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Sensory pollution from bag filters, carbon filters and combinations

Abstract Used ventilation filters are a major source of sensory pollutants in air handling systems. The objective of the present study was to evaluate the net effect that different combinations of filters had on perceived air quality after 5 months of continuous filtration of outdoor suburban air. A panel of 32 subjects assessed different sets of used filters and identical sets consisting of new filters. Additionally, filter weights and pressure drops were measured at the beginning and end of the operation period. The filter sets included single EU5 and EU7 fiberglass filters, an EU7 filter protected by an upstream pre-filter (changed monthly), an EU7 filter protected by an upstream activated carbon (AC) filter, and EU7 filters with an AC filter either downstream or both upstream and downstream. In addition, two types of stand-alone combination filters were evaluated: a bag-type fiberglass filter that contained AC and a synthetic fiber cartridge filter that contained AC. Air that had passed through used filters was most acceptable for those sets in which an AC filter was used downstream of the particle filter. Comparable air quality was achieved with the stand-alone bag filter that contained AC. Furthermore, its pressure drop changed very little during the 5 months of service, and it had the added benefit of removing a large fraction of ozone from the airstream. If similar results are obtained over a wider variety of soiling conditions, such filters may be a viable solution to a long recognized problem.

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Key words: Ventilation filters; Perceived air quality; Activated carbon filter; Sensory pollution; Supply air quality.

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Practical Implications
The present study was designed to address the emission of sensory offending pollutants from loaded ventilation filters. The goal was to find a low-polluting solution from commercially available products. The results indicate that the use of activated carbon (AC) filters downstream of fiberglass bag filters can reduce the degradation of air quality that occurs with increasing particle loading. A more practical solution, yet comparably effective, is a stand-alone particle filter that incorporates AC. In either case, further testing under a variety of conditions is recommended before making design decisions regarding the type of filters best suited to efficient building operation.

Introduction

The benefits of using supply air filters in ventilation and air-conditioning units are well known (Fisk et al., 2002). However, used filters can emit sensory pollutants, which degrade the perceived quality of the ventilation air (Alm, 2001; Clausen, 2004; Pasanen, 1998; Pasanen et al., 1994; Pejtersen, 1996; Pejtersen et al., 1989). At the same time they can contribute to sick building syndrome (SBS) symptoms (Clausen et al., 2002) and negatively impact occupant performance (Wargocki et al., 2004a; Wyon et al., 2000).

Within 6 months of operation, the surface area of particles captured by an outdoor air filter can be two orders of magnitude larger than its cross-sectional area (Weschler, 2003). Various organic compounds such as those emitted by combustion processes or vegetation are associated with the captured particles. Some of these can desorb into the airstream while others can react with ozone contained in the air passing through the filters. The latter process results in the removal of ozone from the ventilation air by used ventilation filters (Bekö et al., 2006, 2007; Hyttinen et al., 2003, 2006; Zhao et al., 2007). However, the products of ozone-initiated oxidation reactions and other chemical transformations may desorb to the airstream and contribute to the degradation of perceived air quality (Weschler, 2004). Desorption processes may be amplified when Heating Ventilation and Air Conditioning (HVAC) fans are first turned on after periods during which the ventilation system has not been in operation (Mølhave and Thorsen, 1991). Mysen et al. (2003) demonstrated that, in comparison with continuous operation, turning off or reducing the airflow through a filter outside working hours increased the sensory pollution emitted from a used bag filter immediately after the ventilation system was turned back on. Similarly, Bekö et al. (2006) found that when a filter is in continuous service, the formation and subsequent off-gassing of oxidation products is much smaller than when a filter initially returns to service after a break in operation.

The extent to which the above-mentioned chemical processes occur on used filter surfaces may depend on the amount of particulate mass captured on the filter surface (Hyttinen et al., 2006), location, season, filter type and position of the filter in the ventilation unit. The studies of Hyttinen et al. (2001, 2007) and Pasanen (1998) indicate that loaded pre-filters have higher odor emission rates than loaded final filters. Pasanen et al. (1994) concluded that the use of pre-filters decreased the odorous emissions coming from final filters. The authors recommended frequent changes of pre-filters, designed to remove primarily coarse particles, to minimize odorous emissions from ventilation units.

Activated carbon filters can effectively remove ozone and selected organic pollutants from airstreams. Shair (1981) investigated the use of activated charcoal filters for the removal of ozone in a demonstration project and concluded that this was an economically viable approach to significantly reduce the outdoor-to-indoor transport of ozone. Weschler et al. (1993, 1994) and Shields et al. (1999) examined the ozone removal of several AC filters over several years of operation. The authors found that a carbon filter downstream of both a pre-filter and an 85% filter (equivalent to an EU7) still removed 90% of the ozone in air passing through it after 5 years of continuous operation. Another carbon filter similarly protected by particle filters removed 70% of the ozone in the airstream after 7 years of continuous operation. A carbon filter protected by only a pre-filter removed 60% of the ozone after 8 years of continuous operation. In a recent laboratory study of a scaled-down AC filter (Zhao, 2006), the filter removed close to 100 % of the ozone in a test airstream over a period of 5 months. However, this evaluation was conducted at a decreased airflow, with a face velocity of 0.0036 m/s.

