How efficiently can HEPA purifiers remove priority fine and ultrafine particles from indoor air?

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Highlights

1. It is currently unclear how particles of different sizes are removed by air purifiers
2. Three popular models were tested in China's largest indoor smog chamber
3. Particles <100nm were removed efficiently
4. 200-250nm particles were least efficiently removed
5. Ambient air particles were removed at a similar rate to standard particle types

Abstract

More than 1 million premature deaths in Asia annually are estimated to be associated with indoor air quality. HEPA (high-efficiency particulate air) filter air purifiers (APs) are widely used in urban Chinese residences by the growing middle class, as public awareness of air pollution increases. Currently, understanding of how particle size affects particle removal is inconsistent, and the rate at which different particle types are removed remains largely unknown. Therefore, this investigation aimed to determine the relationship between particle size and the removal efficiency of particles, and how efficiently ambient air is filtered compared to standard particle types which are typically used for such tests (tobacco smoke, dust and pollen). Three of the most popular AP models in China were tested in China's largest indoor controlled chamber laboratory and the removal efficiencies of particles in the 18-514nm range were identified. Each AP had a distinct profile of removal efficiency against particle size, but the three APs shared similarities in performance, with removal efficiency consistently lowest at 200-250nm. This size fraction is important in an exposure context as these particles are abundant in ambient air in mega-cities, can penetrate through building shells effectively, remain airborne for long periods of time and can penetrate the deepest areas of the lungs. Ambient air particles were removed at a similar rate to test particles; this confirms that the Association of Home Appliance Manufacturers' (AHAM) standards are a suitable proxy for "real world" performance.

Keywords: HEPA, Air Purifiers, Air Filtration, Particulate Matter, Ambient PM

1. Introduction

An estimated 4.2 million premature deaths globally were attributed to indoor air pollution in 2016, compared to 3.8 million from outdoor air pollution (WHO, 2018). It is estimated that 90% of people breathe air that does not comply with the World Health Organization Air Quality Guidelines (WHO, 2016). Poor indoor air quality is estimated to be the 9th largest global burden of disease risk (Forouzanfar et al., 2015). The Institute for Health Metrics and Evaluation (2017) attributed 2.6 million premature deaths to indoor air pollution in 2016; Roser and Ritchie (2018) partitioned this estimate by continent with Asia, Africa, Europe and the Americas contributing 74%, 23%, 1% and 2% respectively, demonstrating the significance of premature deaths in Asian countries. On average, modern populations spend more than 80% of their time indoors (Duan et al., 2015; Klepeis et al., 2001), with the indoor environment contributing 19-76% of an individual's ultrafine particle (UFP) exposure (Morawska et al., 2013).

Particulate matter (PM) is defined as the total of all solid and liquid particles suspended in air and is a major determinant of indoor air quality (IAQ) (Lowther et al., 2019). PM is strongly associated with negative health outcomes including strokes, heart failure, asthma and lung cancer (Lim et al., 2012). Size is an important property of PM with regard to its potential health effects. Therefore, PM is commonly categorized based on its aerodynamic diameter into the commonly regulated standards of <10µm (PM_{10}), <2.5µm ($PM_{2.5}$), and <100nm (UFPs). Smaller particle size fractions are able to penetrate further into the respiratory tract and are thought to have a higher toxicity per unit mass due to a larger surface area to mass ratio (Harrison and Yin, 2000; HEI Review Panel, 2013).

In China, more than 1 million premature deaths were attributed to long-term exposure to $PM_{2.5}$ in 2016 (Health Effects Institute, 2018). In 2017, the average annual ambient $PM_{2.5}$ concentration across 338 Chinese cities was 44 µg/m^3, with 73% of these cities failing to meet the national air quality standard of 35 µg/m^3 (Ministry of Ecology and Environment the People's Republic of China, 2018). Furthermore, in China it is estimated that 66-87% of total exposure to $PM_{2.5}$ of outdoor origin occurs within indoor environments (Xiang et al., 2019). It should, however, be noted that although PM levels in China are severe, rapid reductions in PM concentrations are being observed. For example, the average $PM_{2.5}$ concentration in Beijing dropped from 90 μg/m^3 in 2013 to 58 μg/m^3 in 2017 (Ministry of Ecology and Environment of the People's Republic of China, 2018).

