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Efficiency of portable HEPA air purifiers against traffic related combustion particles

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ABSTRACT

Exposure to diesel combustion particles is known to cause and exacerbate respiratory conditions, including asthma. High efficiency particulate air (HEPA) purifiers can provide health benefits by reducing concentrations of these particles. National standards call for air purifiers to be tested using tobacco smoke, as well as aerosolized dust, pollen, and potassium chloride (KCl) particles. Little is known about the efficiency of HEPA air purifiers against diesel particles. Previous studies performed with respirator filters have shown higher penetration of combustion generated particles compared to standard test particles. Within a controlled laboratory setting, we compared the Clean Air Delivery Rate (CADR) of six models of air purifiers with diesel and KCl particles, and measured noise during operation. CADR was determined for total concentration and size-selectively for particles of 0.03–1 μm. Lowest CADRs were consistently found for particles <0.1 μm. Results showed significant differences between CADRs obtained with diesel and KCl aerosols. This was found for CADRs calculated from total concentration data as well as from size-selective data. Unexpectedly, CADR for diesel exceeded the one for KCl particles indicating lower penetration of diesel particles through the HEPA filter. It was concluded that KCl particles may underestimate the actual CADR against diesel particles. The measurements of noise levels produced by the tested air purifiers revealed a low positive association between noise and CADR ($r^2 = 0.55$). Thus, both noise and CADR should be considered when selecting an air cleaner.

1. Introduction

Indoor air quality (IAQ) is a growing concern for both public health and occupational health sectors. Health effects due to poor IAQ can result from a wide variety of pollutants, including airborne particles, such as combustion products, chemical evaporates, and microbes or allergens [1,8]. This is a widespread issue that can affect everyone. Respondents to an EPA sponsored human activity study reported spending an average of 87% of their time indoors [24]. It has been shown that air filtration is beneficial for the health of occupants [14]. Emerging technologies developed to combat these issues have led to an increasing use of air purifiers within various indoor environments such as homes and workplace. Among various air purifiers available today, those using true high efficiency particulate air (HEPA) filters have been proven to reduce the concentrations of indoor air particles without producing harmful by-products [5,6]. At the same time the highly efficient purifiers are often noisy.

A major IAQ concern in homes and workplaces located near highways in urban areas is exposure to traffic related airborne particles (TRAP), which have been shown to exacerbate the effects of existing asthma, as well as increase the incidence of asthma and other respiratory conditions [19]. It has been shown that a decrease in TRAP by as little as 25% can have a significant impact on asthma control in adults [13]. HEPA air purifiers can be effective at reducing the concentration of indoor air particles [11,34]. However, very little is known about the efficiency of HEPA air purifiers against TRAP. In trying to reduce indoor concentrations of TRAP, ultrafine combustion-generated diesel particles (diameter <0.1 μm) are a major concern, as they have been shown to most efficiently infiltrate from outdoor to indoor environments [20]. At the same time, the testing of HEPA air purifiers has been primarily conducted using larger particle sizes. One would expect that these size differences may plausibly affect the outcome.

When testing the efficiency of these air purifiers, the US manufacturers determine the efficiency in terms of the Clean Air

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Delivery Rate (CADR) [3]. CADR describes the flow rate (ft^3/min) of contaminant free air delivered by the air cleaner. Determination of CADR is based on the Association of Homeowner Appliance Manufacturers (AHAM) tests using three types of particles: cigarette smoke (0.1–1.1 μm), dust (0.5–3 μm), and Paper Mulberry pollen (5–11 μm) [3]. This differs from the standard of testing HEPA filters set by the American National Standards Institute (ANSI) and the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), which calls for the use of potassium chloride (KCl) test particles when determining removal efficiency by particle size [4].

Many studies in the past have used CADR to report air purifier efficiency data collected under laboratory conditions and in the field [2,7,25,26,29,31,33,34]. The quoted studies were conducted with sodium chloride (NaCl), cigarette smoke, and dust.

Differences in physical properties, such as charge, shape, and density, among aerosol types can affect their penetration through filters. Specifically, ultrafine combustion-generated particles have been shown to penetrate filtration devices such as N95 respirators significantly more readily than such common aerosol challenges as NaCl [15,16,18]. Consequently, these differences may impact the efficiency of air purifiers, including those equipped with HEPA filters. Thus, their efficiency against diesel particles may differ from that obtained in conventional testing with challenges such as KCl, cigarette smoke, dust, or pollen particles. Furthermore, the AHAM testing does not provide the CADR values for specific particle sizes while the efficiency of air purifier is, generally speaking, particle size dependent.

To summarize, the performance of HEPA air purifiers against diesel may not be well predicted by the AHAM-obtained CADRs reported on the product packaging; we believe that consumers, who rely on these products for health benefits, should be aware of this.

The primary objective of this study was to compare the efficiency of HEPA air purifiers for reducing diesel particles versus "model" KCl particles. The secondary objective of this study was to compare various performance characteristics of several chosen models of so-called true HEPA air purifiers, in order to help select one model to be deployed in a subsequent field study.

