Air cleaning technologies – Function requirements and energy efficiency

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SUMMARY
A state-of-the-art review of various air cleaning technologies has been carried out based on scientific papers and a screening of the market for new technologies. The technologies were categorized by functionality and specificity for removal and/or destruction of specific contaminant types. It is suggested that air cleaning systems need to be based on more than one single technology in order to achieve optimal system performance. There is also a need to clear the market from inferior and even hazardous air cleaning equipment. One important step in this direction would be to include, not only traditional fibre filters, but also alternative air cleaning technologies in future standards.

KEYWORDS
Air cleaning, Indoor environmental quality, Air quality, Ventilation, Volatile organic compounds, Particulate matter

INTRODUCTION
A recently published European ventilation standard suggests substantially higher outdoor airflow rates than applied by common practice today (EN 15251). Another European standard prescribes the use of efficient air filters for cleaning of the air supplied to buildings (EN 13779). Both these standards have the objective of securing a good indoor air quality, but application of the standards also contributes to an increase of the use of both heat and electric energy, compared to the present common practice. Moreover, simply increasing outdoor airflow rates is no guarantee for adequate indoor air quality (IAQ) mainly for two reasons. Firstly, used particle filters, which are not replaced in due time, may comprise potential sources of pollutants and have a negative impact on the perceived air quality (Fanger, 2004). Secondly, outside air can, especially in large cities, be more polluted that indoor air. Also, to counteract a substantial increase of the use of electricity the fan work in ventilation systems needs to be reduced, e.g. by reduction of the pressure drop over components in the air handling unit. In this respect it is of great importance that the entire system is carefully designed.

One important component in this context is the ventilation air filter, which may contribute to about 25 % of the total pressure drop of the ventilation system in an office building. Recent studies have shown that it may be feasible to reduce this figure to about 5 % by the use of novel energy efficient air filtration technologies. Another way could be to reduce the amount of outside air while delivering an equivalent amount of “cleaned” and re-circulated indoor air, thus reducing heating and cooling loads. Such a solution requires that the air really can be cleaned, with sufficient efficiency, from a very wide variety of pollutants, including particulate matter of various size fractions and organic as well as inorganic gases and vapours. All of these types of pollutants may be generated by indoor sources and they may also be supplied to the building from outdoors.

Design guidelines typically prescribe minimum outdoor airflow rates and provide recommendations regarding air filtration efficiency. Thus, it is common practice to base the design of an HVAC-system on requirements regarding specific technical solutions rather than function requirements about the indoor air quality. This is often due to the lack of scientific evidence regarding the effects of individual air pollutants on health and comfort. However, target values for the maximum acceptable concentrations of various airborne contaminants have been proposed, e.g. by WHO and ISIAQ-CIB. If these target values were commonly accepted as a definition of acceptable air quality, there would be an opportunity for a paradigm shift, from a design process that is "technology specific", towards a process that is based on function requirements.

Today, consideration of the need for air cleaning often leads to glass fibre or synthetic fibre filters being installed in the ventilation system. Fine filters of class F7 according to the European standard EN 779 are often selected (roughly corresponding to a rating of MERV 13 according to the ASHRAE 52.2 standard). Other filter types, based on alternative technologies, are rarely used. The reason is probably that there are widely accepted standards for fibre filters, but not for alternative air cleaning techniques. This may be an obstacle for the introduction and development of new technologies that might function equally well, or even better than the traditional fibre filters. Regardless of the type of filtration principle there are a number of basic requirements that need to be fulfilled. Any filtration system must:

- provide sufficiently high filtration efficiency over the entire service life,
- have low air flow resistance, and preferably a small increase of the pressure drop over time,
- prevent the release of harmful or annoying substances into the airflow being cleaned.

This paper summarizes a state-of-the-art review of various air cleaning technologies, and points out possibilities and limitations of available techniques. The paper is based on reviews of scientific papers and a screening of the market for promising new technologies. The paper addresses traditional and widely accepted technologies, such as particle filtration by fibrous media, gas adsorption filtration and electrostatic precipitation. Occasionally proposed alternative solutions, such as air ionization, ozone generation and photocatalytic oxidation are also critically reviewed. Focus is on using these technologies in non-industrial premises.

METHODS

Scientific papers on air cleaning in general were identified and gathered from on-line data bases (Science Direct, ISI Web of Knowledge, Engineering Village, Scopus, Google Scholar) and proceedings of major international conferences. Databases were browsed without setting a time limit, while conference proceedings were limited to 1999 and later. After the main air cleaning technologies were identified the same procedure was repeated for each particular technology. Parallel with this search the market was browsed for promising new technologies. In total more than 250 peer-reviewed papers, conference papers and technical reports were reviewed.

