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Indoor Air Quality Management by Combined Ventilation and Air Cleaning: An Experimental Study

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ABSTRACT

A combination of ventilation and air cleaning regimes were investigated for the removal of aerosol particles and volatile organic compounds (VOCs) in a test chamber, representing a typical room. A series of portable multi-staged air cleaner efficiency tests were performed examining tobacco smoke as a source of pollution. Portable indoor air cleaners were effective in removing of particles, reaching up to 97% removal efficiency based on particle number concentrations after 30 minutes, while Clean Air Delivery Rate ($CADR_{PNC}$) varied from 37 ± 4 to 237 ± 11 m^3 h^{-1}. The removal of VOCs varied from 21.4 to 45.7% and $CADR_{VOC}$ ranged from 2.2 ± 0.3 to 29.9 ± 2.8 m^3 h^{-1}, indicating substantially lower efficiency. The combination of ventilation and air cleaning provided different responses with respect to pollutant removal and energy efficiency. The air cleaning was the most efficient for removing particulate matter from indoor air, minimizing the requirement for ventilation. On the other hand, the ventilation seemed to be more efficient in the removal of VOCs, while the combination of ventilation and air cleaning increased pollutant removal efficiency by 20% and maximized the energy efficiency.

Keywords: Indoor air quality; Air cleaning; Ventilation; Particulate matter; Volatile organic compounds.

INTRODUCTION

Indoor air quality (IAQ) is among the most important factors affecting indoor climate. The IAQ is mostly affected by air pollution sources indoors and outdoors. Common indoor air pollution sources are smoking, candle and incense burning, household cleaning activities, cooking, furnishing, printers, building materials, and other electronic devices (He *et al.*, 2004; Afshari *et al.*, 2005; Hussein *et al.*, 2006; Gehin *et al.*, 2008; Ciuzas *et al.*, 2015). Air pollution has been associated with a wide variety of health effects (Bernstein *et al.*, 2008; Ruckerl *et al.*, 2011); furthermore, urban particulate matter (PM) has been indicated as a health threat at even low levels (Anderson, 2009). Pollution can also be generated when outdoor air from ventilation mixes with indoor air or comes in contact with surfaces inside, such as ozone reaction with terpenes from detergents or plastics (Wolkoff and Nielsen, 2001).

Due to the improved insulation of homes and subsequently lowered ventilation, the air quality may deteriorate. The influence of indoor sources on IAQ can be reduced by increasing ventilation rate. However, ventilation is often costly due to the heating or cooling needs; it also supplies pollutants from outdoors. Ventilation is characterized by the air change rate (h^{-1}), which shows how many times the air inside a defined space (room, house, or facility) is being replaced by outside air within one hour. Typical air change rates measured in houses in US were found in a range of 0.5–2.2 h^{-1} varying with room type and season (Du *et al.*, 2012). Ventilation rates greater than 4 h^{-1} are usually avoided in residential environments (Yamamoto *et al.*, 2010).

Another way of removing pollutants from indoor air is air cleaning. This form of pollution control is widely applied to reduce PM and selected gaseous phase pollutants (primarily of organic origin) generated by industrial and residential sources. There are numerous technologies used in such devices including filtration, electrostatic precipitation, ion generation, pulsed discharge plasma combined with photo-catalyst, etc. (Chen *et al.*, 2005; Grinshpun *et al.*, 2005; Shiue *et al.*, 2011; Kim *et al.*, 2012). Portable air cleaners have been used in indoor environments to remove smoke from tobacco, wood stoves and fireplaces, VOCs from cleaning products, personal care products, and new furniture (Shaughnessy and Sextro, 2006; Zhang *et al.*, 2011; Jung *et al.*, 2013). Portable air cleaners are popular air cleaning devices that are used in 10–30% of American homes (Shaughnessy and Sextro, 2006).

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Hence, air cleaners are looked at as not the replacement for ventilation, but rather a supplement.

The comparison of the air cleaners is performed based on the specific standards and metrics that allow uniform evaluation. One such metric is the clean air delivery rate (CADR), which is the effective volumetric flow rate of pollutant free air delivered by the air cleaners. The CADR is considered as the best available metric to compare portable air cleaners because it takes into account the flow rate through the air cleaner, the volume of the test room, and the pollutant removal efficiency (Shaughnessy and Sextro, 2006). In case of particles, the CADR was found around 40 m^3 h^{-1} for an ion generator, 70 m^3 h^{-1} for an electrostatic precipitator, and ranging from 100 to almost 300 m^3 h^{-1} for the three filter-based air cleaners for particles with diameters above 100 nm (Mølgaard *et al.*, 2014). At the same time, portable air cleaners are much less efficient in removing organic compounds from indoor air. For example, Kim *et al.* (2012) examined the gas-removal performance of 18 room air cleaners and determined CADR ranging from 6 (acetaldehyde) to 72 m^3 h^{-1} (toluene), with removal efficiency ranging from 20 to 90%, respectively. Chen *et al.* (2005) examined the gas-removal performance of 15 room air cleaners and determined CADR ranging from 0.3 (dichloromethane) to 129 m^3 h^{-1} (1.2-dichlorobenzene), with removal efficiency ranging from 0.1 to 43%, respectively.

The ventilation and air cleaning/purification have been proven as effective ways of reducing occupant exposure to indoor contaminants and improving IAQ. At the same time, the data on the combination of both of these technologies are sparse. It has been shown that the performance of air cleaner strongly depends on the air change rate provided by the ventilation (Cheng *et al.*, 1998; Green *et al.*, 1999; Fisk *et al.*, 2002). A recent study on the combination of air cleaners and ventilation in office buildings has suggested that the optimized combination/trade-off between ventilation and air cleaning may depend on the dynamics of climate conditions, outdoor air quality and indoor occupant pattern (Han *et al.*, 2014).

