Ventilation filters and their impact on human comfort, health and productivity

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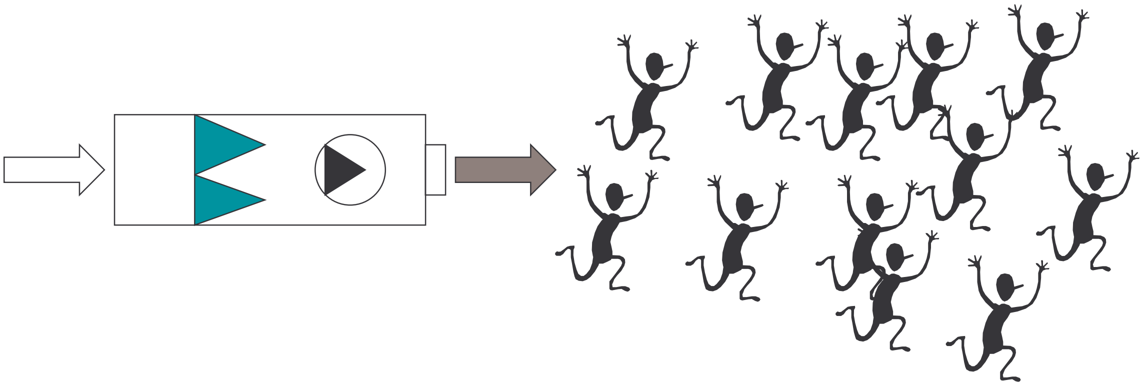

Ph.D. Thesis
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July 2001

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Preface

This thesis is based on the author's research work carried out at the International Centre for Indoor Environment and Energy, Department of Mechanical Engineering, Technical University of Denmark, during the period August 1998 to July 2001. Supervisors during the Ph.D. study have been Professor P. Ole Fanger, D.Sc. and Dr. Geo Clausen, Associated Professor both from the International Centre for Indoor Environment and Energy.

I would like to thank Professor Fanger and Dr. Clausen for giving me the chance to undertake this interesting study.

I warmly thank Dr Jana Sabikova and Love Lagercrantz for their helpful assistance during the preparation and running of the experiment on the influence of used ventilation filters on the acceptability of room air. At the same time, my special thanks to Love Lagercrantz for always having time to give a hand when it was needed, no matter the time of day.

I especially thank Ms Judith Ørting for correcting the English language of this thesis.

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Lyngby, 31 July 2001

Ole Alm

Summary

In **chapter 1** previous work on why the used filter becomes a pollution source after having been used for some time in ventilation system is reviewed.

Chapter 2 describes experiments performed to investigate the reason for the filter becoming a sensory pollution source after having been used for a certain period. The experiments in that chapter investigated some possible solutions that could lead to lowering or changing the sensory pollution load from a used filter.

Chapter 2.1 describes a study of the influence of living microorganisms on perceived air quality downstream of a filter. The air quality downstream two used filters was evaluated twice, first before sterilisation, and then after the sterilisation of one of the filters. The sterilisation was done to kill all living microorganisms on the filter. On the first experimental day, before sterilisation of filter 1, the air quality downstream of the two filters was perceived to be significantly different ($p<0.05$). After the sterilisation of filter 1, there was no significant difference between the two filters. However, the air quality downstream of the filters was improved and was found to be more acceptable on the second experimental day. It is unlikely that microorganisms are the main reason for the deterioration of the air quality downstream of a used filter when used in a climate similar to the Danish climate.

If the sensory pollution load from a used filter is caused by oxidation of the particles on the filter, an exposure to a high ozone concentration could change the perceived air quality. *Chapter 2.2* describes a study where a used ventilation filter was exposed to an ozone concentration of over 1300 ppb for a week. The air quality downstream of the filter was evaluated before and after the ozone exposure. The air quality downstream of the filter evaluated after 7 days with a high concentration of ozone through the filter was not found to be significantly different from the air quality evaluated on the first day. On both occasions, 52 to 65% were dissatisfied with the air quality.

Chapter 2.3 describes an attempt to identify the VOCs emitted from the filter. A sample of dust from a used ventilation filter was heated and a gas chromatography-mass spectrometry (GC/MS) analysis of volatile organic compounds (VOCs) desorbed from the filter was made. The sample (which should not be considered representative) contains probably several hundreds of organic compounds and only a minor number was identified. Roughly described, the identified compounds are mainly ketones, aldehydes, carboxylic fatty acids, alkanes, phthalates and siloxanes. All common organic compounds (naturally occurring compounds and industrial chemicals) also found in house dust.

Chapter 3 describes studies of the influence of a used filter on the perceived air quality, SBS-symptoms and productivity.

The influence of recirculating office air through a ventilation system on the acceptability of the air quality was in *chapter 3.1* tested under two conditions, one with and one without a filter in the ventilation system. Each condition was tested at three different outdoor air supply rates. Subjects evaluated the air in two different ways: on entering the office with the ventilation system, or by evaluating the air extracted from the office. It was then possible to estimate the pollution load from the filter in two ways using the results from the two different methods. Inserting a used filter in a ventilation system recirculating the room air deteriorated the air quality in the room. Two different methods were used to find the pollution load from the filter. When the pollution load was based on evaluations made during facial exposure, it was 30-40 olf/m^2 higher than when it was based on evaluations made during whole-body exposure. However, the difference is mainly caused by the differences in calculation procedures because the difference in acceptability of the same air is not significant. A relationship between the acceptability of the air evaluated during facial exposure and during whole-body exposure was established. However, this was based only on six points. When combining the results from the present study and from the two previous studies, it was possible to establish a stronger relationship. Below an acceptability of 0.2, the air is more acceptable after whole-body exposure than after facial exposure, the opposite tendency applying at acceptability levels above 0.2.

Information on the relationship between exposure and sensory response for the different components is required in order to in the future to be able to model the perceived quality of the air leaving a HVAC system. In *chapter 3.2*, the results of an experiment designed specifically to determine the exposure-response function for air polluted by a used filter is described. A test rig made it possible to assess the air quality downstream of a filter at three different flows through the filter and at the same time to assess each flow at three different concentrations by dilution with clean air. A proportional relationship between the source strength and the face velocity through the filter was found. Increasing the outdoor airflow rate increased the source strength of the filter and the acceptability of the air did not improve. However, by diluting the air downstream of the filter with outdoor air, it was possible to improve the air quality.

One of the objectives in *chapter 3.3* was to investigate the impact of a used ventilation filter on the perceived air quality, SBS symptoms and productivity of office work. Human comfort, health and productivity were assessed by 30 women after 4 hours' exposure in an experimental room with either a used or a new filter present in the ventilation system in the experimental space. All other parameters were kept constant. Upon entering the office, having a used filter in the ventilation system instead of a new filter had a significant impact on numerous perceptions and symptoms. The perceived air pollution was worse, the intensity of the odour was higher, there was greater irritation in the nose, the perceived intensity of the humidity was lower, the perceived intensity of the freshness of the air was lower, the acceptability of the overall environmental conditions was lower, the perceived intensity of headache was higher, the ability to think clearly was lower, the perceived intensity of dizziness was higher, and self-estimated performance in the office was lower. Self-estimated performance was assessed as being significantly higher when the new filter was in the system compared to when the used filter was in it. However, there was no significant influence on the performance of office work.

Chapter 4 is a conclusive discussion of the whole study. A mathematical model describing the mass of particles on the filter and the concentration of odorous gases in the office as a function of ventilated days was established. The model has not been validated but it fits well with the observations from the present studies.

1.0 Introduction

The primary function of a heating, ventilating, and air-conditioning (HVAC) system is to provide the occupants in the ventilated building with a good indoor environment. The HVAC system may be used to provide a comfortable thermal environment and acceptable air quality by providing the building with an adequate amount of outdoor or recirculated air.

However, many studies have found that the HVAC system does not always provide buildings with clean fresh air, and furthermore can constitute an important source of deterioration of the perceived air quality in offices. By evaluating the quality of the air on entering a room on three different occasions (when it was unoccupied and the ventilation system off; when it was unoccupied and the ventilation system was on; and when it was occupied with the ventilation system on), it was possible to estimate the pollution load from occupants, building materials and from the ventilation system. This method has been used to estimate the pollution load in offices, assembly halls, schools, and kindergartens (Fanger et al., 1988; Fanger, 1988b, Pejtersen et al., 1990; Thorstensen et al., 1990; Pejtersen et al., 1991). A total of 50 buildings were investigated. The result was that the main pollution source in the spaces was not the occupants and their activities, as has been specified in ventilation standards based on Yaglou's experimetns in 1936/37. Building materials and especially the ventilation system, were found to be a much greater pollution source in buildings than were occupants. However, these investigations are based on the assumption that the source strength of e.g. building materials, is independent of the outdoor airflow rate. Some newer results indicate that the source strength increases with the outdoor airflow rate (Knudsen, 1997 & 1998; Wargocki, 2000). The source strength of the building materials is therefore higher when the air quality is evaluated with the ventilation system on, compared to when it is off, and this gives a higher estimation of the source strength of the ventilation system.

An attempt to locate the main pollution sources in a ventilation system was made in eight ventilation systems by Pejtersen et al. (1989). The air quality upstream and downstream of each component in the ventilation system was evaluated upon facial exposure to air extracted from the system. The rotating heat exchanger, the filter and the humidifier were found to be the main pollution sources in the ventilation system. The rotating heat exchanger took energy from the outlet air and provided it to the inlet air, but unfortunately, some of the outlet air recirculated to the inlet air as well or pollution were transferred to the inlet air by sorption processes in the heat exchanger, and the air quality deteriorated. All of the humidifiers investigated were turned off but they were dirty, thus making them a pollution source.

This thesis will be concerned solely with the third pollution source: the filter.

Particles in the outdoor air

The filter is placed as the first line of defence in the ventilation system. This is not done to protect the occupants in the ventilated buildings from the particles in the outdoor air, but to protect the ventilation system from being contaminated. A high content of particles will lower the efficiency of the heating/cooling coil and give a higher pressure loss, thus involving the use of more energy.

The particles come from the outdoor air and consist for instance of soil, fragments of plants, microorganisms, organic materials and emissions from industry and combustion products. Depending on the size of the particle, the filter captures up to 100% of all these particles. Particles larger than 20-30 µm falls quickly to the ground, due to gravity, and most of the particles on the filter are therefore smaller than 10 µm.

Figure 1 shows the number of particles, their surface area and the weight as a function of the particle diameter. 99.9% of the particles found outdoors are smaller than 1 µm, and they have around 80% of the total surface area on the filter, but only 30% of the weight. Table 1 gives some of the characteristics of the particles. The total surface area of the particles captured by an EU7 filter used for a year in an urban area can easily exceed 2000 m^2.

Error! Not a valid link. **Figure 1** *The number of particles, their surface area and the weight as a function of the particle diameter.*

Table 1 *Some characteristics of the particles (Danvak, 1999)*

Particle diameter (µm)	Numbers per gram	Surface area per gram (m^2)	Weight per 10^9 particles (g)
0.01	$1.9 \cdot 10^{18}$	600	$0.5 \cdot 10^{-9}$
0.1	$1.9 \cdot 10^{15}$	60	$0.5 \cdot 10^{-6}$
1	$1.9 \cdot 10^{12}$	6	$0.5 \cdot 10^{-3}$
10	$1.9 \cdot 10^{9}$	0.6	0.5

Filter as pollution source

Studies have shown that the sensory pollution load from a new filter is negligible when it has been ventilated for a few days and the accumulated dust therefore constitute the pollution source (Bluyssen, 1993; Pejtersen, 1996b; Gholami et al., 1997).

Growth of microorganisms on the filter is often mentioned as the main factor in deterioration of the air quality downstream of the filter. Laboratory experiments have found that microorganisms, here defined as fungi, bacteria, and yeast smaller than 10 μm, can survive and grow on the filter material if there is enough water and organic material (Elixman et al., 1987).

The filters are subject to large variation in temperature and relative humidity due to placement close to the outdoor air, and both parameters have a strong influence on the growth of microorganisms on the filters. However, the influence depends on the type of microorganism, fungi or bacteria, and also within species there can also be a difference. The optimum temperature for some of the most common fungi, Cladosporum, Penicilium and Aspergillus, is aprroximately 20 - 35˚C. However, growth has been observed with some species at a temperature as low as -6˚C (Flannigan, 1992; Pasanen et al., 1993).

A microorganism can survive on the filter if there is enough organic material to eat and if there is enough water. A used filter is a big reservoir of organic material from the outdoor air, and experiments have found that microorganisms can even survive on a new unused filter. However, many studies have found that the water activity in the filter material has to be above 65% to ensure the survival of the microorganism (Martikainen et al., 1990; Kemp et al., 1995; Pasanen et al, 1991; Möritz et al., 1997; Sugawara, 1997; Ettrup, 1999). Water activity is a measure for the relative amount of water in a material. Low water activity does not necessarily kill the microorganism but the growth is stopped.

Pejtersen (1994) investigated the possibility of reducing the microbiological growth, and thereby, theoretically, reducing the pollution from filters, by keeping the supply air at a low relative humidity. In a laboratory experiment, two filters were installed in two ventilation systems and exposed for 18 weeks to continuous airflow with respectively 40% and 80% relative humidity. After 18 weeks, the amount of microorganisms on both filters was found to be low. The perceived air quality downstream of the filter exposed to an relative humidity of 40% did not differ from the perceived air quality downstream the filter exposed to an relative humidity of 80%. However, the method gave a temperature difference between the two filters as well so the temperature at the humid filter was 6.0˚C and at the dry filter 14.3˚C; this difference could have limited the growth on the humid filter.

The microorganisms emit metabolic volatile organic compounds (MVOC) to the air. If the water activity in the media is high, the microorganism starts to grow and there is a higher emission of MVOC. If the water activity then starts to be lower, the microorganism starts to emit spores to find another place with higher water activity. This will also release MVOCs. If the microorganism is without water over a longer period, it will die, and this will lead to emission of MVOCs. However, the highest release occurs when there is massive growth on the media (Gravsen et al., 1994).

Ettrup (1999) has investigated the growth of the fungi Alternaria tenuissima, Chaetomium globosum, Cladosporium herbarum, Penicillium breicompactum and the yeast Rhodotorula rubra on used and on new filter material. The microorganisms were sprayed on to the material and the water activity was kept close to 100%. The filter material was not ventilated during the experiment and water was added; there was thus no limiting factor. Surprisingly, all of the fungi could survive and grow on the *new* filter material but it was only possible for Penicillium breicompactum to survive on the *used* filter material. However, the microorganisms were sprayed onto the filter together with a nourishing liquid, and this could have led to the survival of the fungi on the new filter. It is unknown why the fungi could not survive on the used filter with the higher content of organic material. The yeast could not survive on any of the materials.

Kemp (1995) investigated the number of microorganisms on three different filters when they were ventilated with outdoor air for a year. The filters were an electrostatic filter, a glass fibre media bag filter, and a polymer fibre media bag filter, and all of them had an efficiency of 60-70%. The amount of microorganisms in the air upstream and downstream of the filters was measured once per month. The air temperature varied in that period between –12 and 32˚C and the relative humidity was between 40% and 95%. The flow through the filter was 900 l/s. The three filters demonstrated a filter efficiency greater than 90% on fungi and bacterial bioaerosols. Over the year-long period, surface samples showed no active growth on any of the filters. Neumeister et al. (1996) counted 2500 CFU/m^3 upstream of the filter and 400 CFU/m^3 downstream of the filter. Subsequently, the calculated amount of microorganisms on the filter after 13 months of use was compared with the actual measured number found on the filter. The calculations revealed that there should have been a 100 times higher amount of fungi on the filter and a 10000 times higher amount of yeast than was found in the actual measurements. Möritz (1999) found the same amount of microorganisms on the filter after it had been used for 1, 3, 5, 7, or 9 months. This indicates that the microorganisms are captured by the filter but they are not able to survive under conditions usually found in ventilation system.

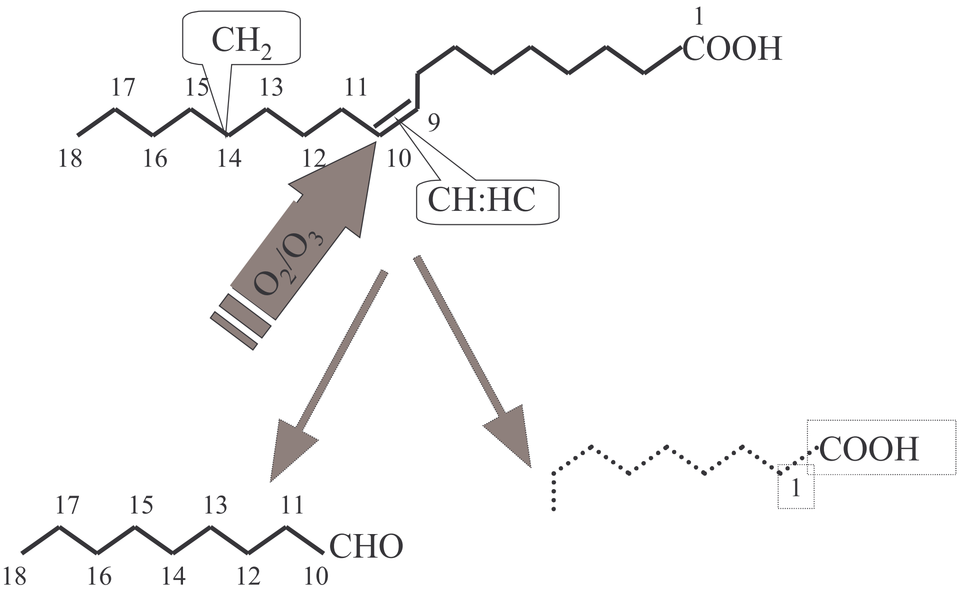
If the deterioration of the air quality originates from dead bacteria, it could be caused by e.g. endotoxin released from the cell of the bacteria when it dies. The contents of endotoxin in 76 filters of different classes has been measured (Möritz et al., 1999). The filters originated from different ventilation systems where they had served for various lengths of time. There was a higher concentration of endotoxin on the lower class filter and it was independent of the service time. Johansson & Rosell found that the concentration of endotoxin in the air decreased when it passed an EU6 filter.

Gas chromatography-mass spectrometry (GC/MS) analysis of volatile organic compounds (VOCs) desorbed from a used EU6 filter has been made by Johansson and Rosell (1998). The result was that the dust could emit pentanal, *hexanal*, heptanal, *oktanal*, *nonanal*, 2-metylpropanal, 3-metylbutanal, and 2-metylpentanal. The findings in *italic* are known metabolic VOCs from Penicilium chrysogenum and Aspergillus niger which are two fungi often found on ventilation filters. However, it was concluded that the VOCs found were products from reactions between fatty acids and an oxidiser such as ozone.

A main reason for the deterioration of the air quality downstream of the filter is due to VOC on the filter. The VOC may come as a reaction product from unsaturated fatty acids from e.g. plant wax. Wax can contain various natural, oily or greasy substances, consisting of hydrocarbons or esters of saturated and unsaturated fatty acids. The unsaturated fatty acids can react with O_2 and O_3, producing VOC. Some of them are known to be odorous and irritating. The oxidising process can be seen in Figure 2, where an oleic acid is oxidised and produces nonanal which is a known irritant in the indoor environment, having a low odour threshold.

When a fatty acid is oxidised it splits into smaller fractions and may form VOCs such as formaldehyde, acetaldehyde, propanal, butanal, pentanal, hexanal, heptanal, oktanal, and nonanal. These products are known to be very odorous and irritating.

$CH_3(CH_2)_7CH{:}CH(CH_2)_7CO_2H$ [Oleic Acid]



$CH_3(CH_2)_7CHO$ [Nonanal]

Figure 2 *Oxidizing of a fatty acid.*

The VOC can become attached to the filter in three different ways:

1. Tiny fragments of plant wax are released from the plant, and become airborne. The fragments are then captured by the filter. The size of the wax is greater than 4-5 µm and will be captured by the coarse filter. On the filter, a reaction takes place with the atmosphere, especially O_3, and VOCs are produced.

2. Plant wax reacts with O_3 before it hits the filter and the VOC will then be adsorbed on particles; these particles will then be captured by the filter. Giving the same density, one gram of fine particles (e.g. 0.1 µm) has a 10 times larger surface area than one gram of particles with a diameter of 1 µm. Therefore, the VOC will mainly be found on the fine particles.

3. VOC from the air will be captured by the filter material and by the particles on the filter, and will therefore be on both the fine and the coarse filter.

Pasanen et al. (1994) investigated whether the particle size of atmospheric dust affects the odour emission rate from filters. Six EU6 filters were investigated during three months of use. Two of the filters were used with a pre-filter (EU3) upstream. The sensory pollution load from the coarse pre-filter was similar to the pollution load from the main filter used without pre-filtration, and the pollution load from the main filters was significantly lower if used with pre-filters. This result indicates that the pre-filters effectively protect the main filters from odour-causing particles, but it is unknown whether it is because of retention of plant wax.

Pasanen et al (2000) made a laboratory experiment with nine glass fibre filters (F5-F8) tested at three different ozone levels (20, 40 and 60 ppb). All filters had been used for one year and then stored in a refrigerated room before being prepared for the test. All filters were tested at all three levels of ozone. The filters were set up in a ventilation system in a laboratory and the ozone concentration and Tenax air samples were made upstream and downstream the filter. With this set-up, it was possible to measure an ozone reduction between 0 and 12 ppb, and a reduction was measured in 90% of the cases. An increase in the concentrations of formaldehydes and acetaldehydes was observed in the samples collected downstream of the filters.

A field experiment was made at the same time in two ventilation systems, one with a single F7 filter and the other with three-step filtration (G4, F6, and F7). The experiment was carried out at ambient ozone level (< 30 ppb) and at an elevated level of 60 ppb. No ozone reduction was found at the ambient level in any of the ventilation systems, but at the elevated concentration a reduction of 5-10% was found at the single F7 filter and up to 30% at the three-step filtration unit. Here the main reduction occurred in the first filter containing the largest dust load.

In a field experiment in Sweden, ozone measurements were made in two ventilation systems (Johansson & Rosell, 1998), one with a F6 filter and the other one with a F8/9 filter. There was continuous flow at 3400 m^3/h through the filter for 6 months before the measurements, and subsequently the ozone concentration was measured for 15 days. It was not possible to detect any reduction in the ozone concentration.

The experiment was at the same time performed with a ventilation system with intermittent airflow, where the flow was 3400 m^3/h during the day and only 200 m^3/h during the night and at weekends. With intermittent airflow, it was possible to detect a 30% decrease in ozone concentration over the filter.

These results from Pasanen and Johansson support the theory, that unsaturated fatty acids sits on the filter and react with ozone, thereby producing VOC.

2.0 Sensory pollution from air filters

Many studies have found that the HVAC system, while providing the buildings with clean fresh air, can also be an important source of deterioration of the perceived air quality in offices. This chapter describes experiments performed to investigate the reason for the filter becoming a pollution source after having been used for a certain period. The experiments described in this chapter investigate some possible solutions that could lead to lowering or changing the sensory pollution load from a used filter.

Chapter 2.1 describes a study of the influence of living microorganisms on perceived air quality downstream of a filter. The air quality downstream of two used filters was evaluated twice, first before sterilisation, and then after the sterilisation of one of the filters. The sterilisation was done to kill all living microorganisms on the filter.

If the sensory pollution load from a used filter is caused by oxidation of the particles on the filter, an exposure to a high ozone concentration could change the perceived air quality. Chapter 2.2 describes a study where a used ventilation filter was exposed to an ozone concentration of over 1300 ppb for a week. The air quality downstream of the filter was evaluated before and after the ozone exposure.

Chapter 2.3 describes an attempt to identify the VOCs emitted from a filter. A sample of dust from a used ventilation filter was heated and a gas chromatography-mass spectrometry (GC/MS) analysis of volatile organic compounds (VOCs) desorbed from the filter was made.

2.1 The influence of microorganisms in the filter on the perceived air quality

Objective

- To study the influence of living microorganisms on perceived air quality downstream of a filter

Experimental plan

The air quality downstream of two filters was evaluated twice, once before and once after nuclear radiation of one of the filters. The nuclear radiation sterilised the filter and killed all microorganisms on the filter.

Methods

Facilities

A test rig consisting of two Fläkt ventilation systems, each with a filter and a ventilator unit (both of type KLAA-20-102-1), was placed in a 26.8 m^3 stainless steal chamber (Albrechtsen, 1988). Each ventilation unit was $1.0 \cdot 0.66 \cdot 0.75$ metre (w·h·d). The outdoor air was filtered with clean new filters (EU7) before it was let into the chambers. Used EU7 ventilation filters were placed in the test rig. The air upstream and downstream of the filter was extracted with glass tubes and a small fan to cones where it was possible to make facial evaluations of the air.

Subjects

An untrained panel (15-20 persons) assessed the perceived air quality. The panel consisted of employees and students at the International Centre for Indoor Environment and Energy. Not all members participated in all assessments.

Experimental conditions

Pollution source

The filters used as pollution sources had been used previously as outdoor air filters with no recirculation for 14 months in a Copenhagen suburban area. The flow through each filter had been at 1800 m^3/h for 12 hours per day, giving an approximate total of $9 \cdot 10^6$ m^3 filtered air. The filters were $0.5 \cdot 0.6$ metre EU7 glass fibre filters with eight bags with a total surface area of 6 m^2. Visual inspection showed that the filters were highly contaminated with particles from the outdoor air.

Thermal parameters

The parameters relating to the thermal conditions were unchanged for all conditions. The air temperature in the chamber was 20˚C and the relative humidity 55%. The air in the cones for facial exposure was conditioned to 24˚C and 45% relative humidity.

Ventilation

The chamber was ventilated with an outdoor air change rate of 40 h^{-1}. The airflow through the cones was 1 l/s.

Measurements

Physical measurements

The flow through the filter was measured with tracer gas techniques using Brüel & Kjær 1302 – Multi Gas Monitor and Brüel & Kjær 1303 – Multi Point Sampler and Doser.

The air temperature and the relative humidity were measured occasionally with a Brüel & Kjær Indoor Climate Analyzer (1213).

Subjective measurements

The subjective measurements of air quality were made using a graded acceptability scale. The scale is slightly altered from that used by Gunnarsen & Fanger (1989). The scale goes from “Clearly acceptable” to “Clearly unacceptable” and to force the subjects to choose between acceptable and unacceptable air quality, the line was divided in two, giving two extra end-points “Just acceptable” and “Just unacceptable”. In the data analyses, the scale was assumed linear from “Clearly acceptable” to “Clearly unacceptable”, and “Clearly acceptable” was assigned the value +1, “Just acceptable” the value +0.01, “Just unacceptable” the value –0.01, and “Clearly unacceptable” the value –1. The scale can be seen in Figure 3.

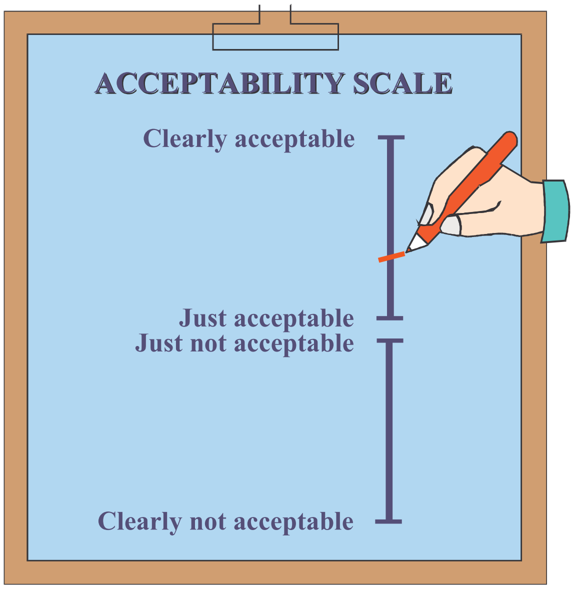


Figure 3 *The acceptability scale*

Procedure

The two used filters, filter 1 & 2, were placed in the test rig 4 days before the experiment started, and ventilated with 200 l/s chamber air. The air through the filter had the same temperature and relative humidity as the air in the chamber. On the first experimental day, the subjects assessed the air upstream and downstream of the filter. The four cones were assessed in random order. After the first experimental day, filter 1 was sent for sterilisation where it was radiated twice with 20-kGy-gamma radiation. Filter 1 was installed in the test rig again after 7 days. During that period, filter 2 was ventilated in the test rig continuously with 200 l/s filtrated outdoor air. Both filters were then ventilated for three days in the test rig with 200 l/s filtrated outdoor air. There was a time span of ten days between the first and the second experimental day. On the second experimental day, the subjects assessed the air quality upstream and downstream of the filter again.

At the end of the experiment, the filters were analysed for content of microorganisms. A tape was pressed gently on the front and on the back of the surface of the filter. The tape was then analysed by microscopy. This was done by Tanja Ettrup from BioCentrum, Technical University of Denmark.

It was not possible for the subjects to see where in the ventilation system the assessed air was extracted. In addition, the purpose of the experiment was unknown to the subjects.

Results

Statistical analyses

The distributions of the data obtained from the questionnaires were tested for normality with Shapiro-Wilk's W test. They were normally distributed and they were tested by means of analysis of variance, ANOVA.

Subjective measurements

Using [1], the percentage of dissatisfied can be calculated from the data obtained on the acceptability scale.

$$PD = \frac{\exp(-0.18 + 5.28 \cdot ACC)}{1 + \exp(-0.18 + 5.28 \cdot ACC)} \cdot 100 \qquad [1]$$

where:
PD: the percentage of dissatisfied (%);
ACC: the mean value of the acceptability voting.

The quality of the air upstream of the filters was evaluated as good and less that 3% were dissatisfied.

On the first experimental day, before sterilisation of filter 1, the air quality downstream of the two filters was perceived to be significantly different ($p<0.05$). After the sterilisation of filter 1, there was no significant difference between the two filters. However, the air quality downstream of the filters was improved and was found to be more acceptable on the second experimental day. The results are shown in Figure 4.

The subsequent analyses of the microorganisms on the filter showed microorganisms on both filters. However, a higher number of CFU (colony-forming units) were found on the untreated filter compared with the sterilised filter. The type of microorganisms was not identified.

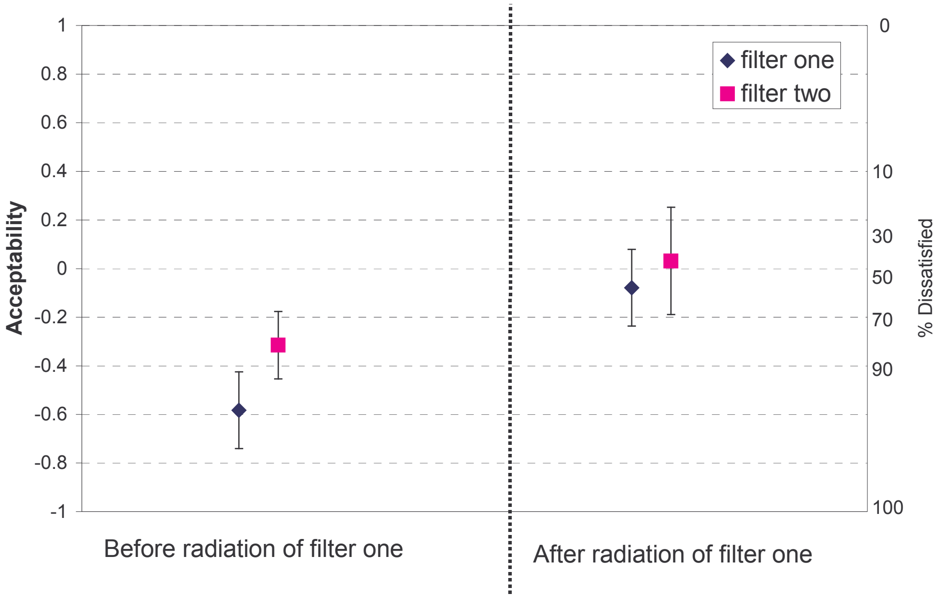


Figure 4 *The air quality downstream of filters 1 & 2 before and after the sterilisation of filter 1.*

Discussion

The air quality downstream of both filters improved when one of the filters was sterilised. The improvement was probably caused by the continuous ventilation with filtrated outdoor air. Without further contamination of the filter, the odorous gases on the filter start to desorb and the source strength is lowered. However, if growth of microorganisms was the main factor in deterioration of the air quality, the quality of the air downstream of the sterilised filter should have been even better. Subjectively, the air downstream of the filter was evaluated as being no different. Sterilisation killed all the microorganisms, including bacteria, on the filter and thereby stopped the emission of metabolites from the microorganisms, but emission is still to be expected from chemical degradation.

Microorganisms were found on both filters and that result could indicate that the sterilisation had been ineffective. However, the sterilisation method had been used successfully numerous times by BioCenter (DTU). The number of microorganisms on the sterilised filter was less than on the untreated filter, and they probably come from handling the filter or from the outdoor air.

There was no visible growth on the filters before the experiment started and the relative humidity in the experiment was 55% which has been found to be too low for the growth of microorganisms (Martikainen et al., 1990; Kemp et al., 1995; Pasanen et al, 1991; Möritz et al., 1997; Sugawara, 1997; Ettrup, 1999). However, the growth of microorganisms is possible in a more humid climate (Halonen, 2000), but it is unknown whether the air quality downstream of a filter previously used and tested at a higher relative humidity could give an improvement of the air quality by sterilisation of the filter.

The number of microorganisms on the filter before the experiment started and before sterilisation is unknown. Such measurements would have led to better and more conclusive results.

Conclusion

- It is unlikely that microorganisms are the main reason for the deterioration of the air quality downstream of a used filter when used in a climate similar to the Danish climate.

2.2 The influence of ventilating with an increased level of ozone on the perceived air quality downstream of a filter

Objective

- To study the influence of ventilating a filter with an elevated level of ozone for a period on the perceived air quality downstream of the filter

Experimental plan

The air quality downstream of a used filter was evaluated before and after the filter had been ventilated with air with a high concentration of ozone.

Methods

Facilities
A Fläkt ventilation system with a filter and a ventilator unit (both of type KLAA-20-102-1), was placed in chamber 2 of the two 26.8 m^3 stainless steal chambers [Albrechtsen, 1988]. The ventilation unit was 1.0·0.66·0.75 metre (w·h·d). The outdoor air was filtered with clean new filters (EU7) before it was let into the chambers. A used EU7 ventilation filter was placed in the ventilation system. The air downstream of the filter and the air from chamber 2 were extracted with glass tubes and a small fan to cones in chamber 1, where it was possible to make facial evaluations of the air.

The ozone generation was made with a lamp with an OSRAM bulb (HNS 10W/U OZ) emitting a high amount of UV light. The layout is depicted in Figure 5.