2. Methods

2.1. Selection of air purifiers

The criteria for selecting HEPA air purifiers for the testing included information on CADR (provided by manufacturers and AHAM), as well as the noise level generated by their operation, and their cost of ownership. We inventoried portable HEPA air purifiers commercially available in local stores as well as from online retailers. The inventory was carried out for all models classified as true HEPA purifiers, i.e., those capable of removing 99.97% of airborne particles down to the size of 0.3 μm (European Norm EN1822-2009). It was noted that many commercially sold models were the so-called "HEPA-Type" purifiers, which operate in the same manner as true HEPA devices, but do not adhere to the same standards; the "HEPA-Type" purifiers were not selected for this study. Altogether, the preliminary list contained 21 true HEPA air purifiers, from which six were selected for the laboratory testing (Table S1 of Online Supplement).

The purifiers were first categorized by the CADR provided by the manufacturer. We pre-selected the purifiers with CADR ranged from less than 50 to over 350. The devices were then sorted into four groups with CADR <100, 100–200, 200–300, and >300. The first group was totally eliminated from consideration in relation to the subsequent field study because of their insufficient efficiency. It was decided that two purifiers from each remaining group (100–200, 200–300, and >300) would be chosen in order to test a fairly wide spectrum of CADRs.

When selecting the two purifiers from each of the three categories, several criteria were used, such as AHAM certification, CADR, Energystar certification, and cost of ownership. Table 1 shows those six air purifiers chosen for the study and relevant information that led to their selection.

All the tested air cleaners have four operating modes, except Idylis AC2123 has three modes. When comparing the purifiers' performance against diesel and KCl particles, we used two of the Honeywell purifiers; the most powerful (HPA300) operating on its maximum setting, and least powerful (HA106) operating on its minimum setting. In doing so, we were able to assess differences among diesel and KCl CADR at extreme high and low operating speeds. After this, each of the remaining purifiers was also tested using only diesel aerosol while operating on maximum and minimum settings.

2.2. CADR calculation

To define the filtration efficiency of the HEPA treatment, CADR was calculated. For the calculation, we defined the concentration of total particles or particles of diameter *d* at any given time *t* (min) as C(*d*,*t*), the concentration value in a natural decay scenario $C_{natural}(d,t)$, and the concentration while the air purifier was in operation $C_{AP}(d,t)$. The unit for concentrations was particles/cm^3. To determine the CADR (ft^3/min) in a room of volume *V*, the following formula was used:

$$\text{CADR}\ (d,t) = V \times PRR(d,t) \tag{1}$$

Where *PRR* is the particle removal rate exclusively due to the air purifier:

$$PRR(d,t) = 1/t\ \ln\left[(C_{AP}(d,t=0))/(C_{AP}(d,t))\right] - 1/t\ \ln\left[(C_{natural}(d,t=0))/C_{natural}(d,t))\right] \tag{2}$$

CADR calculations were computed using Microsoft Excel 2007 software.

2.3. Experimental setup

Experimental testing was conducted in the 860 ft^3 (24 m^3) walk-in chamber located in the Center for Health Related Aerosol Studies in University of Cincinnati [35]. Setup and the experimental protocol was based on the ANSI/AHAM AC-1 standard [3]. Test aerosol was prepared according to the ANSI/ASHRAE 52.2–2012 standard [4]. A simplified schematic of the experimental testing chamber setup is shown below in Fig. 1.

The aerosol generating devices for diesel and KCl were located within the chamber. The diesel combustion particles were aerosolized through combustion of diesel fuel within a portable fuel burning heater (Dyna-Glo Delux 75,000 BTU Multi-Fuel, GHP Group, Inc., Niles, IL, USA). The type of fuel used was type-2 diesel fuel, readily available at gas stations where diesel fuel is sold. The fuel burning was set for 5 s. Flame-based soot generators, including diesel-fueled space heaters have also been used by other investigators and were found to produce fractal-like agglomerates that are characteristic to diesel particles [21,27]. The KCl particles were aerosolized from 20% KCl solution using a system of three 6-jet Collison Nebulizers (BGI Inc., Waltham, MA, USA) each operating at a flow rate of 6 l/min. The nebulization was conducted for 5 min.

For both types of aerosols, a 3-min generation interval was allowed before beginning the data recording at t = 0 in order to

Table 1
Features of tested air purifiers.

Feature	Whirlpool Whispure AP51030K	Honeywell HPA-300	Coway AP-1512HH	Honeywell HA202	Idylis AC-2123	Honeywell HA106
AHAM Certified[a]	Yes	Yes	Yes	Yes	Yes	Yes
Cigarette Smoke CADR (ft^3/min)	315	300	233	200	150	100
Dust CADR (ft^3/min)	325	320	246	190	160	106
Pollen CADR (ft^3/min)	401	300	240	180	180	100
EnergyStar Certified[b]	Yes	Yes	Yes	Yes	No	Yes
Purchase Cost ($)	270	240	250	205	155	140
One yr filter replacements ($)	95	90	50	70	60	60
Recommended Room Size (sq ft)	500	465	361	310	233	155
Total Energy Consumption (Watts)	104	127	79	84	N/A	52

[a] ahamdir.com.
[b] energystar.gov/productfinder.