The ventilation is irreplaceable in cases of spaces occupied by large amounts of occupants. However, air cleaning should be considered in premises with low occupancy but increased particle or VOC emissions, especially if outside air is of unsatisfactory quality. The goal of this study was to assess the effect of combined ventilation and air cleaning on pollutant removal in a chamber, representing a typical room equipped with the forced ventilation and several multistage portable air cleaners. The data obtained in the study is discussed from the point of managing the IAQ.

METHODS

Test Chamber and a Source of Pollutants

The experiment was conducted in a test chamber representing a typical room with a floor area of 13 m^2 and a volume of 35.8 m^3, which was installed in 150 m^3 laboratory premises. Fig. 1 shows the schematic diagram of the experimental setup. Walls, floor, and ceiling of the chamber were fabricated using conventional construction materials, such as painted dry-wall, PVC floor lining, and a panel ceiling. The test chamber had one door and one window (broader descriptions are provided in Jurelionis *et al.* (2015)).

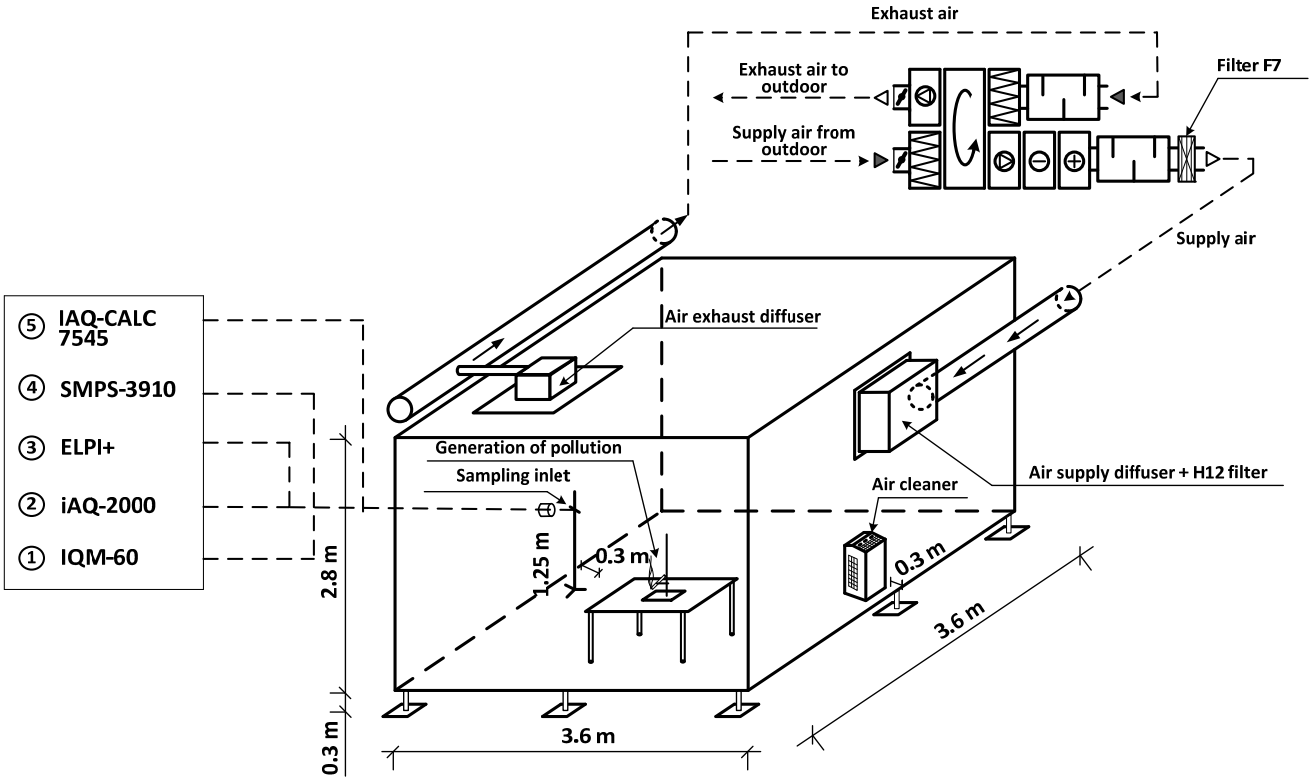

Fig. 1. Test chamber with air supply and exhaust system via air handling unit with heat exchanger.

Sampling probes were positioned in the breathing zone of a seated person, 1.25 m above the floor adjacent to the opposite wall of an air cleaner.

Cigarette smoke was utilized as a surrogate source of air pollutants. It is a well-known indoor air pollutant with adverse health effects, therefore used in air cleaner testing standards (JEMA, 1995; AHAM, 2006). Cigarette smoke contains aerosol particles and VOCs (including acetone, 2,3-butanedione, 2-butanone, benzene, ethylbenzene, styrene, toluene, etc. (Polzin *et al.*, 2007)), making it suitable for co-testing air cleaner performance both on solid and gaseous phase pollutants. A cigarette having a declared yield of nicotine (0.5 mg), tar (6 mg), and CO (7 mg) was placed in a holder on a table inside the chamber and burned for about 10 min. Background air quality was monitored for three minutes before the start of each experiment. The variation of pollutant concentrations due to the ventilation and air cleaning was monitored for 90 minutes. The experiments included the variation of pollutant concentration only due to cigarette smoke itself. In real-life environments, the activities of residents could cause either resuspension of indoor deposited coarse particle or delay in the deposition process, which would have affected the performance of the readings. The flow of the chamber was mopped after each day of experiments with cleanser free water. It has been shown that wet mopping may not fully remove particles from floor surfaces (Hunt *et al.*, 2006), but we expect that the resuspension of these were insignificant due to restricted movement of humans in the chamber.