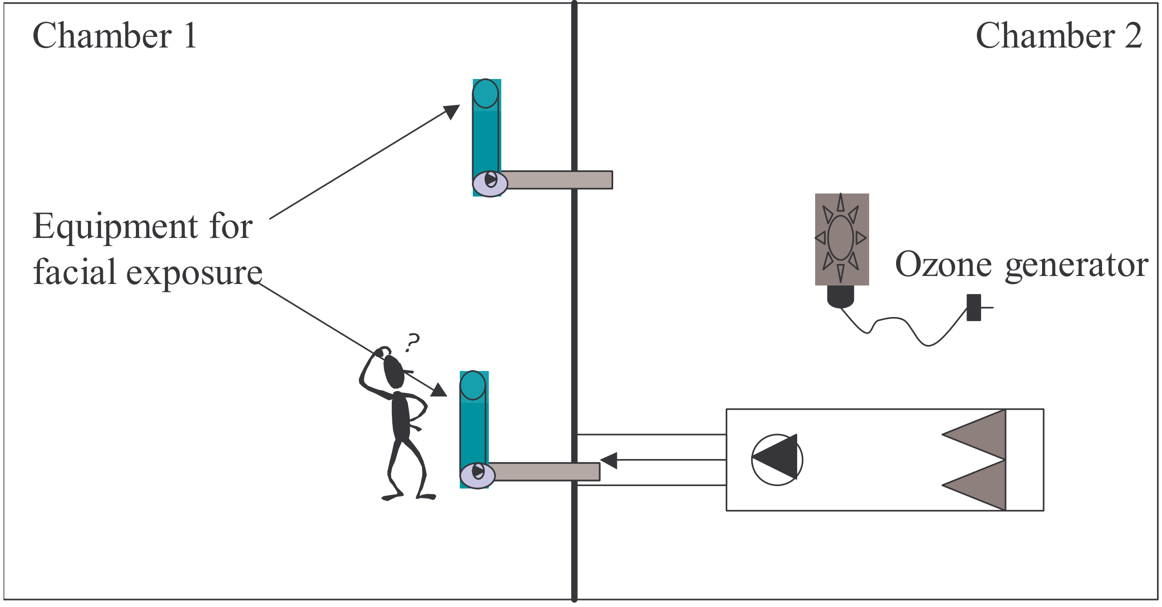


Figure 5 *Layout of the experimental set-up in chamber 1 and 2.*

Subjects

An untrained panel (12-15 persons) assessed the perceived air quality. The panel consisted of employees and students at the International Centre for Indoor Environment and Energy. Not all members participated in all assessments.

Experimental conditions

Pollution source

The filter used as a pollution source had been used previously as an outdoor air filter with no recirculation for 14 months in a Copenhagen suburban area. The flow through the filter had been at 1800 m^3/h for 12 hours per day, giving an approximate total of $9 \cdot 10^6$ m^3 filtered air. The filter was a 0.5·0.6 metre EU7 filter with eight bags with a total surface area of 6 m^2. Visual inspection showed that the filter was highly contaminated with particles from the outdoor air. The filter had previously been used as the untreated filter in the experiment described in chapter 2.1.

Thermal parameters

The parameters relating to the thermal conditions were unchanged for all conditions. The air temperature in chamber 2 was 20˚C and the relative humidity 55%. The air in the cones for facial exposure and chamber 1 was conditioned to 24˚C and 45% relative humidity.

Ventilation

On the experimental day, chambers 1 & 2 were ventilated with an outdoor air change rate of $40h^{-1}$. The airflow through the cones was 1 l/s. The flow through the filter was continuously ventilated with 200 l/s chamber air.

Measurements

Physical measurements
The flow through the filter was measured with tracer gas techniques using Brüel & Kjær 1302 – Multi Gas Monitor and Brüel & Kjær – 1303 – Multi Point Sampler and Doser.

The air temperature and the relative humidity were measured occasionally with a Brüel & Kjær Indoor Climate Analyzer (1213).

The ozone was measured occasionally by a Seres OZ2000 ozone analyser.

Subjective measurements
All the assessments of the air quality were made on the acceptability scale (Figure 3).

Procedure

The filter was placed in the Fläkt ventilation system inside chamber 2 three days before the start of the experiment and ventilated with 200 l/s chamber air. On the first experimental day, standing in chamber 1, the panel assessed the quality of the air downstream of the filter and the air from chamber 2. At the end of the experimental day, the fans for extracting the air from chamber 2 were turned off and the ozone generator was started. The air change in the chamber was turned off and it was then possible to reach an ozone concentration of over 1300 ppb, which was the highest possible concentration that could be measured with the ozone measuring equipment. In chamber 2, the ventilation system with the used filter was recirculating the chamber air. After 7 days at >1300 ppb ozone, the bulb was turned off, and the chamber ventilation system was turned on (air exchange = 30 h^{-1}). The filter was then ventilated with clean air for two days. The air quality downstream of the filter and the air from chamber 2 were then assessed again.

Results

Physical measurements
The ozone concentration in chamber 2 was ~0 ppb before and after the ozone generation period. The concentration of ozone was over 1300 ppb during the period when ozone was generated in chamber 2. The temperature and relative humidity was not measured during the period with high ozone concentration.

Statistical analyses
The distributions of the data obtained from the questionnaires were tested for normality with Shapiro-Wilk's W test. They were normally distributed and were tested by t-test for independent samples.

Subjective measurements
Using equation [1] on page 23, the percentage of dissatisfied can be calculated from the data obtained on the acceptability scale.

The quality of the air in chamber 2 was evaluated as good and less that 5% were dissatisfied.

The air quality downstream of the filter evaluated after 7 days with a high concentration of ozone through the filter was not significantly different from the air quality evaluated on the first day. On both occasions, 52 to 65% were dissatisfied with the air quality (Figure 6).

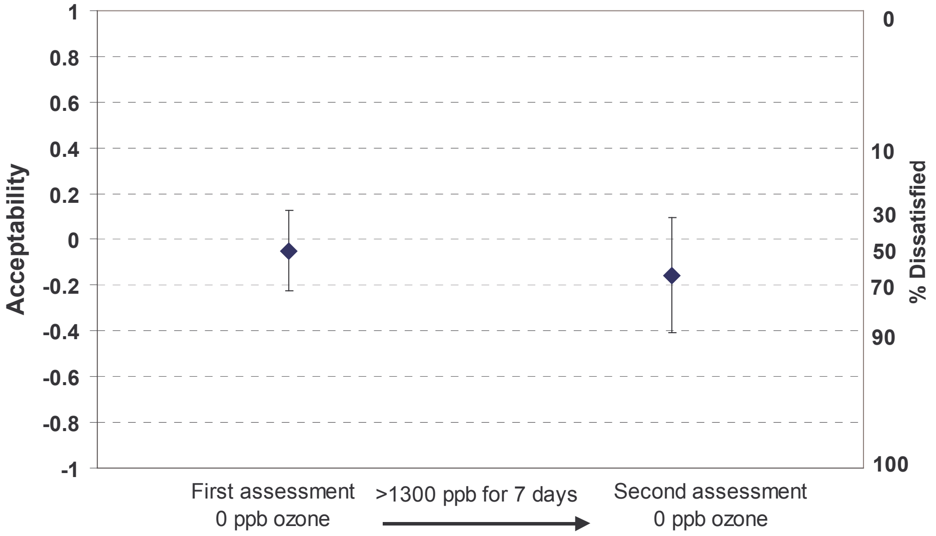


Figure 6 *Mean acceptability of the air quality downstream of a filter before and after ventilating with ozone at a concentration >1300 ppb.*

Discussion

The air downstream of a used filter was not significantly changed after having been ventilated with air with an ozone concentration higher than 1300 ppb. The ventilation system in the chambers was stopped during the period with high ozone concentration and therefore the filter was not ventilated with outdoor air in that period. The emission from the chemical reactions that occur between the ozone and the particles on the filter would pass through the filter many times during that period. It is therefore possible that reaction products emitted from the filter were adsorbed again on the filter. However, it did not lead to a change in the air quality.

No chemical measurements were made during the exposure period, and it is therefore unknown whether any reactions occurred and what the reaction products were. The filter was highly contaminated with particles from the outdoor air, and earlier findings indicates that the filter could be filled with fatty acids (Johansson & Rosell, 1998) capable of reacting with ozone. The products of such reactions are aldehydes, which are known to be irritating and to have a very low odour threshold.

After the period with the elevated ozone concentration, the filter was ventilated for two days with chamber air. If reaction products have been adsorbed on the filter, it is possible that the two days of clean air was not enough to remove the possible odorous reaction products from the filter.

The filter had been used with outdoor air for 14 months before the start of the experiment. The ozone concentration in the outdoor air varies with the time of day, weekday and the seasons (DMI). Over a year, the concentration in the area where the filter had originally been used varied between 0 and 60 ppb. It is therefore possible that all reactions have taken place and that the smell downstream of the filter has been caused by slow desorption of the reaction products.

Conclusion

It was not possible to improve the air quality downstream of a filter by ventilating it with a high concentration of ozone.

2.3 Chemical analysis of organic compounds desorbed from the dust collected by the filter

Objective

- To investigate desorption of volatile organic compounds (VOCs) from the dust from a used ventilation filter.

Experimental plan

A sample of dust from a used ventilation filter was heated and a gas chromatography-mass spectrometry (GC/MS) analysis of volatile organic compounds (VOCs) desorbed from the filter was made.

Experimental conditions

The filter used in this experiment had been used previously as an outdoor air filter with no recirculation for 14 months in a Copenhagen suburban area. The flow through the filter had been at 1800 m^3/h for 12 hours per day, giving an approximate total of $9 \cdot 10^6$ m^3 filtered air. The filter was a $0.3 \cdot 0.6$ metre EU7 filter with six bags with a total surface area of 2 m^2. Visual inspection showed that the filters were highly contaminated with particles from the outdoor air. The filter originated from the same ventilation system as the filters in chapters 2.1 and 2.2, but the filter had not been used for experiments.

Methods

The measuring method described by Wolkoff and Wilkins (1994) was modified. With a pair of tweezers, 50 mg of dust was collected from the used ventilation filter and packed in a Perkin-Elmer desorption tube ($90 \cdot 6.0$ mm) between two degassed silanized glass wool plugs. The tube was connected to a nitrogen (99.99%) flow with a T-piece and placed in an aluminium block so that 15 mm protruded from each end. The aluminium block ($120 \cdot 110 \cdot 60$ mm), fitted with holes (ca 6 mm) and a thermometer, was placed in an electrically heated steel cavity ($170 \cdot 80 \cdot 55$ mm) and warmed to 120 ± 2˚C. An ATD 400 (Perkin-Elmer) sampling tube containing 200 mg Tenax TA (Chrompack, 60-80 mesh) was attached to the desorption tube with a teflon tube (ca 15 mm) and nitrogen (ca. 50 ml/min) was passed through the system for 60 minutes.

The volatile compounds collected on Tenax were desorbed with an ATD 400 (Perkin-Elmer)/Kratos Profile GC/MS system. CP 19CB (Chrompack) silica capillary columns

(60m·0.32μm) were used. A split ratio of 1:7 was maintained at the ATD/GC interface for MS detection.

The Tenax tube was desorbed at 250˚C for 20 minutes. Box and transfer line = 225˚C and cold trap = -30˚C → 300˚C. The GC program was 20˚C for 2 minutes increasing 4˚C/minute to 250˚C (15 minutes). A piece of deactivated silicia capillary column was inserted to about 2 cm from the cold trap through the transfer line and connected directly to the analytical column. Column flow was 2.0 ml/minute.

Furthermore, as a blank sample, 76 l of N_2 was sucked through a Tenax tube and the desorption equipment without any sample.

The method was modified and the measurements were carried out by Kjeld Larsen and Per Axel Clausen from the National Institute of Occupational Health, Denmark (Larsen & Clausen, 2001).

Results

The tentatively identified organic compounds in a sample of dust analysed by thermal desorption and gas chromatography combined with mass spectrometry (TD-GC-MS) can be seen in Table 2. Compounds identified in the same chromatographic peak have a common id number and are added with a +. A chromatogram of compounds desorbed from filter and dust is shown in appendix E.

Table 2 *Volatile organic compounds from dust from a used filter identified by GC/MS analysis (Larsen & Clausen, 2001).*

1. Acetaldehyde[1, A]
2. acetone[1]
3. 2-propanol[1, 2]
4. 2-methylpropanal[1,2, 3, A]
5. 2-butanal + 2-metylfuran[1]
6. 3-methylfuran[2]
7. metyl-1,3-pentadien + butanal[1, A]
8. methylvinylketon
9. 2-butanone[1, 2]
10. benzene1 + 2-methyl-4,5-dihydrofuran
11. 3-methylbutanal[1, 2, A]
12. 2-methylbutanal[1, 2, A]
13. 2-ethylfuran
14. 2-pentanon + butanol
15. pentanal[1, 3, A]
16. acetic acid[1, F]
17. 2-ethylhexen

43. octanal[1, 3, A]
44. siloxane[1]
45. 2-ethylhexanol[1]
46. hexanoic acid[1, F]
47. octanol[1]
48. nonanal[1, 3, A]
49. methylbenzaldehyd
50. acetophenone[1]
51. phenol[1]
52. heptanonoic acid[1, F]
53. 2-ethylhexanoic acid[1, 3, F]
54. naphthalen[PAH]
55. decanal[1, 3, A]
56. 2-(butoxyethoxy)ethanol[1]
57. 4-ketopentanoic acid
58. octanoic acid[1, F]
59. benzothiazole

18. toluene[1]
19. hexamethylcyclotrisiloxan[1]
20. pentanol[1]
21. hexanone
22. hexanal[1, 3, A]
23. mesityloxid
24. propanoic acid[1, F]
25. ethandiol
26. butanoic acid[F]
27. xylene
28. 2-heptanon[1]
29. 1,2-propandiol[1]
30. 2-methylpropanoic acid[F]
31. butandiol
32. styrene[1]
33. 2-furancarboxaldehyd
34. butanoic acid[1, F]
35. heptanon[1]
36. heptanal[1, 3, A]
37. siloxane[1]
38. cyclohexan + ethyltoluene
39. acetamid
40. 2-ethylhexanal[1, A]
41. 2-pentylfuran[1]
42. benzaldehyde[1, A]
60. benzoic acid[1]
61. nonanoic acid[1, F]
62. sesquiterpene
63. 5-hydroxymethyl-2-furancarboxaldehyd
64. dodecanoic acid[1, F]
65. isobenzofyrandion or phthalic acid
66. 2,6-di-tert-butylquinon
67. hexadecane
68. BHT[1]
69. 2,6-di-(tert-butyl)-4-hydroxy-4-metyl-2,5-cyclohexadien-1-one
70. 2,4-di-tert-butylphenol
71. heptadecane[1]
72. dodecanoic acid[1, F]
73. diethylphthalate[1, P]
74. octadecane[1]
75. nonodecane
76. tetradecanoic acid[F]
77. anthracene or phenanthrene[PAH]
78. eicosane
79. iso-buthylphthalate[P]
80. heneicosane[1]
81. trichloroethylphosphate
82. dibuthylphtalat[1]
83. docosane

[1] Also found in household floor dust (Wolkoff and Wilkins; 1994), [2] known metabolic VOC from microorganisms (Ettrup, 1999), [3] also found in emission from a used filter (Johansson & Rosell, 1998), A = Aldehyde, F = Fatty acid, P = Plasticizer, PAH = Polycyclic aromatic hydrocarbons.

The background concentrations, estimated from the blank sample, was < 1% of the sample concentrations.

Discussion

The relatively high desorption temperature (120°C) was used in order to desorp compounds in sufficiently high amounts to allow GC/MS identification within a short period. The desorption temperature should be low enough to prevent significant thermal degradation of the filter material and the dust (Wolkoff and Wilkins, 1994). The number of VOCs desorbed from the dust is therefore probably higher than the number desorbing at normal outdoor temperatures. However, the results show the potential number of VOCs desorbing from the dust on the filter.

The dust was removed from the filter with a pair of tweezers and it was impossible to do so without removing some parts of the filter as well. Thus the method reveals compounds that might be desorbed from filter material as well.

The analysis is purely qualitative and does not show (neither absolute nor relative) the amounts of all compounds, if any, that might be desorbed.

The sample contains probably several hundreds of organic compounds and only a minor number was identified. Roughly described, the identified compounds are mainly ketones, aldehydes, carboxylic fatty acids, alkanes, phthalates and siloxanes. All common organic compounds (naturally occurring compounds and industrial chemicals) also found in house dust (Wolkoff and Wilkins, 1994).

From an odour point of view, the aldehydes and carboxylic acids are the most interesting. They probably originate from degradation (oxidation) of fatty acids from fatty substances (from vegetation). With the GC column that was used it is possible to register only fatty acids with a chain length up to approximately 14 carbon atoms. The most common unsaturated fatty acids have 18 carbon atoms in the chain.

Conclusions

- 83 volatile organic compounds were identified in the desorption from dust from a used ventilation filter

- The compounds identified are mainly ketones, aldehydes, carboxylic fatty acids, alkanes, phthalates and siloxanes.

3.0 Effects of exposure to air polluted with a used ventilation filter

This chapter describes studies of the influence of a used filter on the perceived air quality, SBS-symptoms and productivity.

In some buildings in the European Audit Project (Bluyssen et al., 1995), the air quality in the supply air was unexpectedly evaluated to be of lower quality than the air in the office. Assessments of the supply air were made during facial exposure whereas assessments of the office air were made during whole-body exposure. The influence of recirculating office air through a ventilation system on the acceptability of the air quality was tested under two conditions, one with and one without a filter in the ventilation system (chapter 3.1). Each condition was tested at three different outdoor air supply rates. Subjects evaluated the air in two different ways: on entering the office with the ventilation system, or by assessing the air extracted from the office. It was then possible to estimate the pollution load from the filter in two ways using the results from the two different methods.

Whereas some work has been performed on modelling perceived air quality in spaces polluted with off-gassing of chemicals from building materials, little has been done on modelling the perceived quality of air leaving a heating, ventilation and air-conditioning (HVAC) system. A difference between modelling air polluted with materials and with HVAC components is that materials in an office pollute the air “in parallel”, whereas HVAC components pollute the air “in series”. Theoretically, this should lead to an increase in the concentration of pollutants as the air passes through the HVAC system. Information on the relationship between exposure and sensory response to the different components is required in order to be able in future to model the perceived quality of the air leaving a HVAC system. In this chapter, the results of an experiment designed specifically to determine the exposure-response function for air polluted by a used filter is described. Laboratory experiments have indicated that the sensory pollution load from a used filter increases with the velocity through the filter (Bluyssen, 1990). Chapter 3.2 describes an experiment where a test rig made it possible to assess the air quality downstream of a filter at three different flows through the filter and at the same time to assess each flow at three different concentrations by diluting with clean air.

Intervention studies have found that exchanging the used ventilation filter with a new filter improves the air quality in the system (Pejtersen, 1994). However, it has not been investigated whether a deterioration of the air quality by the ventilation system has an impact on SBS symptoms or the performance of office work. One of the objectives in chapter 3.3 was to investigate the impact of a used ventilation filter on the perceived air quality, SBS symptoms and productivity of office workers. Human comfort, health and productivity were assessed by 30 women after 4 hours’ exposure in an experimental room with either a used or a new filter present in the ventilation system in the experimental space. All other parameters were kept constant.

3.1 Sensory source strength of a used ventilation filter

Objectives

- To study the influence of a used filter on the acceptability of the air quality in a ventilation system and in an office.
- To explore the differences in calculating the pollution load after assessments made during a whole-body exposure compared with assessments during a facial exposure.

Experimental plan

The influence of recirculating office air through a ventilation system on the acceptability of the air quality was tested under two conditions, one with and one without a filter in the ventilation system. Each condition was tested at three different outdoor air supply rates. The air was evaluated in two different ways: entering the office with the ventilation system or by evaluating the air extracted from the office. It was then possible to estimate the pollution load from the filter in two ways using the results from the two different methods. The full matrix describing the experimental conditions can be seen in Table 3.

	Outdoor air supply rate		
Filter present in the system	10 l/s (ACH 1 h^{-1})	30 l/s (ACH 2.8 h^{-1})	60 l/s (ACH 5.8 h^{-1})
yes	X (6)	X (4)	X (5)
no	X (1)	X (2)	X (3)

Table 3 *Experimental matrix (order of the experimental day in brackets).*

The experiment was carried out on Monday, Wednesday, and Friday in two subsequent weeks between 15 and 29 January 2001.

Methods

Facilities and Equipment

The experiment was carried out in two adjacent normal offices (office 1: 12.4 m^2 floor, 37.5 m^3 volume; and office 2: 24.8 m^2 floor, 75 m^3 volume) on the second floor in building 402, Technical University of Denmark. In both offices, axial fans provided the outdoor air supply, and table fans ensured full mixing of the air in the room. The layout is depicted in Figure 7.

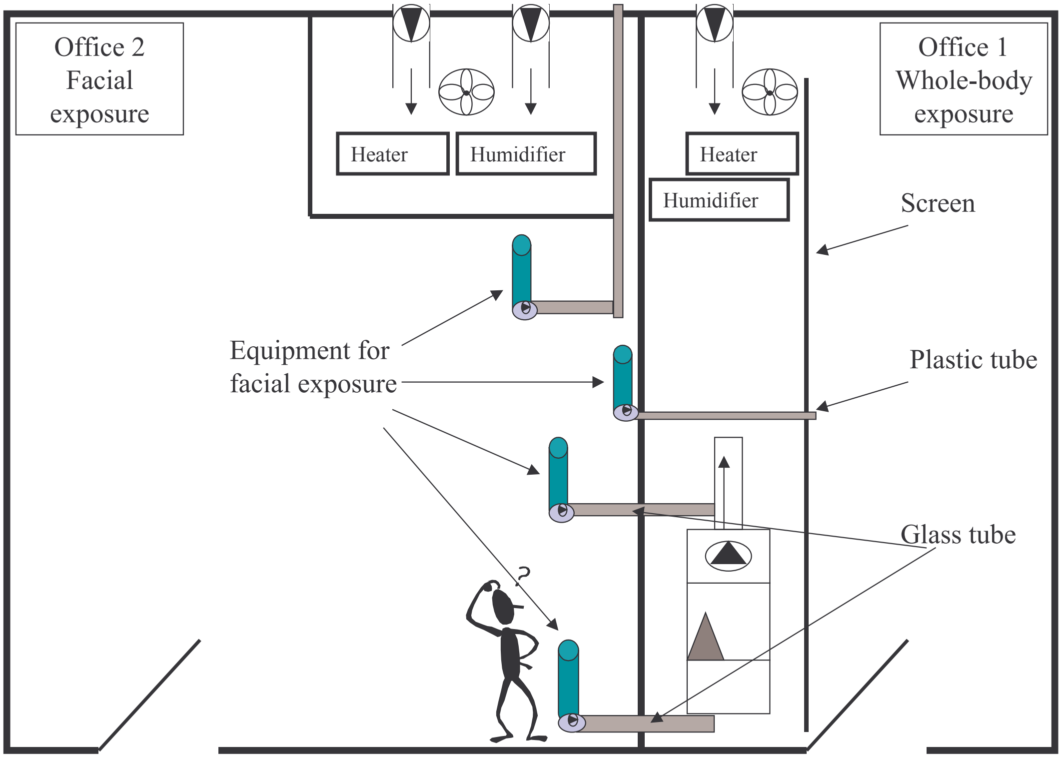


Figure 7 *Layout of the experimental set-up in offices 1 and 2.*

Oil-filled electric heaters (Adax – 2000W) and ultrasonic humidifiers (Boneco 7131) kept the temperature and relative humidity at a constant level. A screen was placed in office 1 and behind it a ventilation system (NOVENCO, type ZL-04 SF/FF/CL) with a filter unit for 0.3·0.6 m pocket filter and a fan. The whole unit is 1.5·0.72·0.46 m (W·H·D). The system recirculated the air at a constant flow (80 l/s) under all conditions. The ventilation system was placed with the inlet opposite the outdoor air supply inlet (see Figure 1). The screen made it impossible to see the set-up in the room on entering. Air upstream the ventilation system, from the outlet of the system and from the room was extracted by means of small fans and supplied via 50 mm glass or odourless poly-vinyl chloride plastic tubes to office 2. The set-up made it possible to evaluate the air quality in the office in two ways: on entering office 1, or in office 2 evaluating the air coming from a cone. In office 2, it was also possible to make facial evaluations of the air upstream the ventilation system, from the outlet of the system, and from outside. The layout is depicted in Figure 7, Figure 8, and Figure 9. To ensure good air quality in office 2, the outdoor air supply rate was 160 l/s ($8h^{-1}$). The outdoor air supply rate varied in office 1 as a part of the experimental plan.

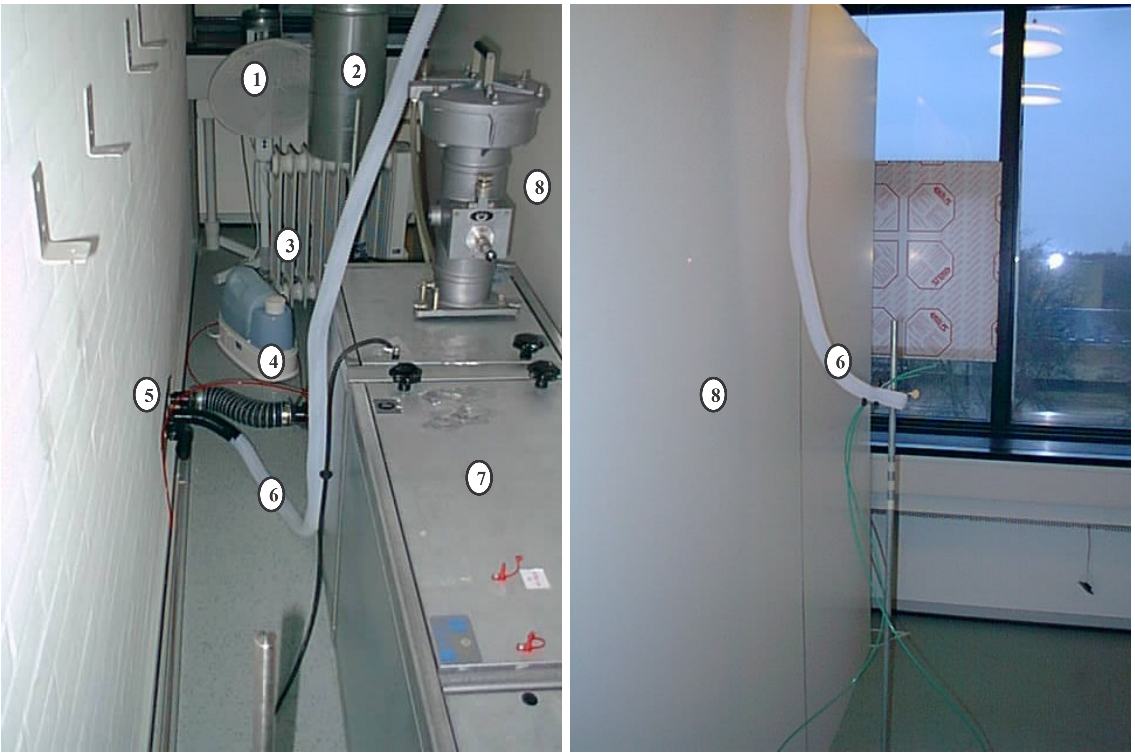


Figure 8 *From office 1: Left - Behind the screen; 1) Table fan, 2) Inlet for the outdoor supply air, 3) Heater, 4) Humidifier, 5) Passage for the air to office 2, 6) Plastic tube, 7) Ventilation system, and 8) Screen. Right - The view when entering the office 6) Plastic tube and 8) Screen.*

Figure 9 *Left; Office 1 – whole-body exposure, Right, Office 2 – equipment for facial exposure.*

Depicted in Figure 8 (left) is a subject evaluating the air quality, standing in the room with the ventilation system. In Figure 9 (right), the subject is using the equipment for facial exposure. The airflow for the facial exposure was 1 l/s at a velocity of 1 m/s, resulting in a total travelling time for the air of 4-8 seconds.

Subjects

Fifty students wanted to participate in the study. All were recruited by advertisements on Technical University of Denmark and on student hostels. Before the start of the experiment, they had to pass a ranking test, in which four samples of 1-butanol (10, 80, 320, and 1280 PPM (vol./vol.)) had to be ranked according to strength (ISO 8587; 1987). Two students failed in this test and they were excluded from the experiment. In total, 48 people participated, 18 of them female. Between 30 and 39 human subjects participated each day (on average 34). The ages ranged between 18 to 31, and they were all students who were paid 100 DKr. per hour for participating. Two of the participants did not speak Danish. The subjects were only asked about their age, height and weight, and not about smoking habits, or whether they suffered from asthma or allergies or any other kind of diseases. Some of the anthropological characteristics are shown in Table 4.

Table 4 *Some anthropological characteristics of the participants (average ± std.)*

Age	18-31 years (21.5 ± 2.7)
Height	157-195 cm (177.1 ± 9.2)
Weight	44-91 kg (69.7 ± 10.5)
Gender	30 male, 18 female
Total number of subjects	48
Number of subjects per day	30-39 (34)

Experimental conditions

The filter

The filter had been used previously as an outdoor air filter with no re-circulation for two years in a Copenhagen suburban area. The flow through the filter had been at 8000 m^3/h for 10 hours per day giving an approximate total of $40 \cdot 10^6$ m^3 filtered air. The filter was a 0.6·0.6m EU7 filter with four bags with a total surface area of 3 m^2. To lower the sensory pollution load from the filter, it was decided after a pre-experiment that only one filter bag with an area of 0.75 m^2 would be used in the experiment. All filter pockets were visually equally contaminated. The specially built filter bag can be seen in Figure 10.

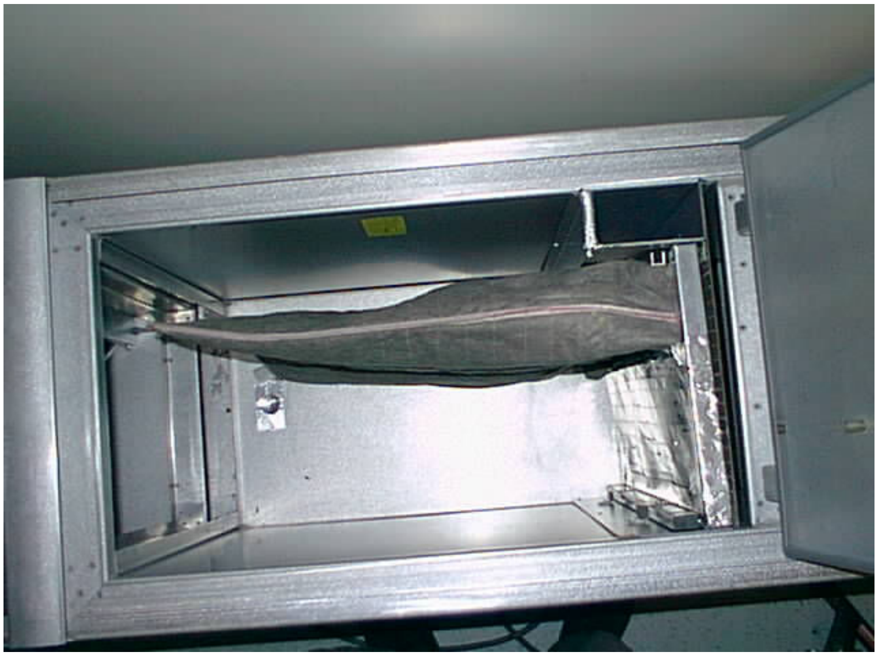


Figure 10 *The specially built filter placed in the ventilation system.*

Temperature and relative humidity

The air temperature was kept constant at 22°C and the relative humidity at 40% for all experimental conditions.

Measurements

Physical measurements

The temperature and relative humidity in offices 1 & 2, and in the corridor were measured and sampled every minute with VAISALA HMP 140 Series Humidity transmitters. The measuring range for the temperature was –20 to +80°C with an accuracy of ± 0.2°C. The measuring range for the relative humidity was 0-100% with an accuracy of ± 2 % point (in the area 0 to 90%RH, in the area 90 to 100%RH with an accuracy of ± 3% point).

The outdoor air supply rate was measured with tracer gas (SF_6) using the decay method, a Brüel and Kjær Multi-gas Monitor (1302) and a Multipoint Sampler and Doser (1303). The flow through the ventilation system was measured with the constant dosing method. Measurements of the concentration at different places in the room were made to check that the room air was fully mixed. Coherent constant concentration measurements in the offices and in the corridor showed that the corridor was ventilated primarily with the air coming from office 2.

Subjective measurements
The subjective measurements of air quality were made using a graded acceptability scale. A detailed description can be found in chapter 2.1.

Procedure

During the experiment, the subjects were seated in the corridor in front of the rooms where the experiments took place. The offices were illuminated by daylight and by artificial lighting from the ceiling. The corridor was only illuminated by artificial light.

The subjects were instructed to make the evaluation after the first or second inhalation of the air in the room or the air from the cone. Each day the subjects participated for one hour. All assessments were randomized and the order differed between experimental days.

On the experimental day, the subjects were instructed to come for one hour of experiments between 12:00 and 17:00. This flexibility varied the number of people in the experiments at a given time and the temperature in the corridor because of the different total heat loss from the participants (see table 5). On arrival, each participant was given a clipboard with questionnaires to evaluate the air quality on the acceptability scale. Each questionnaire informed the participant to which room he/she should go. They were instructed on how to evaluate the air quality using the acceptability scale. The assessments were made by one participant at a time and there were 4 minutes between assessments for each subject. The subjects were allowed to talk with each other during the experiment, as long as the topic did not concern the ongoing experiment. They were not given any information about the origin of the materials tested, but they were informed that the air was similar to everyday exposure. All subjects were instructed to abstain from alcoholic beverages, spicy food or garlic the day before each exposure, and not to use strong deodorants or perfume on the day of exposure. The subjects were not allowed to smoke during the exposures.

Between each experimental day, the axial fan ensured a constant outdoor air supply rate at 30 l/s (3 h^{-1}) in office 1. At night the temperature and relative humidity varied with outdoor values, but were kept constant from 8 am each day. Four hours before each experimental day the damper in front of the axial fan was altered to obtain the right outdoor air supply rate and the ventilation system was started.

The ventilation system was stopped again at the end of each experimental day. The experiment with the filter was performed at the last three experimental days and between each experimental day the filter stayed in the stationary ventilation system. This was done to ensure that the sensory pollution load from the filter changed as little as possible during the experiment.

Results

In Table 5 are the results of physical measurements during the experimental session shown.

Table 5 *Physical measurements (average ± std.).*

	w/o filter (10 l/s)	w/o filter (30 l/s)	w/o filter (60 l/s)	w. filter (10 l/s)	w. filter (30 l/s)	w. filter (60 l/s)
Air temperature, office 1 (°C)	22.2 ± 0.1	22.1 ± 0.6	22 ± 0.2	22 ± 0.1	22 ± 0.1	21.9 ± 0.2
Relative humidity, office 1 (%)	40 ± 0.3	30 ± 2.2	29 ± 1	40 ± 1.1	40 ± 0.3	33 ± 0.8
Air temperature, office 2 (°C)	20.2 ± 0.2	22 ± 0.1	21.8 ± 0.2	22 ± 0.1	22 ± 0.1	22 ± 0.2
Relative humidity, office 2 (%)	28 ± 0.3	25 ± 0.7	29 ± 1.2	26 ± 1.3	40 ± 0.5	33 ± 1
Air temp., facial exposure (°C)*	23.1 ± 0.3	23.1 ± 0.3	23.1 ± 0.3	23.1 ± 0.3	23.1 ± 0.3	23.1 ± 0.3
Relative hum., facial exposure (%)*	26 ± 9	26 ± 9	26 ± 9	26 ± 9	26 ± 9	26 ± 9
Air temperature, corridor (°C)	21.1 ± 0.2	22.1 ± 0.2	21.5 ± 0.2	21.2 ± 0.3	22.3 ± 0.2	22.3 ± 0.2
Relative humidity, corridor (%)	27 ± 0.6	25 ± 0.7	29 ± 0.8	29 ± 0.9	38 ± 0.5	32 ± 0.8
Ozone, outside (ppb)	1.3 ± 1.1	6.6 ± 2	5.6 ± 2.7	3.8 ± 3.8	1.1 ± 1.4	3.3 ± 2

*Due to loss of data, these values represent the average of all days.

