A New Clean Air Delivery Rate Test Applied to Five Portable Indoor Air Cleaners

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Air pollution has been recognised as one of the major risk factors for the global burden of disease. In modern society the majority of the exposure occurs indoors where people spend most of their time. Indoor air quality may be improved with portable air cleaners utilizing various cleaning techniques, such as filtration, electrostatic precipitation, and ionization. The objective of this study was to quantify air cleaner particle removal by particle size resolved clean air delivery rates (CADR). This was obtained by utilizing particle concentration measurements and indoor aerosol modeling. Our test protocol was applied to five air cleaners designed for household and office use. For particles with diameters above 100 nm and at the chosen settings, the CADR was around 40 m$^3$/h for an ion generator, around 70 m$^3$/h for an electrostatic precipitator, and ranging from 100 to almost 300 m$^3$/h for the three filter-based air cleaners. Similar performances were obtained for ultrafine particles, except for the ion generator that performed better in this size range.

INTRODUCTION

Indoor air generally contains a wide range of pollutants, which originate either from outdoor or indoor sources. Common indoor sources of air pollution are cooking, heating, printers and other electronic devices, candle burning, cleaning activities, smoking, furnishing, and building materials (He et al. 2004; Afshari et al. 2005; Hussein et al. 2006; Wallace 2006; Destaillets et al. 2008; Géhin et al. 2008; Carazo Fernández et al. 2013). Moreover, in some buildings also fungal colonies provide various air pollutants (Khan and Karuppayil 2012). Air pollution is responsible for a wide variety of health effects (Bernstein et al. 2008; Rückerl et al. 2011) and for urban particulate matter there seems to be no threshold below which no effect exists (Anderson 2009).

The influence of indoor sources on indoor air quality can be reduced by increasing ventilation rate. However, ventilation brings in pollutants from outdoors and is often costly due to heating or cooling needs, so ventilation rates greater than four air changes per hour are usually avoided (Yamamoto et al. 2010). Another way of removing pollutants is indoor air cleaning. Portable air cleaners for home and office usage utilize various techniques depending on which pollutants they target (Zhang et al. 2011). No air cleaner removes all pollutants, and some even produce harmful by-products, such as ozone (Niu et al. 2001; Britigan et al. 2006; Waring et al. 2008). Hence, air cleaners should not replace ventilation, but they may supplement it.

The pollutant removal ability of the air cleaners should preferably be quantified in terms of the Clean Air Delivery Rate (CADR) for easy comparison (Shaughnessy and Sextro 2006; Zhang et al. 2011). For the removal of particles, which is the focus of this study, CADR has been reported by some studies (Offermann et al. 1985; Batterman et al. 2005; Waring et al. 2008; Mang et al. 2009; Agrawal et al. 2010; Sultan et al. 2011; Zuraimi et al. 2011; Kim et al. 2013). Although many of the indoor sources emit ultrafine (diameter <100 nm) particles in large numbers, only a few studies reported CADR for ultrafine particles (Waring et al. 2008; Sultan et al. 2011; Zuraimi et al. 2011). Usually air cleaner CADR tests are done by first emitting the relevant pollutant into a room, then stopping the emission and observing the, presumably exponential, decay of its concentration. This needs to be done both with and without the air cleaner, and to get enough data to avoid high uncertainties in the results high initial concentrations and often also some repetition of the experiment are needed. Sultan et al. (2011) used initial particle number concentrations exceeding $10^6$ cm$^{-3}$. Considering this number concentration and the needed width of the size distribution the particle losses due to coagulation must have been substantial (Hussein et al. 2009; Yu et al. 2013). In another study by the same authors (Zuraimi et al. 2011) they did not report the initial concentration. In that study they reported CADR from 14 nm to 8 μm so the size distribution must have been
wide, so coagulation can have been important even if the initial concentration was substantially lower. Waring et al. (2008) required the number concentration in each of their 104 size bins to be at least 100 cm$^{-3}$. In this study the effect of coagulation may indeed have been small, but some of the decay rates were calculated based on only four data points. None of these studies mentioned any corrections for the coagulation. In this study, instead of repeating the concentration decay experiment we developed a testing method in which data is collected over several hours, and the effect of coagulation was included in the calculations. This study has two main outcomes: (1) suggestions for an improved method for CADR testing and (2) size-resolved CADR values for the five air cleaners tested.