Ventilation

The ventilation process represented a single-pass filtered outdoor air, supplied and exhausted via the air handling unit (GOLD 04, Swegon AB, Sweden). During the experiments the supply air temperature was set to +20°C. The temperature and relative humidity of the air ranged between 18–19°C and 38–49% in the chamber during the experiments, respectively. Low concentration of particles in the supply air was ensured using a F7 class (adequate to MERV13) filter (constructed inside the handling unit) and subsequently a high efficiency particulate air filter (HEPA 12, General Filter, Italy) installed at the supply diffuser mounted in the wall close to the ceiling (Fig. 1). The gaseous organic pollutants were removed by fixed active carbon bed. Air was exhausted through a single port located in the ceiling in the opposite side of the chamber.

Air change rate inside of the chamber was checked before and after of each experiment via the duct air velocity measurements. Additionally, the air change rate was verified using CO_2 tracer gas decay method (ASTM, 2000) by CO_2 meter (7545 IAQ-CALC, TSI Inc., USA).

Air Cleaning

Air cleaning process was represented by multi-pass air treatment by portable air cleaners. Three commercially available air cleaners (C1, C2, and C3, Table 1) have been tested in this study. All units were designed to serve for similar areas (46–48 m^2) and were rather equally priced. All units operated a fan to draw the air through a combination of particle phase and gaseous phase pollutant removing stages. The first cleaner (C1) passed the air through three filters (a pre filter, a washable activated carbon filter, and a HEPA 13 - equivalent filter), followed by "Plasmacluster ion technology", which is declared to deactivate the suspended airborne bioaerosol and decompose odour molecules. The C2 had a complex set of six-stage pollutant removal sections, including streamer discharge unit, pre filter, plasma ionizer, electrostatic filter, titanium apatite (photo catalyst), and deodorising catalyst filters. The C3 passed the air through a "micro filter" (removing particles > 0.4 μm), oxygen-activating module (ozone based), and a catalyst.

Air cleaners were placed inside the test chamber in accordance with the air cleaner installation guidelines, i.e., on a floor below air supply diffusers. The air cleaning was activated at the same time as the source of pollution.

Indoor Air Quality Indicators and Monitors

The following physical and chemical parameters of indoor air were selected as proxy parameters to represent the efficiency of ventilation and air cleaners: particle number concentration (PNC) and concentration of VOCs. Table 2 summarizes IAQ indicators measured in this study.

The size-resolved decay of PNC was measured using a Scanning Mobility Particle Sizer (SMPS 3910, TSI Inc., USA) and Electric Low Pressure Impactor (ELPI+, Dekati Inc., Finland). The SMPS scanned across 13 size bins from 10 to 420 nm (further referred as fine particle range) of electrical mobility diameter during 60 s, or was used as a counter for single size mode at 1 s resolution, with the flow

Table 1. Specifications of the tested air cleaners as provided by the manufacturers.

Device	Manufacturer	Model	Dimension, mm	Approx. Price, €	Applicable area, m^2	Technology
C1	Sharp Corporation, Japan	KC-A60	643 H × 416 W × 295 D	500	48	Pre filter, washable activated carbon filter, HEPA 13 filter, "Plasmacluster technology".
C2	Daikin, Japan	MC70L	576 H × 403 W × 241 D	575	46	Streamer discharge, pre filter, plasma ionizer, electrostatic dust collection filter, titanium apatite filter, deodorising catalyst filter.
C3	Zepter International, Germany	Therapy Air	400 H × 515 W ×140 D	575	46	Pre filter, "micro filter", oxygen activating module, catalyst.

Table 2. Summary of measured IAQ indicators.

Indicator	Units	Accuracy	Time resolution	Monitor	Measurement method
Particulate matter					
Fine particles (0.01–0.4 μm) –number concentration	particles cm^{-3}	N/A	60 s	SMPS Model 3910, TSI Inc, USA	Radial differential mobility analyser and isopropanol-based condensation particle counter
Fine and coarse particles (15 fractions 0.006–10.0 μm) –number concentration	particles cm^{-3}	N/A	1 s	ELPI+ Dekati Inc., Finland	Low pressure multi stage impactor with real time sensing via electrometers
Gaseous compounds					
Total VOC	ppm	PID < ± 10% NMHC < ± 10%	120 s	IQM-60 Aeroqual Ltd, New Zealand	Photo-ionization detector, metal oxide semiconductor sensor
Total VOC	ppm	N/A	1 s	iQM-2000, ams AG, Germany	Metal oxide semiconductor sensor
O_3	ppm	< ± 0.005 ppm	120 s	IQM-60 Aeroqual Ltd, New Zealand	Metal oxide semiconductor sensor
CO_2	ppm	± 3% of reading or ± 50 ppm	1 s	IAQ-CALC 7545 TSI Inc, USA	Non-dispersive infra-red sensor

rate of 1 L min^{-1}. ELPI+ divided aerosol particles to 15 fractions (0.006–10.0 μm) sampling at a flow rate of 10 L min^{-1}. This instrument utilizes the cascade impaction principle and also has a direct-reading capability. Aerosol samples were collected on 25 mm diameter aluminium foil substrates covered with Apiezon L grease. Real-time concentrations of aerosol samples were registered in one-second intervals. Aerodynamic diameter data obtained by ELPI+ was converted to mobility diameter using cigarette smoke density of 1180 ± 113 kg m^{-3} (Khlystov *et al.*, 2004; Johnson *et al.*, 2014).