Data analyses

The distributions of the data obtained from the questionnaires were tested for normality with Shapiro-Wilk's W test. If they were normally distributed, they were tested by means of analysis of variance, ANOVA, or by t-test for independent samples. Data without normal distributions were tested with Kruskal-Wallis one-way analysis of variance.

Subjective measurements

Using [1], the percentage of dissatisfied can be calculated from the data obtained on the acceptability scale.

$$PD = \frac{\exp(-0.18 + 5.28 \cdot ACC)}{1 + \exp(-0.18 + 5.28 \cdot ACC)} \cdot 100 \qquad [1]$$

where:
PD: the percentage of dissatisfied (%);
ACC: the mean value of the acceptability voting.

The sensory pollution load of the source can be calculated with [2] and [3]. In this experiment, the perceived air quality upstream and downstream the pollution source (filter) can be calculated from an evaluation made after facial exposure to air upstream and downstream the ventilation system relative to the flow through the system. However, it can also be calculated as an evaluation of the air quality made during a whole-body exposure relative to the outdoor air quality and outdoor air supply rate.

$$C = 112 \cdot \left[\ln\left(PD\right) - 5.98\right]^{-4} \qquad [2]$$

where:

C: Perceived Air Quality (decipol);
PD = percentage of dissatisfied (%).

$$G = \frac{Q \cdot (C_{After} - C_{Before})}{10 \cdot A} \qquad [3]$$

where:
G: Sensory pollution load (olf);
Q = ventilation rate (l/s);
A = surface area of the filter (m^2) [when the filter was absent A = 1];
C = Perceived air quality (decipol).

Outdoor air quality
The quality of the outdoor air was evaluated as good and varied little throughout the experimental days, Table 11.

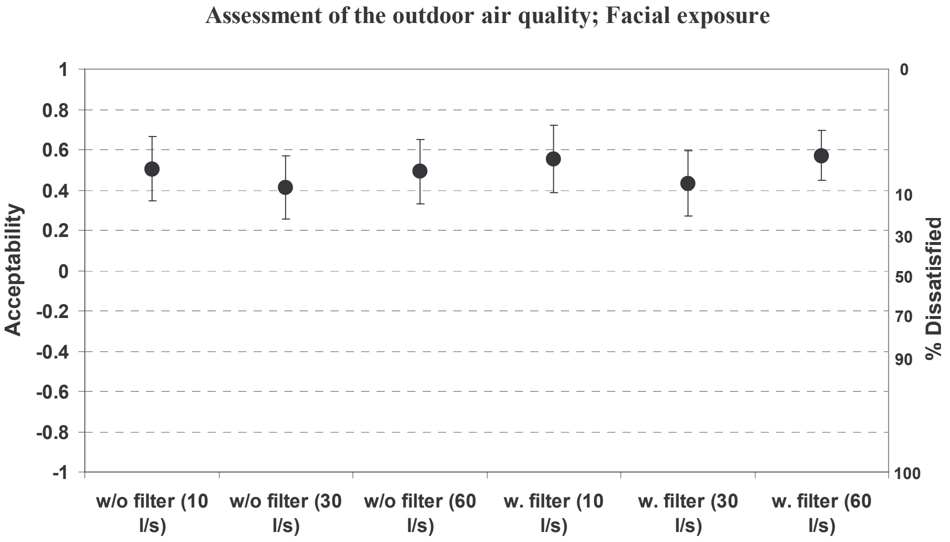


Figure 11 *Percent dissatisfied with the quality of the outdoor air. Each column represents the average of 30-39 evaluations. Also depicted is the 95%-confidence interval.*

Whole-body exposure
Figure 12 gives depicted the results of assessments of the room air made after whole-body exposure. The results with and without filter in the ventilation system are shown as a function of the outdoor airflow to the room. At 10 l/s the air quality was unexpectedly found to be better when the filter was in the ventilation system than when it was not. However, these two assessments are not significantly different ($p<0.19$). At 30 l/s, the acceptability of the air quality with or without the filter in the system was found to be significantly different ($p<0.01$), like-

wise at 60 l/s ($p<0.02$). In both cases, the presence of the filter in the system reduces the acceptability of the air quality. The outdoor air supply rate had a significant influence on the acceptability of the air quality when the filter was not present ($p<0.01$). When the filter was present, the acceptability of the air quality did not improve when the outdoor air supply rate increased ($p<0.26$). Testing with two-side ANOVA shows that the presence of the filter in the system had an almost significant influence on the acceptability ($p=0.068$) and the supply rate was significant ($p<0.00002$). Furthermore, the interaction between the presence of the filter in the system and the outdoor air supply rate was significant ($p<0.01$). This indicates the improvement of the air quality by increasing the outdoor air supply rate is dependent on the presence of the filter in the system *or* the sensory pollution load from the filter is not constant, but changes with the outdoor air supply rate.

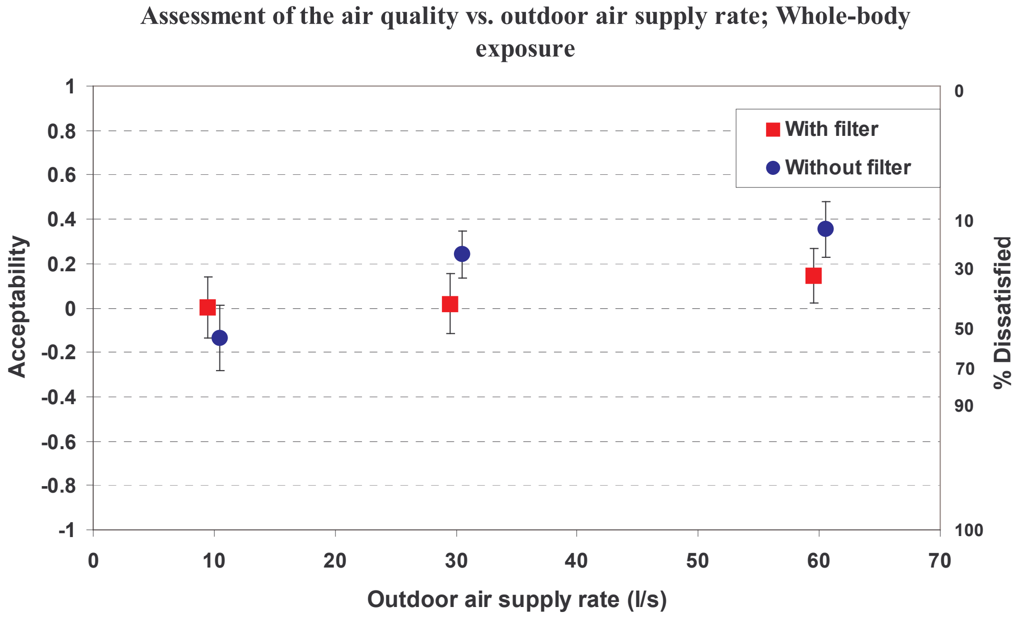


Figure 12 *Acceptability of the room air, based on assessments made during whole-body exposure. Each point representing the average of 30-39 evaluations. Also depicted is the 95%-confidence interval.*

Facial exposure

Figure 13 gives the assessment of the room air of office 1 made during facial exposure in office 2. The presence of a filter in the ventilation system had no significant influence on the acceptability of the air quality when evaluated after facial exposure ($p<0.43$). Increasing the outdoor air supply rate improved significantly the acceptability of the air quality with or without the filter in the system ($p<0.001$).

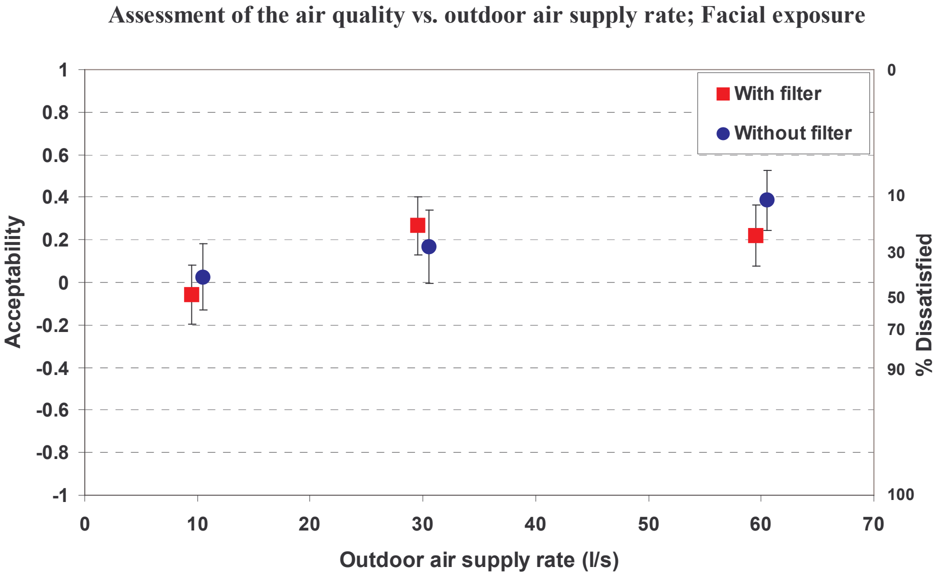


Figure 13 *Acceptability of the room air, based on assessments made during facial exposure, each point representing the average of 30-39 evaluations. Also depicted is the 95%-confidence interval.*

Figure 14 depicts the acceptability of the air quality upstream and downstream the ventilation system when the filter was not present as a function of the outdoor air supply. The ventilation system without the filter did not decrease the air quality evaluated during facial exposure ($p<0.2$). However, at 60 l/s it was evaluated that there was a significant difference between upstream and downstream of the empty ventilation system ($p<0.01$).

Figure 15 shows the effect of the presence of the filter in the ventilation system on the acceptability of the air quality downstream of the ventilation system. Both the presence of the filter and the outdoor air supply rate had a significant effect on the acceptability of the air quality, $p\ll0.0001$ and $p<0.0001$, respectively.

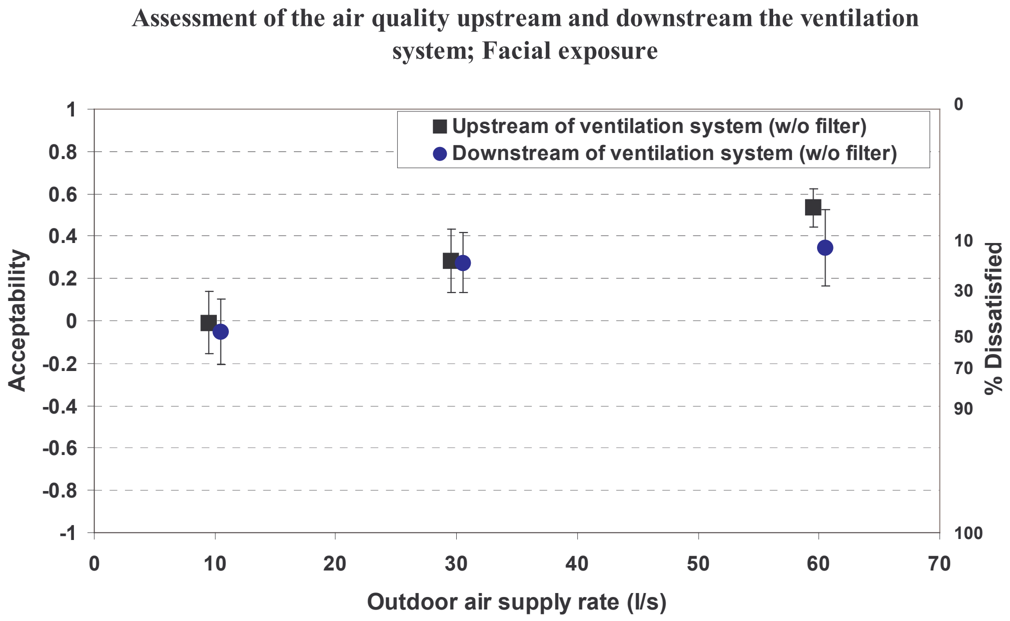


Figure 14 *Acceptability of the air upstream and downstream of the ventilation system when the filter was not present, the assessments being made during facial exposure. Each point represents the average of 30-39 evaluations. Also depicted is the 95%-confidence interval.*

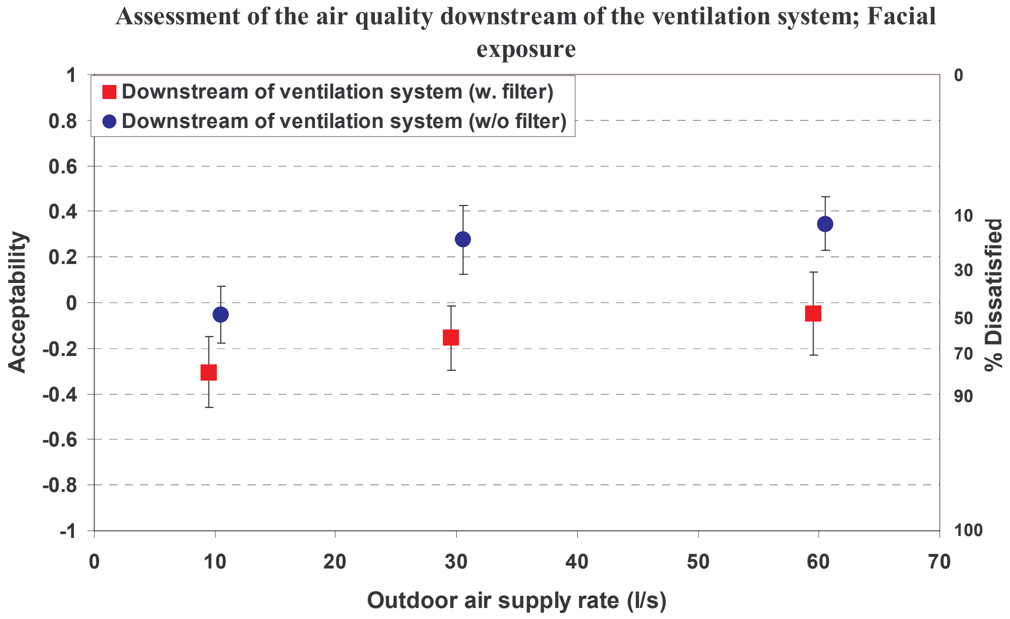


Figure 15 *Acceptability of the air downstream of the ventilation system when the filter was present and when it was not, assessments being made during facial exposure. Each point represents the average of 30-39 evaluations. Also depicted is the 95%-confidence interval.*

Figure 16 gives the acceptability of the quality of the air upstream and downstream of the ventilation system when the filter was present. The results shown as a function of the outdoor air supply rate. The difference of the air quality between upstream and downstream of the ventilation system having a filter in the system or not, increases with increasing outdoor air supply, but this trend is not significant ($p<0.16$). However, at an outdoor air supply rate of 60 l/s there is a significant difference in acceptability of the air upstream and downstream the system ($p<0.003$).

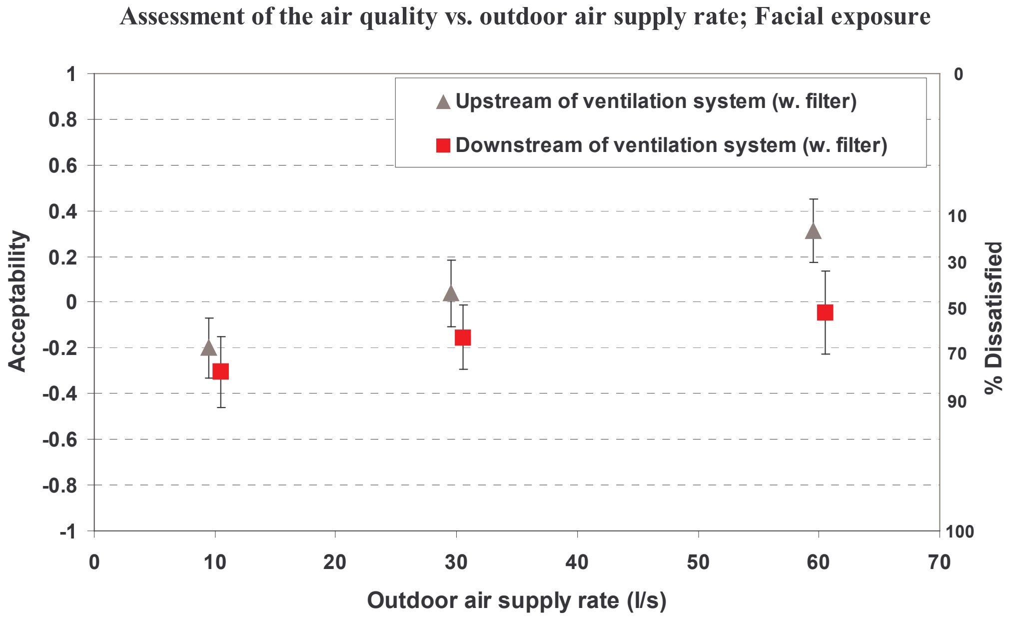


Figure 16 *Acceptability of the air upstream and downstream the ventilation system when the filter was present, the assessments made during facial exposure. Each point represents the average of 30-39 evaluations.*

Sensory pollution load

Facial exposure

From equations [1], [2] and [3] it is possible to calculate the sensory pollution load as the difference in perceived air quality upstream and downstream the filter, multiplied by 1/10'th of the flow-rate per surface area of the filter ($l/s \cdot m^2$filter) through it. The results of such calculations can be seen in Figure 17 for the three cases of outdoor air supply rate. As can be seen, when the filter was in the ventilation system, the sensory pollution load per square meter filter material was between 50 and 70 olf/m^2 and that the system itself including background pollution load from the office, being a minor pollution source, 0-10 olf/m^2filter. The sensory pollution load from the filter was therefore 40-70 olf/m^2filter.

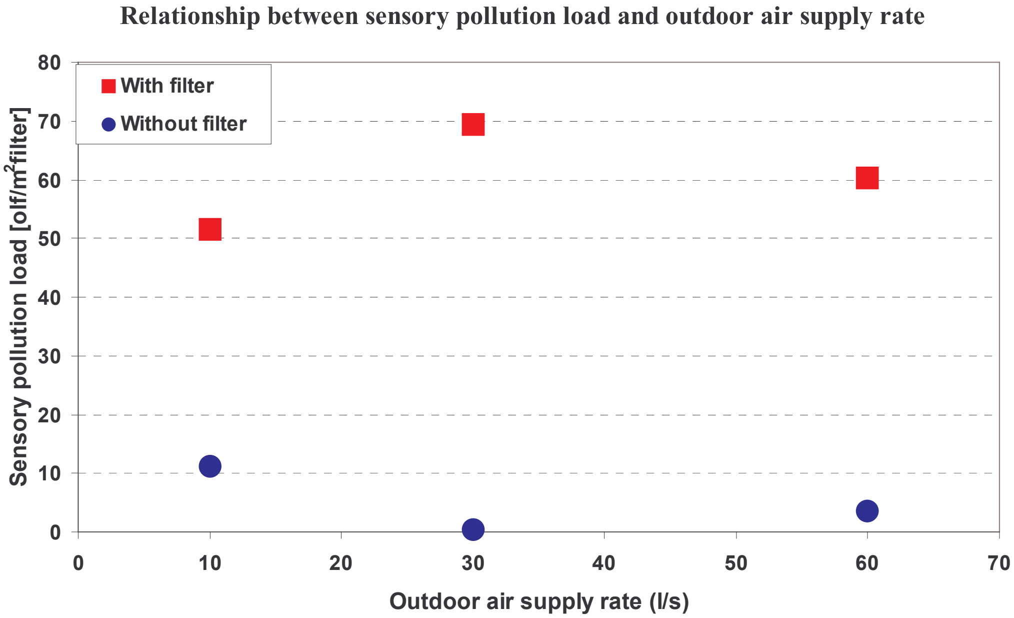

Relationship between sensory pollution load and outdoor air supply rate

Figure 17 *Sensory pollution load based on evaluations made during a facial exposure.*

<u>Whole-body exposure</u>

The ventilation system with or without the filter could also be considered as a “normal” pollution source in the office. The sensory pollution load from the filter can then be calculated as the pollution load of the room when the filter is present, subtracted by the pollution load when the filter is absent. Figure 18 shows the results of such calculations. The perceived air quality is calculated from assessments of the room air made during whole-body exposure. At 10 l/s, the pollution load was higher when the filter was absent from the system than when it was present, and therefore, the pollution load from the filter was negative. At 30 and 60 l/s the pollution load was higher with the filter than without. In both cases, the level of the pollution load was constant (16 and 3 olf/m^{2}filter, respectively) and the difference between the two cases was constant (13 olf/m^{2}filter).

The pollution load based on evaluations made during facial exposure is 40-55 olf/m^{2}filter higher than when it is based on evaluations during whole-body exposure. On average, the pollution load was 55.4 olf/m^{2}filter when evaluated after facial exposure and 8.4 olf/m^{2}filter when evaluated after whole-body exposure. Figure 19 depicts the sensory pollution load from the filter when it is evaluated after facial exposure or whole-body exposure, respectively.

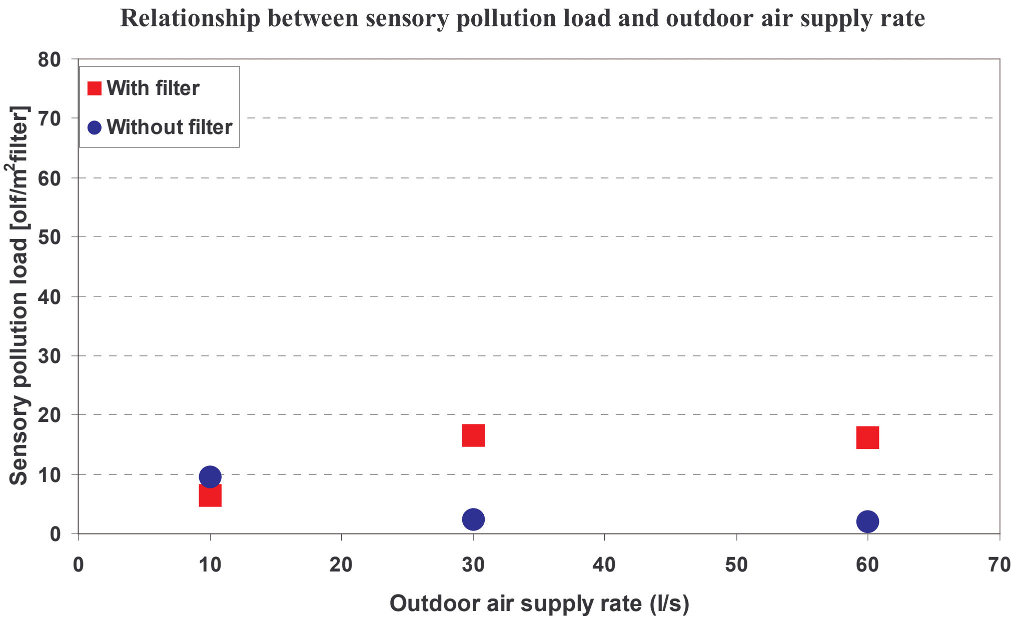


Figure 18 *Pollution load in the room as a function of the outdoor air supply rate, results being calculated from assessments made during whole-body exposure.*

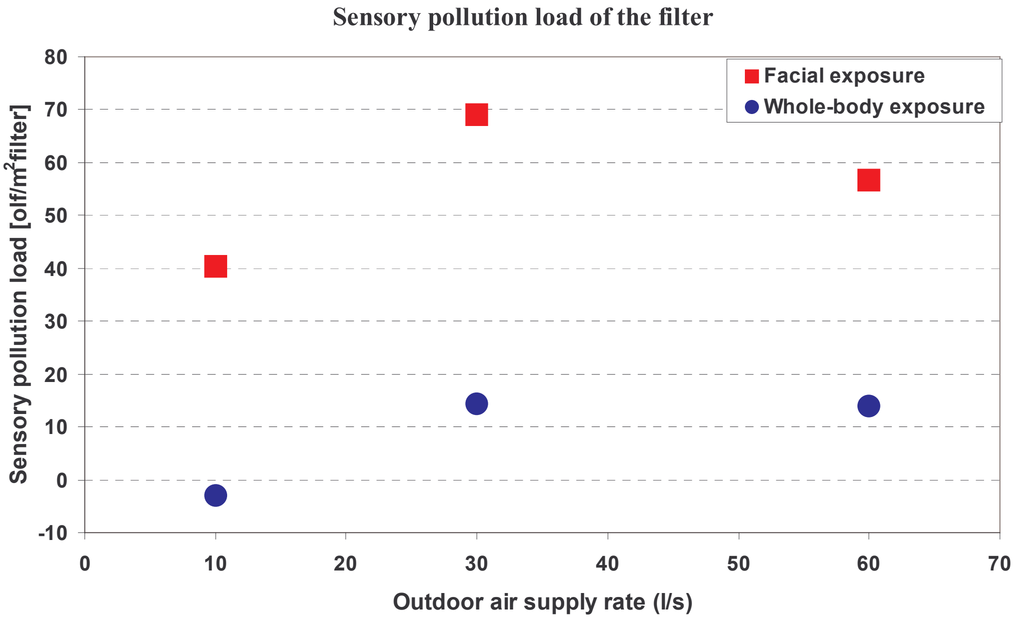


Figure 19 *Sensory pollution load according to the two different measuring methods.*

Whole-body exposure versus facial exposure

Results from evaluation of the quality of the room air of office 1 made during facial exposure in office 2 are shown in Figure 20 as a function of evaluations of the room air of office 1 made during whole-body exposure. As can be seen, there was almost no difference between evaluations made during whole-body and facial exposure. However, there was a tendency at low pollution levels for the air to be found more acceptable after facial exposure than after whole-body exposure.

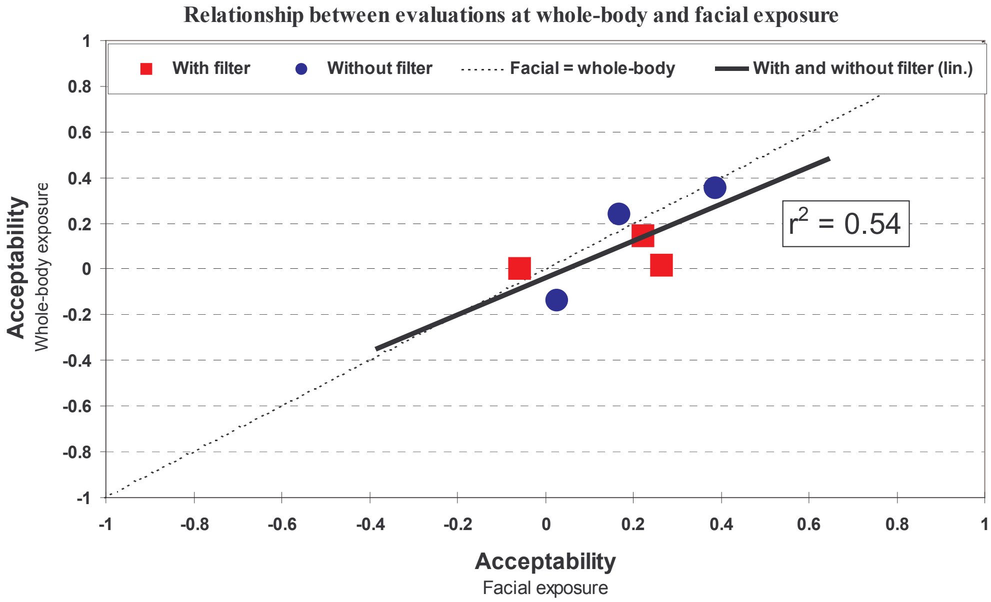


Figure 20 *Relationship between evaluations of the air quality in the room made after whole-body and after facial exposure.*

Using linear regression on the six sets of observations, the transfer function was found to be:

$$\text{Acc(whole-body)} = 0.8 \cdot \text{Acc(facial)} - 0.03,\ r^2 = 0.54,\ p<0.1.$$

The sensory pollution load calculated on the results obtained from whole-body exposure as a function of the sensory pollution load obtained from facial exposure is depicted on Figure 21. The relation between pollution load from whole-body exposure and facial exposure is very poor, $r^2 = 0.03$.

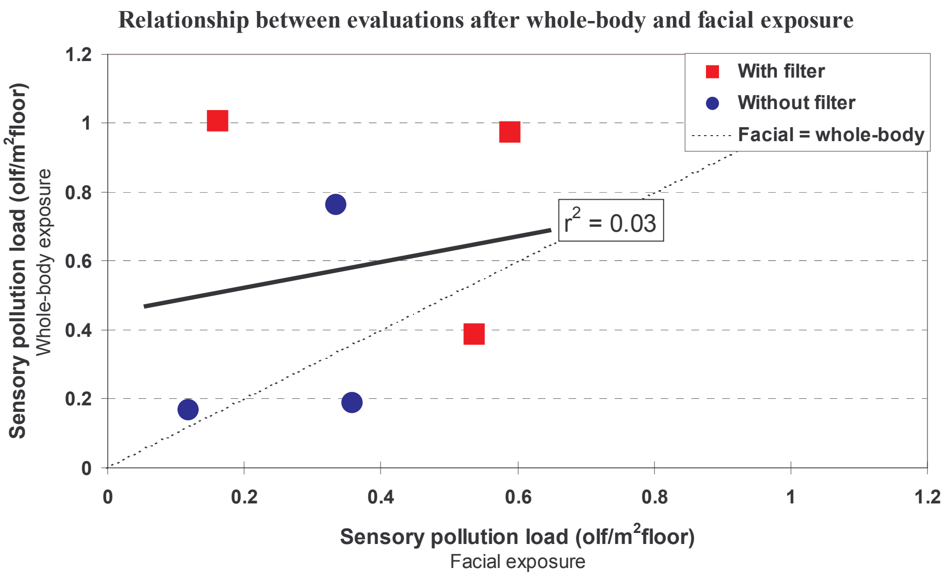


Figure 21 *Relationship between sensory pollution load calculated on the basis of assessments made after whole-body and facial exposure, respectively.*

Discussion

The experimental set-up made it possible to calculate the pollution load of the filter using two different methods. One method based on evaluations during facial exposure to the air up-stream and downstream of the filter and one method based on evaluations during whole-body exposure on entering the room, with or without the filter being present in the system. The two methods gave a difference of 40 to 55 olf/m^{2}filter with the facial method giving the highest value (Figure 19, on average 4.5 times higher). Using linear regression on the three sets of observation, the transfer function was found to be:

$$\text{Pollution load(whole-body)} = 0.63 \cdot \text{Pollution Load(facial)} - 26.4,\ r^2 = 0.83.$$

Obviously, this transfer function is valid only for a pollution load(facial) higher that 42 olf/m^{2}filter. Forcing the linear regression through [0; 0], and thereby setting the intercept at 0, gives a regression that is valid in a wider area of pollution loads:

$$\text{Pollution Load(whole-body)} = 0.17 \cdot \text{Pollution Load(facial)},\ r^2 = 0.37.$$

However, the regression is based on only three observations in this experiment, and should only be used for Pollution Load(Facial) $\in$ [40; 70] and Pollution Load (Whole-Body) $\in$ [0; 15]. The observations and the two regression lines can be seen on Figure 22.

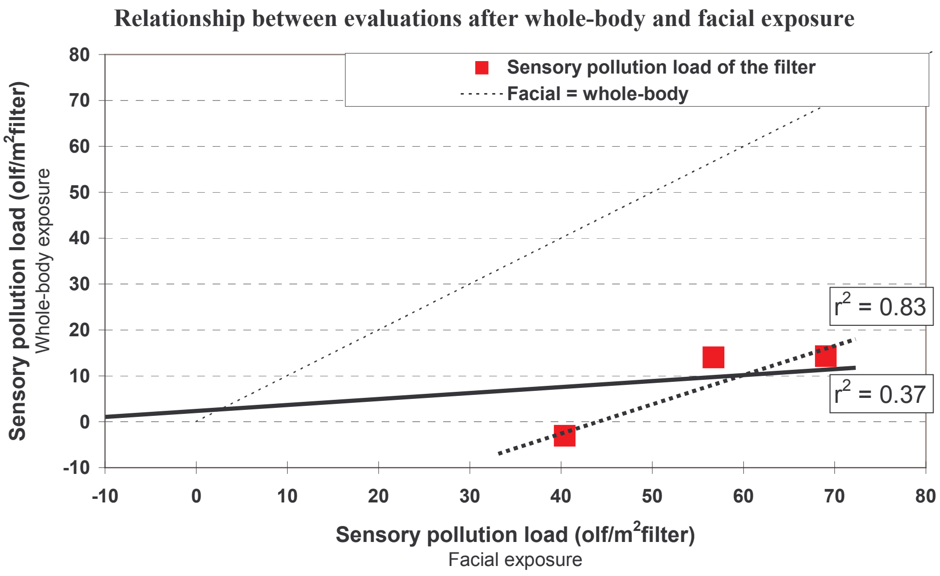


Figure 22 *Relationship between sensory pollution load calculated on the basis of assessments made after whole-body and facial exposure, respectively.*

Sensory evaluations made in office 2 of the quality of the air upstream and downstream of the filter indicate that the source strength of the filter increases when the air quality upstream the filter improves. Consequently, the acceptability of the air quality in the room does not improve with the supply rate when the filter is present in the ventilation system (Figure 12). Wargocki (2000) investigated in a similar office the sensory pollution load of a used carpet at three outdoor air flow rates (18, 60 and 180 l/s) and the result was that the sensory pollution load increased when the outdoor air supply rate increased. If the source strength is dependent on the quality of the air upstream of the filter, it is important to know this when trying to model the air quality in a room or in a ventilation system.

Even if there seems to be no difference between the acceptability made after whole-body exposure and after facial exposure, the result was not exactly the same (Figure 12 and Figure 13). After whole-body exposure, the acceptability did not improve with increasing outdoor airflow when the filter was in the system, but it did improve after facial exposure.

The participants waited in the corridor during the experiments and the air quality in the corridor may have had an impact on the whole-body evaluations due to adaptation. The air quality in the corridor was decreased by the bioeffluents from the participants. It was therefore not of the same high quality as it was possible to achieve in office 2 where the facial exposure took place. If adaptation took place, it could have an influence on the evaluations made during whole-body exposure. If the subjects olfactory senses have been lessened due to adaptation, they have evaluated the room air as more acceptable than they would have done without adaptation. The slope of the results in Figure 20 would therefore have been smaller and the linear regression line would have been more horizontal than the one depicted. That means that the subjects evaluate the air as being more acceptable after whole-body exposure than after facial exposure when the acceptability is less than approximately 0.1.

There was approximately 4 minutes between each exposure for each subject, and this should provide sufficient time for the olfactory senses to recover and thereby to prevent the possibility of cross adaptation (Berglund et al., 1978).

The small fans used to extract the air from office 1 to office 2 heated the air, and a difference in temperature of 1.1°C and 13% points in relative humidity were observed. This difference can have had an influence on the assessment of the acceptability (Fang, 1997). Fang et al. investigated the quality of polluted and unpolluted air in a wide range of enthalpy of the air. From these results, it is possible to convert results obtained in acceptability in this experiment at one enthalpy, to a result obtained at a different enthalpy. The conversion can be made with [4]:

$$ACC_0 = \frac{ACC + 0.00416(E - 45.39)}{1 - 0.0416(E - 45.39)} \qquad [4]$$

where:
ACC_0: acceptability of the air at 23°C and 50%RH;
ACC: acceptability at the given temperature and relative humidity;
E: enthalpy at the given situation (kJ/kg).