Mysen et al. (2006) compared the perceived air quality downstream of a regular F7/EU7 bag filter with that from a bag filter that incorporated AC. Both filters were in service for 3 months under identical conditions. In subsequent evaluations, the air quality was perceived to be significantly better downstream of the used carbon-containing bag filter than downstream of the standard bag filter.

Clausen (2004) has observed: 'The most obvious solution (to polluting filters) would be to completely remove the particles from the air stream. …If particles are collected by a filter media it is important to somehow remove the collected particles on the filter surface….' Until such advances occur, emissions from used filters must be minimized using available technology. The objective of the present study was to find one or more combinations of commercially available HVAC filters that have low emissions of sensory offending pollutants after extensive use under realistic conditions. Sensory evaluations were performed for eight filters or filter combinations; the combinations included either pre-filters or AC filters. Each filter or filter set was soiled under identical service conditions. Achieving lower emissions of sensory offending pollutants from used filters would have the potential to improve air quality, reduce SBS symptoms and increase performance with only a modest increase in operating costs.

Methods

Eight test plenums were assembled to evaluate various filter types or filter combinations.

The units were situated outdoors in a suburb of Copenhagen, Denmark, at a distance roughly 150 m from a moderately active highway. Each test plenum consisted of one or more 0.3×0.6 m filter boxes, reduction pieces, connecting ductwork, circular duct fans and a damper to regulate the flow of air through the filters (Figure 1). The duct fans were sized to overcome the predicted total pressure drop of the system at the end of the experiments. The inlets of the units were protected from large objects, leaves, tree litter and precipitation. The airflow through the systems was adjusted to $\sim$1300 m^3/h to achieve a standard 2 m/s face velocity through the filters. This corresponds to 75% or 85% of the maximum recommended airflow through bag filters or cartridge filters,

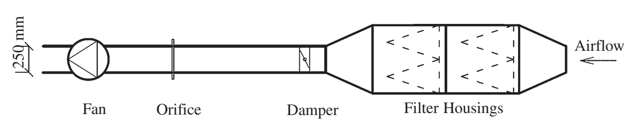

Fig. 1 Test plenum configuration used for soiling and testing several filter types, either alone or in combinations. The number of filter boxes within each unit was based on the number of filters in a given filter set

respectively. As part of the adjustment of the required airflow in each setup, the pressure drop over an integrated orifice was measured. The eight orifices were initially cross-calibrated, to achieve identical airflow in each unit. The units were continuously operated from August 18, 2006 to January 24, 2007 – a little over 5 months. The acceptability of air that had passed through each filter or filter combination was then evaluated subjectively in a laboratory setting as described below.

The eight filter sets placed in the respective plenums were: (i) single EU7 fiberglass filter, intended to serve as the reference condition; (ii) EU7 fiberglass filter, protected by an EU4 pre-filter that was exchanged monthly. A fraction of the sensory offending pollutants was removed by the pre-filters; (iii) EU7 fiberglass filter with an AC filter upstream, intended to limit ozone-initiated reactions on the surface of the EU7 filter; (iv) EU7 fiberglass filter with an AC filter downstream, intended to remove a fraction of the sensory offending pollutants desorbing from the EU7 filter; (v) EU7 fiberglass filter with AC filters both upstream and downstream, combining the intended benefits of AC filters in the previous two sets; (vi) stand-alone EU7 bag filter with carbon-containing fiberglass media; (vii) stand-alone EU7 synthetic fiber cartridge filter that incorporates AC, and (viii) single EU5 fiberglass filter, intended to represent a commonly used configuration. The AC in the two combination filters [sets (vi) and (vii)] is anticipated to capture sensory offending pollutants and possibly reduce surface chemistry. Further descriptions of the filters and their combinations can be found in Table 1.

Each filter was weighed before and after the 5-month soiling period to determine the mass change during the period that the filters were in service. The measurements, made in duplicate and subsequently averaged, took place in a climate chamber at 21°C and 65% RH. All filters equilibrated at these conditions for approximately 20 h prior to weighing, both before and after the 5-month service time.

