Development of an advanced supply air filter

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ABSTRACT
An advanced supply air filtration unit has been developed, and its performance was evaluated in the laboratory. The filter consists of an electrically enhanced particle filter and an adsorbent filter for gases. It has been designed for installation near supply air outlets. The performance of the filtration unit was measured in the laboratory. The results showed that the filtration efficiency for submicron particles was over 95% during the whole lifetime of the filter. The removal efficiency of the gas filter for toluene was also high, over 95%. An important advantage is the high efficiency with a low pressure drop that allows the filter to be installed in existing HVAC systems without extensive modifications. With the aid of the filter, protection against harmful or hazardous air contaminants can be improved energy efficiently in specific rooms or areas of a building.

INDEX TERMS
Air filter; Ventilation; Charcoal filtration; Innovation; Building protection

INTRODUCTION
In urban environments the outdoor air contains a variety of contaminants that are harmful to human health. Therefore, it is necessary to have a supply air filtration system that removes these contaminants efficiently to provide clean and healthy indoor air quality. However, conventional air filters in central heating, ventilation and air conditioning (HVAC) systems do not remove gaseous air contaminants. Moreover, they are rather inefficient for small particles, since a large fraction of submicron particles penetrate the filters.

In addition to the more conventional concerns caused by environmental pollution, fear is currently growing about the intentional release of toxic chemicals or biological aerosols (fine particles) near air intakes or inside buildings. After such a release, the ventilation system can transport the contaminated air rapidly to various parts of the buildings with serious consequences. The best protection against airborne hazardous materials is high efficiency filtration (U.S. Army 2001). However, if the efficiency of the supply air filtration is improved with solutions based on current technology, large and expensive modifications in the ventilation systems are needed. More efficient filters would increase the pressure drop notably and would thus result in airflow reduction through the ventilation system and subsequently in inadequate ventilation. There is a clear need for a low pressure drop filter that removes hazardous or harmful contaminants effectively.

The aim of this study was to develop an advanced filtration unit that can remove both particulate and gaseous contaminants from the supply air with low flow resistance and high efficiency. The unit is intended for installation in ductwork near the air terminal device or diffuser in each room that needs safe and healthy indoor air quality (IAQ).

THEORY
Indoor air quality is affected by variables such as ventilation flow rate, supply air

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concentration, pollutant infiltration, and generation. Indoor sources typically include emissions from building materials and machines and sources associated with occupant activity. Outdoor sources may be the main contributors of many indoor pollutants, especially in urban areas, close to industrial zones or streets with heavy traffic (Jones, 1999). Indoor air quality can be improved by the following means: eliminating or controlling the indoor sources, improving supply air filtration, increasing the flow rate of clean air, or using room air cleaners that mix the treated air with the indoor air to dilute the concentration of the pollutants.

A simple one-compartment model can be used to study the effect of various factors on indoor air quality (Wadden and Scheff, 1982). With the assumption of perfect mixing in the whole volume V, the following mass balance equation for indoor air contaminant concentration C can be derived using the one-compartment model shown in Figure 1:

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = q_0C_0(1-E_0) + q_1C(1-E_0) + q_{\mathrm{INF}}C_0 - q_{\mathrm{EXF}}C - q_{\mathrm{EXH}}C + G - S - q_{\mathrm{AC}}E_{\mathrm{AC}}C \tag{1}$$

where C is the indoor and C_0 is the outdoor contaminant concentration, E_0 is the efficiency of the supply air filter, q_0 is the make-up airflow rate, q_1 is the recirculation airflow rate, q_{INF} is the infiltration, q_{EXF} is the exfiltration, G is the indoor contaminant generation rate, and S is the indoor sink removal rate. In this model it is assumed that the room contains cleaner air with an airflow rate of q_{AC} and an efficiency of E_{AC}. With a constant emission and removal rate, the steady-state solution for Eqn (1) is as follows ($q_{\mathrm{INF}} = q_{\mathrm{EXF}}$, $q_{\mathrm{EXH}} = q_0 + q_1$):

$$C = \frac{q_0C_0(1-E_0) + q_{\mathrm{INF}}C_0 + G - S}{q_0 + q_1E_0 + q_{\mathrm{INF}} + q_{\mathrm{AC}}E_{\mathrm{AC}}} \tag{2}$$

It can be seen from Eqn 2 that the use of a room air cleaner corresponds to an increase in the make-up airflow rate by an amount q_{AC} times the efficiency E_{AC}.