The two fundamental sources of PM in indoor environments are: (i) PM generated by indoor sources and activities and (ii) PM generated by outdoor (ambient) sources penetrating indoors. Important indoor PM sources in China include solid fuel use, cooking, smoking and incense burning (Apte and Salvi, 2016; Tse et al., 2011). Solid fuel use is especially dangerous in China from a health perspective (Zhang and Smith, 2007), with solid fuel combustion generating high levels of PM with substantial concentrations of carbon, iron, lead, cadmium and silica (Apte and Salvi, 2016). However, in the absence of major indoor sources, outdoor to indoor air exchange is the most significant source of PM indoors. In a study of 41 Beijing residences, a strong correlation ($R \geq 0.90$) was found between ambient and indoor $PM_{2.5}$, with ambient levels accounting for ≥84% of the variance of indoor levels (Huang et al., 2015). In a summary of 77 studies involving over 4000 homes, indoor/ambient $PM_{2.5}$ ratios were found to vary substantially, from 0.5-3.5 (Chen and Zhao, 2011). Additionally, buildings in China are often ineffective in preventing ambient fine particles from entering indoor environments, with standards for air tightness of residential buildings being less restrictive than in the United Kingdom or United States (Hu et al., 2018). Given that ambient air strongly influences indoor air in China, the composition and properties of the air are likely to be very similar, in contrast to conditions where indoor sources dominate. Therefore, this study focuses on ambient particles that contribute significantly to indoor environments, to estimate the performance of HEPA type air purifiers in real world indoor environments.

High-efficiency particulate air (HEPA) filters are an effective technology for improving IAQ when removing PM is the priority (Zhang et al., 2011). To be defined as such, a HEPA filter must be able to remove 99.97% of particles greater than or equal to 0.3 μm. In a HEPA Air Purifier (AP), air is forced through the HEPA filter and particles are physically captured. The four key mechanisms through which particles are captured are diffusion, interception, inertial impaction and sieving. Diffusion causes the smallest particles to be removed, whereas interception, inertial impaction and sieving processes are more effective at removing the largest particles (Yang, 2012). This means that particles of an intermediate size (100-400nm) are the least efficiently removed (Kowalski et al., 1999). Particle size, charge and shape are the controlling factors determining how effectively particles are removed by the HEPA medium. Studies have shown that HEPA filters can reduce particulate mass and particle number concentrations by >50% (Batterman et al., 2012, 2005; Kelly and Fussell, 2019; Ward et al., 2017; Wheeler et al., 2014). There is also limited evidence to suggest that these reductions lead to improvements in cardio-respiratory health (Fisk, 2013; Morishita et al., 2015). Collectively, studies have reported that use of indoor APs may be associated with reductions in blood pressure, oxidative stress, systematic inflammation and improved lung function (Kelly and Fussell, 2019). Health benefits are most consistently observed in Asian mega-city homes, likely due to higher baseline indoor concentrations and therefore more significant absolute reductions (Kelly and Fussell, 2019).

The Chinese AP market stood at $ 2 billion in 2017 and is predicted to surpass $ 4.3 billion in 2023 (BIS Research, 2018). HEPA AP technology held ~40% of market share in 2016 and is the fastest growing segment of the market (BIS Research, 2018). This growth in the market can be attributed to the growing Chinese middle class and improved awareness of IAQ, with APs mainly used by more affluent members of Chinese society.

The Association of Home Appliance Manufacturers (AHAM) is the main body which verifies the performance of HEPA APs and although they are based within the United States, they produce certified ratings for AP brands all over the world. They measure the filtering efficiency of HEPA APs using the Clean Air Delivery Rate (CADR) metric - the flow rate of particle-free air output in cubic feet per minute (ft^3/min; note: 1 ft^3/min = 0.028 m^3/min). AHAM test the CADR of HEPA APs for three particle types, tobacco smoke (0.09-1 µm), household dust (0.5-3 µm) and pollen (5-11 µm) (AHAM, 2002). However, within a laboratory context it is currently unknown how efficient HEPA APs are in removing “real world” particles, i.e. those found in ambient air. Therefore, it is valuable to investigate how well ambient air particles are removed in comparison to AHAM standard particle types, to see whether the selected particle types are representative of real-world performance.