During the soiling period, the airflow through the systems was checked on a monthly basis and, when necessary, readjusted to the original value (1300 m^3/h). The pressure drop across each filter was also measured monthly using a Testo 511 temperature-compensated pressure meter (Testo Ltd., Alton, Hampshire, UK). The accuracy of the instrument is ± 3 Pa for values between 0 and 100 Pa and $\pm 1.5\%$ of measured value up to 1000 Pa. Fifteen values, each recorded over a 1-s interval, were averaged for each filter. Pressure drops were measured on days without precipitation to avoid complications from moisture-laden air. The outdoor air temperature and relative humidity varied between 7 and 19°C and 70–90% RH for the days on which the monthly pressure drops were measured. On the day of the first pressure-drop measurements the conditions

Table 1 Filter sets evaluated for sensory pollution after ~5 months of continuous service in outdoor test plenums operated at 1300 m^3/h

Set No.	First filter	Second filter	Third filter	Key to *x*-axis for Figure 3	Comments
1	EU7/F7 fiberglass, bag-type	–	–	1. EU7	Common configuration
2	EU4/G4 pleated 2" panel[a]	EU7/F7 fiberglass, bag-type	–	2. Pre-f. + EU7	Fraction of the sensory offending pollutants on the pre-filter
3	Activated carbon, V-cell cartridge[b]	EU7/F7 fiberglass, bag-type	–	3. AC + EU7	First filter (AC) anticipated to reduce ozone chemistry on second filter
4	EU7/F7 fiberglass, bag-type	Activated carbon, V-cell cartridge[b]	–	4. EU7 + AC	Second filter (AC) anticipated to remove fraction of sensory offending pollutants from first filter
5	Activated carbon, V-cell cartridge[b]	EU7/F7 fiberglass, bag-type	Activated carbon, V-cell cartridge[b]	5. AC + EU7 + AC	Benefits of AC filters in both set No. 3 and No. 4
6	EU7/F7 with activated carbon-containing fiberglass media; bag-type[c]	–	–	6. EU7 w/AC bag-type (fiberglass)	AC may reduce surface chemistry and capture sensory offending pollutants
7	EU7/F7 pleated synthetic fiber with activated carbon; V-cell cartridge[d]	–	–	7. EU7 w/AC cartridge (synthetic)	AC may reduce surface chemistry and capture sensory offending pollutants
8	EU5/F5 fiberglass, bag-type	–	–	8. EU5	Common configuration

[a]Exchanged monthly, assessments conducted with the last 1-month-old pre-filter.
[b]No particle removal properties, total shipping weight ~5.5 kg, estimated nominal weight of activated carbon ~1.7 kg.
[c]Bag-type fibrous particulate filter containing activated carbon, total shipping weight ~3.5 kg, estimated nominal weight of activated carbon ~1.3 kg.
[d]Pleated V-Cell particulate filter containing activated carbon, total shipping weight ~5.5 kg, estimated nominal weight of activated carbon ~1.3 kg.

were 19°C, 70% RH, and a wind speed of 7.2 m/s. On the day of the last pressure-drop measurements the conditions were 7°C, 80% RH, and a wind speed of 8.3 m/s (Weather Underground, 2007).

After 5 months of operation, the filters were taken out of the test plenums, which continued to run at airflows of 1300 m^3/h for an additional day to purge the units of sorbed contaminants left over from the used filters. During this period, the filters were stored outdoors in sealed plastic bags. Three of the test plenums were then washed and moved into separate 55 m^3 field laboratories, each ventilated with 110 l/s outdoor air (seven air changes per hour). To avoid contamination of the room air with air that had passed through used filters, the exhaust from each plenum was vented to the outside using flexible duct that passed through a window (Figure 2). Prior to sensory evaluations, the three units ran for 2 days without filters, at an airflow of 1300 m^3/h, to equilibrate with indoor conditions. All used and new filters were moved indoors and ventilated for 45 min with 130 m^3/h of room air (one-tenth of the nominal flow) 2 days prior to their sensory evaluations. The average temperature and relative humidity in the rooms during the period of pre-treatment were 20.5°C and 30%, respectively. The ozone concentration in the three field laboratories was between 15 and 25 ppb.

On the day of the sensory assessments, each filter set was again ventilated for 45 min with 130 m^3/h of room air prior to the sensory evaluations. The same airflow was used during the assessments. It corresponds to an air velocity of 0.2 m/s through the filter and 0.7 m/s at the point of sensory assessment. The average temperature and relative humidity in the test rooms during the assessments was 21°C and 25%, respectively, while the ozone concentration was 20–25 ppb on the first day and 5–15 ppb on the second day.

In total, 16 filter sets were evaluated. Eight of them consisted of one or more used filters, all of them having been soiled under identical conditions during the previous months (Table 1). The other eight sets matched the first ones, but consisted of new filters of the same types. The new filter sets were pre-conditioned in a manner that was identical to that employed for the used ones (i.e. they were ventilated twice for 45 min with 130 m^3/h of room air). In addition, each of the three test plenums, without filters, was evaluated several times during the two assessment days. Hence, 24 conditions were evaluated in random order in three field labs. The evaluations were carried out during two consecutive days, using the same panel of subjects. Randomization of conditions was limited by the number of filters in every experimental set and the number of filter housings available within the three test plenums.