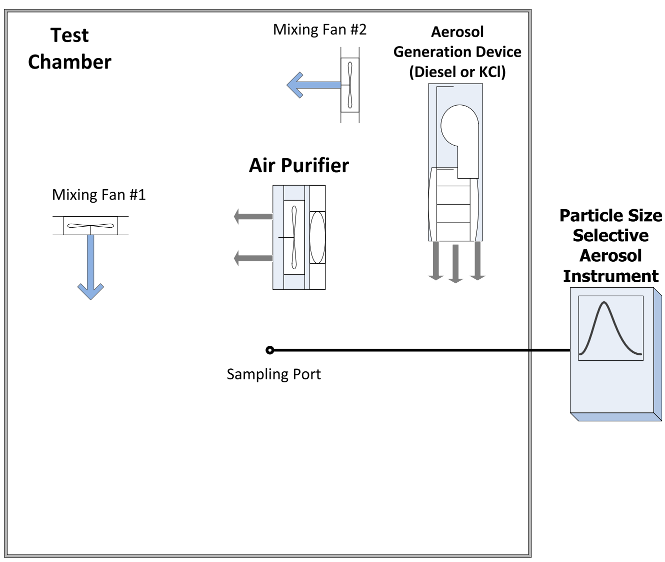

Fig. 1. Top view of experimental setup in the test chamber.

achieve a uniform aerosol concentration throughout the chamber in each experiment. The initial total concentration had to be kept under a threshold of 500,000 particles/cm^3 in order to avoid overloading the aerosol instrument, but also had to be high enough (>300,000particles/cm^3) to allow for a sufficient HEPA treatment time to achieve appropriate accuracy of the CADR determination.

The aerosol concentrations during natural decay and during HEPA treatment were measured particle size selectively using an Electrical Low Pressure Impactor (ELPI) (Dekati Ltd., Kangasala, Finland). This device consists of a 12-stage cascade impactor which measures particle concentrations of sizes 0.03–10 μm at a flow rate of 30 l/min. The D_{50} cut-off sizes for the ELPI stages are: 0.030, 0.060, 0.108, 0.170, 0.260, 0.400, 0.650, 1.000, 1.600, 2.500, 4.400, 6.800 and 9.970 μm. The respective medians for each size range are: 0.042, 0.081, 0.140, 0.210, 0.330, 0.510, 0.810, 1.3, 2.0, 3.2, 5.3, and 8.4 μm. Total concentration was calculated by summing up the size-selective concentrations. A sampling tube was placed within the testing chamber and connected to the ELPI, which in turn was connected to a computer. Both the ELPI and the computer were located outside of the test chamber, where real-time concentration measurements could be seen and operation of the ELPI and data recording could be controlled by an operator outside the test chamber.

Two small fans were placed in the room in order to mix and recirculation the aerosols; these were left “on” during the duration of the experiments. When testing the HEPA treatment, the air purifier in use was placed on a 21” (53 cm) high stand located in the center of the room. During natural decay testing no air purifier was operating or present in the chamber.

2.4. Chamber preparation and measurement of diesel and KCl aerosols

Before starting each experiment, the test chamber was being cleaned by recirculating air through a HEPA filter using a built-in ventilation system until the ambient concentration within the chamber fell down to 3000 particles/cm^3 or below. Temperature and relative humidity, noted from ELPI device display during the test, varied from 18 to 26 °C and 30–50%, respectively. Thus, the conditions were well within the ranges specified in the ANSI-ASHRAE guidelines: 10–38 °C (50–100 °F) and 20–65%, respectively [4].

Once the desired initial aerosol concentration was achieved in the chamber, the data were recorded in 10 s increments for both natural decay and HEPA treatment testing. Since the chosen air purifiers were capable of a rapid cleaning of the chamber, the sampling window established for the testing ranged from 10 to 30 min, depending on the purifier (a longer testing produced an aerosol concentration level too low to distinguish from ambient concentration). For the most efficient air purifier, this window was $t = 10$ min. Consequently, this time interval was utilized for measurement and data analysis under both the control and test experiments (natural decay and air purifying). Each 10-min measurement interval produced a total of 60 data points.

2.5. Noise measurements

Sound pressure levels were measured for each of the air purifiers while operating on all their settings. The measurements were conducted in the Acoustics Laboratory in the Department of Mechanical and Materials Engineering, University of Cincinnati. Sound level measurements were performed using a ten-microphone (Larson Davis Model 2541, Larson Davis Inc., Provo, UT, USA) system that was designed to measure the sound power level according to the standard ISO 3744:2010 [22]. The sound pressure level (dBA) was measured at a steady-state condition, therefore it is the same as L_{eq}-A. The microphones were placed on the hemispherical surface of 2-m radius surrounding the air purifier, and an additional reference microphone was placed 0.3 m (1 foot) from the source. In addition to the A-weighted sound power level, the A-weighted (dBA) sound pressure levels (SPL) at 2 m from the air purifiers were obtained by averaging the SPLs measured at the ten microphones according to the logarithmic addition rule.

2.6. *Statistical analysis*

Using the CADR data, we compared the filtration efficiencies for the two aerosol types for both size selective and total concentrations. The analysis consisted of two-sample t-tests assuming unequal variances between the diesel and KCl particles for the DADR calculated both from total concentration and size specific concentrations, using Microsoft Excel 2007 software. Analysis of variance (ANOVA), with pairwise post-hoc comparisons and Tukey adjustments were also performed using SAS software in order to determine differences among aerosol type, particle size, and air purifier model. Regression analysis was performed to investigate the association between CADR and noise level, and the coefficient of determination (denoted as R^2) was calculated using Microsoft Excel 2007.