The concentration of total gaseous organic compounds was measured using several instruments operating photo ionization detector (PID) and metal oxide semiconductor (MOS) sensor. These technologies are some of the most wide spread currently for measurement of real-time total organic compound concentration, although having some differences in the responses to various substances, selectivity, and accuracy. The IQM-60 monitor (Aeroqual Limited, New Zealand) detected VOCs via PID and MOS sensor (the latter referred to as gas sensitive semiconductor (GSS) sensor by the manufacturer). IQM-60 provides concentration readings in ppm of VOC concentration based on the calibration isobutylene with every 120 seconds. The measurement range was 0–20 ppm for PID and 0–25 ppm from MOS, and detection limit 0.01 ppm and 0.1 ppm, respectively. IQM-60 also measured ozone at a measurement range of 0–0.5 ppm for O_3 and detection limit 0.001 ppm. With the aim to obtain higher temporal resolution, another MOS sensor (iAQ2000, AMS AG, Germany), measuring every 1 second, was co-located. The quantitative response of this sensor was expressed as CO_2 - equivalent ppm values (Herberger *et al.*, 2010).

The CO_2 monitor (7545 IAQ-CALC) and the VOC sensor (iAQ-2000) together with temperature and relative humidity sensors (PT907, Pace Scientific, USA) were installed inside the chamber, approx. 1.25 m above the floor. The IQM-60 and PM monitors were positioned outside the chamber and the air samples have been delivered via 0.5 m long Tygon tubes of 6 mm in diameter. Obtained results were adjusted for diffusion losses, which ranged from 3% (particle size 0.01 μm) to < 1% (0.1–0.3 μm) (Baron and Willeke, 2001). The electricity consumption of the air cleaners was monitored using an energy meter (EL-EPM02HQ, Nedis B.V, Netherlands).

Experiment Design and Data Analysis

The study was designed as two-phase experiment. During the first phase three portable air cleaners were characterized in the test chamber under the minimum ventilation conditions according to their flow rate (min and max modes), particle and VOC removal efficiency (E_{PNC} and E_{VOC}), CADR based on particle and VOC concentration decay ($CADR_{PNC}$ and $CADR_{VOC}$), power draw, and energy efficiency performance index (EEI_{PNC} and EEI_{VOC}). All experiments were repeated three times to obtain an estimate of a random error.

During the second phase, the combined effects of ventilation and air cleaning to the air quality were analysed in a frame of controlled experiment, designed and fitted to

regression models by the aid of a software package (Modde 10, MKS Umetrics, Sweden). Experimental variables included ventilation intensity (0.2 h^{-1}; 0.6 h^{-1}; 1.0 h^{-1}) and air cleaning device regime (min and max modes) expressed as relative air changes per hour (h^{-1}), i.e., cleaner flowrate divided by the chamber volume. Full factorial experiment with three middle points was conducted. Twenty two experiments were performed experimentally to obtain the response parameters, including the concentration decay rate (k), $CADR_{PNC}$, $CADR_{VOC}$, E_{PNC}, E_{VOC}, EEI_{PNC}, and EEI_{VOC}. The experimental data was then fitted to the partial least squares regression model in order to obtain polynomial function based response surface plots, relating experimental variables and responses.

The concentration decay rate was calculated following a first-order decay model:

$$C_t = C_0 e^{-kt} \quad (1)$$

where C_t is the concentration at time t (particles cm^{-3} or ppm), C_0 is the initial concentration at t = 0 (particles cm^{-3} or ppm), k is the concentration decay rate (h^{-1}), t is the time (h).

The pollutant removal efficiency was calculated as follows (JEMA, 1995; KACA, 2006):

$$E_P = (1 - C_t/C_0) \times 100 \quad (2)$$

where E_P is the pollutant removal efficiency (%, further represented as E_{PNC} and E_{VOC}), C_0 is the initial concentration at t = 0 (particles cm^{-3} or ppm), C_t is the concentration at time t = 0.5 h (particles cm^{-3} or ppm).

The CADR was calculated using method by AHAM (2006), additionally subtracting concentration decay due to pollutant loss in the chamber:

$$CADR_P = V(k_e - k_n - k_c) \quad (3)$$

where $CADR_P$ is the clean air delivery rate (m^3 h^{-1}) for a certain pollutant (further represented as $CADR_{PNC}$ and $CADR_{VOC}$), V is the volume of the chamber (m^3), k_e is the total decay rate, including both cleaner and ventilation (h^{-1}), k_n is the natural decay rate, including only ventilation (h^{-1}), k_c is decay rate of the pollutant concentration, reflecting loss of pollutants due to deposition or adsorption (h^{-1}), which was indicated as an important parameter by (Mølgaard *et al.*, 2014).

The CADR was based on the concentration decay slopes with R^2 value above 0.97 derived from 30 data points (0.5 h of decay). CADR was calculated for particles up to 1.2 μm, since the cigarette smoke did not generate sufficient amount (> 100 particles cm^{-3}) of larger particles.

It must be pointed out that the chamber in which experiments were performed did not meet standardized requirements for the chamber volume and surfaces. Air cleaner testing was performed using additional air mixing with a fan, while combined ventilation and air cleaning experiments were performed with both full mixing and no additional mixing. It was found that there was a good agreement between well-mixed and no mixing conditions (Fig. S1), possibly due to a fact that air cleaners provide substantial air flow to facilitate mixing of pollutants in the room.