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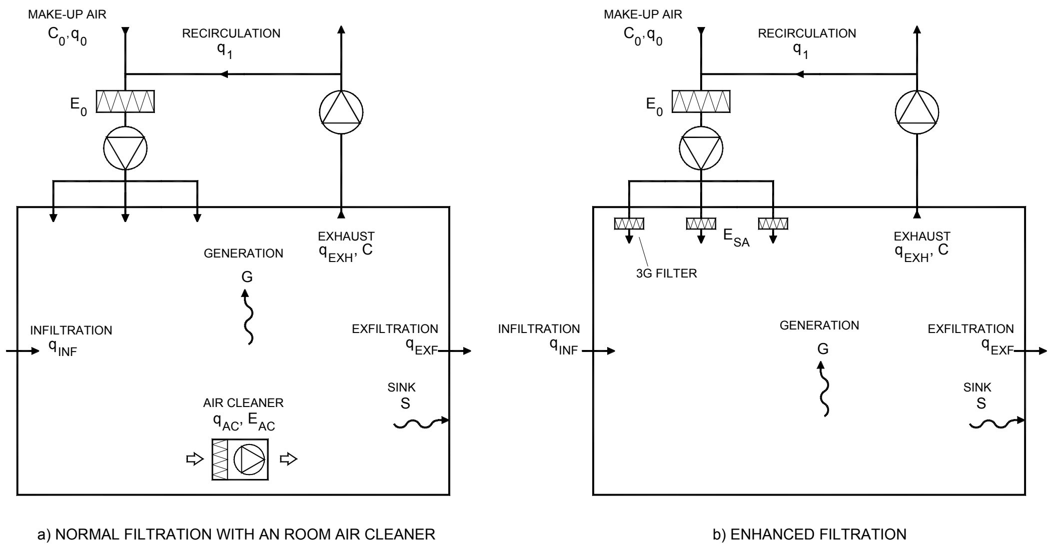

Figure 1 One-compartment model of indoor air quality for a ventilation system using normal and enhanced supply air filtration.

Another way to control the transport of contaminants through the HVAC system is the use of enhanced supply air filtration. In this method, high-efficiency filters are installed near the supply air devices. The mass balance equation then becomes the following when enhanced supply air filtration is used with an efficiency of E_{SA} for the considered contaminant (Figure 1):

$$V\frac{\mathrm{d}C}{\mathrm{d}t} = \left[q_0 C_0(1-E_0) + q_1 C(1-E_0)\ \right](1-E_{\mathrm{SA}}) + q_{\mathrm{INF}}C_0 - q_{\mathrm{EXF}}C - q_{\mathrm{EXH}}C + G - S \qquad (3)$$

The steady-state solution for this equation is

$$C = \frac{q_0 C_0(1-E_0)(1-E_{\mathrm{SA}}) + q_{\mathrm{INF}}C_0 + G - S}{q_0 + q_1 + q_{\mathrm{INF}} - q_1(1-E_0)(1-E_{\mathrm{SA}})} \qquad (4)$$

The effect of improved supply air filtration on IAQ can be examined with the assumption of a known efficiency for the central HVAC and enhanced supply air filters in Eqns (2) and (4) (E_0 and E_{SA}). Assuming a recirculation ratio of 60% and generation G and sink S values of zero, we get the results shown in Figure 2. The calculations have been made using different infiltration flow rates to demonstrate the effect of leakage on the concentration levels.

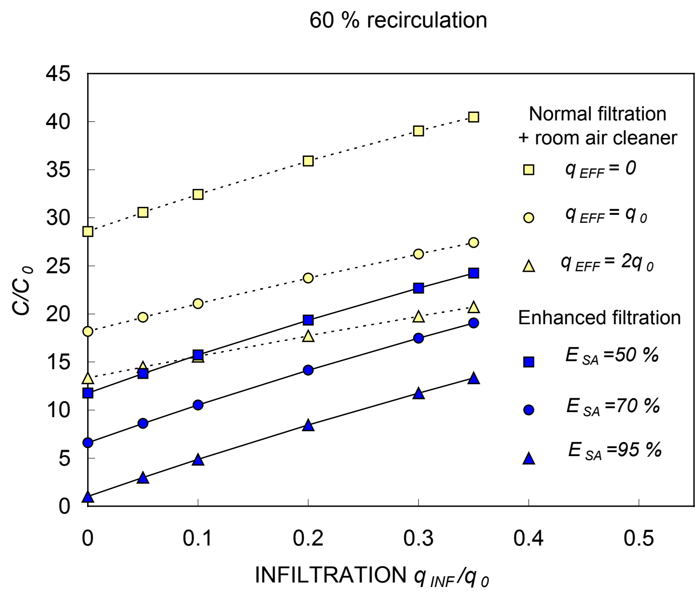

Figure 2 Relation between the indoor and outdoor concentration with various filtration efficiencies and leak flow rates. E_0 = 50%, $q_{INF} = q_{EXF}$.

