these fluctuations increased variability in the efficiency measurements also. Few particles larger than 3 μm in diameter were present upstream from the test filters because relatively few of these particles reside in the ambient environment and because the prefilters were effective at removing particles of this size. Therefore, efficiency measurements by the APS for large particles were highly variable because a change of even a single particle in the upstream or downstream count could influence the efficiency measurably. This variability was especially important for particles larger than 2 or 3 μm in diameter because they were susceptible to the APS phantom particle problem.

With the DMPS, the largest particles measured by the instrument exhibited more variability because fewer of the larger particles were present in the sampled air. Furthermore, the fan speeds in the air-handling units were not constant during tests. The units responded to ventilation requirements within the building as determined by the computer control. Thus, velocity through the filters sometimes varied by several percent within a single test. Filtration theory suggests that the differences in efficiency caused by even a 20% change in velocity, the maximum difference observed throughout the tests, were within the variability of the data in this study.

In addition to temporal variability, comparison of the four efficiency readings across the face of each filter bank showed some variability. For both air-handling units, efficiency measured in front of the filter in the fourth row from the top of the bank and the fifth column from the sampling instruments was lower than the efficiency for the filters in the fourth row and second column, the second row and second column, and the second row and fifth column. For most particle diameters larger than 0.5 μm, this difference in efficiency was significant. The reasons for these differences and why they would occur in both air-handling units are unknown. Because the lower readings occurred in both air-handling units, the overall efficiency results were not biased by this variability by location.

Figure 5 shows pressure drop versus time for the entire test period. The actual pressure drop readings were normalized for airflow using Eq. 2. Within each day, the 24 hourly normalized pressure drops were averaged to produce the data shown in the figure. Initially, the pressure drop for the glass fiber filters was lower than the pressure drop for the polyolefin fiber filters. By the end of two weeks of testing, however, the pressure drop was the same for the two kinds of filters. Between Weeks 3 and 7 of testing, the glass fiber filters showed several rapid reductions in pressure drop before returning to a level that was higher than the pressure drop for the polyolefin fiber filters. The reasons for the three distinct decreases in pressure drop are not clear. However, the changes coincided with the three periods of hottest daily high temperatures during the test period. The cooling load placed on the air-handling units may have had something to do with the fluctuations in pressure drop measurements. After 7 weeks, the pressure drop gradually increased for both types of filters at about the same rate. In the final 3 weeks of testing, the pressure drop increased more rapidly for both kinds of filters. This result suggests that the filters may have been starting to clog. For the entire test, ΔP_{norm} for the glass fiber filters increased 67% from 0.60 in. H_2O to about 1.0 in. H_2O. The polyolefin fiber filter ΔP_{norm} rose 42% from about 0.67 in. H_2O to 0.95 in. H_2O. This larger pressure drop increase for the glass fiber filters probably resulted from the higher collection efficiency offered by these filters during most of the test.

Table I presents the air velocity measured in the air-handling units at the conclusion of the testing period. The average and standard deviation of 30 measurements taken for each set of filters are shown for percentages of the maximum fan speed

TABLE I. Velocity of Air Moving Through the Air-Handling Units for Different Fan Speed Settings at the Conclusion of the Testing Period

Fan Speed, Percent of Maximum	Glass Fiber Filter Velocity Mean/Standard Deviation (ft/min)	Polyolefin Fiber Filter Mean/Standard Deviation (ft/min)
80	570/68.2	565/87.5
85	584/74.3	627/105
90	613/64.4	669/139
95	619/68.0	711/175
100	636/66.2	748/173

Note: The mean and standard deviation of 30 readings are presented for each condition.