Combustion-generated particles can penetrate National Institute for Occupational Safety and Health (NIOSH) N95 filtering face-piece respirators more efficiently than standard sodium chloride particles (Gao et al., 2015). Peck et al. (2016) investigated whether this applied to HEPA APs, concluding that diesel combustion particles were removed more efficiently than both NaCl and AHAM test particles, with lowest and highest removal efficiencies at 42-100 nm and 100-700 nm respectively. For standard particle types Sultan et al. (2011) and Waring et al. (2008) both observed erratic CADR performance below ~40 nm (potentially due to instrument sensitivity), and consistent performance above 40 nm. Mølgaard et al. (2014) tested two HEPA APs between 12-660 nm; one performed consistently with increasing size whilst the other experienced a peak in removal efficiency at ~200 nm. Furthermore, Lee et al. (2015) found the lowest filtration efficiencies for three APs to fall within the UFP size range. The findings of these studies contradict our current understanding of the filtration efficiency of HEPA filters - a minimum efficiency of around 200-300 nm varying from filter to filter (Kowalski et al., 1999). However, it is worth noting that a filter may not perform as efficiently within an AP as it does in laboratory tests, given processes like filter bypassing (a result of AP design) and short circuiting of filtered air (Shaughnessy and Sextro, 2006). Therefore, it is currently unclear how effectively "real world" particles of different sizes are removed by commonly available household APs, and why some measurements of performance do not align with the current understanding of the removal processes of HEPA APs. This paper aims to resolve these uncertainties.

Using the Guangzhou Institute of Geochemistry's state of the art chamber laboratory, the largest indoor chamber in China (Wang et al., 2014), this investigation aimed to determine: (a) which particle sizes from ambient air are most and least efficiently removed by APs and explain how this might be important in a real-world context; and (b) whether ambient air particles are removed more or less efficiently than AHAMs standard particle types (tobacco smoke, dust and pollen) and whether AHAM should therefore consider adjusting their CADR measurements accordingly.

2. Methodology

Selection of air purifiers

For this investigation, three HEPA APs were selected to represent the small (CADR 100-200), medium (CADR 200-300) and large (CADR >300) AP sizes (Table 1). All three APs were purchased on the Chinese market and were certified by AHAM. They were selected as popular models that represent different filter, AP design types and sizes. AHAM certification provides a means of allowing performance comparisons to be made between models for the removal of different particle types and their associated size fractions. The reason that tobacco smoke (90-1000 nm), dust (500-3000 nm) and pollen (5000-11000 nm) CADRs for the same AP are different is due to differential removal based on their respective particle sizes.

	CADR (ft^3/min)		
	100-200	200-300	300<
Model	Blueair 203	Midea KJ400G-E33	Philips AC6608
Referred to as	AP(Small)	AP(Medium)	AP(Large)
AP Type	Compact	Tower	Cube
Filter type	Single Filter	Circular Filter	Dual Filter
Tobacco Smoke CADR (ft^3/min)	155	226	369
Dust CADR (ft^3/min)	155	229	389
Pollen CADR (ft^3/min)	155	236	451
Purchase Cost RMB (USD)	2000 (200)	1700 (250)	4000 (700)
Filter Replacements RMB (USD)	200 (50)	600 (90)	600 (90)
Recommended Room Size (sq ft)	240	350	572

*RMB costs represent the cost on the Chinese market, USD represents price on the US market
* 1 ft^3/min = 28.3 litres/min

Table 1. Summary of selected HEPA APs (AHAM, 2018).

Experimental setup

The atmospheric chamber laboratory at the Guangzhou Institute of Geochemistry, Chinese Academy of Science was used for this investigation. The properties of this chamber are described in detail by Wang et al. (2014). It consists of a $30m^3$ fluorinated ethylene propylene Teflon film reactor (hereon referred to as a Teflon reactor) housed within a temperature-controlled enclosure (hereon referred to as the chamber enclosure). The Teflon reactor can be filled and vented using pumps with a flow rate in excess of $1m^3$/min, meaning that it may be filled entirely within 30 minutes. A blower motor from a high-volume air sampler using a tube with a 6 cm bore was used to minimize particle losses. Figure 1 illustrates the layout of the chamber laboratory.