The average temperature of the air for facial exposure was 23.1°C and the average relative humidity was 26%. In office 1, the average temperature was 22°C and the relative humidity 37%. The results from assessments made during facial exposure and during whole-body exposure, and the converted facial exposure results can be seen in Table 6. The difference between the results obtained at 23.1°C/26%RH and those that would have been obtained if it was assessed at 22°/37%RH is maximum 0.01 on the acceptability scale and can therefore be disregarded.

Table 6

Experimental condition	Facial exposure at 23.1°C/26%RH	"Converted" facial exposure at 22°C/37%RH	Whole-Body exposure at 22°C/37%RH
w. filter at 10 l/s	0.22	0.23	0.15
w. filter at 30 l/s	-0.06	-0.06	0.00
w. filter at 60 l/s	0.27	0.28	0.02
w/o filter at 10 l/s	0.03	0.03	-0.13
w/o filter at 30 l/s	0.17	0.17	0.24
w/o filter at 60 l/s	0.39	0.4	0.36

The experiment was carried out over several days with only one condition per day. From previous studies, it is known that the assessments from the participants can vary from day to day and that the influence from the different items of equipment and from outdoor conditions can also vary. The results could have been different if the experiment had been carried out with and without the filter on the same day, but it was not possible to do so with the given set-up.

Lagercrantz (2001) tested building materials using two different methods: small-scale, using assessments from facial exposure with the materials in 200 l glass chambers; and full-scale, using assessments from whole-body exposure by entering a room with the materials behind a screen. The airflow per m^2 material was the same in the small-scale and in the full-scale set-up. The experiment was carried out at the same time as present study, using of the same participants. The results are shown in Figure 23 together with the results from the present study. The majority of the results from building materials were in the "unacceptable" range of the scale, whereas the results from the present study were in the "acceptable" range of the scale.

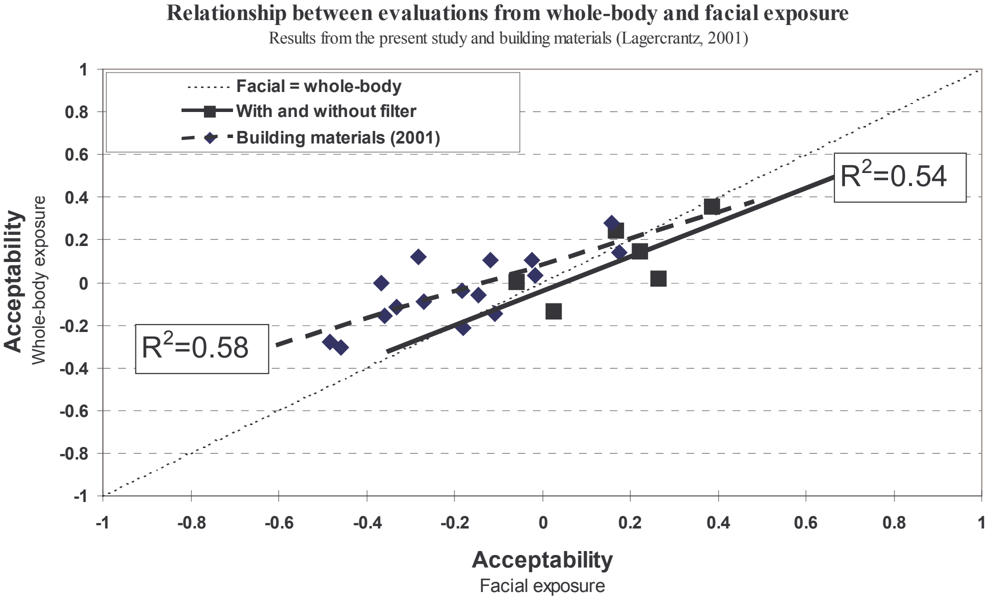


Figure 23 *Relationship between evaluations of the air quality in the room made during whole-body and facial exposure; results from the present study and a study with building materials [Lagercrantz, 2001].*

Jørgensen and Vestergaard (1998) studied the relationship between acceptability of the air quality assessed during whole-body exposure and during facial exposure. The study included several types of building material, each material being evaluated by entering a chamber containing a specific material or by assessing the air coming from a cone. Thirty people participated in this experiment. The results are shown in Figure 24 together with the results from the present study.

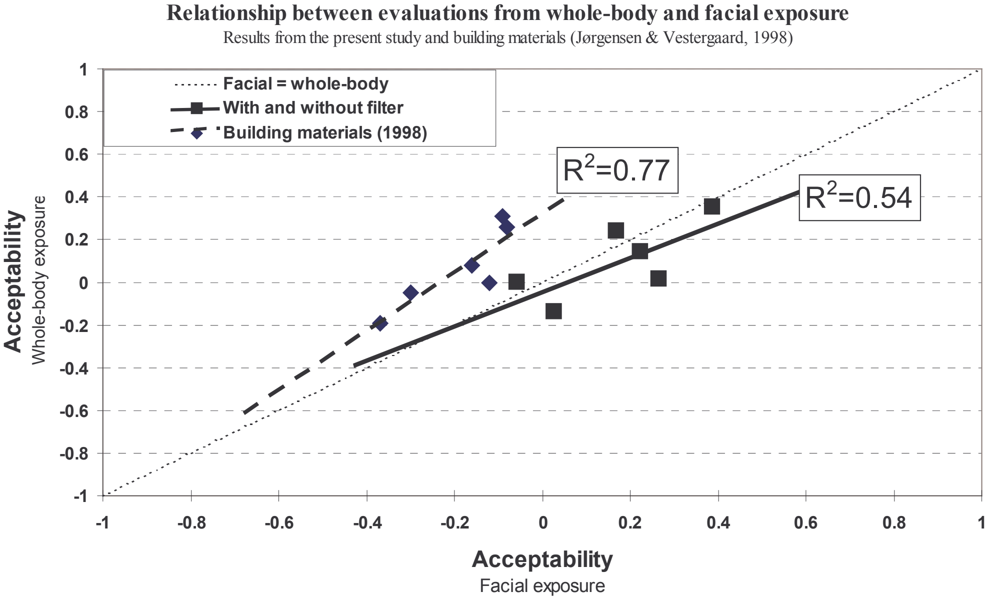


Figure 24 *Relationship between evaluations of the air quality in the room made during whole-body and facial exposure; results from the present study and a study with building materials [Jørgensen & Vestergaard, 1998].*

All three studies (present, Lagercrantz (2001), Jørgensen & Vestergaard (1998)) are depicted together in Figure 25. All observations are an average of 30-40 assessments. Below an acceptability of 0.2, the air is more acceptable after whole-body exposure than after facial exposure and the opposite tendency applies at acceptability levels above 0.2. Around 0.2 the acceptability of air assessed after whole-body exposure is the same as after facial exposure. Using linear regression, the transfer function was found to be:

$$\text{Acc(Whole-body)} = 0.55 \cdot \text{Acc(Facial)} + 0.08,\ r^2 = 0.5,\ p \ll 0.01.$$

The experiments were performed in almost the same manner, but whereas the results with filter were mostly in the area above 0 on the acceptability scale, the results from building materials were generally in the lower part of the scale. The same people participated in the present study and in the study by Lagercrantz (2001), but different people took part in the study of Jørgensen and Vestergaard (1998); this can give rise to variations in the results due to the individual differences. To find a more accurate relationship between the two measuring methods, further experiments should be made in the area above acceptability equal to 0.2 and in the area below acceptability equal to -0.4.

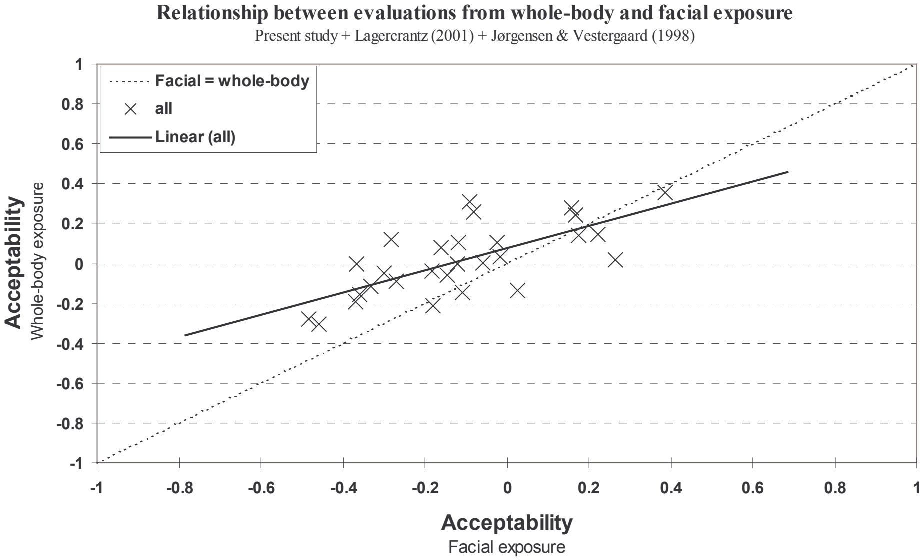


Figure 25 *Relationship between evaluations of the air quality in a room made during whole-body and facial exposure. Results from the present study, Lagercrantz (2001), and Jørgensen & Vestergaard (1998).*

The filter was not ventilated with outdoor air between each experimental day, and it is therefore possible that the source strength decreased over the period. On the last experimental day the filter was tested with an outdoor air supply rate of 10 l/s. The air in the office that day was perceived to be of *better* quality than the day when the filter was absent of the system but with the same outdoor supply rate. This could indicate that the source strength of the filter had decreased. However, the pollution load on the two other experimental sessions with the filter was the same.

Conclusions

- Inserting a used filter in a ventilation system recirculating the room air deteriorated the air quality in the room.

- Two different methods were used to find the pollution load from the filter. When the pollution load was based on evaluations made during facial exposure, it was 30-40 olfs higher than when it was based on evaluations made during whole-body exposure. However, the difference in acceptability of the same air is not significant.

- A relationship between the acceptability of the air evaluated during facial exposure and during whole-body exposure was established. However, this was based only on six points. When combining the results from the present study and from the two previous studies, it was possible to establish a stronger relationship. Below an acceptability of 0.2, the air is more acceptable after whole-body exposure than after facial exposure, the opposite tendency applying at acceptability levels above 0.2.

- Increasing the outdoor airflow rate increased the source strength of the filter and the acceptability of the air did not improve.

3.2 Exposure-response relationships for emissions from used ventilation filters

Objective

- To determine the exposure-response function for air polluted by a used filter
- To estimate the pollution load from a used filter

Experimental plan

A test rig made it possible to assess the air quality downstream of a filter at three different flows through the filter and at the same time it was possible to assess each flow at three different concentrations by dilution with clean air. The experimental matrix can be seen in Table 7.

Table 7 *Experimental matrix*

Dilution level	Flow through the filter (l/s)		
	50	100	200
1 (100% air from downstream of filter)	*X*	*X*	*X*
2 (50% air from downstream of filter + 50% chamber air)	*X*	*X*	*X*
4 (25% air from downstream of filter + 75% chamber air)	*X*	*X*	*X*

Methods

Facilities

A test rig was designed (Figure 26) and placed in a 26.8 m^3 stainless steal chamber (Albrechtsen, 1988). The chamber was ventilated with an outdoor air exchange rate of 40 h^{-1}. The temperature was 20°C and the relative humidity 55%. The outdoor air was filtered with clean new filters (EU7) before it was let in to the chambers. The test rig was made of a Fläkt ventilation system consisting of a filter and a ventilator unit (both of type KLAA-20-102-1). Each unit was 1.0·0.66·0.75 meter (w·h·d). The air upstream and downstream of the filter was extracted with glass tubes and small fans to cones where it was possible to make facial assessments of the air. The air extracted downstream of the ventilation system was divided into three glass tubes. With small valves, it was possible to dilute the extracted air with the air in the chamber. The test rig made it possible to assess the air quality downstream of a filter at three different flows through the filter (Q=50, 100 and 200 l/s corresponding to 10, 20 and 40% of the nominal flow). At the same time it was possible to assess each flow at three different concentrations (dilution factor 1 (no dilution), 2 and 4). The airflow through the cones for assessment was 1 l/s. To obtain dilution levels 2 and 4, the air was diluted with 50% or 75% chamber air, respectively. Two test rigs were placed in the chamber at the same time, in that way it was possible to investigate the pollution load of two filters simultaneously. The airflow through both test rigs was identical. The air in the chamber was also assessed. In total, there were seven assessments for each airflow. The assessed air at the sniffing cones was conditioned to 24°C and 45% relative humidity.

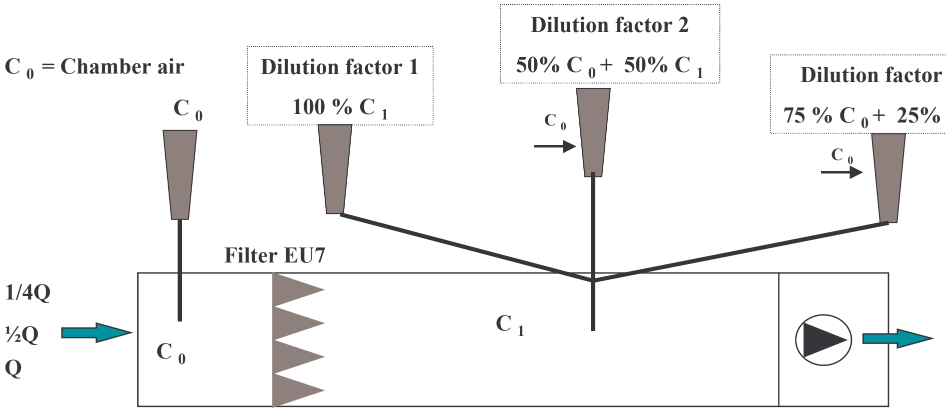


Figure 26 *The rig for studying the exposure-response function for one filter at 3 different flows and at 3 different dilutions. The experiment was made with two rigs.*

Subjects

An untrained panel (8-13 persons) assessed the perceived air quality. The panel consisted of employees and students at the International Centre for Indoor Environment and Energy. Not all members participated in all assessments.

Experimental conditions

Pollution source

The filters used as a pollution source, had been used previously as outdoor air filters with no recirculation for 14 months in a Copenhagen suburban area. The flow through each filter had been at 1800 m^3/h for 12 hours per day, giving an approximate total of $9 \cdot 10^6$ m^3 filtered air. The filters were 0.5·0.6 meter EU7 filter with eight bags with a total surface area of 6 m^2. Visual inspection showed that the filters were highly contaminated with particles from the outdoor air.

Measurements

Physical measurements
The flow through the filter and through the assessment cones was measured with tracer gas techniques using Brüel & Kjær 1302 – Multi Gas Monitor and Brüel & Kjær – 1303 – Multi Point Sampler and Doser. The tracer gas used to measure the flow of the extracted air and to ensure the dilution levels in this experiment was 1% SF_6, 99% N_2. This was done to ensure that the measurements were made within the possible measuring area of the Brüel & Kjær equipment.

Subjective measurements
All the assessments of the air quality were made on an acceptability scale (see chapter 2.1 for a more detailed description).

Procedure

The two used filters were placed in the test rig 14 days before the experiment started, and ventilated with 200 l/s chamber air. The air through the filter had the same temperature and relative humidity as the air in the chamber.

In total, each member of the panel assessed seven glass cones for each flow through the filter. The assessments were made in random order, and only the glass cones for assessment were visible for the subjects during the assessments. When the panel had made the assessments at one flow, the flow was changed and after two hours, the panel assessed the air again. With a total of three assessment periods, the experiment was conducted in the course of one day.

Results

Statistical analyses
The distributions of the data obtained from the questionnaires were tested for normality with Shapiro-Wilk's W test. If they were normally distributed, they were tested by means of analysis of variance, ANOVA, or by t-test for independent samples. Data without normal distributions were tested with Kruskal-Wallis one-way analysis of variance.

Subjective measurements
Using equation [1] in chapter 2.1, the percentage of dissatisfied can be calculated from the data obtained on the acceptability scale.

The quality of the outdoor air was evaluated as good and less than 8% were dissatisfied.

The mean acceptability of the two used filters is depicted in Figure 27 for dilution level 1. The background air pollution is included in these results. However, the load of the background was found insignificant and will not be included in the following results. The two filters were of the same type and had been used in the same ventilation system, and there was no significant difference in air quality between the filters at any flow through the filters (Q=50l/s, p=0.74; Q=100l/s, p=0.45; Q=200l/s, p=0.81). Therefore, further results from the two filters will be presented as an average of the findings of the two filters.

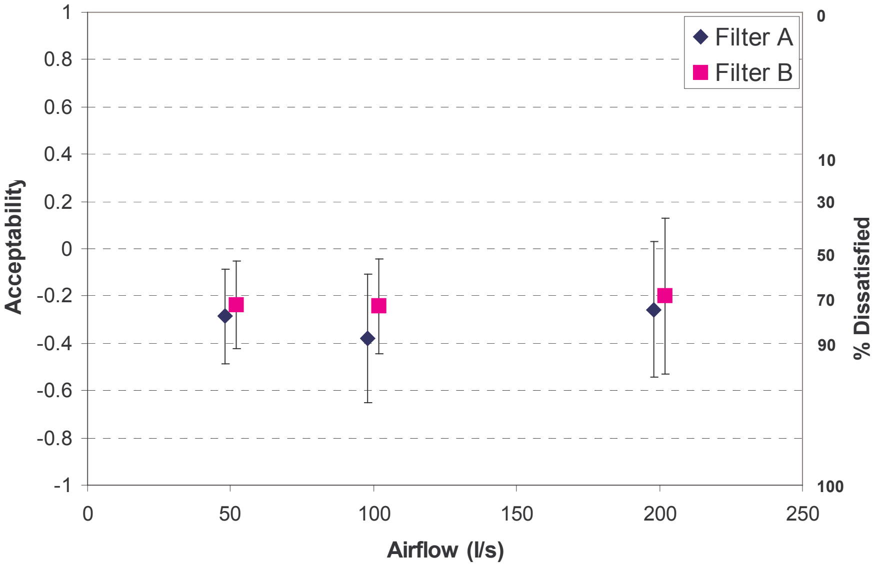


Figure 27 *The mean acceptability for the two tested filters as a function of the air through the filters. Also depicted is the 95% confidence interval.*

The average acceptability of the air from two filters is shown in Figure 28 for the different airflows and dilution factors. For each constant flow, dilution of the air downstream of the filters improved the air quality. There is a statistical difference between the different dilution factors (p<0.00001). However, for each dilution level, the mean acceptability was constant and independent of the airflow through the filter. It was thus not possible to improve the air quality by increasing the airflow through the filter. The linear relation between the mean acceptability and the logarithm of the dilution factor was found and is shown in the figure. The equations for the linear relations are shown in Table 8.

Table 8 *The equations for the linear relation between the mean acceptability and the logarithm of the dilution factor*

Flow through the filter (l/s)	Linear equation	Regression coefficient, r^2
50	Acc = 0.4·Ln(dilution) – 0.26	1
100	Acc = 0.4·Ln(dilution) – 0.34	0.98
200	Acc = 0.5·Ln(dilution) – 0.23	1

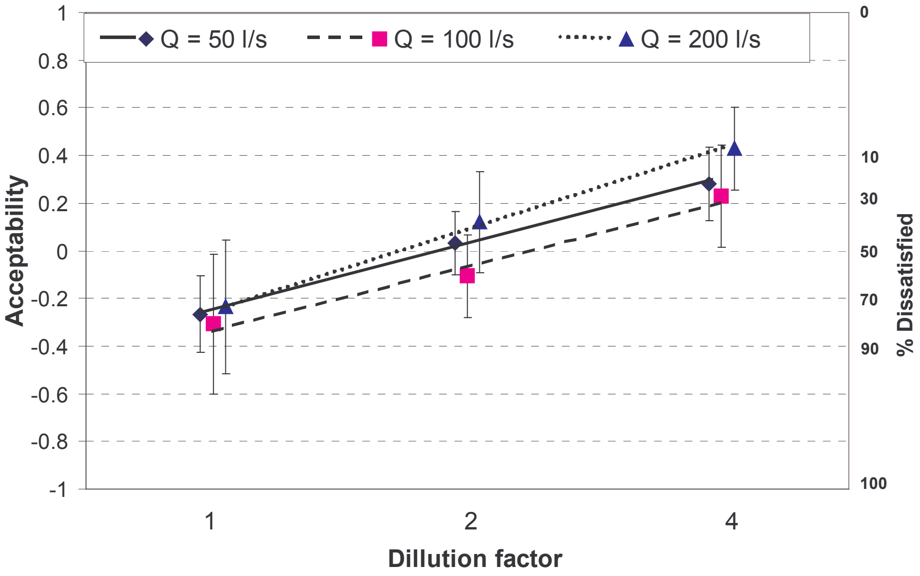


Figure 28 *The mean acceptability at different flows as a function of the dilution factor. Also depicted is the 95% confidence interval. Average of filter A and B. X-axis is a logarithmic scale.*

Discussion

It was not possible to improve significantly the air quality downstream of a filter by increasing the airflow. The source strength in olf [equation 3, chapter 3.1] is shown in Figure 29, and it can be seen that the strength is not constant, but increases with increasing flow. The relation between sensory pollution load measured as olf per square metre filter as a function of the flow through the filter is as follows:

$$\text{Sensory pollution load (olf/m}^2\text{filter)} = 0.25 \cdot \text{(flow (l/s))},\ r^2 = 0.96$$

The relationship is based on only three measuring points.

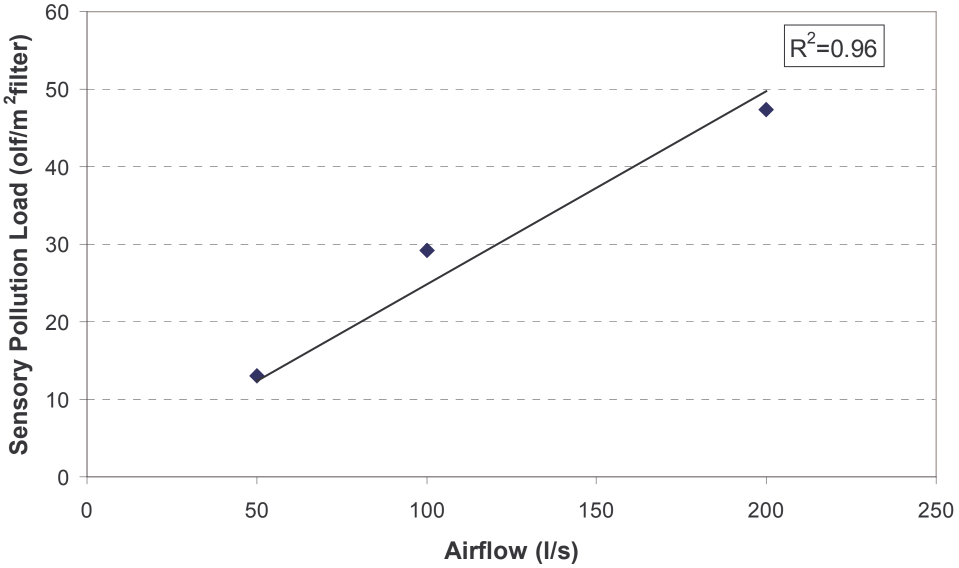


Figure 29 *The source strength of the filter at three different flows through the filter, here depicted at dilution factor = 1.*

Linear relationships between the dilution factor and the acceptability of the air quality have been established for the three flows through the filter. Dilution improved the air quality significantly, but increasing the flow through it did not, and it is therefore possible to base a linear relationship on the average of the assessments of the air quality at the three airflows:

$$\text{Acc} = 0.3 \cdot \text{Ln(dilution)} - 0.56,\ r^2 = 1$$

From earlier studies with building materials (Knudsen et al., 1998), a linear correlation between acceptability and the logarithm of the dilution factor has been found. Figure 30 gives a comparison of the earlier results and the average result from this study. The slope of the exposure-response relationship for the filter is similar to the slope of the building materials sealant and carpet, but is different for the polyolifine. The position of the relationship on the figure depends on the pollution load.

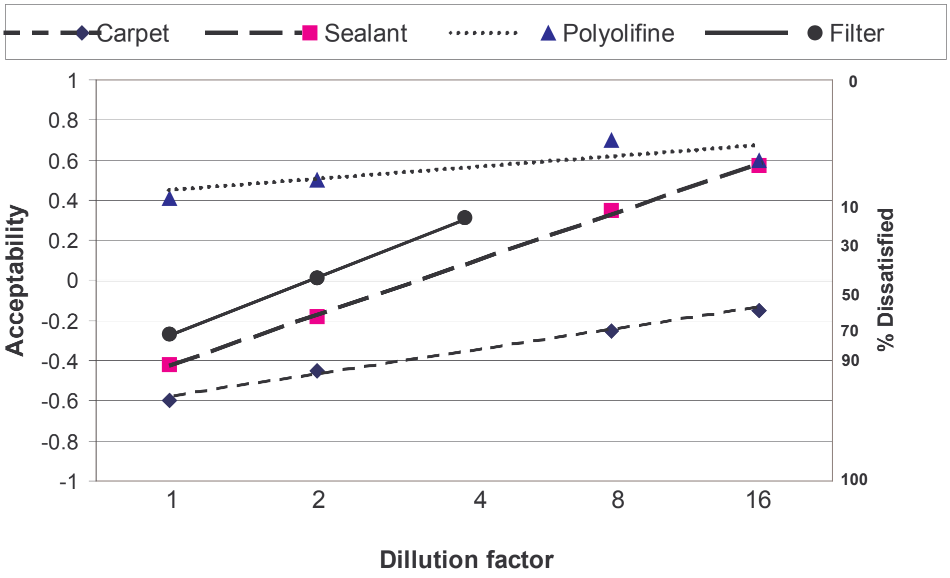


Figure 30 *Exposure-response relationship between the dilution factor and the mean acceptability vote for filters (this study) and sealant, carpet and polyolifine (Knudsen et al., 1998).*

Conclusion

- It was not possible to improve the air quality downstream of a used filter by increasing the airflow through the system.
- The source strength increased with increasing flow.
- A function between the mean acceptability and the logarithm of the dilution factor has been established.

3.3 Impact of a used ventilation filter on perceived air quality, SBS symptoms and productivity

Objectives

- To investigate the impact of a used ventilation filter on the perceived air quality, SBS symptoms and productivity of office work
- To estimate the pollution load from a used filter

Experimental matrix

Human comfort, health and productivity were assessed several times during a 4 hours' exposure in an experimental room with a used or a new filter present in the ventilation system in the experimental space. All other parameters were kept constant.

Methods

Facilities

The experiment was carried out in an office on the second floor of building 402 at the Technical University of Denmark. The office has a floor area of 36 m^2 and a volume of 108 m^3 ($6 \cdot 6 \cdot 3$ m ($L \cdot W \cdot H$)), and three years prior to this study, the office was renovated with a new low-polluting polyolefine floor covering, and the walls were painted. The office faces east and is fitted with two windows with a total area of 6 m^2. The office is shown in Figure 31.

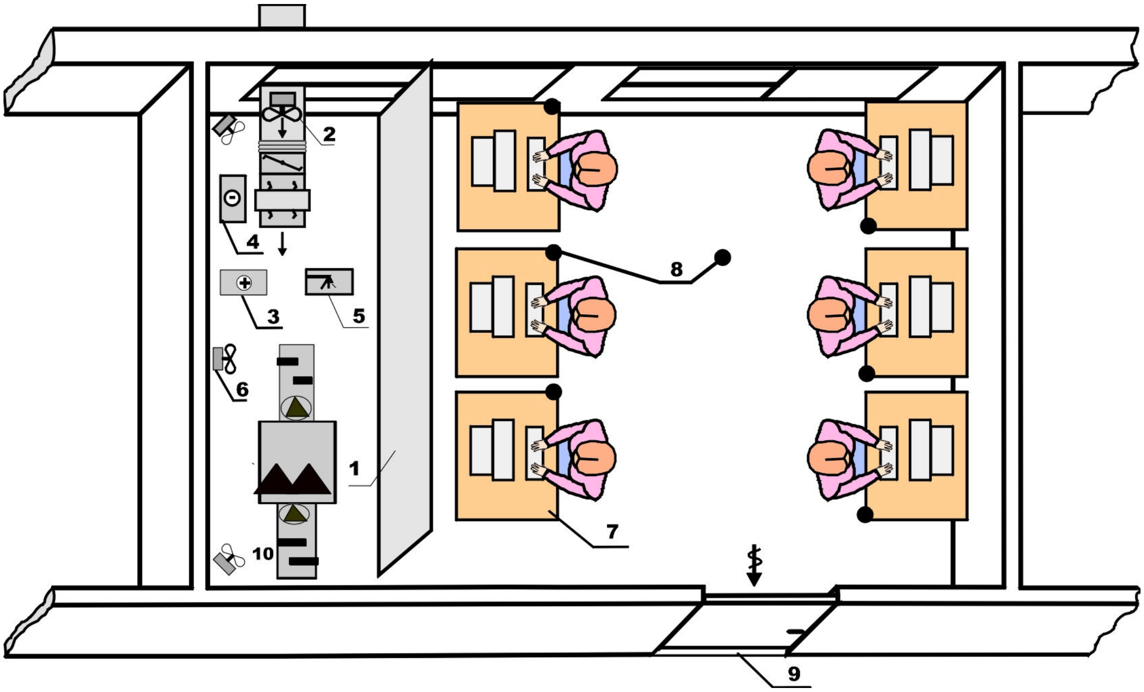


Figure 31 *Plan of the experimental office. 1: partition, 2: outdoor supply fan with damper and silencer, 3: electric oil-based heater, 4: air-conditioning unit, 5: electric humidifier, 6: mixing fan, 7: workstation, 8: measuring points for air temperature, relative humidity and concentration of tracer gas and* CO_2*, 9: ventilation exhaust, 10: recirculating ventilation system with a filter.*

The office was divided into two areas by a 2-metre high partition. The height ensured that it was impossible to see what was behind the partition but the air from one side could still mix with the air from the other side. Six workstations were placed in the larger area, each workstation consisting of a table, a chair, an anglepoised lamp with a low-energy bulb, a computer monitor and a keyboard. The monitor and the keyboard were connected to a personal computer, and to lower the background noise level the computers were placed either outside of the office or behind the partition. Three of the workstations faced a brick wall, and the other three faced the partition. In that way the subjects were placed back-to-back in two rows of three persons. All the workstations were placed perpendicular to the window to ensure as low a glare as possible. A video camera made it possible to monitor the subjects during the experiment.

Behind the partition, outdoor air was provided to the room by an axial fan in the window. With a damper it was possible to alter the outdoor airflow rate and a silencer lowered the noise from the fan. The air left the room again through an opening under the door. Oil-filled electric heaters (Adax – 2000W) and ultrasound humidifiers (Boneco 7131) connected to a PID controller kept the air temperature and the relative humidity constant. The air was cooled by an air-conditioning unit (DAIKIN REY22G7V1). Table fans ensured full mixing in the entire space.

A ventilation system was placed behind the partition to recirculate the air. The system consisted of a unit for 0.3·0.6 m pocket filters (NOVENCO, type ZL-04 SF/FF); the unit is 0.99·0.46·0.72 m (w·h·d). Both upstream and downstream of the unit a fan (Lindab 224W CBU 315 B and Östberg 210W CK 250 C EXP.) and a silencer were installed. The ventilation system was placed with the inlet opposite the outdoor air supply inlet.

Subjects

Thirty female subjects participated in the experiment, all recruited through advertisements at universities and student hostels in the greater Copenhagen area. To participate in the experiment, all applicants answered a questionnaire regarding occupation, general health status, smoking status, SBS symptoms history, etc. Women who understood Danish fluently, had some experience with using a PC, were under 33 years of age, were non-smokers, and did not suffer from hay-fever, asthma or other respiratory diseases were approved in that order as they returned the questionnaire. Regular "everyday" smokers were excluded from the experiment, but "party smokers" were accepted. As the experiment was performed during spring with a high concentration of pollen, this could have a strong influence on subjects with respiratory diseases and consequently these persons were excluded. All the participants were students. To check for olfactory sense, all the subjects undertook a ranking test, in which four samples of 1-butanol (10, 80, 320, and 1280 ppm (vol./vol.)) had to be ranked according to strength (ISO 8587; 1987). No one was excluded from the experiment because of the result of this test. Some of the anthropological characteristics are shown in Table 9.

Table 9 *Some anthropological characteristics of the participating women (average ± std.)*

Age	20-30 years (23.4 ± 2.6)
Height	151-178 cm (167.1 ± 6.9)
Weight	50-80 kg (61.8 ± 7.5)
Body mass index[1]	18-27.3 (22.1 ± 2.3)
Number of everyday smokers	0
Number of subjects with hay-fever	0
Number of subjects with asthma	0
Results in ranking test[2]	0-4 (2.9 ± 1.2)

[1] BMI=weight divided by the square of the height in metres. [2] The test was made before or after the last experimental session

All participants were paid 120 DKr. per hour for their participation. As a motivating factor, they were told that they could earn up to 15% more if they worked satisfactorily during the experiment.

None of the participants dropped out during the experiment.

Experimental conditions

Pollution source – the ventilation system with the filter

The experiment was carried out with two bag filters: a new filter and a used filter, both of the same type, EU7 *air*Bag® from Luftfilter, with a size of 0.3·0.6 m. The filter had 6 bags and the total surface area of the filter was 2 m^2. Studies have shown that the sensory pollution load from a new filter is negligible when it has been ventilated for a few days and the accumulated dust therefore constitute the pollution source (Bluyssen, 1993; Pejtersen, 1996b; Gholami et al., 1997). The new filter used in this experiment had been ventilated in a ventilation system for 3-4 days at 500 l/s before use. After approximately one week of ventilation, it was possible to see a change in the colour of the filter due to contamination with particles, and it was possible to detect this contamination with the olfactory senses. Consequently, the new filter was only used for one or two experimental sessions. One filter had to be changed because the flow through it had made a rip. A total of four new filters were used in this experiment. All filters were bought on the same day. The used filter had been used for one year in a Copenhagen suburban area and was changed one month prior to the start of this experiment. The filter was changed as a normal procedure because it had been used for one year. The flow through it had been at 1800 m^3/h at 12 hours per day, giving an approximate total of $7.8 \cdot 10^6$ m^3 filtrated air. The used filter was, before the start of the experiment and between experimental days placed, in a normal ventilation system and ventilated with 250 m^3/h outdoor air.

In the office, the filter was placed in the NOVENCO ventilation system recirculating the room air. The filter was placed in the system 3 hours prior to the start of the experiment and was returned to the normal ventilation system after the end of each experimental day.

The flow through the recirculating ventilation system was kept constant at 105 l/s throughout the experiment.

Noise

The background sound pressure level in the unoccupied office was 37 dB(A). This was mainly due to the outdoor air supply fan, the table fans, and the cooling coil. With the recirculating ventilation system on, the sound pressure level was 45 dB(A) for both conditions (average of all six workstations). This was the lowest achievable level and is the same as the maximum ventilation noise level required for Category C landscaped offices according to CEN Report 1752 (1998). According to Witterseh (2001), it was expected that approximately 48% of the subjects would be dissatisfied with the ventilation noise. The sound pressure level differed between the workstations; however, the subjects were seated at the same workstation each time they participated. In Figure 32 the frequency spectrum of the two conditions and of the background is depicted. There was no difference between the two conditions, but the sound pressure level was in all frequency bands higher than when the ventilation system was off. According to the RC method proposed by ASHRAE (1997) the ventilation noise for both conditions could be classified as RC-37R.