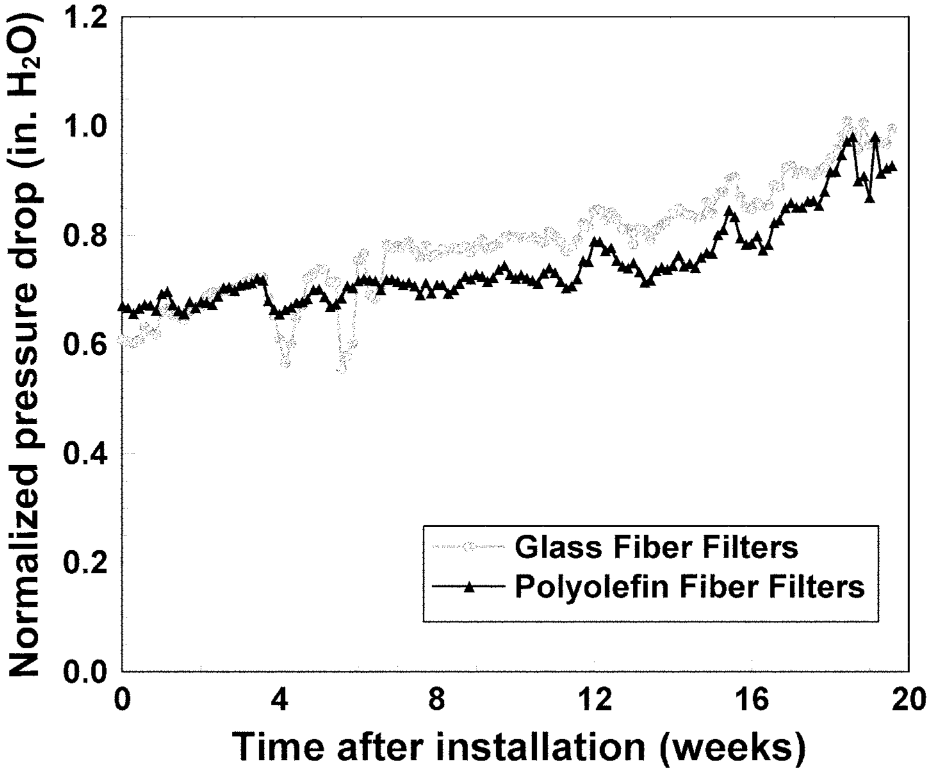

FIGURE 5. Pressure drop vs. time for the glass and polyolefin fiber filters used in the air-handling units. The pressure drop has been normalized by dividing by the fan rotational speed as indicated in Eq. 2.

ranging from 80 to 100%. For the same fan speed, the velocity was generally higher in the air-handling unit containing the polyolefin fiber filters than in the unit housing the glass fiber filters. However, this difference may have been influenced by the variance in the measured velocities for the polyolefin fiber filters. The measured velocity varied widely for the polyolefin fiber filters both from filter to filter and within the area covered by a single filter. The thermal anemometer indicated that the polyolefin fiber filters had regions within a single filter that had substantially higher velocities than other sections. In some cases, these "jets" could be felt by holding a hand near the filter's downstream surface. No jets were observed for the glass fiber filters. The reasons for the jets in the polyolefin fiber filters are not clear; no obvious rips were observed, for example. However, these jets may indicate that the polyolefin fiber filter media was stretched out in places or developed small voids, or that the particles deposited non-uniformly within the filters.

The findings in this article apply to only one comparison of filters at one location during one period of time. However, these findings in a field test agree with the majority of data obtained from laboratory studies.

When industrial hygienists, environmental health specialists, or others select filters for HVAC or other applications such as respiratory protection or local exhaust ventilation, they should consider the implications of using filters enhanced by electrical charges. Although these filters may offer performance advantages initially when compared to filters carrying no electrical charges, the performance advantages may not be maintained over time. If filters carrying electrical charges are used, additional monitoring of filter performance with time may be warranted.

CONCLUSIONS

Filters made from uncharged glass fibers and filters made from polyolefin fibers that carry electrical charges were placed in almost identical HVAC systems operated continuously for more than 19 weeks. Properties such as filtration efficiency, pressure drop, and filter mass were tracked with time.

Results show that the efficiency of the polyolefin fiber filters declined substantially during the test. For instance, the efficiency of particles 0.3 μm in diameter decreased from 70% to as low as 45% during the 134-day test. For particles 0.6 μm in diameter, the decline was from 85% to as low as 45%. Over the same time period, the efficiency for filters made from glass fibers changed little. The data suggest that the benefits of the electrical charges on the polyolefin fibers diminished with time as dust built up on the fibers and rendered the charge ineffective. The results from these field measurements bolster the findings of several researchers who have loaded aerosols onto electret filters in the laboratory. The higher efficiency of the glass fiber filters relative to the polyolefin fiber filters is a likely reason for the greater mass loading and larger pressure drop increase measured for the glass fiber filters.

Before buying filters, it should be determined if the filters use charged fibers. If so, buyers should consider the implications of any reductions in filter efficiency that could occur with use.

ACKNOWLEDGMENTS

This research was supported by Johns Manville Corporation and the authors' primary contact with Johns Manville, Charles Kern. Don Thornburg of Camfil Farr was instrumental in obtaining proper filters; Andrew Streifel of the University of Minnesota Department of Environmental Health and Safety assisted the authors in setting up this project. The authors acknowledge the essential support provided by Ladang Hak, John Goettl, Dale Runge, and, especially, Bill Allen, of the University of Minnesota Facilities Management for their help in data management, filter handling, and other support.

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