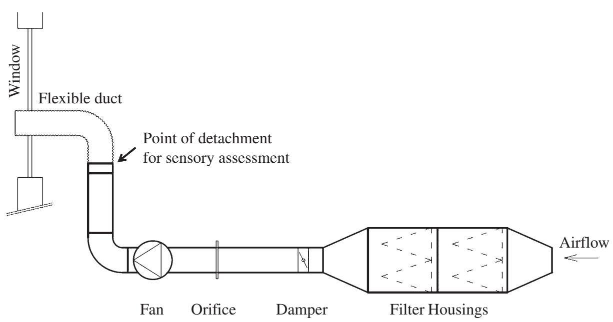

Fig. 2 Scheme for one of the test plenums installed in the field labs during the sensory assessments. The three test plenums contained different number of filter boxes so that all filter sets could be evaluated

Thirty-two untrained human subjects between 20 and 27 years of age assessed the acceptability of air downstream of each set of filters. They used the continuous acceptability scale, which ranges from 'Clearly unacceptable' (−1) to 'Clearly acceptable' (+1). There was a break in the scale in the middle to clearly distinguish between acceptable and unacceptable air quality (Wargocki, 2004b).

During each round of assessments, three filter conditions were installed in three field labs and subsequently evaluated. In the first round of assessments, three subjects were randomly assigned to enter the field labs, one subject at a time in each room. In the next round, three more subjects were randomly assigned to enter the labs. This procedure was repeated until all subjects had conducted assessments in all three rooms. Subsequently, the filter conditions in the rooms were changed, and the assessments were repeated. The subjects were asked to take a deep breath in front of a fan in the well-ventilated corridor before entering the test rooms. After entering, they removed the flexible duct from the end of the ventilation unit, exhaled the corridor air, inhaled the air from the ventilation unit, and subsequently assessed the quality of air based on their facial exposure. This procedure ensured that the same air was used as background before each evaluation. The subjects spent the time between the individual assessments in a well-ventilated room adjacent to the test rooms. The randomization of subjects was constrained by the requirement that each subject had to wait at least three rounds (approximately 3 min) between his/her individual assessments. At the end of each of the 2 days on which assessments were performed the subjects assessed the quality of the room air. This was done to evaluate the quality of the air before it entered the test plenum.

Results

The results of the measurements of filter weight gain and pressure drop across each filter are shown in Table 2. During the 5 months of operation, all of the particle filters (EU4 panel, EU5, and EU7 bag-type)

Table 2 Weights and pressure drops for the filters prior to and after the 5-month service interval

Set No.	Filter position	Filter type	Initial weight (g)	Weight after 5 months (g)	Weight difference (g)	Initial pressure drop (±s.d.; Pa)	Pressure drop after 5 months (±s.d.; Pa)	Pressure drop difference (Pa)
1	First	EU7; bag	1218	1336	118	52 ± 3.2	61 ± 2.9	9
2	First	EU4; panel	460[a]	474[b]	14	24 ± 1.7[c]	33 ± 1.8[d]	9
2	Second	EU7; bag	1202	1261	59	67 ± 0.74	78 ± 1.6	11
3	First	AC; cartridge	5947	5771	−176	48 ± 1.0	59 ± 1.4	11
3	Second	EU7; bag	1203	1272	69	70 ± 0.56	86 ± 1.0	16
4	First	EU7; bag	1201	1317	116	52 ± 1.4	65 ± 3.5	13
4	Second	AC; cartridge	6053	5821	−232	49 ± 0.74	57 ± 0.83	8
5	First	AC; cartridge	5719	5585	−134	52 ± 1.3	52 ± 2.3	0
5	Second	EU7; bag	1220	1265	45	75 ± 0.91	86 ± 1.2	11
5	Third	AC; cartridge	5766	5733	−33	48 ± 0.53	50 ± 0.52	2
6	First	Combined EU7 with AC; bag	3459	3519	60	110 ± 2.7	102 ± 3.0	−8
7	First	Combined EU7 with AC; cartridge	5451	5297	−154	123 ± 1.6	151 ± 3.9	28
8	First	EU5; bag	692	767	75	34 ± 2.0	30 ± 2.0	−4

[a]Average from three new pre-filters.
[b]Average from four 1-month-old pre-filters.
[c]Average pressure drop ± average standard deviation from five new pre-filters.
[d]Average pressure drop ± average standard deviation from five 1-month-old pre-filters.

gained weight, while all of the cartridge-type filters that contained AC, including the combination filter (EU7 with AC, No. 7), lost weight. The bag-type combination filter (EU7 with AC, No. 6) increased in weight; however, only by about half of what had been gained by an EU7 filter positioned as the first filter in the system (see set No. 6 vs. sets Nos 1 and 4). The mass of particles collected on the surface of a stand-alone EU5 filter (No. 8) was only about 60% of that collected by an EU7 filter positioned as the first filter in the system (Nos 1 and 4). Protecting a regular EU7 filter by either a pre-filter (set No. 2) or an AC filter (sets Nos 3 and 5) resulted in a significantly smaller increase in filter weight during the 5-month period. In set No. 2 it is important to note that the weight gain for the EU4 pre-filter (14 g) is for a 1-month interval, because the pre-filter was changed monthly. In the case of the cartridge-type AC filters, the lowest weight loss was observed for the AC filter downstream of an identical AC filter and an EU7 filter (set No. 5). The other cartridge filters containing AC lost considerably more weight – between ~130 and 230 g.