The EEI was calculated based on the electrical power draw for both air handling unit and air cleaners. The power draw of air cleaners was directly measured, while that of the air handling unit was estimated based on the operating time, flow rate and a specific fan-power of 2 $kWsm^{-3}$ for the ventilation with a heat recovery (Nilsson, 1995). The EEI was computed by the following equation:

$$EEI_P = CADR_P / OP \quad (4)$$

where EEI_P is the energy efficiency performance index for a certain pollutant (further represented as EEI_{PNC} and EEI_{VOC}), $CADR_P$ is the clean air delivery rate (m^3 h^{-1}), OP is the electrical operating power of the air cleaner (W).

Data analysis was performed using SSPS 13 (IBM Corp., USA) and Origin 9 (OriginLab Corp., USA) software packages. Every experimental result was reported as the average with the corresponding standard deviation provided where appropriate.

RESULTS AND DISCUSSION

Characterization of Portable Air Cleaners

The particle size distribution (PNC during peak) as generated by a cigarette smoke within a chamber is presented in Fig. 2. Ultrafine particles (0.01–0.42 μm as measured by SMPS) were dominant (dN/dlogDp ranged from ~10^4 to 10^5 cm^{-3}), while larger particles (0.62–2.4 μm as measured by ELPI+) were present at lower concentration levels (~10^2–10^3 particles cm^{-3}). The maximum concentration reached in the chamber was 2.2 × 10^5 particles cm^{-3} as measured by SMPS. Generally, the particle size distribution was obtained similar to earlier studies researching a cigarette smoke (Daher *et al.*, 2010; Wu *et al.*, 2011). Particle size distributions measured by ELPI+ and SMPS were in close agreement, after converting aerodynamic diameter to the mobility diameter, even though these instruments measure different physical

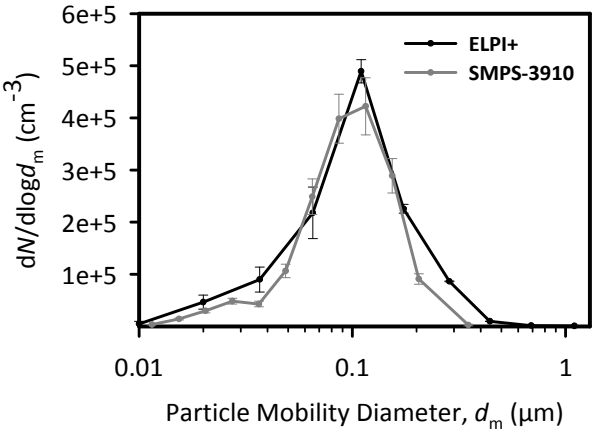

Fig. 2. The initial particle size distribution of cigarette smoke. Error bars represent the standard deviations of three replicates (dN/dlogd_m, particles cm^{-3}).

properties. It must be noticed that Nanoscan SMPS has been found to yield error in the range of 0.55–0.97 as compared to a more robust SMPS, attributed to different particle charging technique (Stabile *et al.*, 2014).

Table 3 lists the main parameters (both declared by the manufacturer and measured ones) of the three air cleaners, including the electrical power draw, air flow rates, $CADR_{PNC}$, $CADR_{VOC}$, E_{PNC}, E_{VOC}, EEI_{PNC}, and EEI_{VOC}.

The air cleaners revealed a relatively large range of measured power draw, i.e., it varied between 6.2 (C1) and 34.7 W (C3) at low setting and from 15.5 (C1) to 109.1 W (C2) at high setting. The power draw did not directly correlate with flowrate among the devices, which varied between 75 (C3) and 126 m^3 h^{-1} (C2) at low setting and between 120 (C3) and 276 m^3 h^{-1} (C1) at high setting. Different power requirements seemed to be associated with the efficiency of VOC removal, as discussed below. Based on these technical parameters, the tested cleaners were comparable to those used in earlier studies (Shaughnessy and Sextro, 2006; Waring *et al.*, 2008; Mølgaard *et al.*, 2014; Noh and Oh, 2015).

$CADR_{PNC}$ also ranged widely among the devices and was significantly lower than the air flow rate. The C1 device was the most effective for particle removal ($CADR_{PNC}$ ranging from 77 ± 5 to 237 ± 11 m^3 h^{-1}). This was supported by high efficiency (E) values (78–97.2%). At the same time, the C3 device was least efficient in particle removal (CADR between 37 ± 4 and 69 ± 9 m^3 h^{-1}, E between 53.8 and 73.7%). The ratio CADR/Flowrate ranged between 0.49 and 0.85. The CADR and E values for particles were found directly proportional to the air flow rate, with the Spearman rank order coefficient of correlation (r) equalling to 0.83 ($p < 0.05$). At the same time, the $CADR_{PNC}$ was not associated with the power draw, reflecting no association between power draw and flowrate, as mentioned above. The particle removal efficiency was associated with the effectiveness of the installed filter. Only C1 device has declared the presence of HEPA class (13) filter, while other devices did not, and this seemed to have a major effect. On the other hand, the C1 device revealed the discrepancy between flowrate and CADR, considering a very high efficiency of the filter installed. It is not likely that the filter was worn out, since the tested units were new with only several hours of operation. The efficiency of the filter may have been lower than declared, or possibly there might have been a leakage within the unit. At the same time, portable air cleaners were able to reach relatively high particle removal rates in a relatively short period of time (0.5 h from the measured PNC peak value).