For particulate contaminants, the efficiency of the filter depends on the particle size. For gaseous contaminants the efficiency is normally negligible. In Figure 2, the indoor air concentration has been calculated in comparison with the outdoor concentration in cases in which the filtration efficiency E_0 is 50%. It can be seen from the results that the enhanced supply air filtration is the most beneficial when the leak airflow rate is minimum. When the leak airflow rate increases, outdoor air pollutants can uncontrolledly enter the indoor air, and even an efficient filter cannot prevent the process.

It can be seen from Figure 2 that, for instance, if the enhanced filtration system had an efficiency of 50% for a certain contaminant, the effective flow rate q_{EFF} of the air cleaner in the room should be equal to about two times the fresh airflow rate (i.e. $q_{EFF} = 2q_0$) in order to achieve the same concentration level. However, if the enhanced supply air filter had an efficiency of 95% in a tight building, then the required airflow rate would need to be $q_{EFF} = 47q_0$ to achieve the same air quality. This requirement is impractically high due to the risks of draught and noise.

DEVELOPMENT OF A NEW SUPPLY AIR FILTER

The theoretical considerations show that, in order to improve indoor air quality effectively, the filter should have a very high filtration efficiency, preferably over 90%, for both particulate and gaseous contaminants. To achieve such a high efficiency for submicron particles with low flow resistance, we employed electrically enhanced filtration.

The second major task was the development of a chemical filter. With adsorbent filters it is essential that the residence time be long enough. Generally, this requirement is met by making the adsorbent beds deep enough. However, the pressure drop caused by the granular activated carbon bed would be excessively high in such cases, and therefore alternative constructions were explored.

The design criteria for the new supply air filter are summarized in Table 1.

Table 1 Design criteria for an integrated supply air filter

Design parameter	Criterion
Airflow rate	Depends on application, typical value 50 l/s
Physical dimensions	Typical size 250 x 250 x 400 mm
Pressure drop	Less than 30 Pa
Particle filtration efficiency	>95% for 0.3 µm particles
Gas filtration efficiency	>95% for volatile organic compounds
Service life	6–12 months
Operating cost	Minimum

RESULTS

The performance of the developed filtration unit, named the 3G Filter, was determined in the laboratory. The fractional filtration efficiency was measured with an optical particle counter (Met One 237B) using DEHS as the test aerosol. The efficiencies were measured in various loading stages with diesel exhaust fumes to study the effect of collected particles on the efficiency. For comparison, the same measurements were made with an electret filter that used charged fibres to improve particle collection. Such electret filters have become increasingly popular due to their high initial efficiency and low flow resistance.

The results of the measurements are shown in Figure 3. It can be seen that the initial efficiency was high for fine particles with both the 3G Filter and the electret filter. However, the efficiency of the electret filter decreased rapidly with loading. This decrease was probably due to the neutralization of the charges (Lehtimäki, 1996). In contrast to that of the electret filter, the efficiency of the 3G Filter for submicron particles remained high, over 95%, over the loading cycle.

The gas filtration efficiency was measured using toluene as the test agent. The test gas was generated using a flow-controlled bubbler, and its concentrations upstream and downstream were measured with a gas analyser (Miran 1 A). The toluene challenge concentration was 80 ppm (306 mg/m^3) according to the DIN 71460 (1994) adsorption filtration standard.

The results are shown in Figure 4. The figure shows that the penetration remains low for a fairly long time before it starts to increase