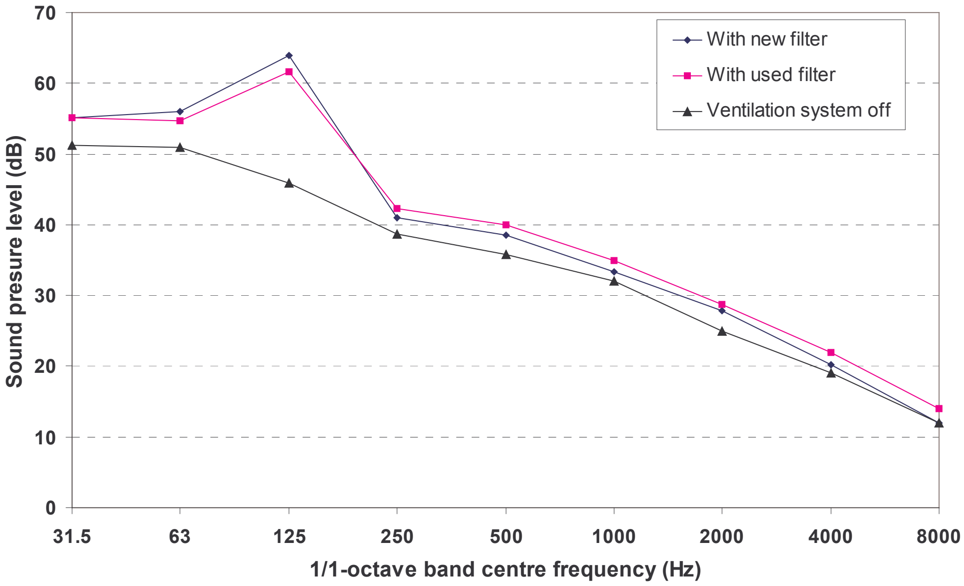


Figure 32 *Frequency spectrum of the two conditions and of the background noise.*

Thermal parameters

The parameters that were related to the thermal environment were unchanged for all conditions. The air temperature was kept constant at 23.5°C, resulting in an operative temperature of 24.2°C. The relative humidity was kept constant at 40%. This meets the design criteria for Category A landscaped offices during the cooling season (CEN, 1998). The subjects were asked to stay thermally neutral during the experiment by adjusting their clothing.

Ventilation

During the experiment, the office was ventilated with a constant outdoor air supply rate of 48 l/s corresponding to 8 l/s·person or 1.6h^{-1} or 1.33 l/s·m^2. This meets the design criteria for Category B landscaped offices during the cooling season (CEN, 1998).

Light

The office was illuminated through the windows and by artificial light. The workstation was also provided with an anglepoised lamp, which the subjects could use when they felt their workstation was too dark. The office faces east, and the experiments were carried out in the evening with no direct sunlight. The sun went down during the experiment and lighting conditions outside went from light evening to dark night.

Measurements

Physical measurements

The air temperature and relative humidity at each workstation, in the middle of the occupied zone of the office, outside, in the corridor in front of the office, and in the waiting area were measured constantly and sampled every minute with Viasala HMP 130Y Humidity and Temperature Transmitters. The measuring range of temperature was –20 to +80°C with an accuracy of ± 0.2°C. The measuring range of relative humidity was 0 to 100% with and accuracy of ± 2% point (in the area 0 to 90%RH, 90 to 100%RH with an accuracy of ± 3% point). The operative temperature was measured with a Brüel & Kjær Thermal Comfort Meter (1212) and sampled every 20 minutes. The operative temperature was measured at 0.7 m above the floor, and the air temperature and relative humidity were measured at 1.2 m above the floor. The air velocity was measured occasionally with a Brüel & Kjær Indoor Climate Analyzer (1213).

CO_2 and SF_6 could be measured at each workstation, in the middle of the occupied zone, and outside. For this purpose a Brüel & Kjær Multigas Monitor (1302) and a Brüel & Kjær Multipoint Sample and Doser (1303) were used. SF_6 was used to measure the outdoor air supply rate in the office with the constant concentration method. CO_2 and SF_6 were measured constantly outside and in five positions inside the office throughout the experiment. SF_6 was also used to check that the air was fully mixed in the room.

The ozone concentration outside and in the middle of the occupied zone was measured continuously by a Seres OZ2000 ozone analyser and sampled every 20 minutes.

Ultra-fine particles were counted continuously by a P-Trak™ Ultrafine Particle Counter Model 8525 in the particle size range 0.02 to greater than 1 μm. The counting range was from 0 to $5 \cdot 10^5$ particles/cm^3. The count was taken in the middle of the occupied zone and outside and sampled every 20 minutes.

The lighting level was measured at each workstation before and after each experimental session by a handheld Hagner EC1 lux meter at a height of a standard work plane, 0.85 m above the floor.

The sound pressure level was measured at each workstation after each experimental session by a Brüel & Kjær Sound Level Meter (2218).

Subjective measurements

On the arrival, the subjects filled out a questionnaire (appendix A – entrance questionnaire) concerning their activities during the day, whether they had taken any medicine, and their general wellbeing. During the experimental session the subjects filled out questionnaires (see appendix B) three times, each questionnaire asking about:

- Perceived air quality[1]
- Odour intensity[2]
- Irritation in eyes, nose and throat[3]

- Air dryness[4]
- Air stuffiness[4]
- Office brightness[4]
- Office noisiness[4]
- Nose dryness[4]
- Throat dryness[4]
- Eye dryness[4]
- Headache[4]
- Difficulty in thinking[4]
- Dizziness[4]
- Tiredness[4]
- Difficulty in concentration[4]
- Fatigue[4]
- Self-estimated performance[4]
- Heat balance[5]
- Thermal environment[1]
- Air movements[6]
- Noise[1]
- Indoor environment[1]

[1]Acceptability scale (continuous from "Clearly acceptable" to "Clearly unacceptable"), [2]Intensity scale (continuous from "No odour" to "Overwhelming odour"), [3]Irritation scale (continuous from "No irritation" to "Overwhelming irritation"), [4]Visual-analogue scale, [5]7-point PMV scale (continuous from "Cold" to "Hot"), and [6]Yes/No and acceptability.

The visual-analogue scale was an approximately 100-mm long continuous scale with clearly marked endpoints with labels. The subject marked on the scale the intensity of a specific symptom or marked to what extent the subject agreed with the statement labelled at the end-point (Wyon et al.; 1995; Kildesø et al., 1999; Witterseh; 2001).

The questionnaire can be seen in appendix B.

Coding of subjective ratings

The subjective ratings given by the subjects were coded in order to perform the statistical tests:

- Acceptability scale: see chapter 3.1
- Intensity scale: No odour = 0; Slight odour = 1; Moderate odour = 2; Strong odour = 3; Very Strong odour = 4; and Overwhelming odour = 5
- Irritation scale: No irritation = 0; Slight irritation = 1; Moderate irritation = 2; Strong irritation = 3; Very strong irritation = 4; and Overwhelming irritation =5
- Visual-analogue scale: Left end-point = 0, and Right end-point = 100.
- Cold = -3; Cool = -2; Slightly cool = -1; Neutral = 0; Slightly warm = 1; Warm = 2; and Hot = 3.

Measuring of performance

Four different tasks were used to estimate the subject's work performance under the two conditions. For all tasks, the subjects were instructed to perform as fast as they could without making any mistakes. Different versions were made for each task and the subject was presented with each version only once. However, all subjects received all versions and all versions were equal in length and difficulty.

Text typing:

Texts from a Danish popular science magazine "Illustreret Videnskab" were retyped. The texts were printed on paper with a 12 point Times New Roman font and triple line spacing. The text was then typed into the PC without thinking of the format of the text. With WORD 6.0 for Windows, it is possible to get a measure for the typing speed (characters/minute). With a macro comparing the original text and the text typed by the subjects it was possible to find the error-rate (number of mistakes/total number of typed characters). One mistake was counted for each misspelled word, for a missing space between words, for missing or wrong punctuation, and for each word missing or added.

Addition:

Five two-digit numbers had to be added on paper. The numbers were generated randomly without zeros. From this test, it was possible to get the speed of addition (additions/minute) and the rate of error (wrong addition/total number of additions).

Proof reading:

Same kind of text used as the one used for text typing. Different types of mistake were added: misspellings (in an obvious way), grammatical errors (verbs conjugated wrongly, verbs in wrong tense) and contextual errors (factually or logically wrong words). This task was on paper. From this test it was possible to get a measure of the reading speed (number of lines read), mistakes found, and mistakes made (correct words considered as mistakes).

These three types of task are typical office work, and are divided here into separate tasks.

Tsai-Partington:

A fourth task was used to measure the subject's level of arousal (Ammons, 1955; Wyon, 1969; Witterseh, 2001). Thirty two-digit numbers ascending from "00" to "99" was spread out on one A4 page and had to be linked by ranking. The numbers were spread so that as few links crossed as possible. The task for the subject was then to start from "00" and to draw a line to that number on the page higher than "00", and from there to the number higher, and so forth. The subject was instructed that if they missed a number they had to go on and it was not possible to go back and correct the line to the missed number. The score of this task was the number of correct links made. Increased arousal and motivation to do well generally reduce the performance of this test. The subjects worked on this task for exactly 40 seconds.

Procedure

The experiment was carried out on every workday in three subsequent weeks in the period 21 May to 11 June 2001. The subjects were divided into five groups, each with 6 women. Each group came on the same workday for three weeks, and each subject participated in three different sessions, first a training session and then one session for each condition. The subjects were not informed that the first session was only for training, and the training session did not differ from the other two sessions. Each condition was repeated five times, every second day with the new filter and every other second day with the used filter. The design was therefore not completely randomized and 3/5 of the subjects experienced the condition with the new filter before the condition with the used filter. Each experimental session lasted from 18^{00} to 22^{30}.

On arrival, the subjects gathered together in a room nearby the office where the experiment took place. The room was ventilated with 40 l/s and the air temperature was kept constant at 23.5°C. In that room they filled out the entrance questionnaire, and were told how to use the different scales and how they should perform the different tasks. They were also told that they should be thermally neutral during the session.

After 15 minutes in that room, the subjects walked to the office. Before entering the office, the subjects were told to spread around when entering the office and to evaluate the air quality, intensity, and the irritation in eyes, nose and throat. It was emphasized that it was important that they evaluated the air quality on the first or second inhalation when they entered the room. After answering the first questions, on the first page in the first questionnaire, they were seated, and they answered the rest of the questions. Each subject had the same place at all three sessions.

They then typed for 50 minutes, did the Tsai-Partington's Test, filled out a questionnaire, and performed a step exercise. The step exercise was done to maintain an activity level typical of office work and at the same time to avoid only sedentary activity; it was carried out by walking over a "two steps up and two steps down" staircase and then walking back to their seat. They were the instructed to do the addition task, step exercise, and then proofreading, after which the sequence was repeated, starting with the text typing. All activities can be seen in Table 10.

Table 10 *Activities during the experimental session*

Time	**Activity**	Duration
-15	Assembling in a room close to the office	15 min
0	Entering the office, assessment of the air quality, questionnaire concerning SBS symptoms	5 min
5	*Simulated office work: Text typing*	50 min
55	Tsai-Partington's Test	40 sec.
56	Filling out questionnaire; Step exercise	5 min
61	Simulated office work: Addition	40 min
101	Step exercise	3 min

104	Simulated office work: Proof reading	17 min
121	Step exercise	3 min
124	Simulated office work: Text typing	50 min
174	Tsai-Partington's Test	40 sec.
175	Filling out questionnaire; Step exercise.	5 min
180	Simulated office work: addition	40 min
220	Step exercise	3 min.
223	Simulated office work: Proof reading	17 min
240	Leaving the office	
243	Re-entering the office, evaluations of the air quality, intensity, and irritation in eye, nose and throat.	1 min
250	Evaluation of the air quality outside the building	1 min.

There was no break during the session, and if anyone had to use the bathroom they had to do so in the small breaks between the simulated office work tasks, and they were instructed to come back as fast as possible. The subjects were not allowed to talk or smoke during the session. Water and biscuits were supplied at each workstation and could be eaten at any time during the session.

Questionnaires (appendix B) were filled out 1, 56, and 175 minutes after entering the office. After 240 minutes the subjects left the office and re-entered 3 minutes later to assess the air quality. Finally, the air outside was evaluated.

In total, the subjects participated for 261 minutes (4 hours and 21 minutes) each day, 240 minutes being in the office.

Results

Statistical analyses

The distributions of the data obtained from the questionnaires were tested for normality with Shapiro-Wilk's W test. If they were normally distributed, they were tested by means of analysis of variance, ANOVA, or by t-test for independent samples. Data without normal distributions were tested with Kruskal-Wallis one-way analysis of variance or Friedman two-way analysis of variance.

Physical measurements of the indoor environment

Table 11 gives the results of physical measurements during the experimental session shown.

Table 11 *Levels of indoor environment parameters in the office (average ± std.).*

	With used filter	With new filter
Air temperature, outside (°C)	9.3 to 15.8 (12.8 ± 1.4)	8.7 to 17.1 (13.4 ± 1.9)
Air temperature, inside (°C)	22.5 to 24.2 (23.5 ± 0.3)	22.4 to 24.2 (23.5 ± 0.3)
Operative temperature (°C)	23.8 to 24.6 (24.2 ± 0.2)	23.8 to 24.6 (24.2 ± 0.2)
Relative humidity, outside (%)	51 to 86 (72 ± 9.8)	48 to 93 (71 ± 11.5)
Relative humidity, inside (%)	34 to 45 (40 ± 2.5)	37 to 45 (40 ± 1.5)
Sound pressure level (dB(A))*	45	46
Air velocity (m/s)	< 0.15	< 0.15
Outdoor air supply (l/s)	46	49
CO_2 , outside (ppm)	423	426
CO_2 , inside (ppm)	1112	1112
Ozone, outdoors (ppb)	10 to 35.1 (26.9 ± 6.7)	20.2 to 34.9 (27.7 ± 4.4)
Ozone, indoors (ppb)	0.8 to 14.6 (7.3 ± 3)	5 to 12.6 (9.1 ± 1.7)
Ozone, I/O-ratio	0.27	0.33
Ultra-fine particles, outside (counts/cm3)	1550 to 14000 (4603 ± 4051)	1780 to 7550 (4322 ± 1387)
Ultra-fine particles, inside (counts/cm3)	1280 to 4200 (2323 ± 1073)	809 to 3010 (1855 ± 628)
Ultra-fine particles, I/O-ratio	0.5	0.43
Lighting level (lux)*	355	450

*Average of measurements at each workstation.

Subjective measurements

Using equation [1] from chapter 3.1, the percentage of dissatisfied can be calculated from the data obtained on the acceptability scale.

The quality of the outside air was evaluated ass good and varied only little between experimental days. On average, approximately 1% were dissatisfied with the air quality.

Changing the filter had a significant influence on the acceptability of the air quality upon entering the office (p<0.0003). With the used filter in the ventilation system, 47% were dissatisfied with the air quality, and only 16% were dissatisfied when the new filter was present in the system. However, after 56 minutes in the office there was no significant difference between the two conditions. The perceived quality of the air improved for both conditions and less than 15% were dissatisfied with the air quality when the subjects left the office. Re-entering the office made it possible to assess the quality of the air in the office when it was polluted with bioeffluents. There was no significant difference between the two conditions, and for the condition with the new filter, there was no significant difference between entering the office with and without bioeffluents. For the condition with the used filter, the air quality was found to be significantly better at the final evaluation as compared with the first. On re-entering, 25% and 18% were dissatisfied with the air quality, respectively with new and old filter. The results are shown in Figure 33.

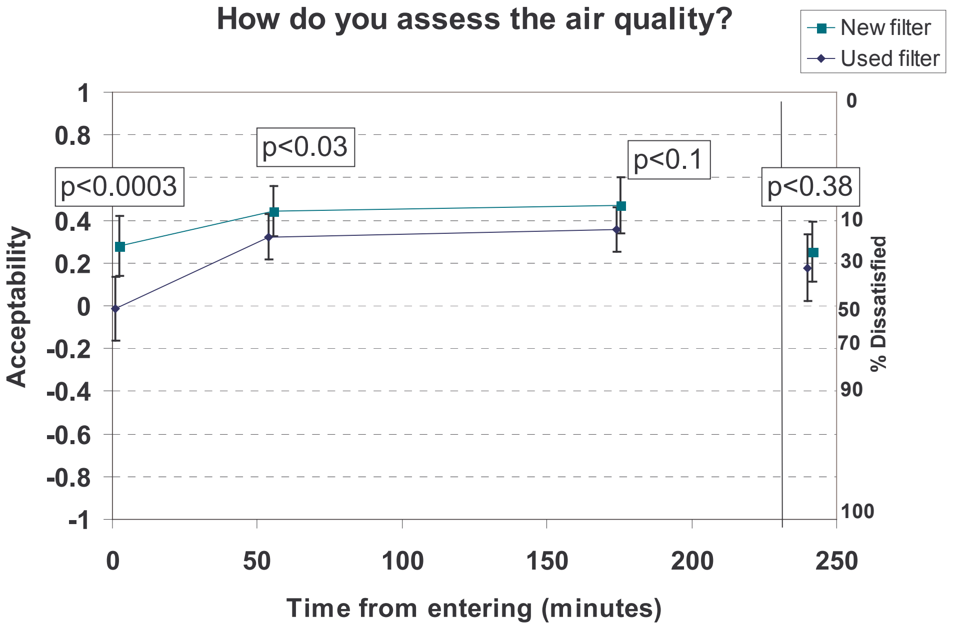


Figure 33 *Time course of acceptability of the air quality in the office. Also depicted is the 95% confidence interval.*

The intensity of the odour in the office was influenced positively by exchanging the used filter with a new one (p<0.00003). With the used filter, the intensity was found to be "Moderate odour" whereas for the condition with the new filter it was found to be "Slight odour". After 56 and after 175 minutes there was no difference between the two conditions; the intensity was, however, significantly decreased (p<<0.001) to less than "Slight odour". Upon re-entering, the intensity of the odour was significant higher when the used filter was present in the system. With the used filter in the system, the intensity was significantly lower at the final evaluation compared with the first (p<0.008). When the new filter was present, there was no difference with or without bioeffluents. The results are shown in Figure 34.

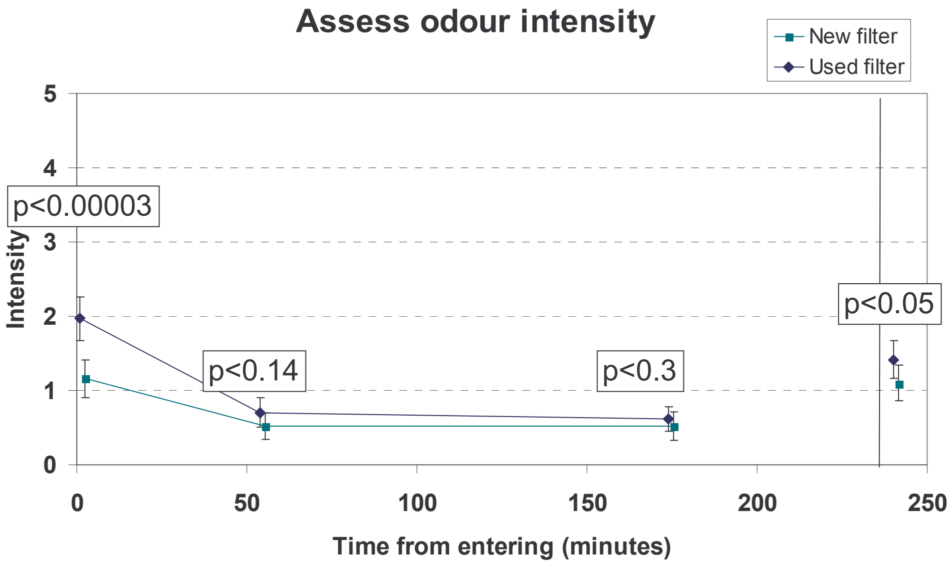


Figure 34 *Time course of intensity of the odour in the office. Also depicted is the 95% confidence interval.*

There was no difference in irritation in the eyes when the filter was changed. However, the irritation became significantly worse during exposure under both conditions (p<0.001), and it was evaluated to be "Slight irritation". There was no significant difference between the final evaluations in comparison with the first. The results are depicted in Figure 35.

On entering, the air in the office was evaluated as giving significantly more nose irritation when it was polluted with the used filter than when the new filter was used (p<0.006). With the used filter in the system, the level of irritation in the nose was evaluated as being "Slight irritation". After 56 minutes, the air polluted with the used filter was perceived to be less irritating and there was no difference between the two conditions. There was no difference in the level of nose irritation at the final evaluation compared with the first. The results are shown in Figure 36.

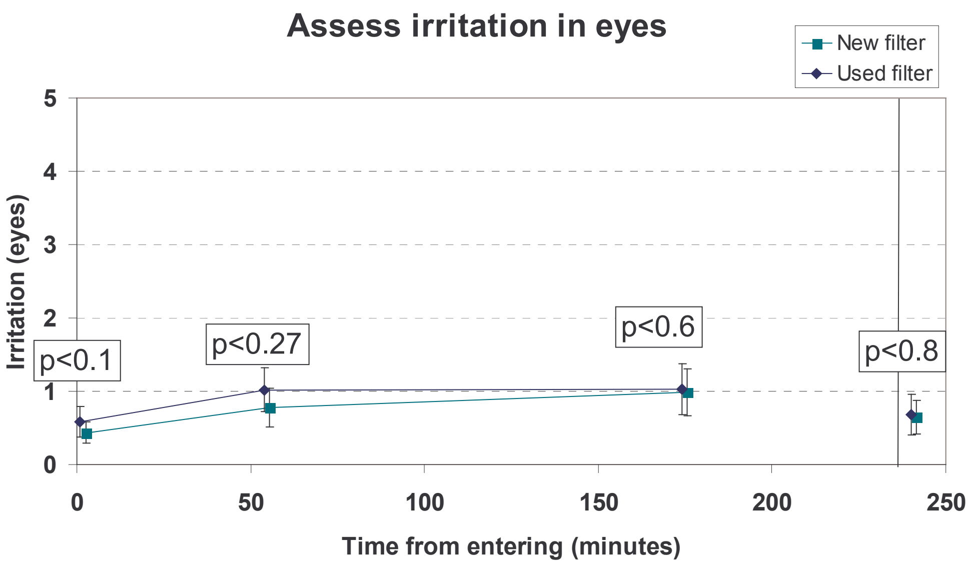


Figure 35 *Time course of eye irritation. Also depicted is the 95% confidence interval.*

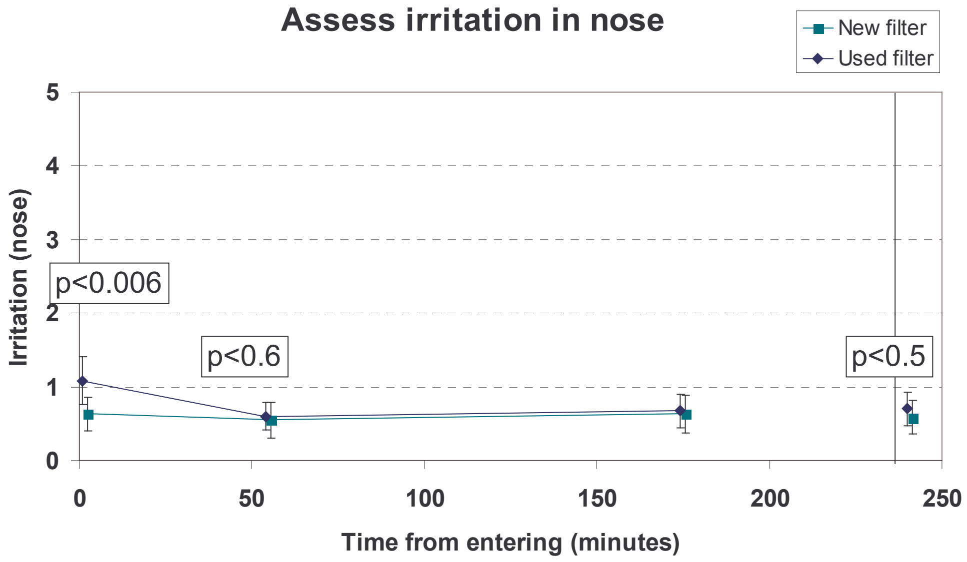


Figure 36 *Time course of nose irritation. Also depicted is the 95% confidence interval.*

The irritation in the throat was not influenced by the two conditions, bioeffluents or time, and was evaluated to be less than "Slight irritation" (Figure 37).

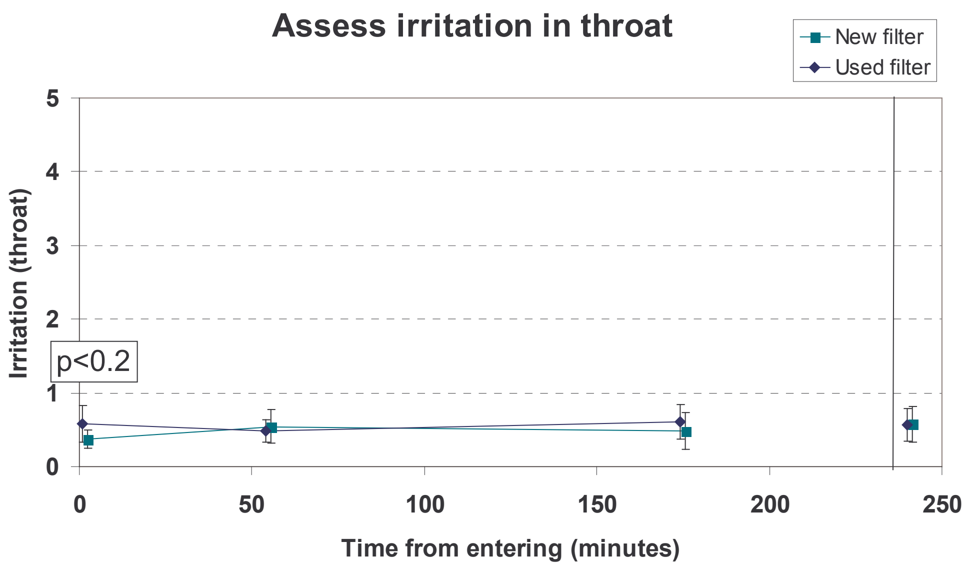


Figure 37 *Time course of throat irritation. Also depicted is the 95% confidence interval.*

When entering the office the air was assessed to be significantly more dry when the used filter was in the ventilation system than when the new filter was used ($p<0.017$). This difference was not found when the air was evaluated after 56 and after 175 minutes.

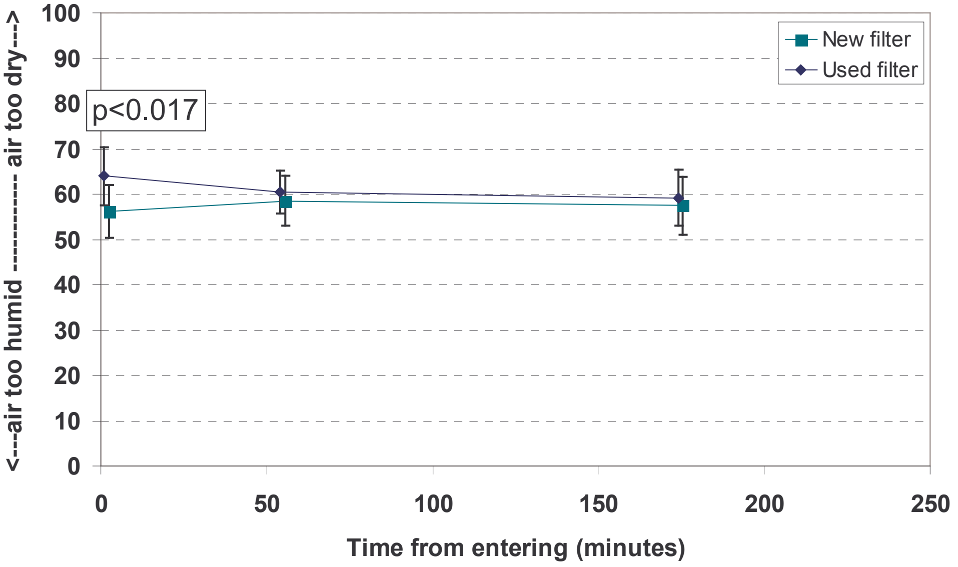


Figure 38 *Perceived intensity of the humidity of the air in the office. Also depicted is the 95% confidence interval.*

On entering the office, the air was found to be significantly more fresh when the new filter was in the system compared to when the used filter was present ($p<0.0002$). The difference was still significant after 56 minutes ($p<0.0057$) but not after 175 minutes. When the used filter was in the ventilation system the air was found to be significantly more fresh after 175 minutes' occupation ($p<0.00001$); this was not the case when the new filter was present. The results are depicted in Figure 39.

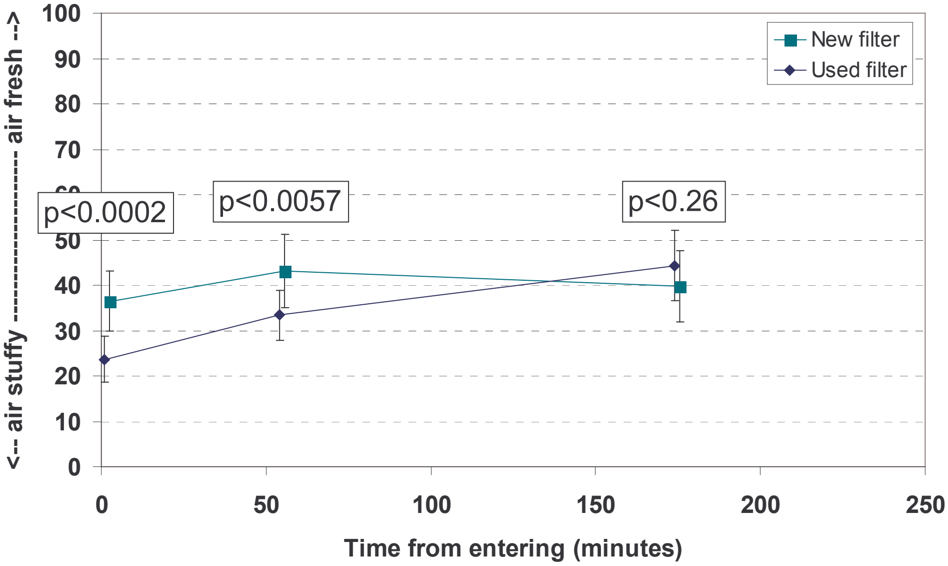


Figure 39 *Perceived intensity of the freshness of the air in the office. Also depicted is the 95% confidence interval.*

Environmental parameters

The two conditions did not have any influence on the perceived brightness of the office at any time during the occupation (Figure 40).

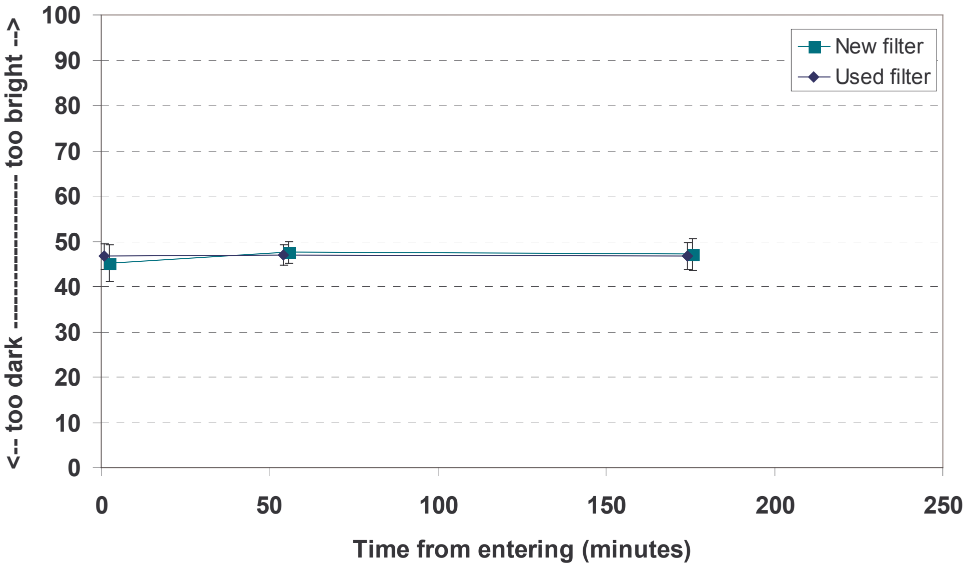


Figure 40 *Perceived intensity of the brightness in the office. Also depicted is the 95% confidence interval.*

Even when the sound pressure level for the two conditions was the same, there was a tendency for the office to be perceived as more quiet when the new filter was present in the ventilation system compared to when the used filter was present. The difference between the two conditions decreased during the time of occupation in the office, and there was no difference between the conditions after 175 minutes (see Figure 41).

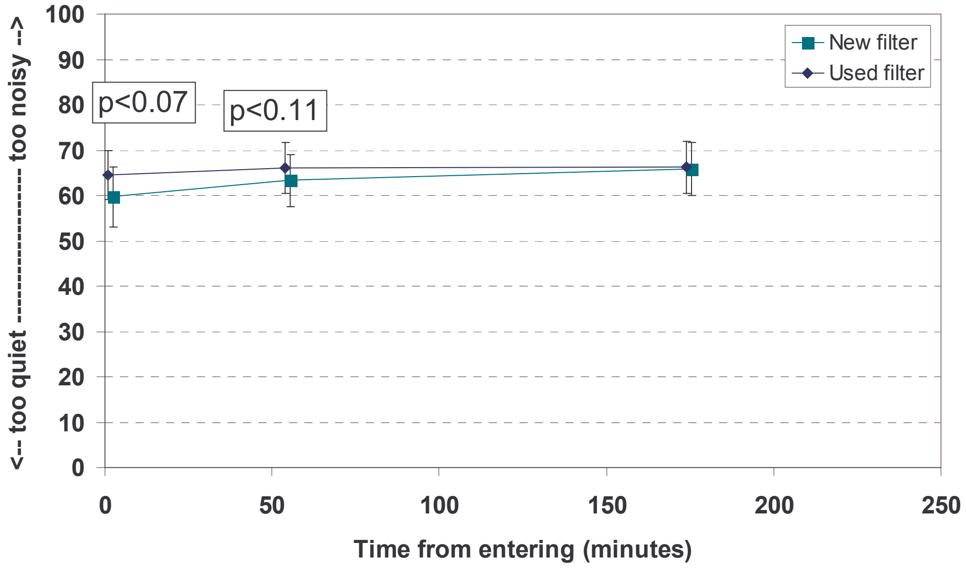


Figure 41 *Perceived intensity of the noise in the office. Also depicted is the 95% confidence interval.*

The noise was also evaluated using the acceptability scale and no difference was found between the two conditions at any time; the acceptability of the noise level did not change during the time of occupation (Figure 42). Approximately 40% were dissatisfied with the noise level.