3. Results and discussion

3.1. *Comparison of diesel and KCl as test aerosols*

Fig. S1 presented in Online Supplement shows the decay in particle concentrations during natural decay and one of the HEPA treatment tests for each of the particle size channels from the beginning ($t = 0$) through the end ($t = 10$ min). The decay slopes for the two aerosol types are similar. The reduction in concentration for both natural decay and HEPA treatment is well described by an exponential function for every particle size tested. As was expected, the decay in concentration during HEPA treatment was much greater than that occurred during natural decay for both diesel and KCl particles.

Fig. 2 shows representative examples of the particle size distributions of the diesel and KCl aerosols recorded at the midpoint of the 10-min sampling window ($t = 5$ min) during the natural decay (a) and HEPA treatment (b) tests. Standard deviations in particle concentrations between experimental repeats were so small that most of the standard deviations are not seen in the figure. The particle size distributions measured at the beginning and end of this period were nearly identical to those obtained at the midpoint.

Average size-specific particle concentrations ranged from 134,000 particles/cm^3 at 0.042 μm to 125 particles/cm^3 at 1 μm for diesel and from 69,000 particles/cm^3 at 0.108 μm to 2200 particles/cm^3 at 1 μm for KCl. The highest concentration of diesel particles occurred in the smallest fraction, 0.042 μm, while for KCl particles the highest concentration was observed at 0.108 μm. For both aerosols the concentration was lowest at 0.65–1 μm.

Fig. 3 presents a normalized view of the same size distributions as shown in Fig. 2. This normalized view was created by dividing an aerosol concentration at each measured particle size by the concentration at particle size of 0.042 μm. By normalization, the size distribution can be seen on a scale of 0–1, and the peak in concentration for each aerosol is more clearly displayed. We believe that this normalization makes it easier to distinguish the differences in the size distribution of the two aerosols.

The peak in concentration for diesel appears to be below 0.042 μm, which was the median size for the smallest size range measured by the ELPI device. This is consistent with previous studies, which have shown that a peak in concentration for diesel particles typically occurs at or below 0.03 μm [10,32]. The peak in concentration for KCl particles was clearly seen around 0.108 μm. Fig. 3b further illustrates the difference in diesel and KCl concentrations during the air cleaning, with diesel concentrations being much lower comparatively, especially at the 1 μm size. The overall shape of each aerosol distribution however, remained fairly similar for natural decay and HEPA treatment and for the two aerosol types.

3.2. *Comparison of CADR against diesel and KCl aerosol*

Fig. 4 shows the differences in CADR between diesel and KCl particles obtained from both the particle size selective measurement as well as the total concentration data. The CADRs for diesel were slightly higher than those for KCl in every test except two (HA106 purifier against 0.081 μm and HPA300 purifier against 1 μm particles). The largest difference, 25%, occurred at 0.042 μm for the HPA300. Other differences between aerosol types, 4–12%, were seen with the HPA300 purifier in the size range of 0.26–0.65 μm. Many differences in this size range were statistically significant ($p < 0.05$) for both the HPA300 and HA106 according to a two sample t-test assuming unequal variances. Although our statistical testing was limited due to such a small sample size (three repeats), the differences are clearly evident.

The finding that CADR was higher for diesel particles compared to KCl particles is not consistent with recently published data on filtration of combustion particles, which were found penetrating through aerosol filters more readily than NaCl test particles, e.g., being filtered less efficiently [15,16,18]. The CADR differences between the two aerosol types demonstrated in our experiments are likely associated with several factors. One contributing factor is the fractal dimensions of diesel particles compared to more compact KCl particles as well as other types of combustion particles. A previous study by Ref. [30] found that the larger the fractile

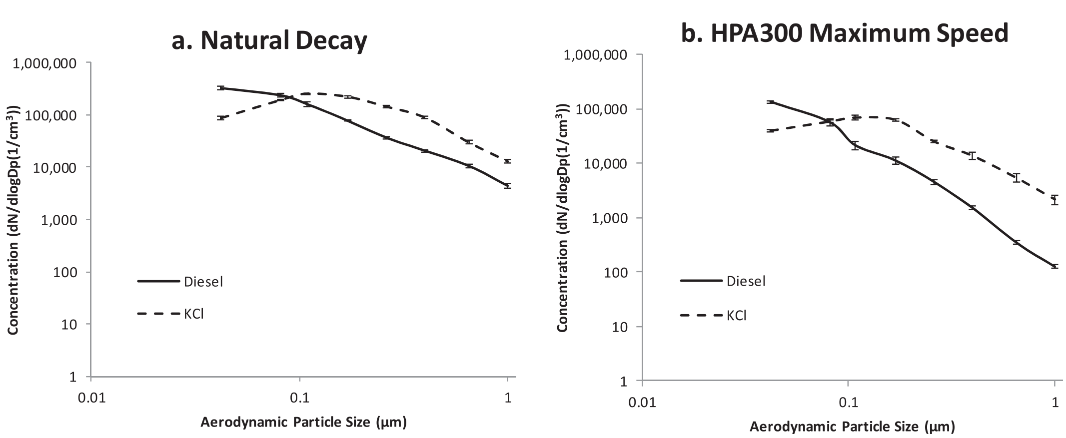

Fig. 2. Particle size distributions as a function of aerodynamic particle size at $t = 5$ min during: (a) natural decay experiments, (b) experiments with air purifier Honeywell HPA300 operating at maximum speed. Each data point represents an average of three repeats and error bars show the standard deviations.