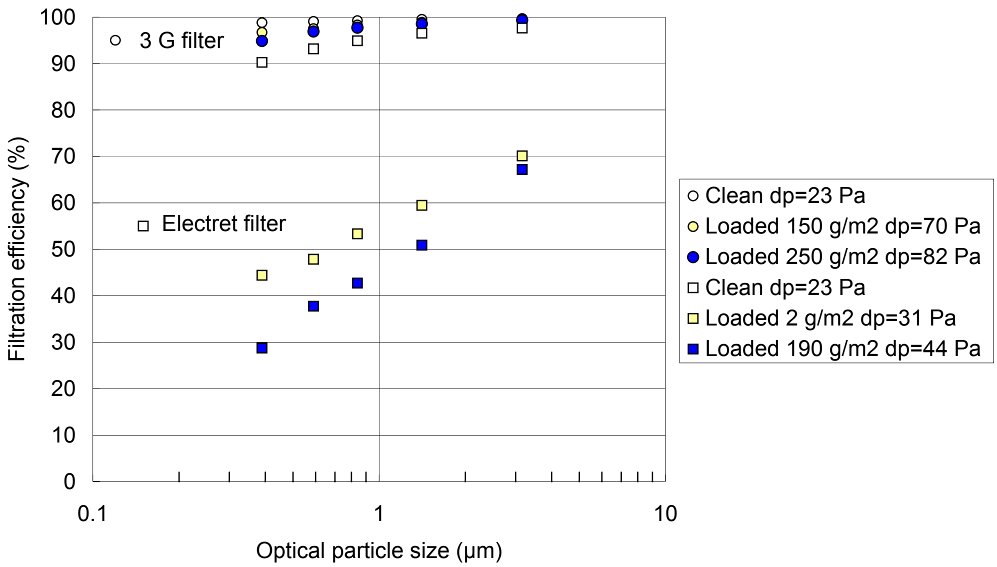

Figure 3 Filtration efficiency of clean filters and filters loaded with diesel exhaust fumes. Loading is expressed as collected mass per face area.

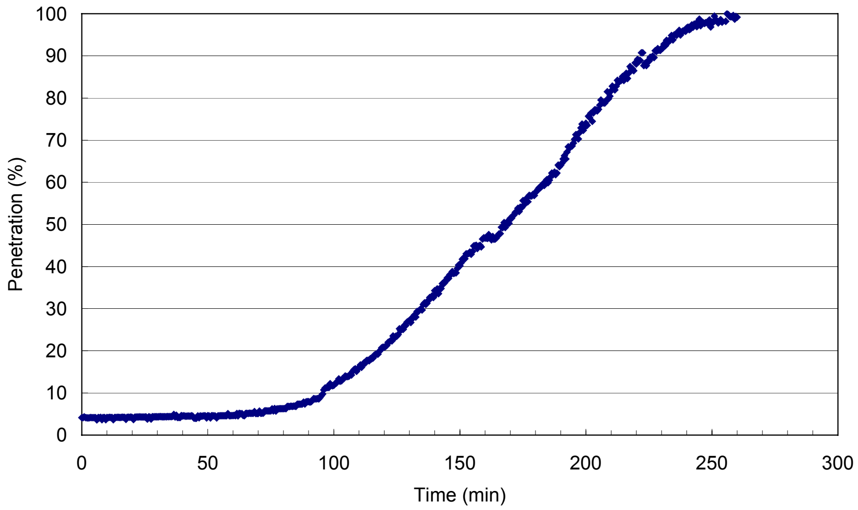

Figure 4 Toluene penetration of the 3G Filter with an 80 ppm upstream concentration.

DISCUSSION

Indoor air quality is affected both by indoor sources and outdoor pollutants. It is generally accepted that contaminants generated by indoor sources are most effectively controlled by source-related solutions. For pollutants originating mainly outdoors, the most efficient control method is to minimize infiltration and remove contaminants using high-efficiency supply air filtration. The disadvantages of conventional high-efficiency particle and chemical filters are the high initial, operation and maintenance costs. Theoretical considerations show clearly that it is more advantageous to remove contaminants before they enter an occupied space than to dilute them with room air cleaners.

The supply air filter developed in this study has a high filtration efficiency for both fine particles and gaseous contaminants such as a wide range of volatile organic compounds, ozone and odours. To filter chemicals of high vapour pressure, impregnants can be added to the carbon. Despite the high efficiency, the pressure drop of the filter is so low that it can be easily installed in existing HVAC systems without expensive modifications. Thanks to the low flow resistance of the filter, the filtration can be done energy efficiently.

It would be possible to apply the 3G Filter in offices, hospitals, schools and other buildings in urban environments where polluted ambient air degrades indoor air quality. The greatest benefits to the indoor air quality can be achieved in buildings in which unwanted inward air leakage is minimized. In addition to outdoor pollutants, the supply air filter can also reduce the concentrations of contaminants that are released in some rooms of buildings and transported via recirculating air to other parts of the same buildings. Such sources may be, for example, emissions from smokers, photocopying machines, paintings and materials. In addition, the supply air filter provides protection against intentionally released hazardous chemical or biological agents into a building.

CONCLUSION AND IMPLICATIONS

Effective control of airborne contaminants transported via HVAC systems can be achieved using efficient supply air filtration. Conventional fibrous filters are an important part of HVAC systems but may not remove all pollutants adequately. Substitution with a more effective filtration system is not always economically and practically feasible, since more efficient filters may be exceedingly expensive and can lead to significant pressure drops and inadequate ventilation.

An innovative solution for improved filtration is to install a high-efficiency, low flow resistance supply air filtration unit in ductwork near the air terminal device or diffuser of rooms in which improved air quality is needed. Optimum control of outdoor pollutants can be achieved in airtight buildings with low infiltration rates. Currently, the 3G Filter protects well against particulate contaminants and many gaseous contaminants. Further work is in progress to develop the filter so that it provides improved protection against various chemical agents released deliberately to HVAC systems.

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