RESULTS

Air cleaning technologies have been categorized by functionality and specificity for removal and/or destruction of particulate matter (PMx) and/or volatile organic compounds (VOCs) and their installation position (Air Quality Sciences, 2006; ALA, 1997; Daniels, 2001, 2002, 2007; USEPA, 1990a, 1990b, 2007; Zhang et al., 2006). The various function principles include physical-, physicochemical- and electronic processes and various combinations thereof. Air cleaning processes fall into one or more of six overlapping classifications of the technologies (Table 1). Alternatively, the technologies can be categorized into five overlapping classifications of the contaminant types being treated: filtration (PMx and bioaerosols or microbial), electrostatic precipitation (PMx and bioaerosols), reaction with charged species (PMx and VOCs), sorption onto solid sorbents (VOCs) and reaction with oxygen species (VOCs) (Daniels, 2007). Finally, air cleaning can be local (table top units and room units) or central (ALA, 1997).

Table 1. Comparison of air cleaning systems (modified from Daniels, 2007).

Technology Description	Filtration - Solid Materials	Filtration Gaseous - Materials	Bipolar Air Ionization	Electrostatic Precipitation	Ozone Generation	Photocatalytic Oxidation
Function	Mechanical	Physico-chemical	Electric	Electric	Electric	Physico-chemical
Process	Collection on fibrous media (thin fibres, large area)	Sorption and reaction	(+) & (-) Ion generation. Reactive oxygen & charged species	Ionization, charging and collection of particulate matter	Ozone generation by sparking discharge or UV-light	Solid catalysts with radiant energy (UV). Reactive oxygen species
Health Concerns	Contami-nated filter disposal	Break-through of VOCs, used media disposal	Charged particles deposit in the airways	Exposure to high voltages and ozone	High ozone exposure	Catalyst disposal or recovery
Organic gases and vapors	N/A	Adsorption	Chemical oxidation	N/A	Chemical oxidation	Chemical oxidation
Inorganic gases	N/A	Chemisorp-tion if me-dia impreg-nated	CO_2, particles	N/A	CO_2, O_3	O_3
Particles	Collection in media	Unwanted collection - pre-filter needed	Agglomeration and deposition indoors	Collection on plates	N/A	N/A
Microbials	Particle removal	N/A	Inactivation destruction, agglomeration	Particle removal	Inactivation	Inactivation

Filtration – Solid materials

Filtration of PMx is probably the most common and the most mature technology. This air cleaning method mainly involves mechanical collection of particles on porous or fibrous media. The mechanisms of removal are diffusion, interception, inertial deposition and the sieve mechanism. Higher filtration efficiency implies a higher pressure drop and consequently higher energy consumption for fans. Therefore it is very important to select a filter class to match the real need. Fisk and Faulkner et al. (2002) studied performance and costs of particle filtration technologies in both, central systems and stand-alone fan-filter units. They concluded that filters in HVAC systems with ASHRAE Dust Spot Efficiencies of 65 to 80 % should be used. This corresponds roughly to fine-filters of at least class F6 or preferably class F7 according to the European standard, EN 779. Furthermore, they claimed that the lower efficiency filters used commonly in today's HVAC systems decrease indoor concentrations of fine particles only marginally, while increasing the fine-filter efficiency above 85 % results in only modest incremental reductions in indoor particle concentrations. If this statement holds, it would be of little marginal benefit to install a filter of class F9 instead of F7. The main effect could actually be the drawback of a substantially increased pressure drop.

Portable fan-filter units do not necessarily need to be equipped with high efficiency particulate air (HEPA) filters, as is rather common today. To decrease the costs, energy consumption and noise generation without significantly sacrificing particle control performance, such units could instead be manufactured with lower efficiency filters e.g. with an 85 % Dust Spot Efficiency. Similar conclusions were derived in other studies (Burroughs, 2005; Lam et al., 2006). Increasing the airflow rate through the fan-filter unit must then compensate for the lower filtration efficiency of such filters, compared to the efficiency of HEPA-filters. However, a common conclusion of these and similar studies is that although more efficient filters have higher energy penalties and total costs, these tend to be negligible relative to salaries, rent, health insurance cost and reduced failures in telephone switching and computing equipment.

One factor that has been neglected in previous economic evaluation of filtration is the potential release of sensory pollutants from used filters (Beko et al., 2007). Loaded filters have been found to be a serious source of sensory pollutants and to have a negative impact on sick building syndrome symptoms and occupant performance (Beko et al., 2006). Beko et al. (2007) studied sensory pollution of various combinations of bag filters and carbon filters with very positive results. However, further research is needed to confirm the results. Used filters must be replaced sufficiently frequent, not only by concern for the air quality, but also in order to reduce the pressure drop, and consequently the use of energy for fans. For example, the Finnish indoor climate guidelines recommend that filters exposed to outdoor air (pre-filters) be replaced every 6 months, and filters exposed to air that has been pre-filtered every 12 months.