MATERIALS AND METHODS

Air Cleaners

The tested air cleaners are listed in Table 1. F1, F2, and F3 use a fan to make the air run through filters. F3 passes the air through two particle filters and then an activated carbon filter to remove odors. F1 and F2 remove odours first and then pass the air through a HEPA filter. ESP differs by using an electrostatic precipitator after a coarse filter and finally passes the air through an activated carbon filter. IG is a negative ion generator with no fan or filters. It has a collector on which negatively charged particles deposit. Most of the air cleaners had a few settings to choose between (see the online supplemental information [SI]), and we chose the settings according to the manufacturers’ recommendation.

Test Setup

Air cleaner performances were tested in an 81.4 m$^3$ emission room designed for aerosol studies (Figure 1), and its conditions were followed from the adjacent monitoring room. The walls were made of stainless steel and glass. The emission room was continuously mixed with two fans (a Philips type HR 3270/B 28W and a Domesto Mod. Gliding Grille, Art.-Nr.: 16401 80). Room temperature, relative humidity (RH), and pressure were measured with a Thermo TR-73U logger, and their ranges were 23–25°C, 5–20%, and 979–1032 hPa, respectively. The electricity consumption of the air cleaners was monitored with an FHT-9992 energy meter.

In an air-tightness test performed in 2011 according to the EN 13829 standard, the leakage was 0.5 h$^{-1}$ at 50 Pa overpressure. During our experiments the emission room was operated at atmospheric pressure at an air exchange rate of about 0.6 h$^{-1}$ according to our analysis of the particle measurements (explained below). Leakage flow from the emission room to the monitoring room through a tube (diameter ~1 cm) was found to be 6 ± 3 L min$^{-1}$ (TSI General Purpose Thermal Mass Flowmeter 4043). The small leakage flow shows that the ventilation flows were in balance. The direction of this flow shows that there was a slight overpressure in the emission room. The ventilation air was filtered with HEPA (High-Efficiency Particulate Air filter, Camfil FARR) and activated carbon filters. To the ventilation air, NaCl and DEHS (Bis(2-Ethylhexyl)-Sebacat) particles were produced with two atomizers. When the RH (as in this study) remains below 40% the hygroscopic growth of NaCl particles can be neglected (Hämeri et al. 2001; Biskos et al. 2006). The particles were neutralized with a $^{63}$Ni (activity 370 Mbq in 1999) bipolar aerosol neutralizer and were mixed to the ventilation air with a fan. This resulted in the particle number size distribution shown in Figure 2.

Particle Measurements

Particle size distributions were measured in parallel with a scanning mobility particle sizer (SMPS) and optical particle sizer (OPS, TSI model 3330, sample flow 0.97 L min$^{-1}$, refractive index 1.47 + 0i that correspond to the DEHS oil refractive index). The SMPS consisted of a classifier (TSI Classifier model 3080, TSI 0.071 cm preimpactor with a D$^{50}$ cut-size of 550 nm, and 10 μCi TSI $^{85}$Kr neutralizer model 3077A), differential mobility analyzer (DMA, Hauke, length 28 cm, inner diameter 2.5 cm and outer diameter 3.3 cm, sheath air flow 6 L min$^{-1}$), and a condensation particle counter (CPC, TSI model 3776, sample flow 1.43 L min$^{-1}$).