Over the 5-month period there was a small increase in the pressure drop across each individual filter. The highest increase, nearly 30 Pa, was observed for the EU7 combination cartridge filter that contained AC (No. 7). There was an increase of ~15 Pa or less for the rest of the filters, while in two cases (sets Nos 6 and 8) a small decrease from the initial pressure drop was observed by the end of the soiling period. Configurations with two or three filters (sets Nos 2–5) had higher combined initial and final pressure drops than sets with stand-alone EU5 or EU7 filters (sets Nos 1 and 8). However, the pressure drop across an EU7 filter in series with an AC cartridge filter (sets Nos 3 and 4) was not much greater than that across an EU7 filter in series with a pre-filter (set No. 2). The pressure drop across the bag-type combination filter (EU7 with AC, No. 6) was also comparable to that across an EU7 filter in series with a pre-filter. Its pressure drop remained relatively constant over the 5-month period.

Figure 3 shows the results of the sensory assessments of air that had passed through either used or new filters. Prior to making pairwise comparisons between conditions using parametric statistics, the Shapiro–Wilks test was applied. Data obtained from 22 of the 24 test conditions were found to be consistent ($P < 0.01$) with a normal distribution expected under the Null Hypothesis of only random differences in scale-marking between conditions. Hence, the differences observed between assessments obtained under these 22 conditions were tested for statistical significance using repeated measures analysis of variance. The non-parametric Wilcoxon matched pairs signed

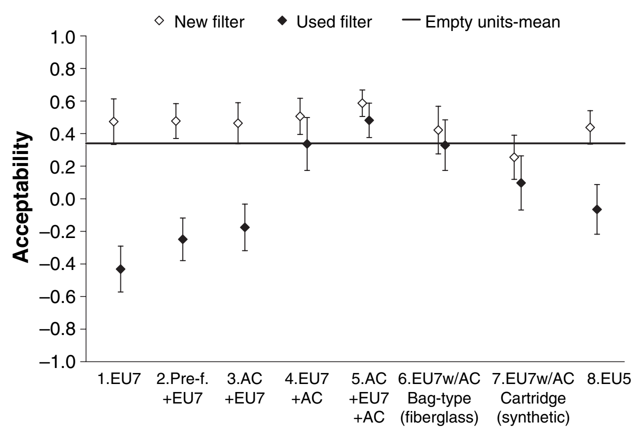

Fig. 3 Acceptability of air downstream of the new and used filters or filter combinations. Mean assessed values and 95% confidence intervals are shown. The solid line depicts the mean acceptability assessed for air that had passed through the three empty test plenums. See Table 1 for key to *x*-axis labels

rank test was used to test for significance between pairs of assessments obtained under the remaining two conditions, as the validity of this test does not depend on the assumption that the data are normally distributed.

No significant differences were found between assessments of the empty test plenums. The mean acceptability obtained for air downstream of the three empty test plenums was +0.34; this is shown as a line in Figure 3.

On average, the quality of air in the three test rooms was assessed as almost identical with the air from the empty test plenums (acceptability of 0.37 vs. 0.34, respectively). The acceptability of air downstream of the new filters was slightly higher than the acceptability of air that passed through the empty units. The only exception was the new synthetic fiber EU7 filter that incorporated AC (No. 7 in Table 1), which showed significantly lower acceptability than the rest of the new filter combinations ($P < 0.05$). Air passing through the test plenum that contained a new AC filter both upstream and downstream of the new EU7 filter (No. 3) was evaluated as the most acceptable. However, new set No. 3 differed in a statistically significant way only when compared with the new stand-alone EU5 filter (No. 8; $P < 0.05$) and the new stand-alone synthetic EU7 filter that incorporated AC (No. 7; $P < 0.01$).