Filtration – Gaseous materials

Gas-phase air filters remove gases and odours by using a sorbent, to adsorb the pollutants. Activated carbon is the most common adsorbent. Alternatives are activated aluminum, silica gel, zeolites, organic synthetics etc. (Spry, 2007). A variety of gases and vapours are sorbed onto surfaces and into pores of solid media, with or without chemical reaction. A variety of VOCs can be sorbed but the process is typically not efficient for low molecular weight constituents and permanent gases (Daniels, 2007). However, reactive gases, e.g. nitrogen dioxide, may be captured with high efficiency if the adsorption filter has been impregnated with a suitable substance. Thus, gas-phase filters are typically specific to one or a limited number of gaseous pollutants; they will not reduce concentrations of pollutants for which they are not designed. Some air cleaning devices with gas-phase filters may remove a portion of the gaseous pollutants and some of the related hazards, at least on a temporary basis. However, none can be expected to remove all of the gaseous pollutants present in the air of a typical home or office (Muller and England, 1995). For example, carbon monoxide is a dangerous gaseous pollutant that is produced whenever fuel such as gas, oil, kerosene, wood, or charcoal is burned, and it is not readily captured using currently available residential gas-phase filtration products (USEPA, 2007).

Electrostatic precipitation

Electrostatic precipitators (ESPs) are the most common type of electric air cleaners based on electrostatic attraction to trap charged particles. Air is drawn through an ionization section where particles obtain an electrical charge. They employ a one-stage or two-stage design for particle collection. In the less expensive but also less effective single-stage design, a charged medium acts to both charge and collect airborne particles. A two-stage design employs a high voltage electrode or wire, which places a charge on the incoming airborne particles. In the second stage the charged particles are drawn between a series of oppositely charged metal plates, which attract the charged particles from the air causing them to precipitate onto the metal plates. Charged particles passing through the collection section of the equipment, and consequently supplied to the indoor air, are sometimes deemed as a potential health risk.

Bipolar air ionization

Ion generators or ionizers disperse charged ions into the air, i.e. produce local clusters of positive, negative or bipolar (±) ions. Clustered ions then electrically charge airborne particles so that they attach to nearby surfaces such as walls or furniture, attach to one another and settle faster. Furthermore, the removal by filtration may be facilitated if the particles are charged. Cluster ions are sometimes claimed to also chemically react with and destroy VOCs (Daniels, 2002; USEPA, 2007). Air ionizers are distinct from both electrostatic precipitators and ozone generators. In air ionization, PMx is electrically charged through direct contact with bipolar air ions. However, there is a risk of ozone generation both from electrostatic precipitators and air ionizers. In a recent extensive literature review of air ionization devices it has been noted that no firm conclusions can be drawn about positive or negative effects of air ionizers on sick building syndrome symptoms (Siegel et al., 2006). Ozone generation by these devices is an issue although generation rates are considerably lower than from dedicated ozone generators. Several studies found that even weak ozone generating air ionizers are capable of maintaining steady-state levels of ozone in small rooms with nonreactive surfaces that are well in excess of the health-protective standards (Britigan et al., 2006).

Ozone generation

Ozone generators use UV light or electrical discharge to intentionally produce ozone (USEPA, 2007). Ozone (referred to as trivalent oxygen or saturated oxygen by some manufacturers) has been used in water purification since 1893. Introducing ozone into the air stream can have beneficial effects under controlled conditions were humans are not exposed. However, ozone is of concern when considering spaces for human occupancy (ALA, 1997). All reviewed literature does not recommend use of ozone generators as air cleaning device. One further health risk from ozone generators is the potential for formation of ultrafine particles when these devices are operated in the presence of terpenes, which has also been pointed out by (Siegel et al., 2006). Similar conclusions about formation of fine and ultrafine particles in presence of common unsaturated VOCs have been drawn in another study (Alshawa et al., 2007).