Measurement size range was for the SMPS from 12 nm to 660 nm and for the OPS from 300 nm to 10 μm. The distributions were combined by removing the OPS size fractions smaller than 482 nm and the SMPS size fractions of over 487 nm. The SMPS largest size bin was cut so that the upper boundary limit was the same as the OPS smallest size bin lower boundary limit. For the cut size bin new geometric mean size $d_{50}$, $d_{N}$, and $\log(D_{p})$ values were calculated. Thus, the combined distribution was continuous and ranged from 12 nm to 10 μm. Because the OPS mainly measured spherical DEHS particles (see distribution in Figure 2) with known refractive index, the mobility equivalent diameter correspond to the optical diameter (Heim et al. 2008). Also, first removing two size cannels from the OPS reduced the number of coincidence errors, and removing the SMPS over 487 nm size fractions reduced problems in the SMPS multiple charge particle correction routine (Koivisto et al. 2012).

Aerosols were sampled by turns from the room or inside the incoming ventilation air dispenser with a three-way valve (Figure 1). The valve switched position every 3 min. After each
FIG. 1. Experimental setup. The upper part shows the measurement room seen from above, and the lower right part shows the sampling system. Generated particles were first neutralized and emitted to the ventilation duct through which they entered the room. Particles were sampled both within the room with well-mixed air and where the aerosol entered the room.
FIG. 2. Measured particle number size distributions during the steady-state (from 5 to 21 h; Figure 3) of the F1 experiment.

switch, the first 15 s were used for SMPS retrace and for flushing the sampling line between the valve and the instruments. The remaining 165 s were used for measurement. Aerosol samples were diluted with a porous tube diluters ($Q_{PTD1} = 2.72$ L min$^{-1}$, $Q_{PTD2} = 2.73$ L min$^{-1}$) and sampling lines were flushed with excess flows ($Q_{EX1} = 3.95$ L min$^{-1}$, $Q_{EX2} = 3.90$ L min$^{-1}$). Sampling lines were made of conductive rubber and stainless steel. The aerosol sample residence time was approximately 5.4 s. The sampling lines’ diffusion losses were corrected according to Cheng (2001). The OPS sample was further diluted with a $Q_{D2} = 0.68$ L min$^{-1}$ to reduce the number of coincidence counts in the OPS. All sample flows were measured before and after each experiment with bubble flow meters (AP Buck, models M-5 and M-30).

Additionally, in order to detect possible new particle formation the number concentration of particles larger than about 1.5 nm was measured in the room with a particle size magnifier (PSM, Airmodus A09) in combination with a CPC (TSI model 3772).

**Test Protocol**

Because the air cleaners were new, they were left running for a week at minimum power in a room having EU7 filtered outdoor air. This was because unused electrical equipment may emit lubricants, preservatives, and other chemicals when they are first used. After this, the test protocol was the following for each air cleaner:

- Air cleaner was sealed into the emission room
- Aerosol particle injection start at 00:00
- Air cleaner powered at 2:41
- Aerosol particle injection end at 21:00
- Test stop at 24:00

The resulting concentration in the room (Figure 3) increased at the beginning until the air cleaner was turned on. Then it decreased and after a few hours a steady-state was obtained. Finally, when the aerosol generator was turned off the concentration decreased again. In addition to the tests of the five air cleaners, one similar test was done without any air cleaner.

**Data Analysis**

The dynamic behavior of indoor aerosols is usually understood through indoor aerosol modelling based on the balance equation (Nazaroff 2004; Hussein et al. 2005; Hussein and Kulmala 2008). The exact form of this equation depends on its application. In our setting the concentration of the incoming aerosol was measured inside the incoming ventilation air dis- penser, and we assumed that no filtration happened between this measurement point and the chamber. Furthermore, we have assumed that there were no aerosol sources in the chamber. The balance equation for each size section $i$ of the aerosol in the chamber is