The CADR is almost particle size independent in the diameter range from 0.01 to 1.1 μm for cleaners operating at low and max mode (Fig. 3). This is expected because they all draw the air to the filtering system with a relatively high filtration efficiency across all particle sizes. Some increase in CADR was noticed in a sub 0.1 μm range for C1 and C3, at low mode as measured with SMPS, possibly reflecting increased collection efficiency in small particles. The C1 and C2 operating on the max mode had the highest CADR, with increasing CADR values and particle size. CADR values derived from both ELPI+ and SMPS were

Table 3. Operating modes, operating power (OP), air flow rates, clean air delivery rate (CADR), pollutant removal efficiency (E), and energy efficiency index (EEI) of the tested air cleaners (SD - standard deviation).

Device	Setting	OP[a], W	OP[b], W	Air flow rate[a], m^3 h^{-1}	Air flow rate[b] ± SD, m^3 h^{-1}	CADR[a], m^3 h^{-1}	$CADR_{PNC}$[b] ± SD[a], m^3 h^{-1}	$CADR_{VOC}$[b] ± SD[a], m^3 h^{-1}	E_{PNC}[b] ± SD[a], %	E_{VOC}[b] ± SD[a], %	EEI_{PNC}[b], m^3 h^{-1} W^{-1}	EEI_{VOC}[b], m^3 h^{-1} W^{-1}
C1	LOW	~5.3	6.2	94	97 ± 1.7	Dust 230	77 ± 5	2.6 ± 0.4	78.0 ± 1.4	21.4 ± 2.7	14.53	0.49
	MAX	~22	22.8	270	276 ± 3.2	Smoke 224 Pollen 245	237 ± 11	7.6 ± 1.4	97.2 ± 2.2	33.1 ± 4.9	10.72	0.34
C2	LOW	~10	9.6	130	126 ± 1.2	N/A	106 ± 8	2.2 ± 0.3	81.5 ± 1.6	30.7 ± 2.7	14.58	0.99
	MAX	~16	15.5	210	204 ± 2.4	N/A	153 ± 7	8.2 ± 1.7	90.2 ± 1.8	36.2 ± 5.1	15.62	1.1
C3	LOW	~35	34.7	N/A	75 ± 1.5	~40 m^3 h^{-1}	37 ± 4	11.2 ± 1.1	53.8 ± 0.9	38.8 ± 4.3	1.05	0.31
	MAX	~100	109	N/A	120 ± 2.8	~82 m^3 h^{-1}	69 ± 9	19.9 ± 2.8	73.7 ± 1.9	45.7 ± 6.4	0.64	0.19

[a] Manufacturer information.
[b] Measured.

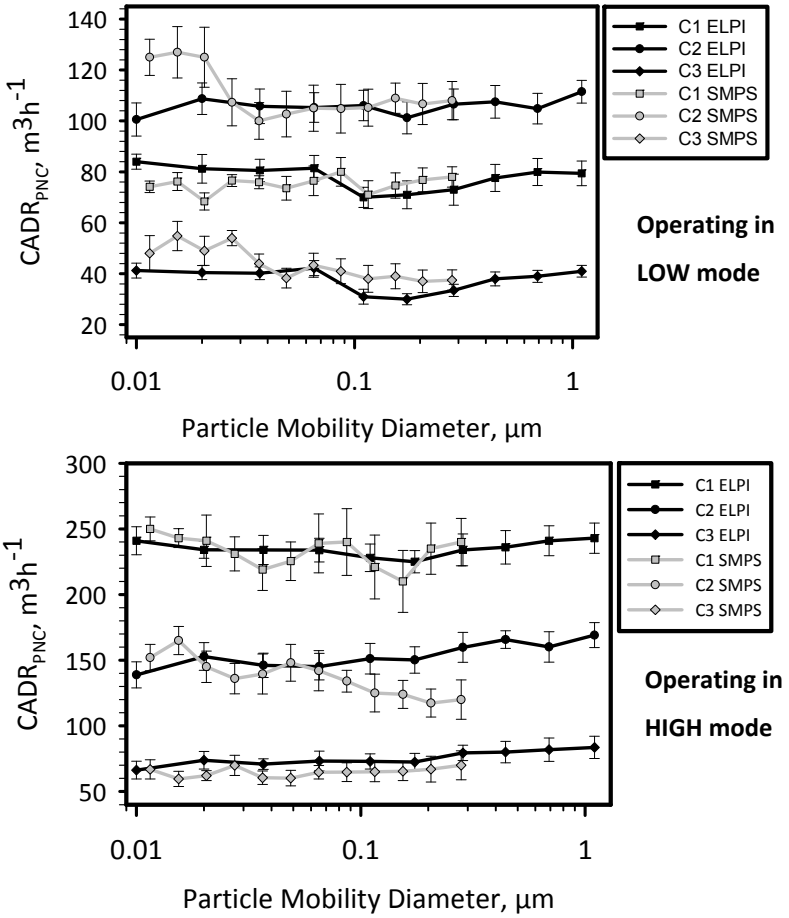

Fig. 3. $CADR_{PNC}$ as a function of particle diameter in case of three tested air cleaners (C1, C2, and C3) derived from measurements by ELPI+ and SPMS (Nanoscan). Error bars represent the standard deviation of the CADR for each size bin.

mostly within a margin of error. The values of CADR against particle sizes were of similar magnitude as recently reported by Mølgaard *et al.* (2014).