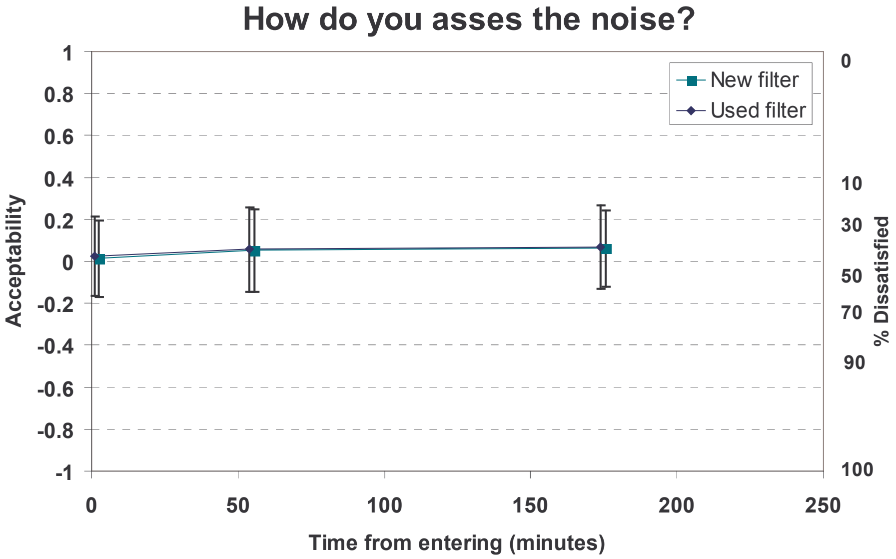


Figure 42 *Evaluation of the noise level as function of time.*

Upon entering the office, the overall environmental conditions were found to be significantly more acceptable when the new filter was in the ventilation system compared to when the used one was present ($p<0.0005$). This difference was found to be almost significant after 56 minutes' occupancy. After 175 minutes the difference was evaluated to be significantly different again ($p<0.0165$). Upon entering, 51% were dissatisfied with the overall indoor environment when the used filter was in the ventilation system, but this decreased to approximately 30% dissatisfied after 175 minutes' occupation. There were constantly 20% dissatisfied with the indoor environment when the new filter was in the ventilation system. The results are depicted in Figure 43.

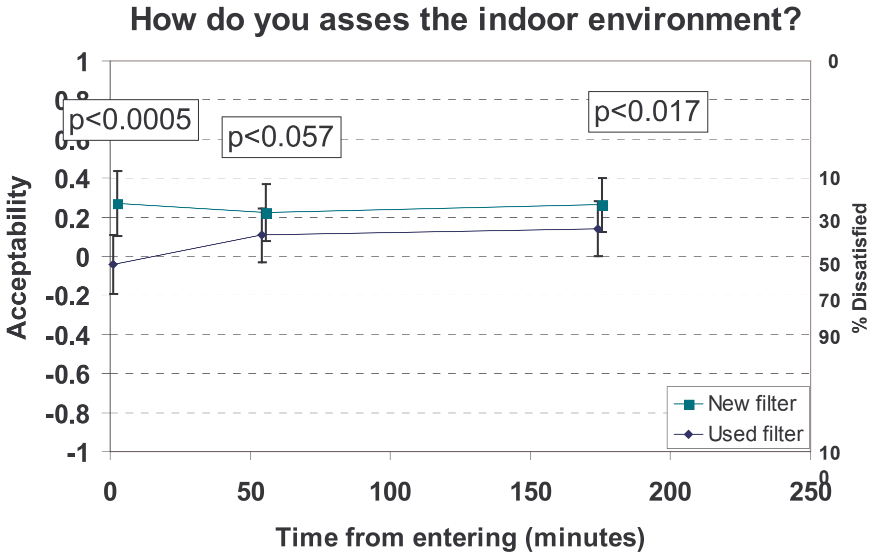


Figure 43 *Ratings of the indoor environment as a function of time. Also depicted is the 95% confidence interval.*

Intensity of SBS symptoms

No significant difference on the intensity of runny nose under the two conditions was found. Neither did the time of occupation have an influence (Figure 44).

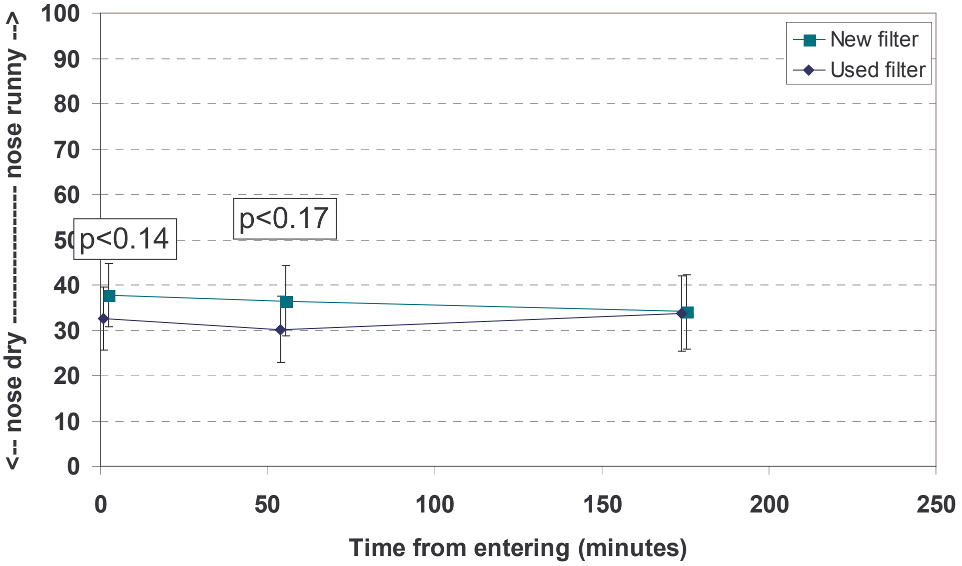


Figure 44 *Perceived intensity of running nose in the office. Also depicted is the 95% confidence interval.*

No significant difference on the intensity of dry throat under the two conditions was found. Neither did the time of occupation an influence (Figure 45).

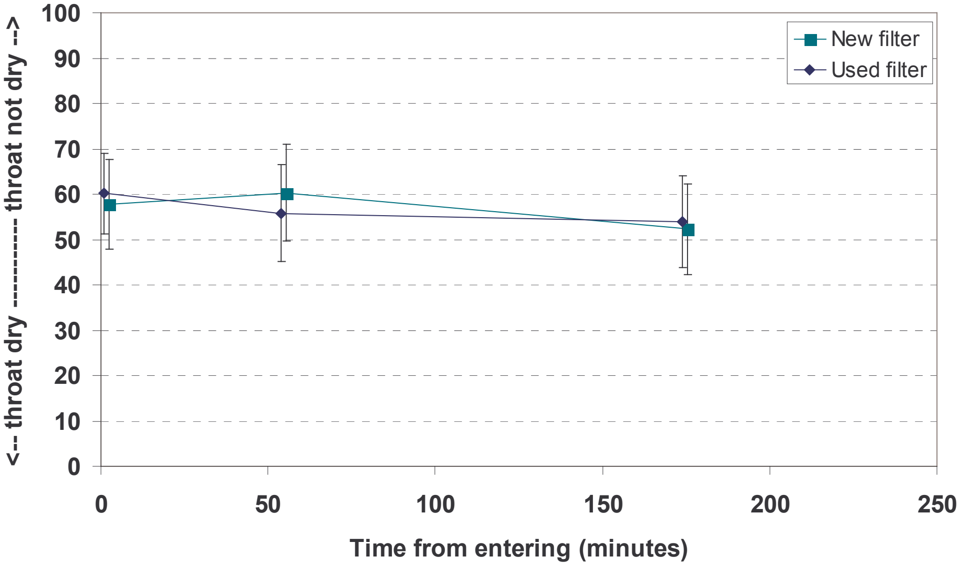


Figure 45 *Perceived intensity of dry throat in the office. Also depicted is the 95% confidence interval.*

No significant difference on the intensity of dry eyes under the two conditions was found. However, the eyes were perceived as significantly more dry after 56 minutes' occupancy under both conditions, than they were upon entering the office ($p<0.05$). The results are shown in on Figure 46.

Upon entering a room polluted by a used filter in the ventilation system, the intensity of headache was assessed to be significantly higher than when entering an office polluted with a new filter in the ventilation system ($p<0.05$). After 56 minutes' occupancy, there was no difference between the two conditions. The intensity of the headaches increased significantly during occupancy when the new filter was in the ventilation system ($p<0.0002$). The intensity did not change when the used filter was in the ventilation system (see Figure 47).

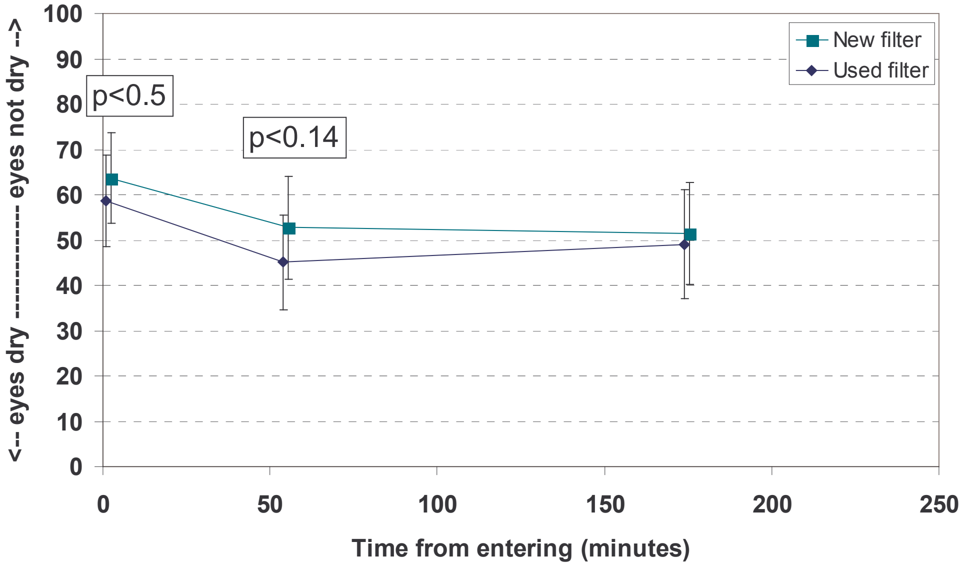


Figure 46 *Perceived intensity of dry eyes in the office. Also depicted is the 95% confidence interval.*

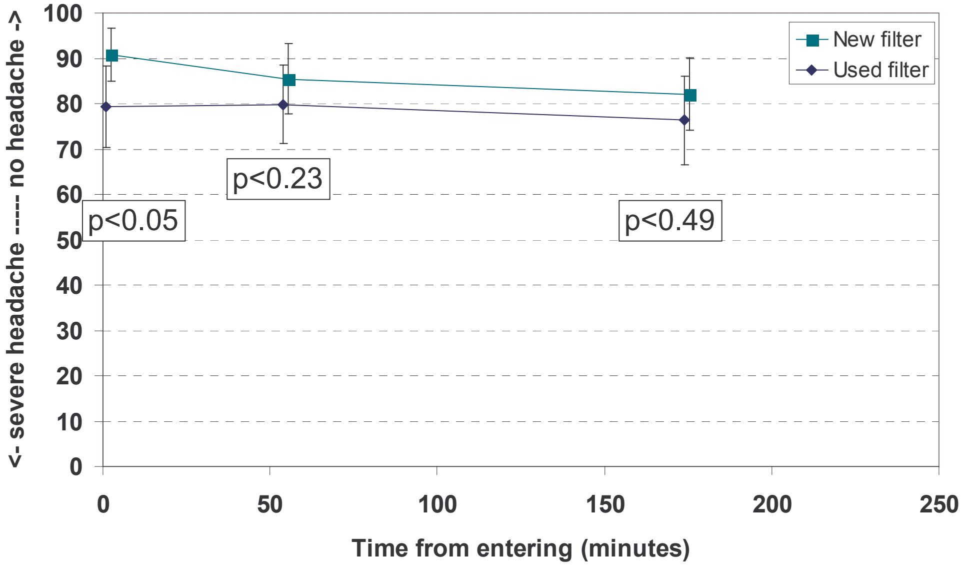


Figure 47 *Perceived intensity of headaches in the office. Also depicted is the 95% confidence interval.*

Upon entering the office, it was assessed to be significantly more difficult to think clearly when the used filter was in the ventilation system ($p<0.01$). The two conditions were not significantly different after 56 minutes' occupancy. However, it was perceived to become significantly more difficult to think clearly during occupancy when the new filter was in the system; this increase in intensity was not found with the used filter in the system. The results are shown in Figure 48.

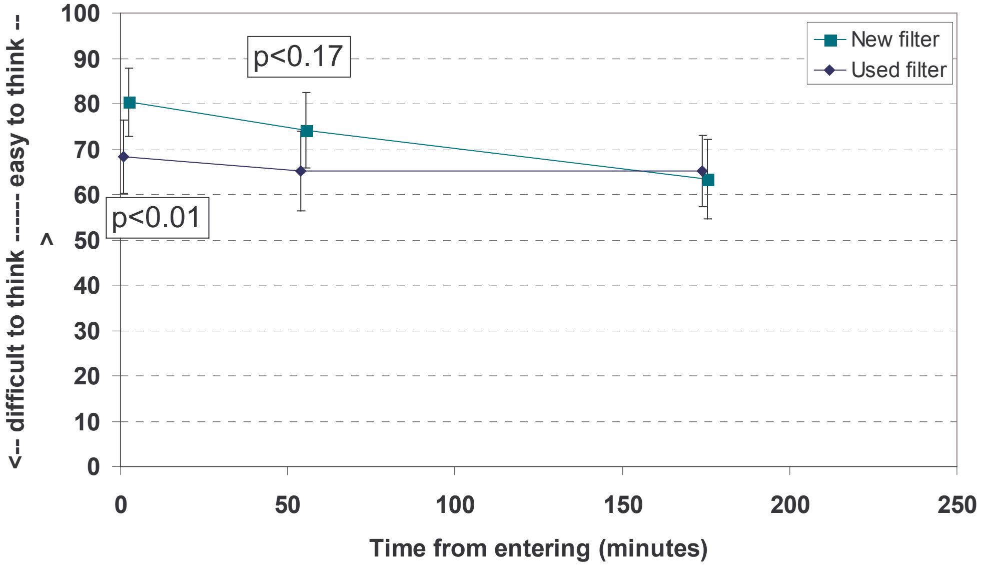


Figure 48 *Perceived intensity of easiness of thinking in the office. Also depicted is the 95% confidence interval.*

Entering an office polluted with a used filter was found to give a significantly higher intensity of dizziness than when there was a new filter in the system ($p<0.05$). The two conditions were not found to be significantly different after 56 minutes' occupancy, but there was such a tendency after 175 minutes' occupancy (Figure 49).

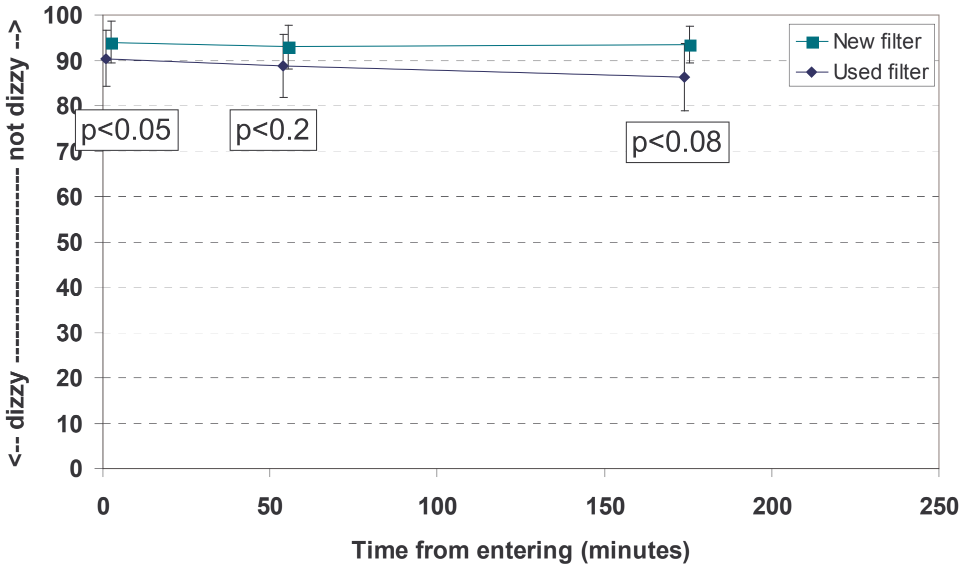


Figure 49 *Perceived intensity of dizziness in the office. Also depicted is the 95% confidence interval.*

There was no significant difference in the intensity of tiredness in the office at any time of occupancy. However, there was a tendency for the subjects to feel more tired after 175 minutes' occupancy than upon entering the office (Figure 50).

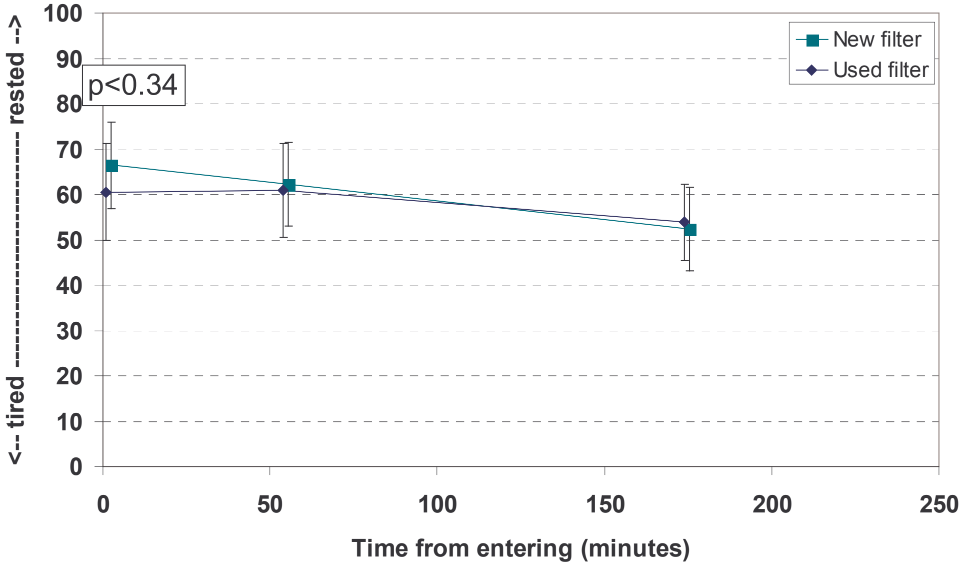


Figure 50 *Perceived intensity of tiredness in the office. Also depicted is the 95% confidence interval.*

There was no significant difference between the two conditions in the ability to concentrate upon entering the office. However, after 56 minutes of occupation it was perceived to be significantly more difficult to concentrate when the used filter was in the ventilation system ($p<0.026$). After 175 minutes' occupancy, there was again no significant difference between the two conditions. Time of occupancy had for both conditions a significant effect on the perceived intensity of concentration ($p<0.005$). The results are depicted in Figure 51.

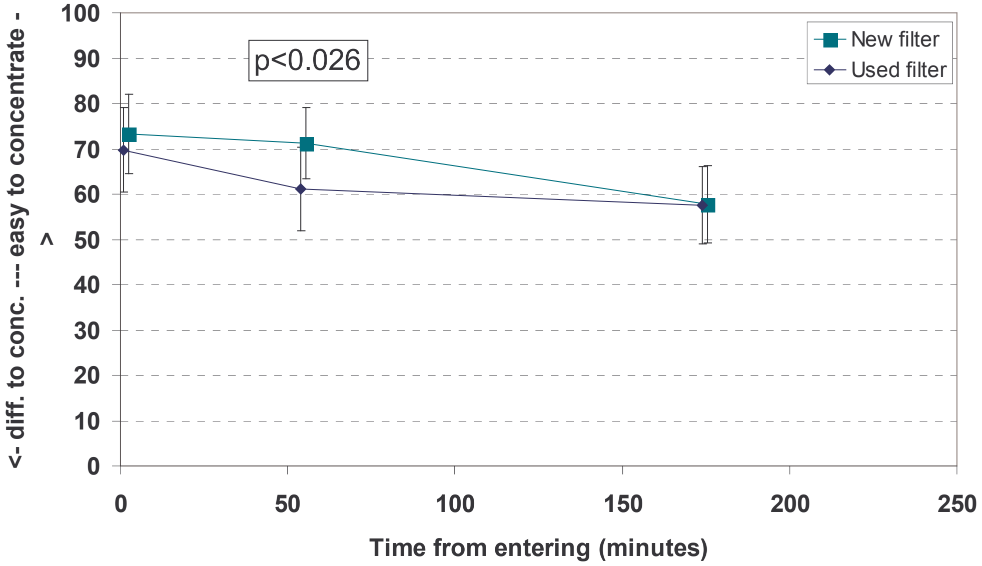


Figure 51 *Ability to concentrate under the two different conditions. Also depicted is the 95% confidence interval.*

There was no significant difference between the two conditions in sleepiness at any time of occupancy. However, time of occupancy significantly increased sleepiness when the new filter was in the ventilation system ($p<0.001$). This did not occur when the used filter was in the system (Figure 52).

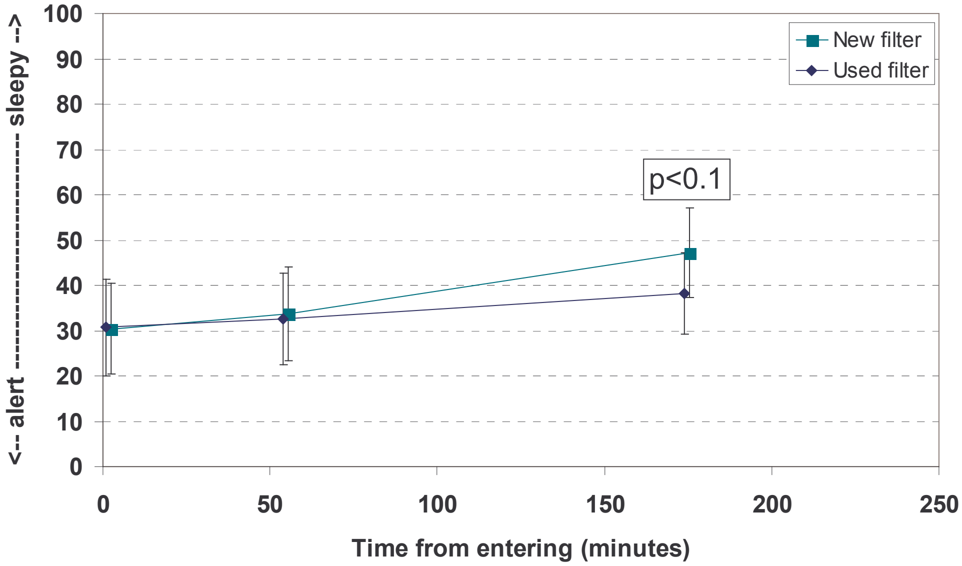


Figure 52 *Perceived sleepiness in the office. Also depicted is the 95% confidence interval.*

Measurements of performance

Self-estimated performance

Three times during occupancy, the subjects were asked about their ability to work at that moment. When the used filter was in the ventilation system the self-estimated performance upon entering and after 56 minutes' occupancy was significantly lower than when the new filter was in the system ($p<0.03$ and $p<0.02$, respectively). There was no difference after 175 minutes occupancy. However, time of occupancy had a significant influence on both conditions ($p<0.001$). The results are shown in Figure 53.

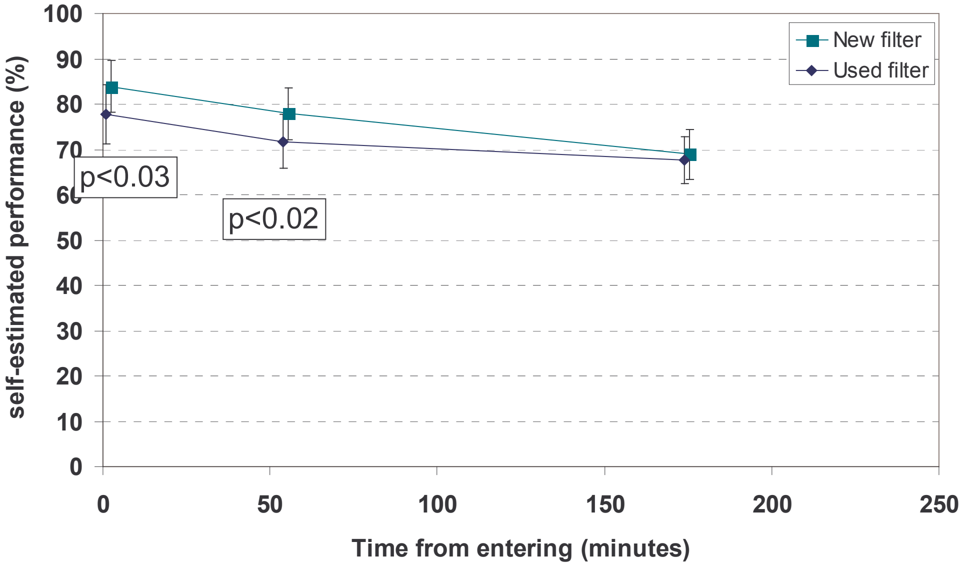


Figure 53 *Self-estimated performance during occupancy in the office. Also depicted is the 95% confidence interval.*

Text typing

During an experimental session, the subjects worked with the text-typing task for two 50 minutes periods. Figure 54 shows the speed of text typing during the first and second periods and the speed for the two periods together. During the first period, there was a tendency for the subjects to work faster when the used filter was in the ventilation system than when the new filter was in the system. This tendency was not found during the second period and not in the total speed during the whole session.

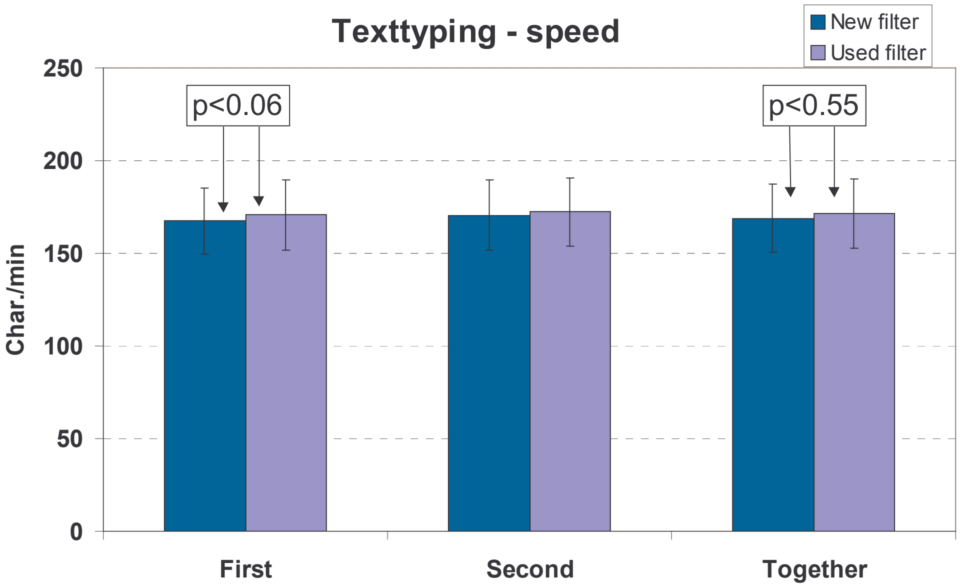


Figure 54 *Speed of text typing, characters typed per minute during first and second periods and characters per minute in total. Also depicted is the 95% confidence interval.*

Text typing errors, estimated as wrongly typed characters per total number of typed characters was not affected by the two conditions at any time (Figure 55).

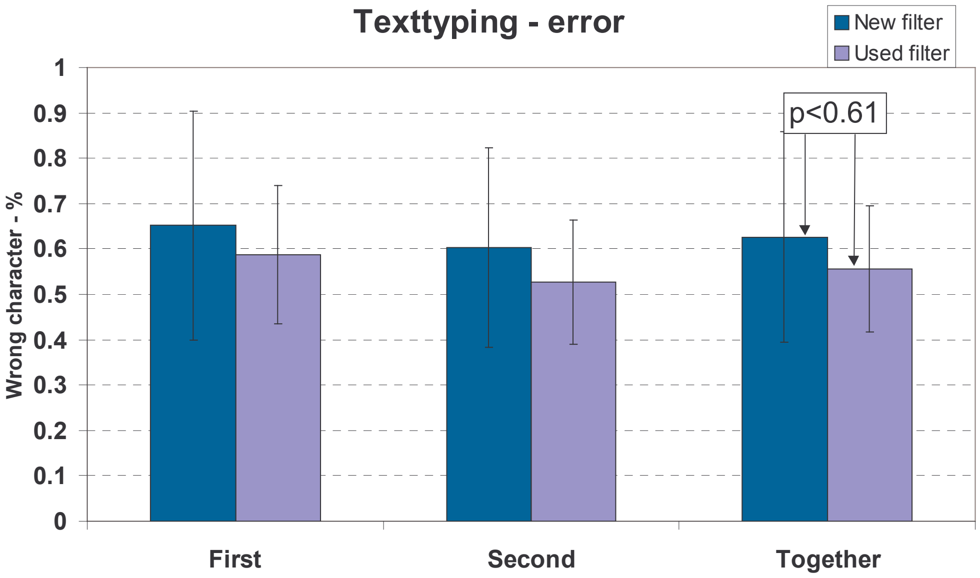


Figure 55 *Errors in text typing. Also depicted is the 95% confidence interval.*

Addition task

The subjects worked with the addition task in two periods, each one lasting for 40 minutes. Neither the speed of addition (number of additions per minute) nor the error rate (wrong result of addition per total number of additions made) was affected by the two conditions (Figure 56 and Figure 57).

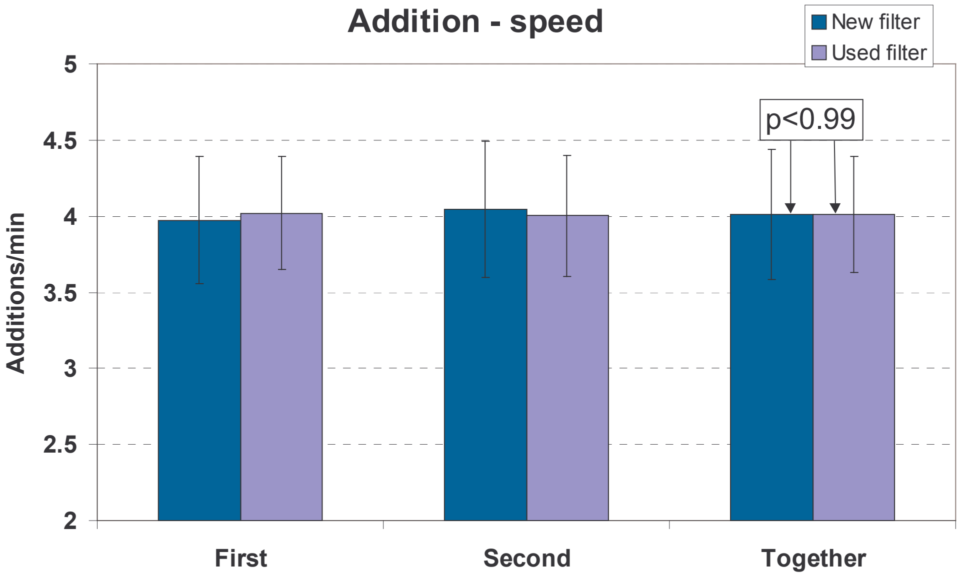


Figure 56 *Speed of the addition task. Also depicted is the 95% confidence interval.*

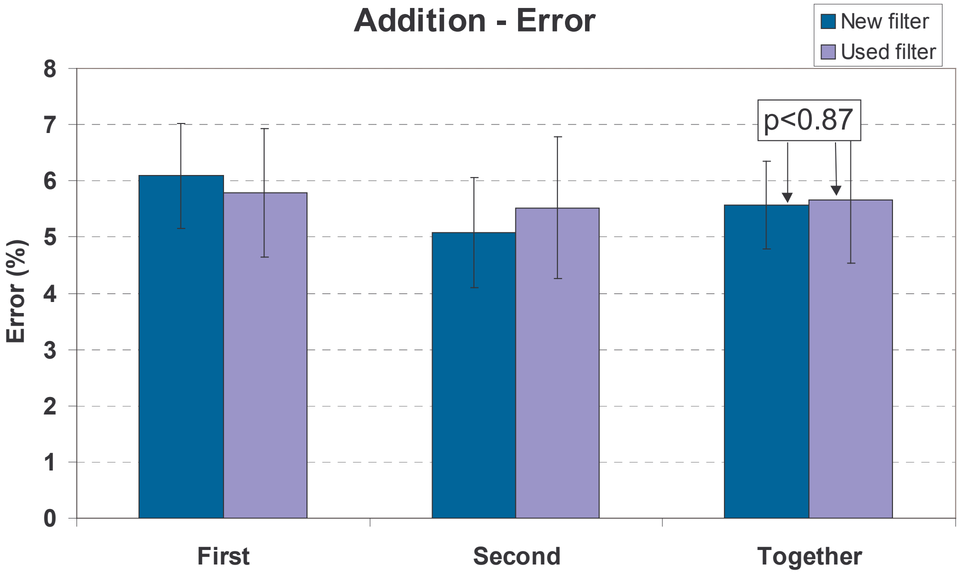


Figure 57 *Errors made in the addition task. Also depicted is the 95% confidence interval.*

Proof reading

During an experimental session, the subjects worked with the proof reading task for two 17-minute periods. The result of this task has not yet been analysed.

Tsai-Partington's test

The Tsai-Partington's test was done twice, each time for 40 seconds. The performance was measured in terms of the number of correct links. The results are given in Figure 58. The two conditions did not affect the test at any time.

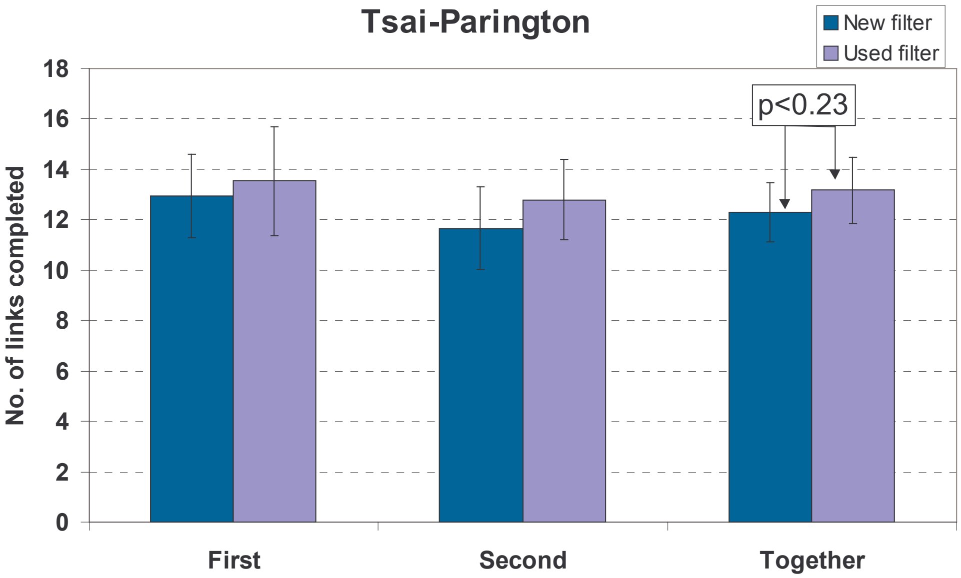


Figure 58 *Results of the Tsai-Partington's test. Also depicted is the 95% confidence interval.*

Sensory pollution load

Using equations [1], [2], and [3], chapter 3.1, it is possible to estimate the sensory pollution load in the office as olfs per square metre of the floor (olf/m^{2}floor). Figure 59 shows the sensory pollution load for the two conditions. The background load of the office is included for both conditions. For the estimations after 56 and 175 minutes the load from bioeffluents is also included. Upon entering, the pollution load from the used filter and the office was estimated to be approximately 0.72 olf/m^{2}floor and approximately 0.13 olf/m^{2}floor with the new filter in the system. Upon re-entering the office, the load was 0.24 and 0.15 olf/m^{2}floor, respectively.