After 5 months of continuous operation each of the used filters adversely affected the quality of the air passing through them. However, there were substantial differences in the magnitude of the effects observed. The subjects assessed the air downstream from the stand-alone EU7 fiberglass bag filter (No. 1) to be worse than air downstream from all of the other filter combinations ($P < 0.01$). Results obtained for the EU7 filter that had a 1-month-old pre-filter (No. 2) or an active carbon filter (No. 3) in front, showed significant improvement in air quality relative to the stand-alone used EU7 filter ($P < 0.01$). However, the air downstream of these filter combinations remained somewhat unacceptable (−0.25 and −0.18, respectively). Air that had passed through filter sets that included an AC filter either downstream (No. 4) or both upstream and downstream of an EU7 filter (No. 5) was judged to be as acceptable or better than air that had passed through the empty test plenums. A very similar evaluation was obtained for air that had passed through the EU7 fiberglass bag filter that contained AC (No. 6). These three combinations (Nos 4–6) were perceived as significantly better than the rest of the tested filters ($P < 0.01$), with no statistically significant differences among them ($P > 0.05$). The perceived air quality downstream of the used synthetic fiber EU7 filter that incorporated AC (No. 7) was significantly worse than that from sets 4–6 ($P < 0.01$), but better than that from the first three sets ($P < 0.05$). However, the negative assessment for No. 7 reflected the fact that the filter had an adverse impact on the quality of air passing through it when it was new, rather than any degradation during its 5 months of service. In fact, in the case of No. 7, the assessments of the new and used filter are not significantly different ($P > 0.05$). Air passing through the used stand-alone EU5 filter (No. 8) was less acceptable (−0.07) than when this filter was new. Still, the air downstream of this filter was more acceptable than that downstream of the stand-alone EU7 filter or the EU7 filter protected by a pre-filter ($P < 0.05$).

Discussion

Prior to this study, we felt that new approaches would be required if particles were to be removed from ventilation air without adversely affecting the resulting quality of the delivered air. The results reported in Figure 3 suggest otherwise. They indicate that methods already exist, using commercially available filters, to remove particles without significantly degrading the quality of the air that passes through the filtration media. In the following paragraphs we discuss these results in greater detail, beginning with the weight changes and concluding with the most important findings to come out of the current studies – the sensory assessments.

Weight change

The weight gains measured for the particle filters after 5 months of service are consistent with their nominal filtration efficiencies and relative position in the test plenum (when present with other filters). For example, when positioned as the first filter, EU7 bag filters gained 115–120 g (Nos 1 and 4) while the less efficient EU5 gained 75 g (No. 8). When protected by a pre-filter, the EU7 bag filter only gained 59 g (No. 2). When protected by an AC filter, not designed to remove particles, the EU7 bag filter still gained only 69 g (No. 3).

Each of the AC cartridge filters (Nos 3–5) lost weight during their 5 months of service. Presumably, most of this weight loss is due to small particles of carbon that break off from the carbon granules in the cartridge filter and are subsequently removed by the air passing through the filter. This process is referred to as 'dusting.' However, it is somewhat surprising that the EU7 bag filters located downstream of AC carbon filters, which are presumably 'dusting,' have not gained more weight than they have (69 and 45 g in sets Nos 3 and 5, respectively). A second mechanism that can contribute to weight loss is oxidation of carbon bonds on the surface of the carbon, followed by carbon–carbon bond scission and release of carbon monoxide or carbon dioxide. With this mechanism in mind, the weight changes measured for the two AC filters in set No. 5 are interesting. The AC filter in front lost 134 g while the AC filter in back lost only 33 g; the AC filter in back had significantly less ozone passing through it than did the one in front. We have calculated the weight loss that could occur from oxidation based on the assumption that ozone, at an average ambient concentration of 30 ppb, was the primary oxidant of surface carbon on the AC. The resulting estimate indicates that ~60 g is the maximum anticipated weight change over 5 months of service. This is insufficient to fully explain the results in Table 2, so it appears that a combination of dusting and oxidation are responsible for the measured weight changes in the AC cartridge filters.

The weight changes measured for the two combination filters (Nos 6 and 7) are sharply different from each other. Both filters are rated EU7 and, based on the results from sets Nos 1 and 4, are anticipated to have removed slightly more than 100 g of particles from the airstream during their time in service. However, both filters are also anticipated to have lost mass from the AC that they contain. The EU7 bag filter that incorporates AC gained 60 g (No. 6), while the EU7 cartridge filter that incorporated AC lost 154 g (No. 7). These results are consistent with 'dusting' as the cause of weight loss. Given the construction of the EU7/AC bag filter compared to the EU7/AC cartridge filter, carbon particles that break off from the carbon granules are more likely to be captured by the former.

Pressure drop

The initial pressure drops across the particle filters match what is anticipated from their filtration efficiencies (i.e. EU7 > EU5 > EU4). The initial pressure drop across the AC cartridge filters was almost as large as those across the EU7 bag filters. In the case of the combination filters, their initial pressure drops were comparable to one another, and roughly twice as large as those across the EU7 bag filters. When the different sets of filters are compared, set No. 5 with an EU7 filter between two AC cartridge filters had the highest initial pressure drop (175 Pa). The sets that had one AC cartridge filter, Nos 3 and 4, had total initial pressure drops (118 and 101 Pa) that were comparable to the initial pressure drops of the combination filters in set Nos 6 and 7 (110 and 123 Pa).