The VOC removal efficiency as reflected by CADR and E was substantially lower, compared to the particle removal efficiency. The cleaner C1 was the least efficient ($CADR_{VOC}$ ranging from 2.6 ± 0.4 to 7.6 ± 1.4 m^3 h^{-1}, E_{VOC} between 21.4 and 33.1%), while the C3 was the most efficient ($CADR_{VOC}$ ranging from 11.2 ± 1.1 to 19.9 ± 2.8 m^3 h^{-1}, E_{VOC} between 38.8 and 45.7%). The ratio of $CADR_{VOC}$/Flowrate ranged only between 0.02 and 0.16. The $CADR_{VOC}$ and E_{VOC} were not associated with air flow rate but with power draw instead ($r = 0.94$, $p < 0.05$). All three cleaners were based on electrical discharge, implying the decomposition of VOC molecules primarily by ozone. The high decomposition of VOCs may be associated not only with power, but also with the technological arrangements to generate ozone. The configuration of C3 was the most technologically efficient, although associated with a trade-off of higher power requirements. At the same time, the higher power in C3 resulted in efficient decomposition of pollutants, reaching lowest values of the EEI (down to 0.19 m^3 h^{-1} W^{-1}).

Combined Performance of Ventilation and Air Cleaning

This section presents results from the regression modelling of the effects of simultaneous variation of ventilation and air cleaning intensity to the pollutant removal. The modelling results (response surface plots) of pollutant removal against various ventilation rates and portable air cleaner regimes are presented in Fig. 4 (C1), Fig. S2 (C2), and Fig. S3 (C3). These plots provide the prediction in CADR, E, and EEI based on the joint variation of ventilation and cleaning intensity.

Total decay rate (k_e), including both cleaner and ventilation, decay rate (k_0) of the pollutant concentration, reflecting loss of pollutants due to deposition or adsorption and natural decay rate (k_n), including only ventilation are listed in Table S1.

The removal of particles from the indoor air as represented by E_{PNC} was affected by both ventilation and air cleaning. Such phenomenon was valid for all tested devices (Figs. 4(A), S2(A) and S3(A)). The removal of particles seemed to be more affected by the increase in ventilation. For example, the increase in E_{PNC} from 40 to 50% would be achieved by changing ventilation rate from 0.4 to 0.9 h^{-1} with no air cleaner in operation. Same efficiency would be reached by increasing cleaner flow rate from 0.7 to 1.9 h^{-1} with minimum ventilation. The E_{PNC} was at ~55% in case of maximum mechanical air ventilation rate (1 h^{-1}) and with no portable air cleaners operating. In the opposite setting, i.e., at the lowest setting of ventilation (0.2 h^{-1}), the E_{PNC} of 55% may be achieved at the device regime of ~2.5 h^{-1}. While the

ventilation seems to be more efficient, the ranges of its operation in residential buildings are rather constrained and go up to 2 h^{-1} (except of kitchen hoods). Thus, the high E_{PNC} values may not be achieved using the ventilation alone, or would take prolonged periods of time. The cleaners become more efficient at the higher flowrates, producing flows equivalent to –4 h^{-1}. Such flowrates allow achieving efficiencies of 75–90% during 30 min period even at the minimum ventilation. Moreover, the model suggests that at the highest air cleaner flow rates the effect of ventilation gets minimized, as represented by isolines almost perpendicular to abscissa axes (Figs. 4(A), S2(A) and S3(A)).

The $CADR_{PNC}$ appeared to be even less affected by the ventilation compared to the air cleaning (Figs. 4(B), S2(B) and S3(B)). The effect of ventilation was only noticeable only in case of device C3 having the lowest efficiency in particle filtration and the lowest CADR. Similar findings extended to the energy efficiency index for PNC (EEI_{PNC}). The EEI_{PNC} did not depend on the changes in ventilation rate (except C3) but it increased with increasing device flowrate. This was due to the fact that increasing flowrate did not cause a dramatic increase in the energy consumption of the tested devices C1 and C2. The C3 showed the lowest energy efficiency which was comparable to that of ventilation. These findings indicate that in areas where cleaners will primarily be used for the removal of particles, the EEI should be observed while selecting a cleaner; these metrics must be provided by the manufacturers. In cases of particle removal in residential areas the strategy of the lowest ventilation coupled with the highest air cleaner operation rate may yield the best results in terms of particle removal efficiency during the shortest amount of time and the lowest energy consumption.

It must be noted that the above results were obtained using certain configuration of filtering efficiency in single-pass (ventilation) and multi-pass (cleaners) processes. Our ventilation supply was equipped with a very efficient HEPA filter, which is not commonly used in dwellings. The penetration of outdoor particles and particle size distribution in the single-pass process greatly depend on a filter class installed (Azimi *et al.*, 2014), while multi-pass process can compensate on the lower efficiency by providing multiple circulation of air through a filter. Thus, having a filter of a lower efficiency at the air handling unit (such as MERV13) may provide higher impact of air cleaners towards the removal of indoor aerosol. On the other hand, if the efficiency of air cleaner filter is boosted by charging (electret based filtration), it may decrease through the operation span and also decrease the cleaner performance. The removal of VOCs in a chamber appeared to be affected more by the ventilation than the air cleaning, as indicated by horizontal direction of regression lines in surface plots. This corresponds to the air cleaner test results, where all tested cleaners scored relatively low in VOCs removal efficiency. The ventilation rate of 1 h^{-1} alone was able to achieve the E_{VOC} at ~40–45%, while similar efficiency E_{VOC} is achieved at 3.5 h^{-1} of cleaner intensity (at a minimum ventilation, C3, Fig. S3(D)) and ~8–9 h^{-1} (C1 and C2, Figs. 4(D) and S2(D), respectively). The opposite strategy to the particle removal would include using no air cleaning and maximum ventilation. This would allow achieving pollutant removal efficiency of 40–45% in 30 min. Adding air cleaning at the lowest setting would increase removal efficiency by ~5%, while additional air cleaning at the maximum flowrate would result in removal efficiency of ~60% in 30 min.