$$\frac{dN_i}{dt} = \lambda N_{vent,i} - (\lambda + \beta_i + \gamma_i)N_i + J_{coag,i} \tag{1}$$
where \( N_i \) is the number concentration (of size section \( i \)), \( t \) is time, \( \lambda \) is the ventilation rate, \( N_{vent,i} \) is number concentration in the incoming aerosol, \( \beta_i \) is the deposition rate of particles, \( \gamma_i \) is the cleaning rate, and \( J_{coag,i} \) is the change rate due to coagulation. Integration of this equation from time \( t_0 \) to \( t \) gives
\[
N_i(t) - N_i(t_0) = (t - t_0)(N_{vent,i} \lambda - N_i \beta_i - N_i \gamma_i + \frac{J_{coag,i}}{\lambda_i}). \tag{2}
\]
where the over-lines denote mean values for the considered time interval. When considering a time interval for which the rates \( \lambda \), \( \beta_i \), and \( \gamma_i \) are roughly constant, this relation can be simplified to
\[
\frac{N_i(t) - N_i(t_0)}{t - t_0} = (N_{vent,i} - N_i) \lambda - N_i (\beta_i + \gamma_i) + J_{coag,i}. \tag{3}
\]

These equations are valid generally, but simpler equations can be derived for the final decay.

During this final decay the concentration of particles in the incoming air is negligible, so the balance equation reduces to
\[
\frac{dN_i}{dt} = -(\lambda + \beta_i + \gamma_i)N_i + J_{coag,i}
\]
\[
= - (\lambda + \beta_i + \gamma_i - J_{coag,i}/N_i)N_i. \tag{4}
\]
Let us now assume that \( \lambda \), \( \beta_i \), and \( \gamma_i \) are roughly constant and consider a particle size range from 200–400 nm (denoted by \( A \)) for which \( J_{coag,A}/N_A \ll \lambda + \beta_A + \gamma_A \). Then \( \lambda + \beta_A + \gamma_A - J_{coag,A}/N_A \) is roughly constant and \( N_A \) decreases exponentially with decay with decay rate \( \lambda + \beta_A + \gamma_A - J_{coag,A}/N_A \):
\[
N_A(t) \approx N_A(0) \exp(- (\lambda + \beta_A + \gamma_A - J_{coag,A}/N_A)t). \tag{5}
\]
By applying the logarithm we get
\[
\log(N_A(t)) \approx - \left( \lambda + \beta_A + \gamma_A - J_{coag,A}/N_A \right)t + \log(N_A(0)), \tag{6}
\]
from which it is clear that we can find \( \lambda + \beta_A + \gamma_A - J_{coag,A}/N_A \) by linear regression. We calculated coagulation rates using the measured particle number size distributions and Fuch’s theory for Brownian coagulation as described by Seinfeld and Pandis (2006). By adding \( J_{coag,A}/N_A \) to the decay rates obtained by the linear regression we can get a good estimate of the sum \( \lambda + \beta_A + \gamma_A \). This sum is needed in the following equation for the calculation of ventilation rate. Rearranging Equation (3) and applying it to size section \( A \) gives:
\[
\lambda = \frac{N_A (\lambda + \beta_A + \gamma_A) - J_{coag,A} + \frac{N_A(t_0) - N_A(t)}{t - t_0}}{N_{vent,A}}. \tag{7}
\]
This equation should be applied to the period during which the air cleaner and the aerosol generators were both on. Using this ventilation rate, data from the same period, and another rearrangement of Equation (3) gives the sum of the deposition and cleaning rate:
\[
\beta_i + \gamma_i = \frac{\lambda (N_{vent,i} - N_i) - (N_{vent,i} - N_i)_{t = t_0}}{N_i} + J_{coag,i}. \tag{8}
\]
We applied the same equation to data from the initial rise \( (\gamma = 0) \) to get the deposition rate \( \beta_i \), and then we calculated the cleaning rate by subtracting \( \gamma_i = (\beta_i + \gamma_i) - \beta_i \). The cleaning rate in itself is not a good measure of the air cleaner performance, because it depends on the volume of the room. By multiplying it with the volume \( V \) of the room we get the CADR, which is a standard measure of air cleaner performance:
\[
\text{CADR}_i = V \gamma_i = V ((\beta_i + \gamma_i) - \beta_i). \tag{9}
\]

RESULTS AND DISCUSSION

The main result of this study is the size-resolved CADR, which will be presented in this section. As described in the previous section, our estimates of the CADR depend on the estimates of the ventilation and deposition rates, which are presented first. Because the cleaning rate \( \gamma \) differs from the CADR only by a factor \( V \), cleaning rates are not presented. Finally, we present results from the electricity measurements.