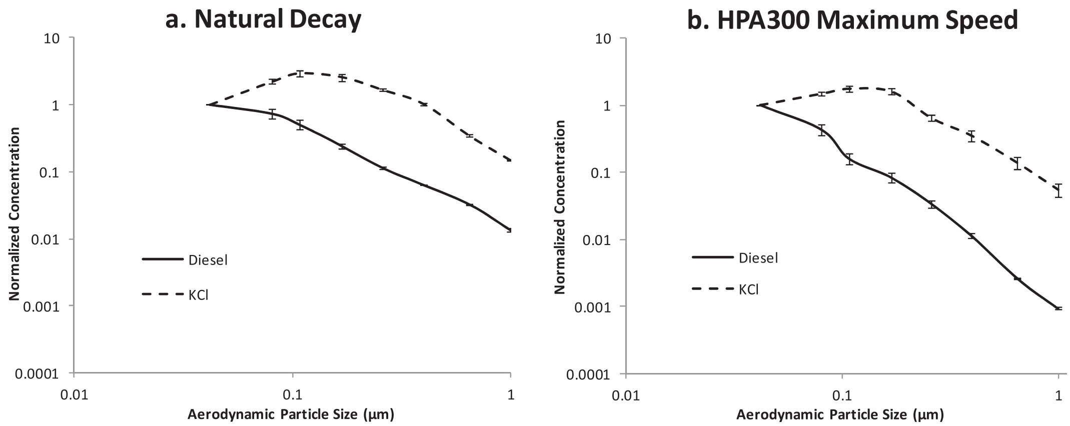

Fig. 3. Normalized particle size distributions (concentration at each particle size is divided by concentration at a size of 0.042 μm) plotted as a function of aerodynamic particle size at t = 5 min. The graphs show: (a) natural decay experiments, (b) experiments with air purifier Honeywell HPA300 operating at maximum speed. Each data point represents an average of three repeats and error bars show the standard deviations.

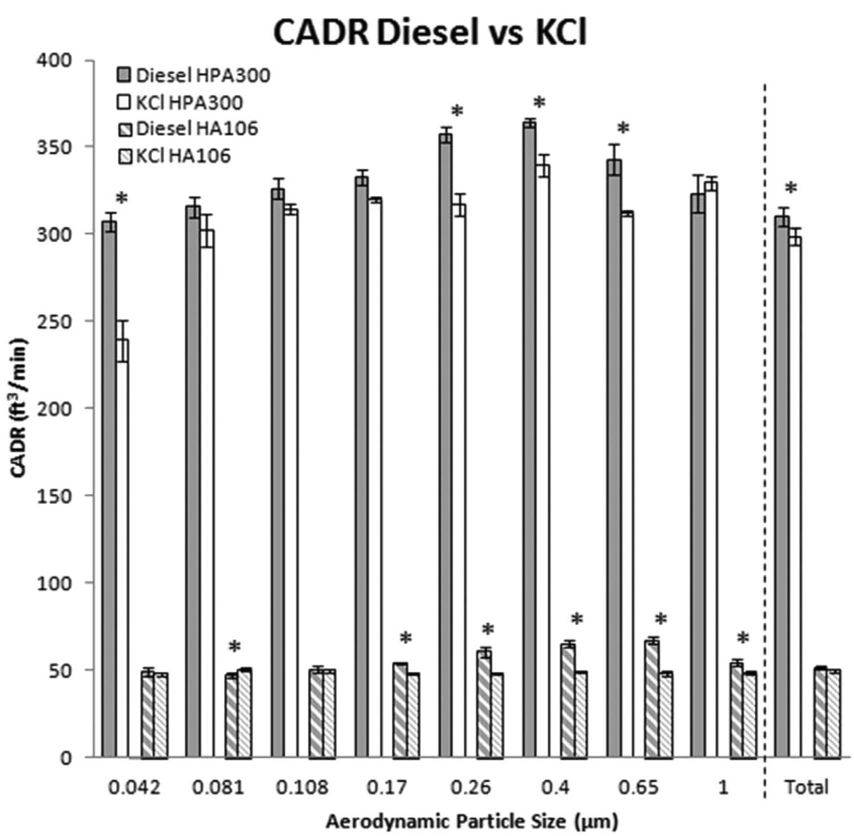

Fig. 4. Particle size specific CADR values obtained for diesel and KCl particles. The CADR values obtained based on the total concentration are also plotted here (Total at far right). Solid bars represent CADR for air purifier Honeywell HPA300 at maximum speed while lined bars represent CADR for air purifier Honeywell HA106 at minimum speed. Each data point represents an average of three repeats and error bars show the standard deviations. Asterisk (*) indicates a statistically significant difference ($p < 0.05$) between aerosol types.

dimensions of a particle, the greater the diffusion will be (as the former is linked with a greater Brownian diffusion coefficient). A greater diffusional deposition of diesel particles corresponds to the higher CADR values. The other may be related to aerosol particle charges. Diesel particles are likely to acquire charges [23], which enhances their mobility and ultimately surface deposition inside the chamber (natural decay) as well as their depositions on HEPA filters as compared to KCl particles, thus making $CADR_{diesel} > CADR_{KCl}$.