The differences between initial and final pressure-drop measurements should be interpreted cautiously, since these were made outdoors on days that were 5 months apart and may have been influenced by differences in air temperature, humidity, and wind conditions. The EU7 cartridge filter that incorporated AC displayed the largest pressure drop increase (28 Pa), while the other combination filter, the EU7 bag filter with AC, showed a slight pressure decrease. This decrease is likely to be an artifact caused by differences in weather conditions on the days when the initial and final pressure drops were measured. The pressure drop across EU7 bag filters increased by 10–15 Pa. The AC cartridge filters spanned a range from almost no increase to an increase of 11 Pa, with no apparent trend. This may have reflected filter-to-filter variations in the settling and redistribution of the carbon granules as the AC filters lost weight.

Sensory assessments

The mean acceptability for air downstream of the three empty test plenums, 0.34, was similar to that of the room air, 0.37, indicating that emissions from the test plenums themselves had a negligible influence on the sensory assessments of new and used filters. With the exception of the synthetic fiber cartridge filter with AC, the perceived quality of air downstream of the new filters was slightly better than that of the air passing through the empty test units (see Figure 3). The new filters may have sorbed a fraction of the sensory offending pollutants present in the ambient air. It is not clear why air passing through the new synthetic fiber cartridge filter with AC (No. 7) was perceived to be less acceptable than air passing through the new filters with fiberglass media. It seems likely that emissions from the synthetic media, and not from the relatively low-emitting polypropylene housing, were responsible for the poor assessments. However, this result should not be generalized to all synthetic filters. The construction of the filter media (the use of coatings, binders, and tackifiers), and thus its impact on indoor air quality, differs from manufacturer to manufacturer.

After 5 months of service, air passing through the stand-alone EU7 filter was judged to be less acceptable than air passing through any of the other filters or filter combinations. When a pre-filter was installed upstream of an EU7 filter, the air passing through this combination was judged to be more acceptable than that passing through a stand-alone EU7 filter. Note that the pre-filter in this combination was replaced monthly. Hence, every time a pre-filter was replaced, ~15 g of captured coarse particles were removed from the filter set (see Table 2). It is interesting to compare sensory assessments and weight gains for the used EU5 filter (No. 8) and the combination of an EU4 pre-filter followed by an EU7 filter (No. 2). The mean assessments indicated that air passing through the used EU5 was more acceptable than that passing through the pre-filter/EU7 combination. The mass gained by the used EU5 filter was almost the same as the total mass gained by the 1-month-old pre-filter and 5-month EU7 filter (75 g vs. 73 g). However, the EU7 filter captures a greater fraction of submicron particles than does an EU4 pre-filter or an EU5 filter, and the total surface area of the 73 g of particles captured by the pre-filter/EU7 combination was presumably larger than the total surface area of the 75 g of particles captured by the EU5 filter. Given the ranking of the sensory assessments, this suggests that acceptability depends more on the total surface area of the captured particles than on the total mass of the captured particles. (Although the air passing through the used EU5 filter was perceived to be more acceptable than that passing through the pre-filter/EU7 combination, the former captures fewer particles from the air that passes through and offers less protection for HVAC equipment and occupants downstream of the filters).

Placing an AC filter upstream of an EU7 bag filter (No. 3) improved the acceptability of air passing through the used filters only slightly more than placing a pre-filter upstream of an EU7 filter (No. 2). However, the pre-filters were replaced monthly, while the AC filter remained in place throughout the 5 months. The AC filter presumably removed some of the larger particles from the airstream (see above), some of the gas-phase organic compounds and a significant fraction of the ozone (see Introduction). The ozone removal means that less ozone passed through the downstream EU7 filter, and less oxidation chemistry occurred on the surface of this filter (Bekö et al., 2006). The fact that this filter set, although better than a stand-alone EU7, was still judged to be relatively unacceptable suggests that oxidation of organics associated with captured particles is not the dominant factor responsible for the sensory pollutants emitted from this combination of used filters.

Placing an AC filter downstream of an EU7 bag filter (Nos 4 and 5) produced a much larger improvement than placing an AC filter upstream of an EU7 filter (see Figure 3). This indicates that the organics responsible for the deteriorated air quality were efficiently removed by the AC filter. In set No. 4, the EU7 filter captured nearly 120 g of particles and was not protected from ozone or other gaseous pollutants. Still, the perceived air quality downstream of this filter set after 5 months of service was nearly as good as that downstream of this set when the filters were new. The performance of the filter set with an AC filter both upstream and downstream of the EU7 bag filter (No. 5) was somewhat better. After 5 months of service, air passing through this combination of filters was judged to be more acceptable than air passing through any of the other filter combinations. The upstream carbon filter protected the EU7 filter from ozone, coarse particles and some organic compounds. However, the relatively large incremental difference between set Nos 3 and 5 (acceptabilities of −0.18 and +0.48, respectively) was due to the addition of the downstream carbon filter.