Photcatalytic oxidation

Photocatalytic oxidation (PCO) is a process where a semiconductor upon adsorption of a photon, acts as a catalyst in producing reactive radicals, mainly hydroxyl radicals, which in turn can oxidize organic compounds and mineralize them. In this way organic molecules are decomposed to form carbon dioxide, water and mineral acids as final products (Goswami, 2003). In the PCO reaction, pure or doped metal oxide semiconductors (e.g., TiO2, ZNO, CdS, Fe(III)-doped TiO_2) are commonly used as the photocatlysts. PCO reaction with TiO_2, which is the most common catalyst, have been described by (Goswami, 2003; Zhao and

Yang, 2003). Both, hydroxyl free radical (·OH) and superoxide anion radical ($\cdot O_2^-$) are highly reactive species that oxidize VOCs. However, the hydroxyl free radical is the most reactive of all reactive oxygen species (ROS) and is the primary oxidant in PCO reaction. Utilizing PCO to remove trace-level organic compounds in air has recently received considerable attention since this technology has a potential to be applied for air purification in office buildings, factories, homes, cars and spacecraft. A number of research groups are currently evaluating the applicability of novel air cleaning technologies including PCO (works at NIST, LBNL, NCEMBT, PenState University and others). Several detailed reviews of PCO have been done, (Daniels, 2007; Zhao and Yang, 2003). Overall conclusion of the reviews is that PCO with TiO_2 as catalyst and UV light is a promising technology that is self-regenerating and potentially cost effective. The performance of a PCO prototype and commercialized systems were considered for destruction of individual VOCs and mixtures of VOCs (Goswami, 2003; Hodgson et al., 2007; Jo et al., 2002; Pershin et al., 2004; Sun et al., 2006). Reported VOC conversion efficiencies varied widely, from 20 % to almost 100 %. Efficiencies in the higher end of this range were reported when the PCO devices were exposed to individual VOCs. Hodgson et al. (2007) concluded that for a prototype device evaluated with realistic mixtures of VOCs, conversion efficiencies typically exceeded the minimum required to counteract the VOC concentration increase predicted to arise from a 50 % reduction of the ventilation air flow rate. However, the device resulted in a net generation of formaldehyde and acetaldehyde from the partial oxidation of ubiquitous VOCs. Other studies done with mixtures of VOCs reported similar by-products due to incomplete oxidation. Models have been developed for PCO (Baturov et al., 2005; Mo et al., 2005). Different operating conditions and physical parameters of PCO design on conversion efficiency have been studied experimentally and mathematically (Mo et al., 2005; Yang and Wang, 2006).

DISCUSSION

The mechanical fiber filter technology is well established and standardized and works well for particulate matter. The replacement frequency is of crucial importance since impaired perceived air quality and excessively high pressure drops will be the result if the filters are not replaced regularly. One important issue, not frequently addressed, is the effect of unfiltered air leaking through the filter/filter housing interface. For example it was shown that the performance of a MERV 15 (F9) filter with large gap (10 mm) only equaled that of a MERV 8 (G4) filter with no gap (Ward and Siegel, 2005).

Gas-phase air filters are very effective for removal of a variety of gases, vapours and odours if appropriate types and amounts of sorbents are used. This may impose quite a high pressure drop. Again, the filter replacement interval is of major importance: -there is generally no possibility to get any indication about when the adsorption filter has become saturated and should be replaced.

Electrostatic precipitators can be very effective for particle removal at pressure drops much lower compared to fiber filters. However, the risk of ozone generation is a serious disadvantage.

Air ionization is an inconclusive technology regarding indoor air quality. As with electrostatic precipitators ozone generation is a serious issue.

Ozone generators produce excessively high concentrations of ozone. Valid objections have been raised to this technique based on ozone toxicity and secondary reactions of ozone with specific types of indoor pollutants. Thus, ozone generators are not of interest for cleaning in environments for human occupancy.

UV-photocatalityc oxidation appears to be a promising air cleaning technology. Recent studies have proven high conversion efficiencies for VOCs at a low pressure drop. There are sound examples of implemented hybrid air cleaning systems which resulted in substantial energy savings and improved indoor environmental quality (Johnson, 2006; Muller, 2006). In these practical applications the ventilation rates were designed using the IAQ procedure from ASHRAE 62.1-2004 standard. The project by Johnson (2006) was awarded 2006 ASHRAE Technology Award. This procedure, as opposed to the ventilation rate procedure (VRP) allows the amount of outside air to be reduced, if compensated for by the use of air filtration and air recirculation. It also allows for direct control of indoor air contaminants, e.g. by the use of room air cleaners, which is not possible under the VRP. Using the ventilation rate as a measure of IAQ is as primitive as it would be to relate human thermal comfort to the supply of cooling power to a space, rather than to the temperature in the space (Fanger, 2004). Unfortunately, European standards have no alternative to the VRP.

CONLUSIONS

Optimized air cleaning systems, capable of addressing both particles and gases would probably include two or more technologies making use of the advantageous characteristics of each employed technology. In order to clear the market from inferior and even hazardous air cleaning equipment, development of standards for alternative air cleaning technologies should be highly prioritized.

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