3.3. Comparison of CADR of the six air purifiers

Fig. 5 presents the CADR values obtained with diesel particles based on the total aerosol concentration for each of the six tested purifiers while operating at maximum and minimum speed. The air purifiers are listed from left to right in order of decreasing CADR based on the highest manufacturer reported CADR for cigarette smoke. ANOVA statistical testing showed that the type of air purifier was a strongly significant factor affecting CADR ($p < 0.0001$) at both maximum and minimum speeds. Pairwise analysis showed

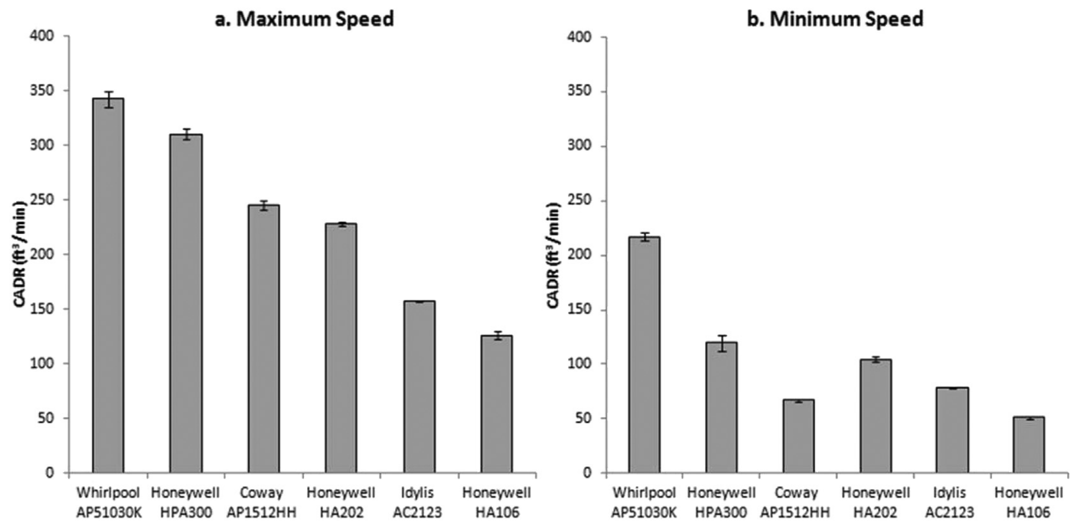

Fig. 5. CADR for diesel particles calculated from the total aerosol concentration data base for each of the six selected air purifiers while operating at: (a) maximum speed, (b) minimum speed. Each data point represents an average of three repeats and error bars show the standard deviations.

that the CADRs for each of the five air purifiers were all significantly different from each other ($p < 0.01$) at both speeds.

While operating at maximum speed, the CADRs for diesel particles ranked in the same order from high to low order as the manufacturer reported CADR for cigarette smoke. The Whirlpool AP5103OK had the highest CADR of 343 ft^3/min and Honeywell HA106 had the lowest CADR of 126 ft^3/min. While operating at minimum speed however, the Coway air purifier ranked as second lowest despite being the third highest at maximum speed. This is in part because this model has an “ECO mode” as its minimum speed setting established for energy conservation, where cleaning efficiency is minimal. While all purifiers showed a significant decrease in CADR when switching from maximum to minimum speed, the Whirlpool purifier still featured a relatively high CADR of 217 ft^3/min in the latter case. With a CADR of 51 ft^3/min, the Honeywell HA106 model had the lowest CADR at minimum speed.

Fig. 6 shows size selective CADRs for diesel particles for each of the six air purifiers while operating at maximum and minimum speeds. Based on ANOVA statistical testing, differences in the particle size specific CADRs were significant ($p < 0.001$) for both maximum and minimum speeds. While operating at maximum speed, the size specific CADRs for most purifiers had a clear peak within the size range of 0.1–0.7 μm. The most distinct peak was seen with Whirlpool AP51030OK at 0.17 μm while the purifier operated at maximum speed. The CADR value at 0.17 μm was 16% higher than the CADR calculated from the total concentration (402 and 343 ft^3/min, respectively), and 23% higher than the Whirlpools lowest CADR obtained at maximum speed which occurred at 0.042 μm (319 ft^3/min). Peaks in CADR were not as noticeable with the air purifiers operating at minimum speeds. The lowest CADR values were found at 0.042–0.1 μm for each of the six purifiers. The finding of maximum CADR at particle size of 0.1–0.7 μm was opposite to what would be expected based on filtration efficiency alone as air filters typically have their minimum efficiency in this size range. The peak was most clearly seen when the air cleaners were operated at their maximum speed. Similar size-selective CADR curve was reported by Ref. [29] for the most efficient among the three HEPA air purifiers they tested. This supports the hypothesis that the operating air cleaner increased the air turbulence and thereby increased the turbulent deposition on the walls of the test chamber. At minimum speed, the size-selective CADR curves were more flat and resembled those presented earlier by