Ventilation Rates

The ventilation rates in the six experiments were similar to each other as seen in Table 2. Note that the ventilation rates are especially similar for consecutive experiments with short time in between. This similarity is fortunate, because a strong variation of the ventilation rate between the experiments would have fitted badly with our assumption of constant ventilation rate during each experiment.

Deposition Rates

Also the deposition rates were expected to be similar to each other, because as long as an air cleaner is off, its effect on the
aerosol is expected to be negligible. However, for most sizes the lowest and highest deposition rate differ by a factor 2 or more (Figure 4, Table 3). The variation cannot be explained simply by uncertainties, so it is either real or caused by some unidentified errors. In each of our cleaning rate calculations we used the deposition rate obtained from the same experiment. Thus, we have implicitly assumed that there are real differences between deposition rates, although the physical reason for such differences is unknown. Alternatively, the deposition rate could have been obtained from the experiment with no air cleaner. This gives slightly different results as can be seen in the SI.

There was a clear problem with the result for the 0.8 μm size section, and adjacent size sections were also affected somewhat. Therefore, we present no results for the 0.5–1.2 μm size range. For particle sizes above 3 μm there were only few particles so the uncertainties were large. Therefore, we decided not to show any results for these particles either. Also for particles with diameters below 30 nm the results were not reliable enough, because of some systematic error. It was probably caused by incomplete neutralization of the atomized particles. One problem related to the neutralization is that the salt particles were not yet dry when passing through the neutralizer. Unless charges were leaving from the particle with the evaporating water, the aerosol became overcharged, because smaller particles generally carry fewer charges than larger ones. Overcharging could cause many problems, such as, increased losses in the sampling lines, especially for the smallest particles. Another issue to consider is the coagulation calculations. We do not know how exact these calculations are so their uncertainty is not included in Table 3, where only the uncertainty due to statistical variation is indicated. For ultrafine particles the losses due to coagulation were comparable to the deposition losses (SI), so the uncertainty of the coagulation rate may be important. In principle, new particle formation could be the cause of the problem for particles below 30 nm, but we find that explanation unlikely because the particle number concentration (PNC) from PSM measurement never exceeded the PNC obtained from the other instruments substantially, and in the end of all experiments the PNC decreased as expected.

Clean Air Delivery Rate (CADR)

For F1, ESP, and F3 the CADR is almost size independent in the range from 30 nm to 500 nm (Figure 5, Table 4). This is expected because they all suck the air through a filtering system with high filtration efficiency. CADR is slightly higher for larger particles, perhaps due to increased deposition related to the extra turbulence caused by the air cleaners. Here we need to keep in mind that the deposition rate estimates are based on data from periods during which the air cleaners were off, so any increase in the deposition will indeed be included in the cleaning rate and, consequently, in the CADR. For some reason F2 show more size dependence. The highest deposition rate was also found for the F2 experiment. If the deposition rate is overestimated for this experiment it would explain some of the size dependence of CADR. Another possible reason for the size dependence is that the solid NaCl particles, unlike the liquid DEHS particles, may bounce when hitting the glass fibres in the filter, and therefore the filtration efficiency may be lower for these particles (Mullins et al. 2003). The CADR for IG differ by being strongly size dependent and by decreasing with increasing particle size. Except