Surprisingly, good results were obtained for the fiberglass EU7 bag filter that incorporated AC (No. 6). The acceptability of air downstream of this filter was as high as that downstream of filter sets that contained an AC filter downstream from the EU7 bag filter (Nos 4 and 5). Although this filter is constructed in a manner that is analogous to a standard EU7 fiberglass bag filter, the inclusion of AC appears to result in effective removal of offending pollutants that emanate from the captured particles.

The other combination filter, the synthetic fiber EU7 cartridge filter that contained AC (No. 7) was expected to produce results similar to its bag-type fiberglass equivalent (No. 6). The assessments, however, revealed significantly poorer air quality downstream from this synthetic–media combination filter than downstream from the fiberglass–media combination filter (acceptability of 0.10 compared with 0.33). This difference between the combination filters was almost entirely due to the difference between these filters when they were new. After 5 months of service, the change in acceptability for these two combination filters was comparable. In either case, incorporating AC significantly reduced the emission of sensory offending pollutants that occurs as filters accumulate captured particles from the airstream.

The sensory assessments in these evaluations were conducted with one-tenth of the airflow used during the 5-month soiling period (130 m^3/h vs. 1300 m^3/h). The relative differences among the filter sets are not anticipated to be meaningfully altered by the reduced airflow. Based on previous studies, this may also be true for the absolute values derived from the sensory assessments. Alm et al. (2000) demonstrated that increasing the outdoor airflow rate through a used filter increased the emissions from a used filter and that the acceptability of the downstream air changed very little. Using an expanded range of airflows, Strøm-Tejsen et al. (2003) reported similar observations and confirmed the proportional relationship between pollution load and rate of airflow through a used filter.

The location used in this study has relatively clean air; the single EU7 filter captured a particle mass of ~120 g, which corresponds to about 1/6 to 1/8 of the filter's dust-holding capacity. At more polluted locations significantly larger mass loadings can occur over the same time interval. On the other hand, the used filters examined in the present study were in service during autumn and winter months. The outdoor temperatures during this period were cooler than the indoor temperatures during the 2 days of assessments. These higher indoor temperatures may have promoted desorption of sensory pollutants from the used filters. A potentially larger issue concerns variations (with season, location, and source of captured particles) in the nature of sensory offending pollutants emitted by used filters.

An especially pronounced difference is anticipated for filters that have been soiled exclusively with outdoor air compared to filters that are used downstream of the mixing box in a recirculating air system. In the latter case, the filters are soiled with a large fraction of indoor air, which often contains elevated concentrations of organic pollutants not commonly encountered outdoors. This includes emissions from cleaning products, paints, polishes, and various floor and wall coverings (Brown et al., 1994; Hodgson and Levin, 2003). The less volatile of these emissions will sorb to the surface of the soiled filter and also be associated with particles captured by the used filter, resulting in sensory offending pollutants that may differ significantly from those in the present study. Still another issue is the time-interval over which the AC filters will continue to remove sensory offending pollutants. The present study indicates excellent performance over a period of 5 months, but would such performance continue for a year or more? How frequently do such filters have to be changed and how does this vary with soiling conditions? Hence, it is important to extend these studies to other situations before large-scale implementation of mitigation procedures illustrated in Figure 3.

The EU7 filter followed by an AC filter downstream and the stand-alone EU7 bag filter that contains AC (the combination filter) both performed well in terms of acceptable perceived air quality achieved at a reasonable overall pressure drop. The latter is particularly promising because it does not require modification of filter housings if the housing already accepts standard bag filters. The bag-type combination filter had a pressure drop after 5 months of service that was lower than that of any of the other sets evaluated except the stand-alone EU7 and EU5. An additional advantage of AC, whether in a cartridge filter or in a combination filter, is its ability to remove ozone from the supply air, which may have meaningful health benefits (Weschler, 2006). Cursory measurements indicated that the used bag-type combination filter removed more than 85% of the ozone from the airstream even after 5 months of continuous operation. However, these results should be reconfirmed in future measurements conducted at various airflows and ozone challenge concentrations.

Conclusions

In the present study, separate AC filters downstream of particle filters meaningfully improved the acceptability of the filtered air. Of the two combination filters that were evaluated, the synthetic fiber filter with AC had less of a positive effect on acceptability than did the fiberglass bag filter with AC. Indeed, the combination fiberglass bag/AC filter improved the acceptability of the filtered air as much as a separate AC filter downstream of a particle filter. Furthermore, its pressure drop changed very little during the 5 months of service and, based on preliminary measurements, it removed a large fraction of ozone from the airstream even after 5 months of continuous operation. Additional experiments are warranted to explore the generality of these striking results before wide scale adoption of such filters can be recommended. If further experiments produce similar results, combination filters that incorporate AC could replace commonly used bag filters. Such filters would have particle removal efficiencies comparable to standard bag filters, would remove sensory offending pollutants and would have the added bonus of removing a significant fraction of ozone from the airstream. This would mean improvements in air quality with little or no modification to the air handling system and, presumably, with only modest additional expense.

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