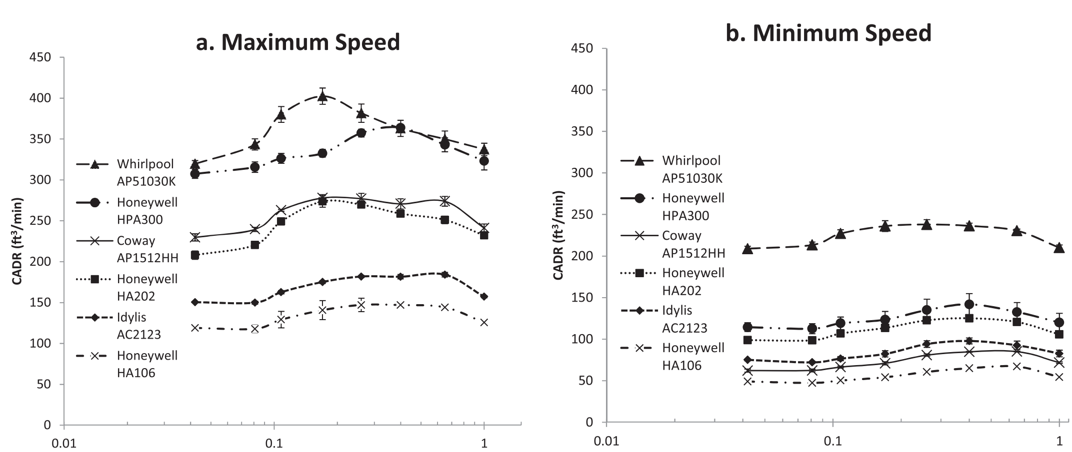

Fig. 6. CADR for diesel particles calculated from the particle size specific concentrations using various air purifiers at (a) maximum speed and (b) minimum speed. Each data point represents an average of three repeats and error bars show the standard deviations.

Refs. [31,33].

AHAM testing is only performed with air purifiers operating at maximum speed, and our diesel CADR values obtained from testing at maximum speed were similar to those provide by AHAM in most instances (Fig. 7). Of the three aerosols tests by AHAM (cigarette smoke, dust, pollen), we expected cigarette smoke to result in CADRs closest to those of diesel, being also generated by combustion. For each of the six purifiers, our measured diesel CADR was actually higher than the AHAM value obtained with cigarette smoke. However, it is notable that AHAM certification does not include size-selective measurements of the CADR, and measures in a different particle size range than the one tested in our experiments. Our results show that the size specific CADRs for diesel particles can vary up to 23% among size ranges and up to 16% as relative to the total concentration. Size selective testing of cigarette smoke, dust, and pollen is expected to show a wide variety of CADRs as well, and therefore the manufacturer stated CADR may not be representative of CADRs at all particle sizes. Special concern is particle size range <0.1 μm where we found consistently lowest CADR values.

3.4. Comparison of noise and CADR

Table 2 shows the SPL obtained for each of the six air purifiers, while operating at different speeds. Interestingly, the Whirlpool purifier had the lowest noise level (45.4 dBA) while operating at maximum speed, despite having the highest CADR. At minimum speed, the Whirlpool purifier had the highest noise level (35.4 dBA) whereas Coway had the lowest (26.6 dBA). The EPA stated indoor activity interference and annoyance level of 45 dBA [12] was exceeded by all air cleaners when they operated at the maximum speed and by two air cleaners (Honeywell HPA300 and HA202 also on their second highest speed. All were below this level while operating at the two lowest speeds.

Fig. 8 shows the association between the noise level and CADR. CADR standard deviations were too small to be visible for on this graph. When examining all data points from both maximum and minimum speeds combined, a low positive linear association was seen between noise and CADR ($r = 0.74$, $p < 0.001$). Next, we examine data points for maximum and minimum speed independently. At minimum speed the linear association was again relatively low ($r = 0.76$, $p = 0.003$) whereas at maximum speed it was nearly zero ($r = 0.15$, $p = 0.003$). While there appears to be some basic relationship between noise and CADR, our data suggest that noise levels cannot accurately be predicted from CADR or vice versa when comparing different air cleaner models. However, within each air cleaner model, increasing the operating speed increases the efficiency but also the noise level. For balancing between the efficiency of the air purifier and noise level, the consumers could use the higher settings intermittently when particle producing sources are present.

Table 2
Total Sound Pressure Level (A-Weighted) at different speeds.

Total sound pressure at different operating modes				
Speed	1 (Minimum)	2	3	4 (Maximum)
Whirlpool AP51030	35.4	39.2	42.5	**45.4**
Honeywell HPA300	31.0	41.7	**46.1**	**53.4**
Coway AP1512	26.6	26.6	34.3	**52.9**
Honeywell HA202	31.6	36.4	**45.2**	**51.0**
Idylis AC2123	29.7	40.5	**46.2**	–
Honeywell HA106	31.8	35.0	40.6	**48.8**

Bolded sound pressure levels were above the EPA indoor activity interference and annoyance level (45 dBA; [12].