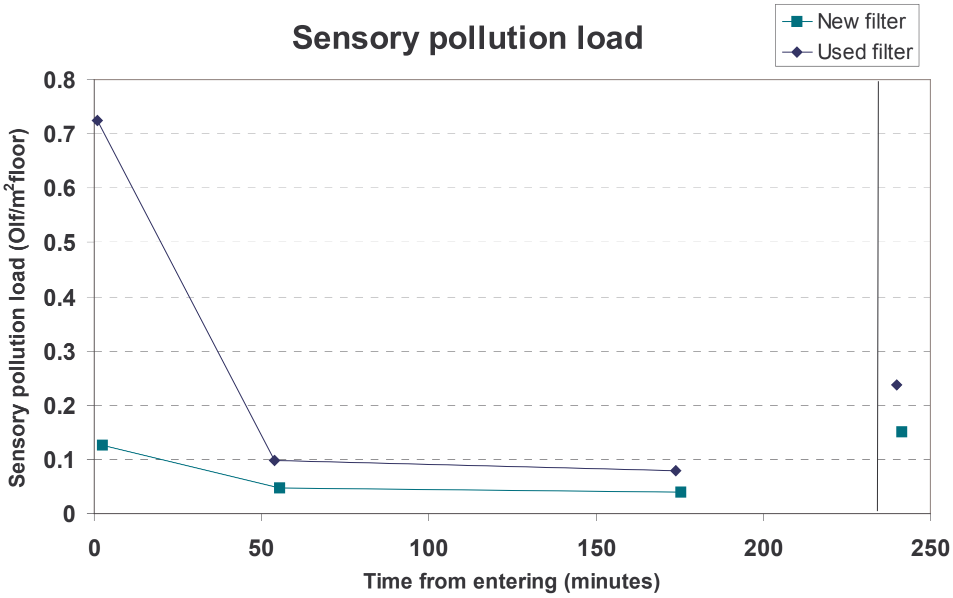


Figure 59 *Sensory pollution load of the filter estimated as olf/m^{2}floor.*

Discussion

An objective of the present study was to investigate the impact of a used ventilation filter on the perceived air quality, SBS symptoms and productivity.

Upon entering the office, having a used filter in the ventilation system instead of a new filter, had a significant impact on numerous perceptions and symptoms. The perceived air pollution was worse, the intensity of the odour was higher, there was greater irritation in the nose, the perceived intensity of the humidity was lower, the perceived intensity of the freshness of the air was lower, the acceptability of the overall environmental conditions was lower, the perceived intensity of headache was higher, the ability to think clearly was lower, the perceived intensity of dizziness was higher, and self-estimated performance in the office was lower. After 56 minutes in the office, the impact was still significant on the perceived air quality, on the perceived intensity of freshness of the air, on the overall environmental conditions and on self-estimated performance. Furthermore, after 56 minutes the ability to concentrate was significant lower when the used filter was in the ventilation system. After 175 minutes' occupation in the office, the impact of the two conditions on the acceptability of the overall environmental conditions was still found to be significantly different.

None of the results showed any improvements of the perceptions or symptoms when the used filter was in the system.

The pollution load from the new filter and the office was estimated to be 0.13 olf/m^{2}floor upon entering. The background pollution load in that office has been estimated to be approximately 0.1 olf/m^{2}floor (calculated from Witterseh, 2001). The pollution load from the new filter was therefore only 0.03 olf/m^{2}floor. After subtracting the pollution load from the new filter and the background load from the office from the pollution load of the used filter and the office, it is possible to estimate the pollution load from the used filter alone. Figure 60 shows the pollution load from the used filter, estimated as olf per surface area of the filter (olf/m^{2}filter). The pollution load, estimated upon entering the office, was approximately 11 olf/m^{2}filter.

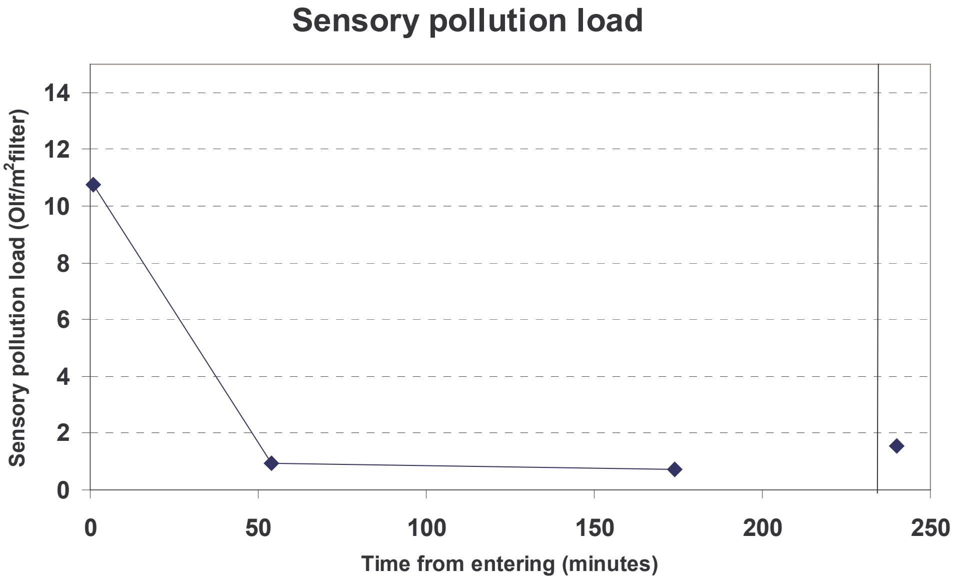


Figure 60 *Sensory pollution load from the used filter estimated as olf/m^{2}filter.*

Upon entering, the intensity of headache and dizziness, and the ability to think clearly were found to be significantly affected by the two conditions. These results were obtained by means of questionnaires filled out during the first 2-3 minutes of occupancy. It is therefore hard to believe that breathing air polluted with a used filter for such a short period could give e.g. headache. Entering an office with unacceptable air quality, generally makes the subjects feel more dissatisfied and symptoms may therefore perceived to be worse.

Hypothetically could all subjects have more headaches and be more tired from the start of the experimental session on the days when the used filter was in the ventilation system. However, because the order of the exposure was balanced, it is unlikely that 30 women divided into 5 groups, coming on 10 different days, should have more headaches and be more tired on the days, unknown to them, when the used filter was in the ventilation system.

There was a tendency for the subjects, upon entering the office to perceive it to be more quiet when the new filter was in the system than when the used filter was in it. The average sound pressure level for the two conditions was 45 and 46 dB(A), respectively, and this difference is just audible. Several experiments have investigated the influence of different indoor environmental parameters on the perception of noise (Clausen et al., 1993; Oseland & Raw, 1996; Alm et al., 1999; Witterseh, 2001). The perception of noise in these experiments was not affected by elevated temperature or by unacceptable air quality. Furthermore, the subjects' assessment of the question "How do you assess the noise?" in the present study was not affected by the two conditions.

Witterseh (2001) found in a similar experiment that the combination of elevated air pollution and ventilation noise caused the subjects to feel more tired than when exposed to the elevated level of only one parameter. The highest level of ventilation noise in that study was 45 dB(A), approximately the same as in the present study. The level of ventilation noise in the present study could have had a negative effect on the intensity of symptoms in the office, both on entering and during occupancy. Repeating the present experiment with a less noisy ventilation system could result in a lower intensity of SBS symptoms.

Upon re-entering the office, the air was perceived to be of the same or of better quality compared to the quality when entering the first time, and gave the same or less irritation to eyes, nose and throat, respectively. Upon entering, the pollution load from the used filter and the office was estimated to be approximately 26 olf (0.72 olf/m^2floor) and approximately 4.6 (0.13 olf/m^2floor) with the new filter in the system. With 6 persons in the room for 4 hours, the total sensory pollution load predicted by adding the load from persons to the load in the office would have been 32 and 10.6 olf, respectively. Upon re-entering the office, the load was 8.6 olf (0.24 olf/m^2floor) and 5.4 olf (0.15 olf/m^2floor), respectively, which is only 25-50% of the predicted value. In earlier experiments using the same set-up, facilities, and procedure, but another pollution source, the office air has been perceived as significantly less acceptable upon re-entering compared with the first entry (Wargocki, 1998). At the end of the occupancy, the subjects left the office and stayed in the corridor in front of the office for three minutes. The length of the time was a compromise between the participants recovering their olfactory senses and the period not being long enough for the air quality in the office to improve due to the ventilation. It would have been a better design if all the assessments of the air quality had also been made by an extra group of 30 subjects located in a well-ventilated low-polluted office nearby. This extra group would always have fresh olfactory senses and would always have assessed the air quality as visitors and not as occupants.

The two conditions did not affect the speed or the errors in the text typing task or the addition task at any time during occupancy. However, the self-estimated performance was significantly affected by the two conditions. Wyon et al. (2000) found that reducing airborne dust levels in an office by replacing a well-used supply air filters with new ones had the effect that the humidity seemed lower, eyes ached less, head felt clearer, the subjects felt better and less tired, and the self-estimated productivity was higher. These findings are very similar to the results from present experiment. However, Wyon et al. (2000) did not find any effect by changing the filter on the perceived air quality or perceived odour intensity.

In the first of the two-period text typing task, the performance, measured as written characters per minute, was almost significantly higher when the used filter was in the ventilation system instead of the new filter. Previous experimental measurements of performance have all found that the air pollution either had no effect on the performance or the performance decreased with increasing air pollution. The performance tasks required skills in either text typing or in addition, both skills that can be learned quickly by performing the tasks. The subjects therefore improved their skills during the experiments and worked faster on the last experimental day compared with the first. Because it was not possible to fully randomize two conditions on five days, 3/5 of the subjects experienced the condition with the new filter before the condition with the used filter.

The participants worked faster and made fewer mistakes during both periods for the two performance tasks when the used filter was present in the system. However, these findings were not significant, and they could be caused by the improvement of the subjects' skills and not by the air pollution. The experiment should have been carried out on six weekdays instead of five. It would then have been possible to exclude the learning effect because half of the participants would have experienced the new filter before the used filter and vice versa. It is possible to do the same with the results from the present study by excluding one of the groups and thereby having 24 participants, half of them experiencing the new filter first, and the other half the used filter first. In the following is the result of an exclusion of the Friday group shown as an example. The results of an exclusion of all groups, one by one, are shown in appendix C. The results of the exclusion can be seen in Figure 61 and Figure 62. After adjusting for full randomisation, the two conditions did not affect the speed or the errors in the text typing task or the addition task differently at any time during occupancy. However, for the speed of text typing, there was still a tendency for the subjects to perform better when the used filter was in the system. The error rate decreased significantly between the first and second periods of the addition task when the new filter was in the ventilation system, but not when the used filter was in it. The first period of addition ended after 101 minutes of occupancy, and the second period after 220 minutes. The subjects were expected to be more tired after 220 minutes' occupancy with different tasks, but it seems to have had a positive effect on the error rate. This effect was not found when the used filter was in the system and the overall environmental conditions were thereby found less acceptable.

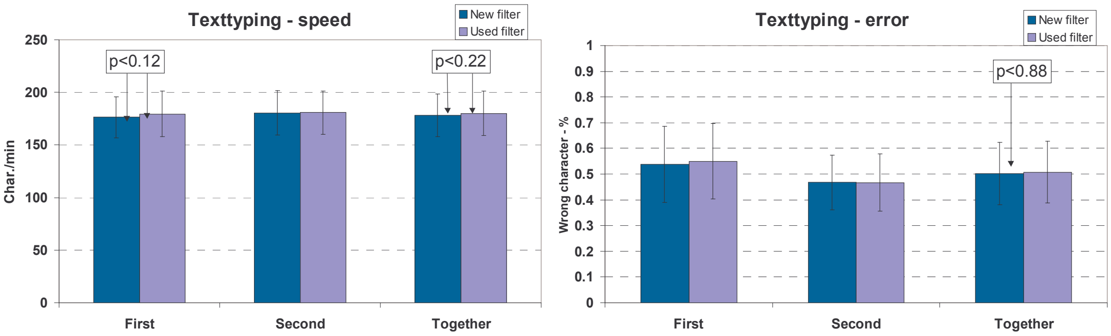


Figure 61 *Speed and error rate of the text-typing task based on the performance of only 24 subjects. Also depicted is the 95% confidence interval.*

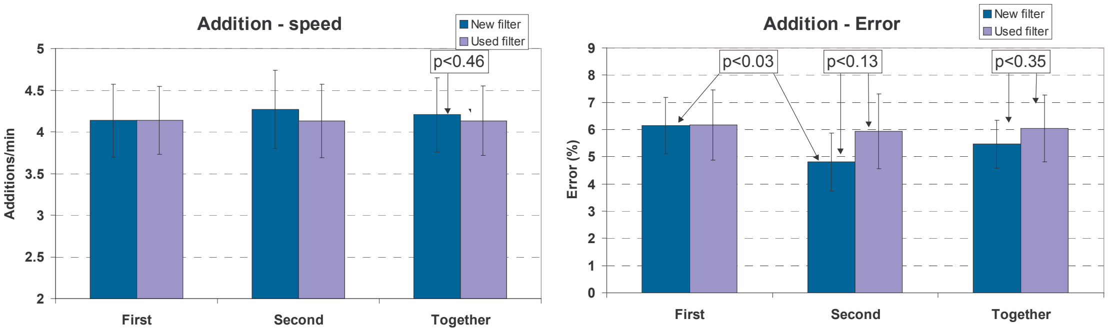


Figure 62 *Speed and error rate of the addition task based on the performance of only 24 subjects. Also depicted is the 95% confidence interval.*

The combination of learning effect and incomplete randomized design of the experiments has been a factor in all the performance experiments that have been carried out lately at the International Centre for Indoor Environment and Energy. In the first one, made by Wargocki (1998) with and without a used carpet as pollution source and with a design similar to the present study, 3/5 of the subjects experienced the low-polluted air first. The results could therefore have been even better if the order of the experimental session had been reversed so that 3/5 of the subjects had experienced the high-polluted air first. Obviously, that would not have made the results more correct. The Wargocki study was repeated in Sweden in 1999 (Lagercrantz, 2000) with the same set-up and pollution source but with the experimental days in reverse order. Some of the same effects were found in that study but to a lesser degree. Hypothetically, if the Lagercrantz study had used the same order of the experimental days as was used in the study by Wargocki, less effect on the performance would have been found. The effect of incomplete design has less influence if there are more than two conditions, and the experiment takes place during more than two weeks. The best design would be if one extra weekday was used, thereby having 36 subjects participating during the week, or having five conditions during five weeks with a different condition on each weekday.

The Tsai-Partington's test is mainly a tool for finding the influence of temperature on the subjects' arousal, and the number of correct links made has been found to be affected by elevated temperature (Wyon, 1969; Witterseh, 2001). In the present study, the test was included to give the participants a break from the longer and more energy-consuming tests such as text typing or addition, and it was not expected that the outcome of the test would be significantly different for the two conditions. There was a learning effect in this test, as was the case for text typing and addition, and the results can be corrected for the incomplete design by using the results from only 24 of the subjects. As expected, there was no significant differently effect of the two conditions on the number of correct links made in the Tsai-Partington's test (Figure 63).

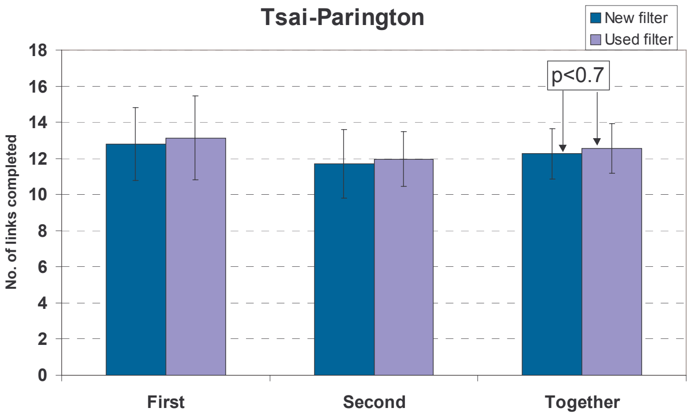


Figure 63 *Results of the Tsai-Partington's test based on only 24 subjects. Also depicted is the 95% confidence interval.*

Conclusions

Upon entering the office, having a used filter in the ventilation system instead of a new filter, had a significant impact on numerous perceptions and symptoms. The perceived air pollution was worse, the intensity of the odour was higher, there was greater irritation in the nose, the perceived intensity of the humidity was lower, the perceived intensity of the freshness of the air was lower, the acceptability of the overall environmental conditions was lower, the perceived intensity of headache was higher, the ability to think clearly was lower, and the perceived intensity of dizziness was higher.

Self-estimated performance was assessed as being significantly higher when the new filter was in the system compared to when the used filter was in it. However, there was no significant influence on the performance of office work.

4.0 Discussion

The sensory pollution load of the filter mentioned in chapter 3.1 was estimated to be approximately 125 olf/m^2face area when it was assessed during whole-body exposure at an outdoor air flow rate of 30 and 60 l/s. (The pollution load at an outdoor airflow rate of 10 l/s was negative and is consequently disregarded in these calculations).

In chapter 3.2, it was found that source strength measured in olf per face area was proportional to the face velocity. The face velocity was 0.9 m/s and the pollution load can therefore alternatively be estimated as 139 olf per m^3 air passing the filter per second.

At a face velocity of 0.61 m/s, the sensory pollution load of the filter mentioned in chapter 3.3 was 119 olf/m^2face area of the filter. Alternatively, the pollution load can be determined as 195 olf per m^3 air passing the filter per second.

In chapter 3.2 the exposure-response function for air polluted with a used filter was determined. The function was established on the basis of assessments made during facial exposure. In chapter 3.1 it was found that the sensory pollution loads determined using results from assessments made during facial exposure are 5.9 times higher than those determined using assessments made during whole-body exposure. The result of a recalculation of the exposure-response function is shown in Figure 64.

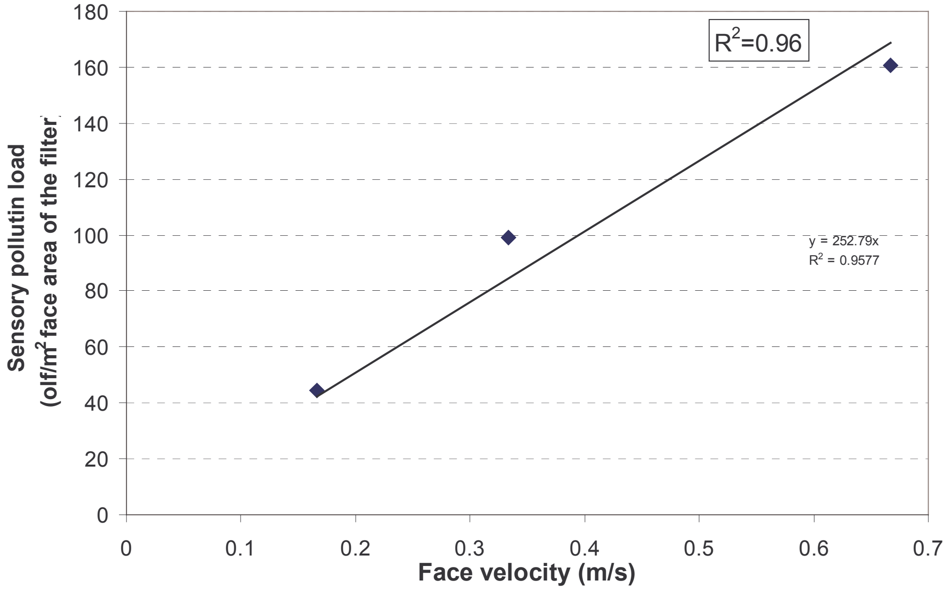


Figure 64 *The source strength of a used filter at three face velocities through the filter.*

The relation between sensory pollution load measured as olf per square metre face area of the filter as a function of the face velocity of the air through the filter is as follows when the relation is forced through [0, 0]:

Sensory pollution load (olf/m^2 face area of the filter) = 253·(face velocity (m/s))

Obviously, the pollution load can also be estimated as 253 olf per m^3 air passing the filter per second.

The pollution loads from the three filters are summarised in Table 12.

Table 12

Results from experiments in:	**Chapter 3.1**	**Chapter 3.2**	**Chapter 3.3**
Type of filter	EU7	EU7	EU7
Number of bags	4	8	6
Area of filter material (m^2)	3	6	2
Original flow (l/s)	1100	500	500
Original face area (m^2)	0.36	0.3	0.18
Original face velocity (m/s)	3	1.67	2.78
Length of use (months)	48	14	12
Flow through total (m^3)	$28.9 \cdot 10^6$	$7.8 \cdot 10^6$	$7.8 \cdot 10^6$
Experimental flow (l/s)	80	50, 100, and 200	110
Experimental face area (m^2)	0.09	0.36	0.18
Experimental face velocity (m/s)	0.9	0.17, 0.33, 0.67	0.61
Sensory pollution load ($olf/(m^3/s)$)	139	253	195

As can be seen, the pollution load differs between the filters tested. The load from the filter used in the exposure-response experiment (chapter 3.2) is almost twice the load from the filter used in the whole-body-facial experiment (chapter 3.1). It is unclear why the filter that had been used for the longest time with the largest total amount of air passing through had the lowest sensory pollution load. Theoretically, the filter from chapter 3.1 should have had the highest load because of the highest amount of particles captured. However, there can have been a difference in the content of particles in the outdoor air where the filters were used originally which could lead to the difference in pollution load. The filters from chapters 3.2 and 3.3 came from the same ventilation system, and the difference in pollution load between these two filters was 30%. The filters came, however, from different periods. In the experiments, the filters from chapters 3.1 and 3.3 were placed in a recirculating ventilation system whereas the filter from chapter 3.2, the filter with the highest load, was placed in a system without recirculation. It is unknown whether this experimental difference could have any influence on the pollution load. Nevertheless, the air upstream of the filter in the recirculating ventilation system was of lower quality than the filter ventilated directly with outdoor air. Sensory evaluations of the quality of the air upstream and downstream of the filter in chapter 3.1 indicated that the source strength of the filter increases when the air quality upstream of the filter improves. Wargocki (2000) investigated the sensory pollution load of a used carpet at three outdoor airflow rates (18, 60 and 180 l/s) and the result was that the sensory pollution load increased when the outdoor air supply rate increased. It is therefore possible that the lower quality of the air upstream of the filter had an influence on the pollution load from the filter.

The experimental conditions for the filters were different from the conditions for original use. However, it is possible to calculate the appropriate size for the filters used in chapters 3.1 and 3.3. The filter used in the experiment described in chapter 3.1 had a face area of 0.36 m^2 (0.6·0.6 metre). It was previously used in a ventilation system at approximately 1100 l/s with a face velocity of 3 m/s. The filter originally contained four bags, but in the experiment only one of the bags was used, giving a face area of 0.09 m^2 (0.15·0.6 metre). In the experiment, the flow through the filter was 80 l/s, giving a face velocity of 0.9 m/s. With a face velocity of 3 m/s and a flow of 80 l/s, the appropriate face area of the filter would have been 0.027 m^2. The area of the filter in the experiment was thus *3.4 times higher*. However, the face velocity in the experiment was *3.3 times smaller* than in the original use. With the proportionality between pollution load and face velocity, the size of the filter used in the experiment in chapter 3.2 was equivalent to the original size.

The face area of the filter used in the experiment described in chapter 3.3 was 0.18 m^2, and the nominal flow for the filter was 500 l/s, giving a face velocity of 2.78 m/s. In that experiment, the filter was used with a flow of 110 l/s and a face velocity of 0.61 m/s. Used under the original conditions, the face area would have been 0.04 m^2 which is 4.5 times smaller than the size used in the experiment. However, the face velocity through the filter was 4.5 times smaller in the experiment, so a nominal-sized filter would have had the same load as the one in the experiment.

With the knowledge of the sensory pollution load from the filter and from the office and occupants, it is possible to calculate the total pollution load in the office at different outdoor supply rates. The office used in chapter 3.3 was ventilated with a filter giving a load of 195 olf per m^3/s ventilated air entering the office. The volume of office 1 was 108 m^3 and the floor area was 36 m^2 and with an air exchange rate of e.g. 1 h^{-1} the estimated sensory pollution load in the office from the filter would be 0.16 olf/m^2floor. The sensory pollution load from the office has been estimated at 0.1 olf/m^2floor (Witterseh; 2001). According to CEN 1752, the normal occupancy for an open-plan office is 0.07 person/m^2, giving a pollution load from persons of 0.07 olf/m^2floor. The sensory pollution load from a new filter was estimated in chapter 3.3 to be approximately 0.03 olf/m^2floor. The calculation of the total sensory pollution load in the office ventilated by a ventilation system with either a used or a new filter present can be seen below:

Office ventilated with used filter present			Office ventilated with new filter present.		
A used filter	0.16	olf/m^2floor	A new filter	0.03	olf/m^2floor
Low-polluting office	0.1	olf/m^2floor	Low-polluting office	0.1	olf/m^2floor
Occupants	0.07	olf/m^2floor	Occupants	0.07	olf/m^2floor
Total	0.33	olf/m^2floor	Total	0.2	olf/m^2floor

The sensory pollution load from the filter would therefore be more than twice the pollution load from occupants, and it is 60% higher than the load coming from the (low-polluting) office. Replacing the used filter with a new filter lowered the total load in the office by 40%. The contribution from the three main pollution sources can be seen in Figure 65. The used filter contributes 49% of the total load, and the new filter contributes only 15%.

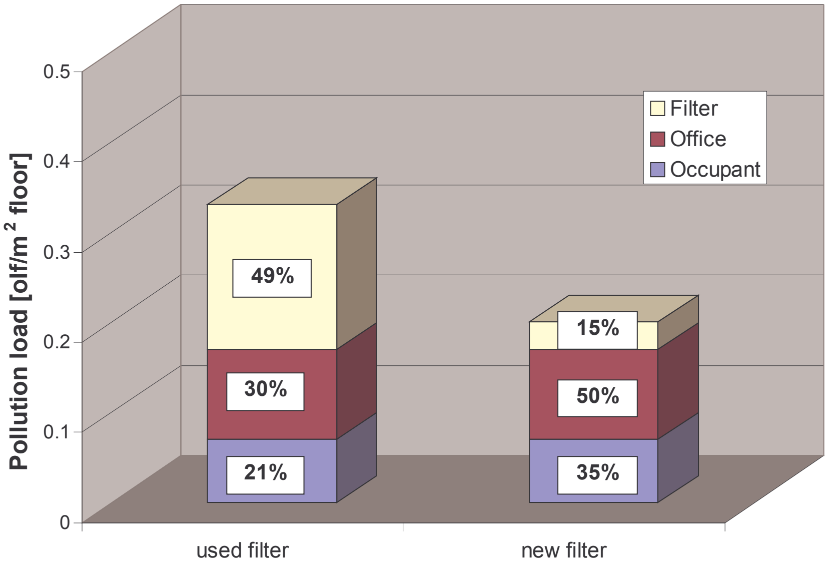


Figure 65 *The absolute and relative contribution from occupants, office, and the filter to the total pollution load in the office.*

Using equations [2] and [3] from chapter 3.1, it is possible to calculate the percentage of dissatisfied people entering the room on the two occasions. The percentage dissatisfied upon entering the office would be 40% when the used filter is in the system, and 30% when the new filter is present.

According to CEN 1752 (1998), the minimum ventilation rate should be 0.7 l/s·m^2 for occupants and 1.0 l/s·m^2 for the low-polluting office (category A). With a floor area of 36 m^2, these design criteria would give a ventilation rate of 61 l/s, equal to 2 air changes per hour. A doubling of the ventilation rate would, with the same face area of the filter, double the face velocity and thereby the pollution load from the filter to 0.32 olf/m^{2}floor instead of 0.16 olf/m^{2}floor. The load from the occupants, the low-polluting office and from the new filter would not change due to the higher ventilation rate. The total load would therefore be 0.49 olf/m^{2}floor when the used filter was present in the system, and 0.2 olf/m^{2}floor when the new filter was present. The contribution from the three main pollution sources can be seen in Figure 64. The used filter now contributes 66% of the total load, and the new filter contributes still only 15%.

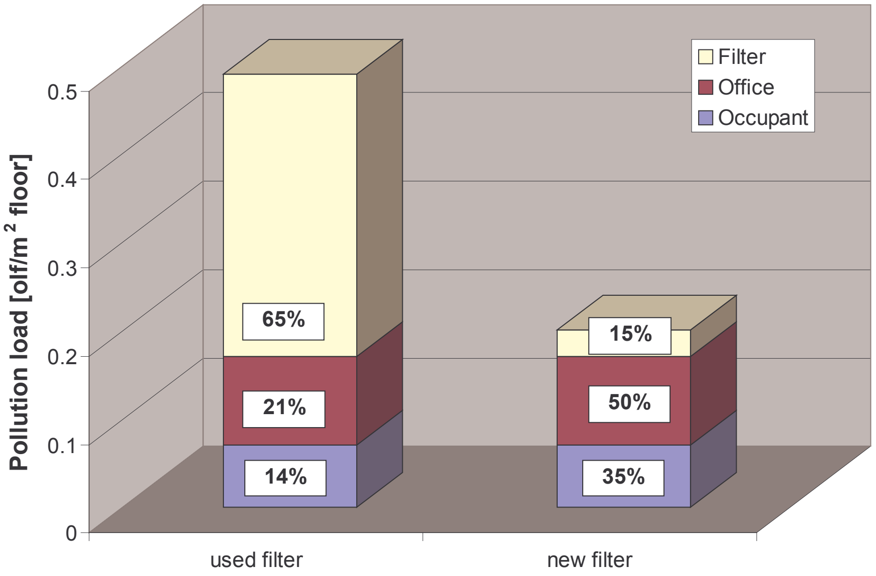


Figure 66 *The absolute and relative contribution from occupants, office, and the filter to the total pollution load in the office when the outdoor air change rate is 2* h^{-1}.

The total pollution load in the office would give 34% dissatisfied upon entering when the used filter was present, and 19% when the new filter was present. This is based on the assumption that the pollution load from the filter increases proportionally with the face velocity through it. An doubling of the outdoor air supply rate lowered the percentage of dissatisfied in both situations, but the improvement was 37% when the new filter was present in the system and only 15% when the used filter was present.

The percentage dissatisfied with the air quality upon entering the occupied low-polluting office is shown in Figure 67 for a new and for a used filter present in the ventilation system as a function of the outdoor air change rate. The air change rate has to be 4 times per hour when the used filter is present in the ventilation system to give the same percentage of dissatisfied as when the new filter is in the system and the air change rate is once per hour. There is only 11% dissatisfied with the air quality when the air change rate in the office is 4 h^{-1} and the new filter is present in the ventilation system, a difference of 19 percentage points. Wargocki (2000) have found that increasing the ventilation rate significantly improved perceived air quality, significantly reduced the intensity of general SBS symptoms, and significantly improved the performance of office work. That experiment was made without any filter in the ventilation system but as seen in Figure 67, the decrement in percentage of dissatisfied would be lower when a used filter is present in the system.

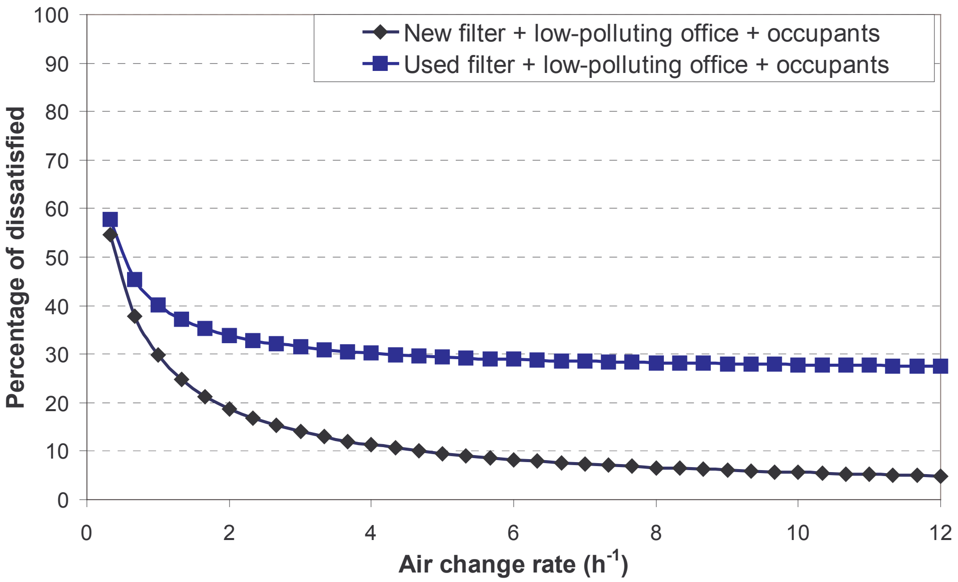


Figure 67 *Percentage dissatisfied as a function of the outdoor air change rate.*

It was expected that significantly improving the air quality by changing the used filter with a new filter would have improved the performance of some of the office work carried out by the subjects, but this was not observed in the present study. Wargocki (1998) found in the same office that improving the air quality by removing a pollution source significantly improved the speed of text typing. By removing the same pollution source as Wargocki (1998), Lagercrantz (1999) found in his study a significant improvement in perceived air quality and in the performance of text typing and addition. In the present study (chapter 3.3), the air quality improved significantly upon entering and after 56 minutes of occupation in the office, but not after 175 minutes or at re-entering, when the used filter was changed with a new filter. This could be caused by adaptation to the office air and thereby lower sensitivity of the olfactory senses for the subjects. However, it is also possible that the pollution source decreased during the experimental day. The filter was ventilated each day in a ventilation system without recirculation and was placed in the ventilation system in the office two hours before the experiment started. This change in placement gave a change in the temperature and relative humidity for the filter. Hyttinen et al. (2000) investigated the adsorption and desorption properties of dust on air filters. The desorption was measured at three different relative humidities (4-5%, 40-50%, 70-80%). The results indicated that relative humidity of air did not affect the rate of desorption, but an increase in humidity during the experiment did have a substantial effect. The change in thermal parameters for the filter in the present study could increase the desorption from the filter initially but after 5-6 hours in the system in the office, the degree of desorption lowered, thereby improved the air quality.

However, previous experiments have found that the 19 percentage points higher proportion of persons dissatisfied with the air quality when the used filter is present, and when the air change rate is 4 h^{-1}, would decrease performance by approximately 2.2% (Wargocki, 2000b). If a person work 8 hours per day and 200 days per year, the loss in person-hours would be

35.2 hours per person. Changing the filter in a small company with 50 people employed would increase the total performance as if one extra person was employed. Assuming an occupancy of 0.07 persons per m^2 in that company, a height to the ceiling of 3 metres in the offices, and an air change rate of 4 times per hour, a total of 8571 m^3 of outdoor air would have to be provided to the office per hour. A ventilation system with four bag filters, each with a face area of 0.6·0.6 metre, would be able to provide the air. The face velocity would be 1.7 m/s. It has been found that the sensory pollution load, at a given face velocity, reaches a steady state after 4 months of use. To ensure good air quality in the offices, the filter has to be changed 6 times per year, giving a total of 24 filters per year. Assuming that the economical benefit of one extra worker is more than the salary of 250,000 DKr., and that the total annual cost for the filters would be 16,000 DKr (typical price is 650 DKr for one EU7 bag filter), the company would earn at least 234,000 DKr. per year. In these calculations is included neither the cost of changing the filter nor the benefit of lowering the energy consumption in the ventilation system by lowering the pressure drop over the filters through changing them. Fisk and Rosenfeld (1997) estimated that the annual cost of a 2% decrease in productivity would amount to $50 billion in the USA. However, the performance of office workers was not found to be significantly affected by changing the filter in the performance experiment in chapter 3.3.