| Particle diameter (μm) | 0.029–0.056 | 0.056–0.11 | 0.11–0.21 | 0.21–0.39 | 0.39–1.5 | 1.5–2.8 |
|------------------------|-------------|------------|------------|------------|----------|---------|
| F1                     | 0.17 ± 0.08 | 0.19 ± 0.03 | 0.14 ± 0.04 | 0.10 ± 0.02 | –         | 0.71 ± 0.22 |
| F2                     | 0.49 ± 0.11 | 0.31 ± 0.07 | 0.22 ± 0.08 | 0.16 ± 0.06 | –         | 0.92 ± 0.36 |
| F3                     | 0.35 ± 0.08 | 0.25 ± 0.03 | 0.19 ± 0.03 | 0.14 ± 0.03 | –         | 0.89 ± 0.25 |
| IG                     | 0.19 ± 0.12 | 0.14 ± 0.05 | 0.07 ± 0.03 | 0.04 ± 0.04 | –         | 0.62 ± 0.23 |
| ESP                    | 0.33 ± 0.08 | 0.23 ± 0.03 | 0.13 ± 0.02 | 0.12 ± 0.03 | –         | 0.73 ± 0.20 |

FIG. 4. Deposition rates obtained by applying Equation (8) to data from the initial rise. Uncertainties are given in Table 3.
for ultrafine particles, IG is clearly less effective than the other air cleaners, and IG has no other setting for additional particle removal. The CADR for IG may be somewhat overestimated because the charged particles are more likely to be lost in the sampling line. However, it should be noted that the efficiency of IG is affected by the electrical properties of the particles and the indoor surfaces, so it may be more effective in some other setting.

Our results fit well with the quantitative information given by the manufacturers. According to Electrolux the CADR of F1 should be 117 m$^3$/h at the setting used, which is close to the result in Figure 5 and Table 4. IQAir reported the fan speed to be 190 m$^3$/h at the given setting. Because of high efficiency filters this should correspond to the CADR rather well, and it does correspond very well for the accumulation mode. The fan speed reported by Plymovent at the given setting is 130 m$^3$/h. The F3 filters do not remove all particles (data not shown), so the somewhat lower CADR was expected. For ESP and IG no CADR or fan speed was reported by the manufacturers. For air cleaners with HEPA filters Offermann et al. (1985) also found the CADR to be close to the fan speed, while their ratio was surprisingly found to be about 0.6 only by Waring et al. (2008) and Sultan et al. (2011).

The CADR values are similar to the ones found in other studies. Air cleaners using filters or electrostatic precipitators generally remove particles more effectively than ion generators (Offermann et al. 1985; Waring et al. 2008; Sultan et al. 2011; Zuraimi et al. 2011). The increase of the CADR for larger particles, which we observed for four of the air cleaners (Figure 5), has also been seen in other studies (Agrawal et al. 2010; Zuraimi et al. 2011; Kim et al. 2013). Also the opposite size dependence, which we observed for IG (Figure 5), agrees with results for ion generators from previous studies (Waring et al. 2008; Sultan et al. 2011; Zuraimi et al. 2011).

Let $N_{i,\text{ac}}$ and $N_{i,\text{nac}}$ be the steady state concentration of particles in size section $i$ in a room of volume $V_r$ with and without an air cleaner, respectively. When ignoring coagulation the air cleaner effectiveness $\varepsilon$ is (Batterman et al. 2005; Shaughnessy and Sextro 2006)

$$
\varepsilon_i = 1 - \frac{N_{i,\text{ac}}}{N_{i,\text{nac}}} = \frac{\text{CADR}_i}{V_r (\lambda + \beta_i) + \text{CADR}_i}. \tag{10}
$$

This equation is valid in a room with well-mixed air, but in homes and offices the air is not necessarily well-mixed. IG has no fan so the effect of this device is likely to be limited in rooms with little air mixing (Offermann et al. 1985). The other air cleaners have fans which contribute to the mixing, but also with these air cleaners the particle concentration is likely to be reduced more in some places than in others. When placing an air cleaner in an indoor environment, indoor air flows and the location of people and pollution sources should be considered (Novoselac and Siegel 2009).