3.5. Limitations

The ELPI, the main aerosol measurement instrument used in our experiments, allows detecting ultrafine particles only above 0.03 μm. Particles of lower sizes, which likely represent a substantial fraction of diesel exhaust aerosol, might thus have not been accounted for in this study. Furthermore, as this was a laboratory study, the actual air purifier efficiency under real conditions could be different due the effect room size and mixing conditions. Simulation of traffic-related diesel particles is challenging in the laboratory conditions due to variation in the characteristics of

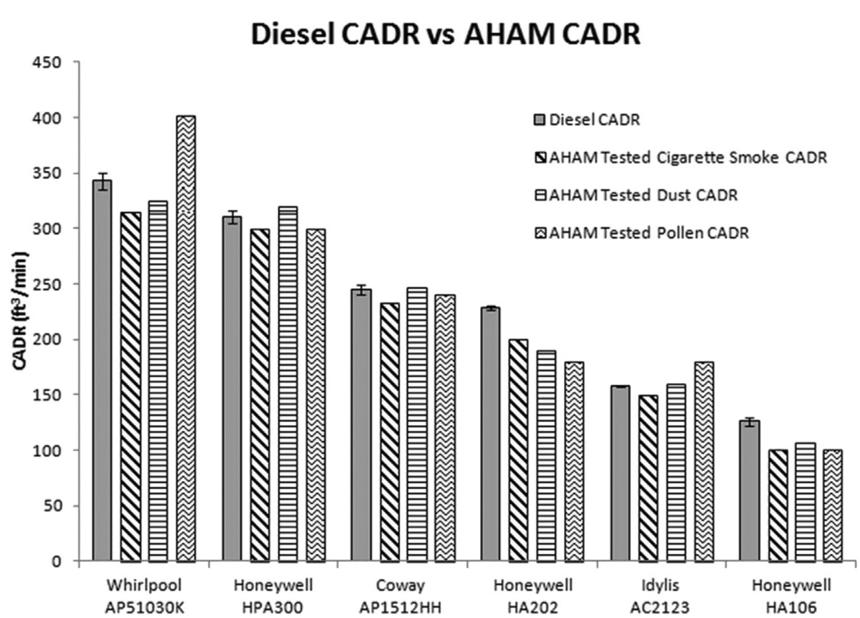

Fig. 7. Diesel CADRs measured in the current study compared to CADRs reported by the Association of Home Appliance Manufacturers (AHAM) (ahamdir.com). Bars represent CADR for each of the six purifiers operating at maximum speed. Error bars show standard deviations for diesel CADR measurements.

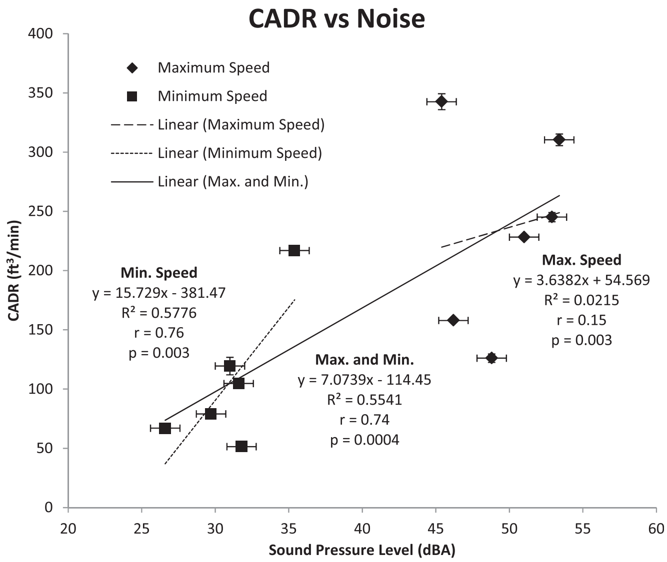

Fig. 8. Association between the noise level and CADR of each air purifier. CADR values were determined with diesel particles while operating on maximum and minimum speeds. Squares indicate CADR values at minimum speed. Diamonds indicate CADR values at maximum speed. Data points represent an average of three repeats and error bars show the standard deviations. Solid line represents the line of best fit for all points. R^2 indicates coefficient of determination.

diesel aerosol by the type of combustion engine, composition of the fuel and emission control equipment. The freshly emitted aerosol rapidly evolves so that the characteristics measured inside buildings near the roadways will be vastly different from those measured at the source [9,17]. However, the ranking order of air purifiers is not expected to change in field conditions.

4. Conclusions

In commercial portable air purifiers which utilize true HEPA filters, filtration efficiency is higher for diesel combustion particles when compared to KCl particles, which are commonly used test particles for filter testing. This result is opposite of what was expected based on previous studies on the efficiency of respirator filters which may be due to fractal structure of diesel particles. Size distributions of KCl and diesel particles differed, with diesel having higher concentrations in the smaller ultrafine range. In nearly all size selective comparisons diesel had a higher CADR than KCl, so use of KCl particles in testing may underestimate the CADR for diesel. Further, our results showed considerable variation in the CADR by particle size showing lowest CADRS for particles <0.1 μm. The size selective CADRs for diesel particles varied up to 23% among the tested size ranges, and up to 16% between CADRs calculated from size selective and total concentrations. Size selective CADR is useful to better target the treatment for specific types of aerosols. Some models of HEPA air purifiers can produce excessive noise at higher settings. Noise levels varied by model, and were not indicative of CADR. Future testing in homes located close to highways will show the efficiency of the air cleaners in real field conditions.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.buildenv.2015.12.018.

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