The participants in the experiments have all been either students or people working with indoor climate issues, and do not therefore represent a general subgroup of the population or office workers. However, in most of the experiments the goal has been to determine the relative difference between conditions and not the general level for each condition. The magnitude of SBS symptoms, speed, and error rate in the performance test should therefore not be seen as a general level, but as the level of this group of persons.

Mathematical simulations

The chemical analysis indicates that one of the main reasons for deterioration of the air quality downstream of the filter is a product of oxidising processes on the filter. In the following, simulations of the concentration of odorous gases in a 108 m^3 office are shown, when it is ventilated with 1 outdoor air change per hour. The model object is schematically shown in Figure 68. The assumption is that the filter retains 100% of the outdoor particles. On the filter, the particles react with some constituent of the outdoor air (e.g. ozone) and odorous gases are produced and released to the space.

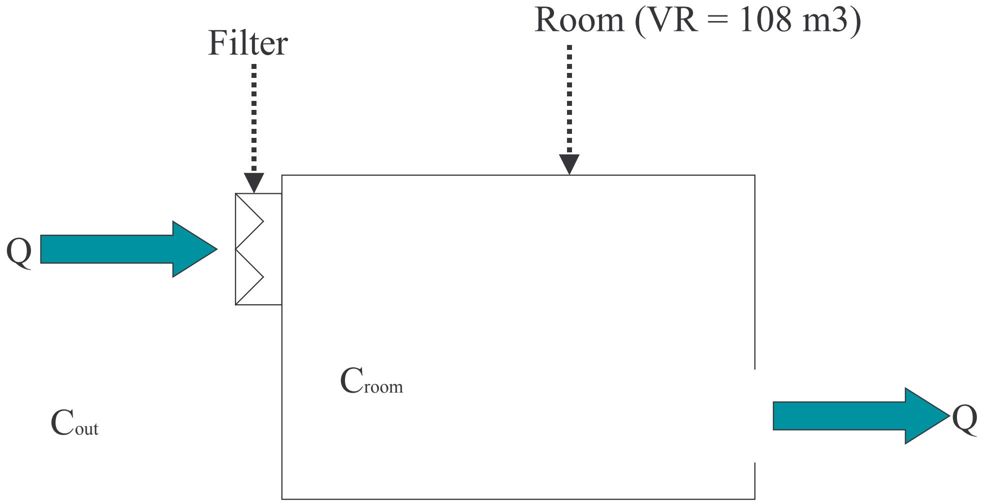


Figure 68 *Model object for the simulations.*

The mass balance modelling is made of three differential equations; one to find the mass of reactive particles on the filter; one to find the concentration of odorous gases in the office, and one to find the mass of reaction products leaving the filter by desorption.

The size of the room is 108 m^3 and an air change rate of 1 h^{-1}, the system delivers approximately 2600 m^3 of ventilated air per day. Earlier results have shown that the sensory pollution load from the filter rises until it reaches a constant level after approximately 90 days of use (Pasanen et al., 1994; Pejtersen; 1994), and the time constant for the equation describing the amount of particles on the filter is therefore set to 30 (days). The outdoor concentration of particles is set to 10 $\mu g/m^3$.

With the first equation, it is possible to find the mass of particles on the filter [y(1)]

$$dy_1/dt = Q \cdot Cout - R \tag{1}$$

where
Q: 2600 (m^3/day)
Cout: 10 ($\mu g/m^3$)
R: y(1)/T (μg/day)
T: 30 (day).

The first part gives the mass entering the filter, and the second part is the mass of particles leaving the filter as odorous reaction products.

With the second equation, it is possible to find the concentration of odorous gases in the office [y(2)]

$$dy_2/dt = \alpha \cdot R/VR - y(2) \cdot Q/VR + y(3)/(T2/VR) \tag{2}$$

where:

Q: 2600 (m^3/day)
R: y(1)/T (µg/day)
T: 30 (day)
VR: 108 (m^3)
α: 0.5
y(3): comes from the third equation (µg).

The first part is the concentration of odorous gases emitted from the filter, the second part is the concentration of gases leaving the office, and the third part is the concentration of odorous gases desorbed from the filter. Alfa is the fraction of the reaction product not adsorbed by the filter and is in the modelling assumed to be 0.5.

With the third equation, it is possible to find the mass of reaction products desorbed from the filter [y(3)]

$$dy_3/dt = (1-\alpha)\cdot R - y(3)/T2 \qquad (3)$$

where
R: y(1)/T (µg/day)
T: 30 (day)
VR: 108 (m^3)
α: 0.5
T2: 6 (day)

T2 is the time constant for the desorption. The first part gives the amount of the mass of reaction products adsorbed, and the second part gives the amount of this mass desorbed again.

A doubling of the flow rate through the filter has been found in chapter 3.2 to give the same concentration downstream of the filter. This result is used as a benchmark for how well the equations fit. Solving the equations with regard to y(1), y(2), and y(3) will give the problem that a change in the flow rate will also change the concentration of odorous gases in the office and this does not agree with the results from chapter 3.2. A limiting factor has to be added to the equations. If the odorous gas from the filter is caused by oxidation processes, the emission depends on the concentration of the oxidant in the air. When the flow through the filter is elevated, further reactions can occur on the filter and thereby increase the emission of odorous gases. The limiting oxidant could be ozone or the oxygen in the air. This limiting factor expresses the idea that not all reactions takes place right away because of the limited concentration of oxidiser. Johansson and Rosell (1998) found a 30% reduction of ozone over the filter, and with an outdoor ozone concentration of 30 µg/m^3 (15 ppb), 9 µg/m^3 can react with the content of the filter. The limiting factor is added as follows

```
Rmax = CR·Q;
        if      R > Rmax
                R = Rmax
```

where:

CR: 9 (μg/m^3)
R: y(1)/T (μg/day)
Q: 2600 (m^3/day)

This factor change with the flow, and it is then possible to have a greater number of reactions on the filter.

The modelling is made in MATLAB, and the programme can be seen in appendix D.

In Figure 69, the mass of particles on the filter, the concentration of odorous gases in the air in the office, and the mass of adsorbed reaction products are shown as a function of days. The flow through the filter is doubled after 350 days, and after 450 days, the concentration of the oxidiser is set to zero.

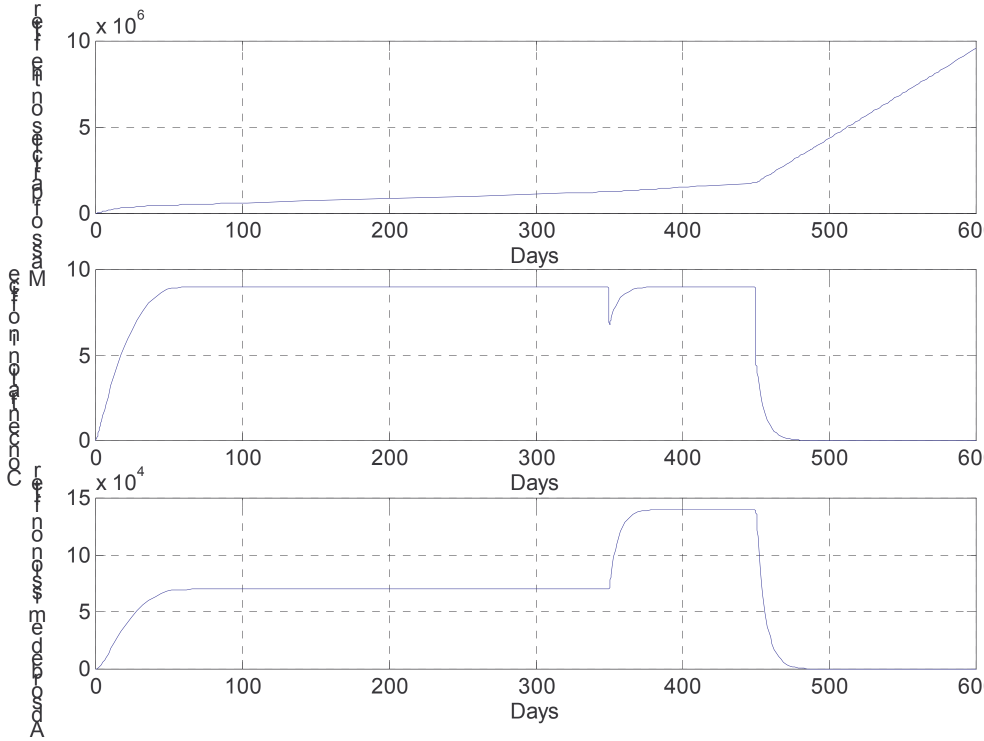


Figure 69 *Mass of particles on the filter and the concentration of odorous gasses in the office as a function of time.*

Because of the limitation of the oxidising process, the mass of particles never reaches a steady state, but continues to rise, and when the concentration of the oxidiser is zero, the particle mass increases further. The concentration of odorous gases in the office reaches steady state after 50 days, and then stays at that level until after 350 days when the flow through the filter is changed. The change in flow gives a slight decrease in the concentration, but the concentration increases again and reaches steady state once more after a short period. The cessation of the oxidising processes causes the concentration to decrease rapidly and reach zero after approximately 20 days. The mass of adsorbed reaction products reaches steady state after 50 days, and stays at that level until the flow is changed after 350 days, giving a doubling of the adsorbed mass. The adsorbed mass decreases when the concentration of the oxidiser is zero and reaches zero after 20 days.

Pejtersen (1994) found in his study that increasing the airflow rate from 150 to 600 l/s, giving a face velocity of 0.4 to 1.7 m/s, did not change the sensory pollution load from the filter. The experiment was made after only 90 days of ventilation of the filter with outdoor air. The amount of particles is therefore less than it is after e.g. 350 days, as in the simulations. The results of a simulation doubling the flow rate after 90 days instead of after 350 days is shown in Figure 70. A change in the flow rate decreases the concentration of odorous gases in the office immediately, but increases hereafter to the steady state level again. The results of this simulation support the findings by Pejtersen.

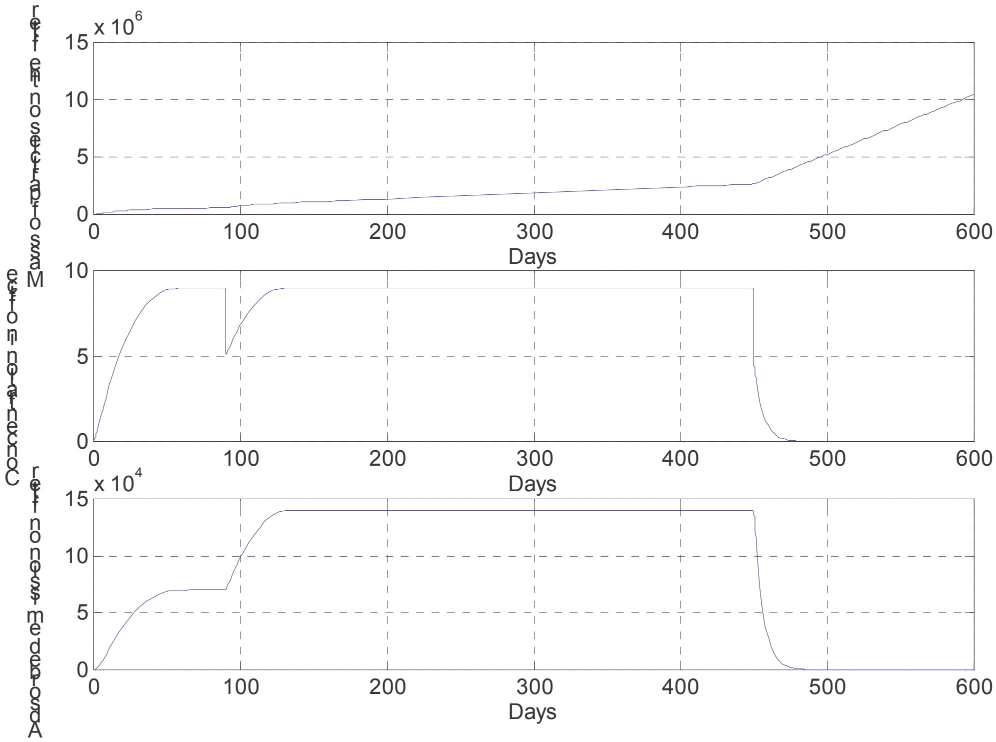


Figure 70 *Doubling of flow rate after 90 days.*

The assumption that either O_2 or O_3 is the limiting factor in the emission from the filter can in future experiments be tested by ventilating the filter with a non-reactive gas such as nitrogen. When the reactions on the filter stop, and the emission from the filter and the concentration in the office will decrease. Adding the adsorption effect to the model gave a small decrease in concentration in the office air when the flow through the filter is doubled.

In the experiment in chapter 3.2, airflow through the filter was 50, 100, and 200 l/s, and the air downstream gave 70 to 90% dissatisfied. Because these assessment are marked to be close to "Clearly unacceptable" on the acceptability scale, it is possible that even after a decrease in the concentration downstream the filter the air was still perceived to be close to "Clearly unacceptable". It is therefore not possible with this method to measure a decrease in the concentration of odorous gasses.

In a future experiment, it will be possible to estimate the amount of reaction products adsorbed on the filter and the halftime of the adsorbed products. The used filter will be ventilated with nitrogen and the decrease in air pollution downstream of the filter will be evaluated by a panel once or twice per day until there is no significant difference between upstream and downstream of the filter.

The model is based on the very rough assumption that all the particles in the air are stopped by the filter, and that oxidation of the particles is the only factor in deterioration of the air quality. However, these simulations support the results from chapter 3.2.

Engineering solutions

An obvious way to improve the air quality in the ventilation system is to change the filter, and as it has been shown earlier in this discussion, this simple solution can save a company money and energy. Nevertheless, if all filters in ventilation systems worldwide would be changed every second month, it would involve considerable many resources in fabrication and transport of these filters. A few alternative solutions are listed in the following:

Pasanen et al. (1994) investigated whether the particle size of atmospheric dust affects the odour emission rate from filters. Six EU6 filters were investigated during three months of use. Two of the filters were used with a pre-filter (EU3) upstream. The sensory pollution load from the coarse pre-filter was similar to the pollution load from the main filter used without pre-filtration, and the pollution load from the main filters was significantly lower if used with pre-filters. This result indicates that the pre-filters effectively protect the main filters from odour causing particles. A relatively cheap way to improve the air quality downstream of the filter unit in the ventilation system is to change the pre-filter more often than the main filter. The typical cost of a pre-filter is only one-sixth of the cost of the main filter.

The suggestions above are made on the basis of present-day the filter technique. Changing the filter, including the pre-filter, is the most effective solution but it will involve energy costs and in big companies it will cost many person-hours to change the entire set of filters every second month. A better solution would be if the filter could change itself, and a sketch of such a filter can be seen in Figure 71. The idea is that the pre-filter should be changed as often as possible without any physical interaction from any persons. The filter will be set up as a role of continuous filter material and will be led either manually or automatically through the ventilation duct. With a change of the filter twice per month, and with a duct height of 0.6 metre, the length of the total filter would have to be 15.6 metres. It has yet to be tested whether a yearly change of the main filter is sufficient to ensure good air quality downstream of the filter. The filter is placed upstream of the fan, and it has to be built tightly to ensure that the low pressure does not lead polluted ambient air into the system. The filters could also be placed upstream of the fan, but then the fan is unprotected from the particles outside and has to be cleaned regularly.

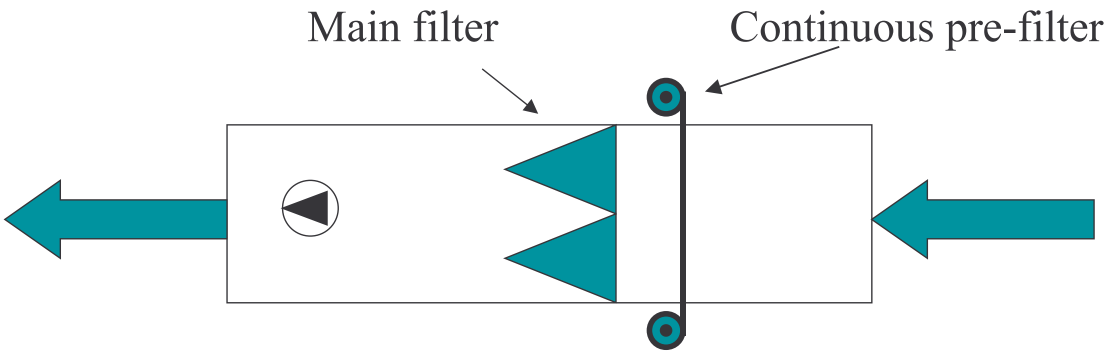


Figure 71 *A sketch of a ventilation system with continuous pre-filter.*

There has been a general belief among many scientists that the deterioration of the air quality downstream of the filter is caused by microbiological growth. This is not supported by the findings in the present study. However, it may still be the case in some countries with high humidity. To prevent the growth, some manufacturers have started to treat the filter material with a biocide as e.g. Intersept. Intersept is a synergistic blend of substituted ammonium salts of alkylated phosphoric acids admixed with a free alkylated phosphoric acid. It is designed to reduce surface growth on a wide range of interior finishes such as carpet, ceiling tiles, fabrics, paints, coatings, resinous flooring, wall coverings, and in products used in the HVAC system such as air filters, air handlers, interior wall coatings, coil coatings, and thermal insulation materials. Ethically, it is not recommendable to use a biocide to prevent microbiological growth in filters. Biocides have for a long period been used in the agriculture preserve the crops from microorganisms. This has leaded to that some of the microorganisms have developed a resistance to the biocide and the growth of them is not so easy to control anymore. This development can in the future make it hard to cure even simple diseases among humans. Price et al. (1993) investigated several filter materials treated with Intersept for growth of microorganisms and compared the results with non-treated filters. Microorganisms could be detected microscopically on all filters after 28 days ventilation with outdoor air, but most obviously on the non-treated filters.

UV-light is known to have a biocide effect and it should therefore be possible to irradiate a filter continuously to exterminate the incoming microorganisms. However, microorganisms coming from outdoors are adjusted to high levels of UV-light, and it can be difficult to kill them. Because of that, Grossi (2000) found that the UV-light only had effect if it was irradiated directly on the filter and not only in the air upstream of the filter. The filter was placed in a closed recirculating ventilation system with humidification to trigger a growth of microorganisms on the filter.

Microorganisms need high relative humidity to survive on the filter and a way to lower the relative humidity downstream of the filter is to heat up the air. Installing a heating coil upstream of the filter is not a solution that makes sense, because the filter is installed to protect the heating coil! The length of the duct from the intake and to the filter unit could be made longer inside the building, thus heating up the air because of the higher temperature inside than outside. However, the duct downstream of the filter unit would then be polluted with particles and would have to be cleaned regularly to prevent it from becoming a sensory pollution source.

Conclusions

- It was found in several experiments that a used filter polluted the air. The sensory pollution load of the filters was found to be 139 to 253 olf/m^3 air passing through per second.

- Two different methods were used to find the pollution load from the filter. When the pollution load was based on evaluations made during facial exposure, it was 5.9 times higher than when it was based on evaluations made during whole-body exposure. However, the difference in acceptability of the same air is not significant. The filter is still a major pollution source but the strength is less than previously reported.

- Entering the office having a used filter in the ventilation system instead of a new filter, had a significant impact on numerous perceptions and symptoms. The perceived air pollution was worse, the intensity of the odour was higher, there was greater irritation in the nose, the perceived intensity of the humidity was lower, the perceived intensity of the freshness of the air was lower, the acceptability of the overall environmental conditions was lower, the perceived intensity of headache was higher, the ability to think clearly was lower, and the perceived intensity of dizziness was higher.

- Having a used filter in the ventilation system instead of a new filter lowered significantly the self-estimated performance. However, the change of filter had no significant influence on the objective measured performance of office work.

- A relationship between the acceptability of air evaluated during facial exposure and during whole-body exposure was established. However, this was based on only six points. When combining the results from the present study and from two previous studies, it was possible to establish a stronger relationship.

- A proportional relationship between the source strength and the face velocity through the filter was found. Increasing the outdoor airflow rate increased the source strength of the filter and the acceptability of the air did not improve. However, by diluting the air downstream of the filter with filtrated outdoor air, it was possible to improve the air quality. A function between the mean acceptability of the air downstream of the filter and the logarithm of the dilution factor has been established and is similar to earlier findings for building materials.

- It was not possible to improve the air quality downstream of the filter by sterilising the filter and thereby killing living organisms. It is unlikely that microorganisms are the main reason for the deterioration of the air quality downstream of a used filter when used in a climate similar to the Danish climate.

- It was not possible to change the air quality downstream of a filter by ventilating it for 7 days with a high concentration of ozone.

- 83 volatile organic compounds were identified in the desorption from dust from a used ventilation filter. The compounds identified are mainly ketones, aldehydes, carboxylic fatty acids, alkanes, phthalates and siloxanes.

- A mathematical model describing the mass of particles on the filter and the concentration of odorous gases in the office as a function of ventilated days was established. The model has not been validated but it fits well with the observations from the present studies.

References

Albrechtsen, O. 1988¨. “Twin climatic chambers to study sick and healthy building”. In: Proceedings of Healthy Buildings’88, Stockholm, Sweden, Swedish Council for Building Research, Vol. 3, 25-30.

Alm, O.; Witterseh, T.; Clausen, G.; Toftum, J.; Fanger, P.O. (1999): “The impact on human perception of simultaneous exposure to thermal load, low-frequency ventilation noise and indoor air pollution”. Proceedings of Indoor Air ’99, Edinburgh, Scotland, Vol. 5, pp. 270-275.

Ammons, C. (1955): “Task for the study of perceptual learning and performance variables”. Perceptual and Motor Skills, 5, pp. 11-14.

ASHRAE (1997): “Handbook of fundamentals”. Atlanta: American Society of Heating, Refrigeration and Air Conditioning Engineers, Inc.

Berglund, B.; Berglund, U.; Lindvall, T. (1978): “Olfactory self- and cross-adaptation: Effects of time of adaptation on perceived odor intensity”. Sensory processes, 2.

Bluyssen, P. 1993. “Do filters pollute or clean the air?”. Air Infiltration Review, Vol. 14, No 2, March 1993, pp. 9-13.

Bluyssen, P.; Fernandes, E. O.; Groes, L.; Clausen, G.; Fanger, P. O.; Valbjørn, O.; Bernhard, C. A.; and Roulet, C. A. 1995. “European audit study in 56 office buildings: conclusions and recommendations”. Proceedings of Healthy Buildings ’95, Milan, Vol. 3, pp. 1287-1292.

Burge, S.; Hedge, A.; Wilson, S.; Bass, J. H.; and Robertson, A. 1987. “Sick building syndrome: A study of 4373 office workers”. Annals of Occupational Hygiene, 3(4A), 493-504.

CEN Report 1752 (1998): “Ventilation for buildings – Design criteria for the indoor environment”. Brussels, European Committee for Standardization.

Clausen, G.; Carrick, L.; Fanger, P.O.; Kim, S.W.; Poulsen, T.; Rindel, J.H. (1993): “A comparative study of discomfort caused by indoor air pollution, thermal load, and noise”. Indoor Air, vol. 3, pp. 255-262.

DMI Ozone concentration from www.dmi.dk. Danmarks Meterologiske Institut.

Elixmann, J. H.; Linskens, H. F.; Schata, M.; and Jorde, W. 1989. “Can airborne fungal allergens pass through an air-conditioning system?”. Environment International, 15, 193-196.

Ettrup, T. (1999): “Skimmelsvampes metabolitter på luftfiltre”. MSc Thesis, BioCentrum, Technical University of Denmark.

Fang, L.; Clausen, G.; and Fanger, P. O. 1996. "The impact of temperature and humidity on perception and emission of indoor air pollutants". Proceedings of Indoor Air '96, Nagoya, Vol. 4, pp. 349-354.

Fang, L. (1997): "Impact of temperature and humidity on perceived indoor air quality". PhD. thesis, ET-PhD. 97-05, Department of Mechanical Engineering, Technical University of Denmark.

Fanger, P. O.; Lauridsen, J.; Bluyssen, P.; and Clausen, G. (1988). "Air pollution sources in offices and assembly halls, quantified by the olf unit". Energy and Buildings, 12 (1988) 7-19.

Fanger, P. O. (1988b). "Introduction of the olf and decipol units to quantify air pollution perceived by humans indoors and outdoors". Energy and Buildings. Vol. 12, pp.1-6.

Fanger, P.O. 1992 "Sensory characterization of air quality and pollution sources". In *Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality – State of the Art in SBS*, Knöppel, H. and Wolkoff, P. (eds.), pp. 59-71.

Finke, U.; and Fitzner, K. 1993. "Ventilation and air-conditioning systems-investigations to the odour and possibilities of cleaning". Proceedings of Indoor Air '93, Vol. 6, pp. 279-284.

Fisk, W.J.; Rosenfeld, A.H. (1997): "Esimates of improved productivity and health from better indoor environments". Indoor Air, Vol. 7, pp. 158-172.

Flannigan, B. (1992): "Indoor microbiological pollutants – sources, species, characteristaion and evaluation". Chemical, Microbiological, Health and Comfort Aspects of Indoor Air Quality – State of the Art in SBS, pp. 73-98.

Gholami, S.; Pejtersen, J.; Clausen, G.; and Fanger, P. O. 1997. "Sensory pollution load caused by HVAC components". Proceedings of IAQ'97 Healthy Buildings, Washington DC, USA, Vol. 1, pp. 545-550.

Gravesen, S.; Frisvad, J.C.; Samson, R.A. (1994): "Microfungi". Munksgård, Copnehagen.

Grossi, L. (2000): "Control of the biologically active particulate by means of filters UV radiation". Proceedings of Healthy Buildings 2000, Vol. 2, pp. 107-112.

Gunnarsen, L.; and Fanger, P. O. 1989. "The influence of adaptation on acceptability of indoor air pollution". Proceedings of CLIMA 2000, Sarajevo. Vol. 3, pp. 49-54.

Halonen, R.; Keskikuru, T.; Kujanpää, Reiman, M.; Kokotti, H. (2000): "Rain entry as a cause to microbial contamination of the ventilation system". Proceeding of Healthy Buildings 2000, Vol 2, pp. 227-232.

Hujanen, M.; Seppänen, O.; and Pasanen, P. 1991. "Odor emission from the used filters of air-handling units". Proceedings of IAQ'91 Healthy Buildings, pp. 329-333.

Hyttinen, M.; Pasanen, P.; Kalliokoski, P. (2000): “Adsorption and desorption of selected VOCs in dust on air filters and in ventilation system”. Proceeding of Healthy Buildings 2000, Vol. 2, pp. 269-274.

ISO 8587 (1998): “Sensory analysis – Methodology – Ranking test.

Johansson, J.; Rosell, L. (1998): “Ger smutsiga luftfilter försämrad tilluft? – En studie av emmisioner med ursprung i filter”. SP Sveriges Provnings- och Forskninginstitut, Energiteknik/Kemi- och Materialteknik., SP RAPPORT 1998:10

Jørgensen, M.H.; Vestergaard, L. (1998): “Sensorisk karakterisering af afgasning fra byggematerialer, udvælgelse af lavemiterende materialer og evaluering af metode”. M.Sc-Thesis ET-EP.98-02, Laboratory of Indoor Environment and Energy, Technical University of Denmark.

Kemp, S. J.; Kuehn, T. H.; Pui, D. J. H.; Vesley, D.; and Streifel, A. J. 1995. “Filter collection efficiency and growth of microorganisms on filters loaded with outdoor air”. ASHRAE Transactions, Vol. 101, Pt.1.

Kildesø, J.; Wyon, D.; Skov, T.; Schneider, T. (1999): “Visual analogue scales for detecting changes in symptoms of sick building syndrome in an intervention study”. Scandinavian Journal of Work Environment & Health, 16 (suppl. 1), pp. 29-38.

Knudsen, H. N.; and Nielsen, P. A. 1997. “Method for sensory characterization of building and furnishing materials”. Proceedings of IAQ'97 Healthy Buildings, Washington DC, USA, Vol. 3, pp. 467-472.

Knudsen, H.N.; Valbjørn, O.; Nielsen, P.A. 1998 “Determination of exposure-response relationship for emissions from building products.” Indoor Air 1998 (8), pp. 264-275.

Larsen, K.; Clausen, P.A. (2001): “*Unpublished data from a GC/MS analysis of volatile organic compounds in dust from a used ventilation filter”*. The National Institute of Occupational Health, Denmark.

Lagercrantz, L.; Wistrand, M.; Willén, U.; Wargocki, P.; Witterseh, T.; Sundell, J. (2000): “ Negative impact of air pollution on productivity: previous Danish findings repeated in new Swedish test room”. Proceedings of Healthy Buildings 2000, Helsinki, Finland, Vol. 1, pp. 653-658.

Lagercrantz, L. (2001): “Transfer model – small scale to full scale”. International Centre for Indoor Environment and Energy. Technical University of Denmark.

Martikainen, P. J.; Asikainen, A; Nevalainen, A; Jantunen, M; Pasanen, P; and Kalliokoski, P. 1990. “Microbial growth on ventilation filter materials”. Proceedings of Indoor Air ’90, Vol. 3, pp. 203-206.

Moritz; Weist, K.; Schleibinger, H. (1999): “Accumulation of endotoxins on air filters in heating, ventilating and air conditioning (HVAC) systems”. Proceedings of Indoor Air ’99, Edinburgh, Scotland. Vol. 2.

Neumeister, H.G.; Möritz, M.; Schleibinger, H.; Martiny, H. (1996): “Investigation on allergic potential induced by fungi on air filters of HVAC systems”. Institute for Hygiene of the Free University of Berlin, Germany. Indoor Air ’96, Vol. 3, pp. 125-130.

Onishi, T.; Pejtersen, P.; and Fanger, P. O. 1991. “Pollution sources in an air handling unit”. Technical University of Denmark, Institute of Energy Engineering.

Oselan, N.A.; Raw, G.J. (1996): “The interrelationship and effect of temperature, air quality and noise on perceived acceptability”. Proceedings of Indoor Air ’96, Nagoya, Japan, Vol. 1, pp. 1043-1048.

Pasanen, P.; Tahanen, J.; and Kalliokoski, P. 1990. “Emissions of volatile organic compounds from air conditioning filters of office buildings”. Proceedings of Indoor Air '90, Vol. 3, pp. 183-186.

Pasanen, P.O.; Hujanen, M.; Kalliokoski, P.; Pasanen, A.-L.; Nevalainen, A.; Ruuskanen, J. (1991): “Criteria for Changing Ventilation Filters”. IAQ ’91, ASHRAE, September 4-8, Washington, DC, USA. pp. 383-385.

Pasanen, P.O.; Pasanen, A-L.; Jantunen, M.J. (1993): “Water condensation promotes fungal growth in ventilation ducts”. Indoor Air, Vol. 3, pp. 106-112.

Pasanen, P.; Teijonsalo, J.; Seppänen, O.; Ruuskanen, J.; and Kalliokoski, P. 1994. “Increase in perceived odor emissions with loading of ventilation filters”. Indoor Air 1994, 4: 106-113.

Pasanen, P.; Salo, J.; Hyttinen, M.; Vartiainen, M.; Kalliokoski, P. (2000): “Ozone reduction in supply air filters”. Proceedings of Healthy Buildings 2000.

Pejtersen, J.; Bluyssen, P.; Kondo, H.; Clausen, G.; and Fanger, P. O. 1989. “Air pollution sources in ventilation systems”. Proceedings of CLIMA 2000, Sarajevo, August 1989, Vol. 3, pp. 139-144.

Pejtersen, J.; Øie, L.; Skar, S.; Clausen, G.; and Fanger, P. O. 1990. “A simple method to determine olf load in a building”. Proceedings of Indoor Air '90, Vol. 1, pp. 537-542.

Pejtersen, J.; Clausen, G.; Sørensen, J.; Quistgaard, D.; Iwashita, G.; Zhang, Y.; Onishi, T.; and Fanger, P. O. 1991. “Air pollution sources in kindergartens”. Proceedings of Healthy Buildings-IAQ 91, Washington D.C., ASHRAE. pp. 221-224.

Pejtersen, J. 1994.”Forureningskilder i ventilationsanlæg”. Technical University of Denmark, Institute of Energy Engineering, Ph.D.-thesis.

Pejtersen, J. 1996a. “Sensory air pollution caused by rotary heat exchangers”. Proceedings of Indoor Air ’96, Vol. 3, pp. 459-464.

Pejtersen, J. 1996b. “Sensory pollution and microbial contamination of ventilation filters”. Indoor Air 1996; 6: 239-248.

Price, D.L.; Simmons, R.B.; Ramey, D.L.; Crow, S.A.; Ahearn, D.G (1993): “Assessment of air filters treated with broad spectrum biostatic agent”. Proceedings of Indoor Air ’93, Vol. 6, pp. 527-532.

Sugawara, F (1997): “Components of dust and microbial proliferation in ducts of air conditioning systems”. Department of Human Life, Koriyama Women’s University, Japan. Healthy Buildings/IAQ ’97 – Global Issues and Regional Solutions. Washington DC, USA, September 27 – October 2, Vol. 1, pp. 563-568.

Thorstensen, E.; Hansen, C.; Pejtersen, J.; Clausen, G.; and Fanger, P. O. 1990. “Air pollution sources and indoor air quality in schools”. Proceedings of Indoor Air ’90, Toronto. Vol. 1, pp. 531-536.

Wargocki, P. (1998): “Human perception, productivity, and symptoms related to indoor air quality”. Ph.D. Thesis, ET-Ph.D. 98-03. Centre for Indoor Environment and Energy, Technical University of Denmark.

Wargocki, P; Wyon, D.P.; Sundell, J.; Clausen, G.; Fanger, P.O. (2000): “The effects of outdoor air supply rate in an office on perceived air quality, sick building syndrome (SBS) symptoms and productivity”. Indoor Air, vol. 4, pp. 222-236.

Wargocki, P.; Wyon, D.; Fanger, P.O. (2000b): “Pollution source control and ventilation improve health, comfort and productivity”. Proceedings of Cold Climate HVAC 2000, Sapporo, Japan, 1-3 November 2000.

Witterseh, T. (2001): “Environmental perception, SBS symptoms and the performance of office work under combined exposures to temperature, noise and air pollution. Ph.D. Thesis, MEK-Ph.D.01-01.

Wolkoff, P.; Wilkins, C.K. !1994): “Indoor VOCs from household floor dust: Comparison of headspace with desorbed VOCs; method for VOC release determination”. Indoor Air, Vol. 4, pp. 248-254.

Wyon, D.P. (1969): “The effects of moderate heat stress on the mental performance of children”. National Swedish Building Research, Document No. 8.

Wyon, D.P.; Wyon, I.; Norin, F. (1995): “Effects of moderate heat stress on driver vigilance in a moving vehicle”. Ergonomics, Vol. 39, #1, pp. 61-75.

Wyon, D.P.; Tham, K.W.; Croxford, B.; Young, A.; Oreszczyn, T. (2000): "The effects on health and self-estimated productivity of two experimental interventions which reduced air-borne dust levels in office premises". Proceeding of Healthy Buildings 2000, Vol. 1, pp. 641-646.

Yaglou, C.P.; Riley, E.C.; Coggins, D.I. (1936): "Ventilation requirements". ASHRAE Transactions, vol. 42, pp. 133-162.

Yaglou, C.P.; Witheridge, W.N. (1937): "Ventilation requirements (part 2)). ASHRAE Transactions, vol. 43, pp. 423-436.