For particles smaller than 400 nm the uncertainties of our results are 4–12% (Table 4). For the same size range, most of the uncertainties reported by Waring et al. (2008) are between 10 and 20%, but some of their uncertainties were even higher. Although the difference is partly explained by a higher size resolution in their study, the accuracy in our study is somewhat better. Sultan et al. (2011) and Zuraimi et al. (2011) did not report uncertainties, but considering the fluctuation of their results we consider the accuracy of our results to be better. The accuracy

### TABLE 4
Size-resolved CADR values with uncertainties [m$^3$/h]

| Particle diameter (μm) | 0.029–0.056 | 0.056–0.11 | 0.11–0.21 | 0.21–0.39 | 0.39–1.5 | 1.5–2.8 |
|------------------------|-------------|-----------|-----------|-----------|---------|--------|
| F1                     | 105 ± 9     | 103 ± 6   | 111 ± 7   | 113 ± 5   | –       | 148 ± 20 |
| F2                     | 160 ± 18    | 172 ± 15  | 191 ± 16  | 193 ± 14  | –       | 257 ± 36 |
| F3                     | 105 ± 9     | 107 ± 6   | 104 ± 16  | 98 ± 4    | –       | 149 ± 22 |
| IG                     | 119 ± 14    | 67 ± 7    | 44 ± 5    | 40 ± 4    | –       | 17 ± 19  |
| ESP                    | 62 ± 9      | 65 ± 5    | 71 ± 5    | 69 ± 3    | –       | 88 ± 17  |

FIG. 5. Estimated CADR. Uncertainties are given in Table 4.
can further be improved by making the following changes to our experiment:

- Measure the ventilation rate using a tracer gas.
- To avoid coagulation keep the size distribution narrow and avoid too high concentrations (Hussein et al. 2009; Yu et al. 2013). With our particle generators this means making two separate tests, one with NaCl particles and another one with DEHS particles.
- Get data from two steady-state periods, one with the air cleaner on and one with the air cleaner off. Apply Equation (8) to each of these periods, and then use Equation (9).
- When following the suggestions above, the right hand side of Equation (8) effectively reduces to the product of $\lambda$ and \( \frac{X_{\text{vent}}}{X_{\text{p}}^N} \). Set the ventilation rate $\lambda$ to a value that allows both factors to be much larger than their uncertainties.
- Ensure neutralization of the generated particles with multiple neutralizers.

When following these suggestions some extra experimental work is required, but the data analysis is simplified and the risk of errors is reduced. The ventilation rate can be measured during each of the steady-state periods to avoid the need to assume constant ventilation rate.

Electricity Consumption

In our tests F2 had the highest CADR (Figure 5), but it came at the cost of higher electricity consumption (Table 2). When considering the CADR and the power simultaneously, especially F1 performed well (Figure 5, Table 2). For IG we did not register any electricity consumption although according to the manufacturers’ information it should use 7 W, which is more than F1 used (SI). Either IG used less than expected or our measurements were inaccurate. In any case, even if the electricity consumption of IG was very low, the performance of IG must be characterized as poor because CADR was low for most of the particle size range.

CONCLUSIONS

We have obtained particle size-resolved CADR for five portable air cleaners. For IG the CADR was strongly size-dependent; the CADR was highest for the smallest particles. At the chosen settings the filter-based air cleaners performed best, and ESP was better than IG for all particle diameters above 100 nm. There were clear differences between the air cleaners in terms of electricity consumption. Our CADR results agree with quantitative information given by the manufacturers and with previous studies of similar air cleaners. To reduce uncertainties of the CADR we used a method that differs from the usual method by exploiting a longer time series of measurements, and in our calculations we accounted for coagulation. Our CADR uncertainties are smaller than the uncertainties in previous studies, although we paid too little attention to the determination of the ventilation and deposition rates when designing the experiment. We have suggested experimental improvements that would improve the accuracy further and probably make the results reliable also for particles smaller than 30 nm.

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SUPPLEMENTAL MATERIALS

Supplemental data for this article can be accessed on the publisher’s website.

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