The $CADR_{VOC}$ curve between the ventilation and air cleaner device regimes is nearly horizontal, showing little impact of air cleaning to the removal of VOCs as compared to the ventilation (Figs. 4(E), S2(E), and S3(E)). Meanwhile, the removal of VOCs by joint ventilation and air cleaning seems to be the most energy-efficient strategy at the maximum mechanical ventilation rate (1 h^{-1}) and maximum device regime, except of the device C3, which was not energy efficient at high flowrates. Similarly to our findings, it has

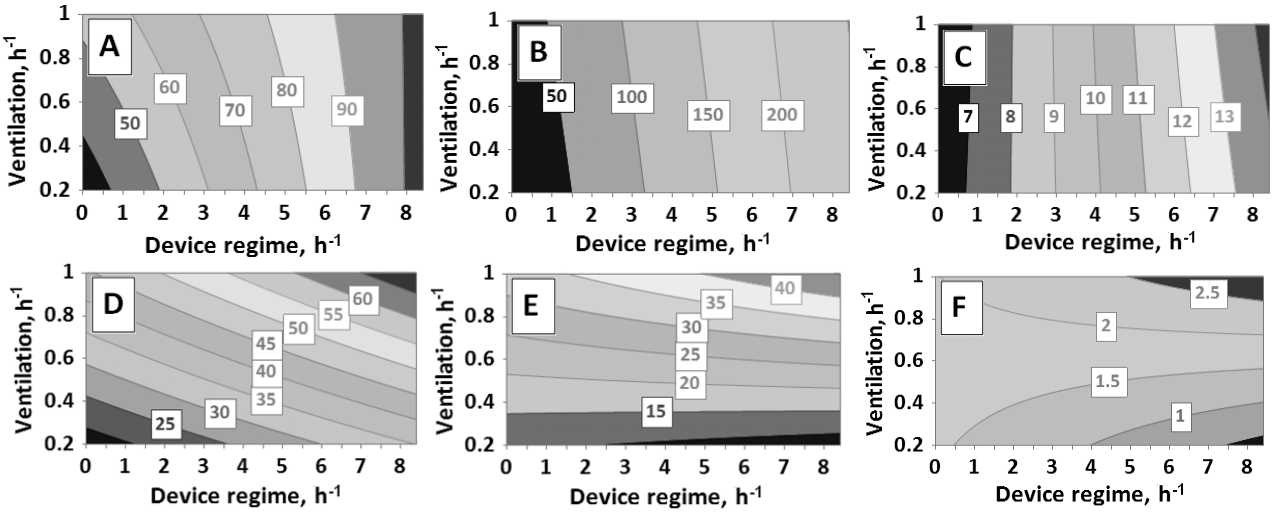

Fig. 4. Prediction of pollutant removal indicators by covariation of ventilation rates and portable air cleaner (device) regimes in case of cleaner C1: A–E_{PNC} (%); B–$CADR_{PNC}$ (m^3 h^{-1}); C–EEI_{PNC} (m^3 h^{-1} W^{-1}); D–E_{VOC} (%); E–$CADR_{VOC}$ (m^3 h^{-1}); F–EEI_{VOC} (m^3 h^{-1} W^{-1}). The device regime represents multi-pass air changes per hour caused by air cleaner.

been indicated that efficiencies of gaseous pollutant cleaners vary greatly from product to product and from VOC to VOC (Chen *et al.*, 2005; Kim *et al.*, 2012). Our surrogate pollution source also contained specific VOCs which may be decomposed differently in other types of air cleaners.

The above presented results indicate that air cleaners, although not very efficient, may add up additional value for the removal of VOCs in indoor air in order to have a faster and energy efficient reduction of pollutant concentrations. At the same time there are doubts associated with the ozone-based decomposition of VOCs, which may release partial decomposition products to indoor air that may be of even higher toxicity than the original VOCs (Waring *et al.*, 2008). Moreover, the release of ozone (if any) may affect human health directly or via formation of nanoparticles during reactions with VOCs occurring in air (Chen *et al.*, 2005). In this study, we did not register ozone levels above the detection limit of the instrument, nor did we detect a smell of ozone. On the other hand, the decreasing quality of outdoor air in specific pollution episodes may not provide suitable air to dilute the indoor VOCs. Thus only well designed and balanced ventilation providing a good quality air may be more feasible strategy for the removal of VOCs from the air (together with other gaseous pollutants, such as CO_2). More advanced IAQ management can be based on the real-time monitoring of indoor and outdoor air and adjustment of ventilation/air cleaning strategies based on the real time air quality data.

CONCLUSIONS

The performance of a three portable air cleaners was evaluated in the test chamber by examining tobacco smoke concentration. Tested cleaners are effective in removing of indoor tobacco smoke particles, reaching 97% particle number removal efficiency after 30 min. The VOCs removal efficiency was lower and varied from 21.4 to 45.7%. $CADR_{PNC}$ varied widely among tested cleaners and their operation intensities, and ranged from 37 (± 4) to 237 (± 11) $m^3 h^{-1}$, while $CADR_{VOC}$ ranged from 2.2 (± 0.3) to 19.9 (± 2.8) $m^3 h^{-1}$.

Generally, air cleaners proved to be more efficient devices than the ventilation to remove aerosol particles. The maximum air cleaning and minimum ventilation allowed reaching efficiencies of 75–90% during 30 min as well as the highest energy efficiency values. With VOCs, ventilation with no air cleaning removed 40–45% of VOCs, and combined with air cleaning the removal efficiency topped at ~60%, however, not taking into account the release of the decomposition sub-products. These results provide data for the consideration for the real-time IAQ management based on measurements of aerosol particles and VOCs indoors.

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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