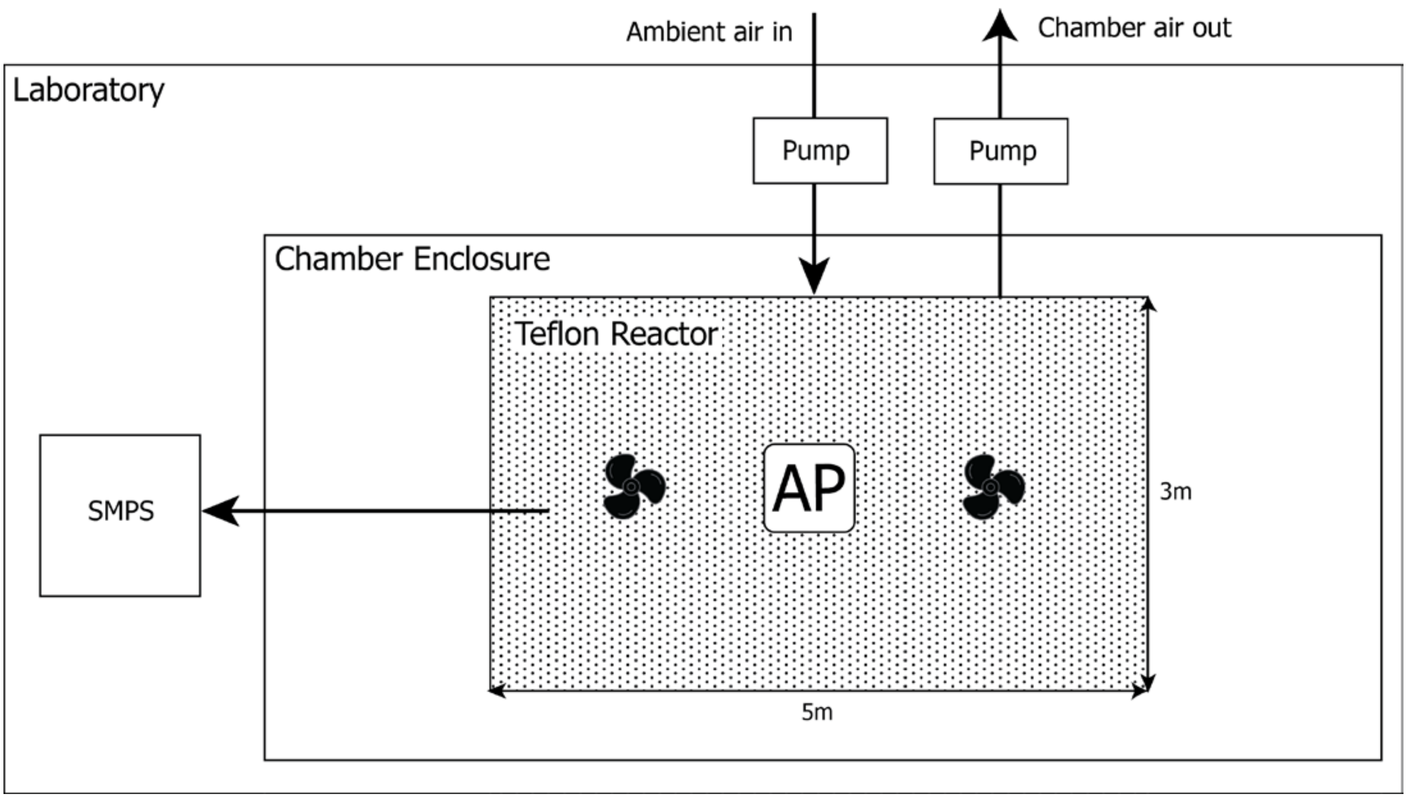

Figure 1. Layout of the chamber laboratory, chamber enclosure and Teflon reactor at the Guangzhou Institute of Geochemistry.

During the experiments, the Teflon reactor was filled entirely with ambient air from outside the laboratory. It is important to understand the composition of this ambient air. Liu et al. (2014) have previously reported that on the Guangzhou Institute of Geochemistry site, carbonaceous aerosols (which contribute a large fraction of $PM_{2.5}$) could be attributed to fossil fuel (46%), non-fossil fuel (51%) and biomass burning (3%).

In a larger study of the city, in the dry season, when this investigation was conducted, ambient PM was largely composed of emissions from vehicular (21%), industrial (20%), residential (4%), power generation (2%) and other unknown sources (53%) (Cui et al., 2015). In 2017 Guangzhou had an annual average $PM_{2.5}$ concentration of 35 µg/m^3 (Ministry of Ecology and Environment the People's Republic of China, 2018), with $PM_{2.5}$ in the dry season of 2013 composed of secondary organic aerosol (23%), primary organic aerosol (14%), sulphate (14%), nitrate (11%), ammonium (7%), elemental carbon (4%) and an unidentified fraction (28%) (Cui et al., 2015). The atmospheric chamber laboratory is located ~250m from an 8-lane highway, and therefore UFPs will likely be of vehicular origin. Air was sampled at a height of 1m, directly outside the atmospheric chamber laboratory.

Before each test the Teflon reactor was evacuated, and ambient air was drawn in from directly outside the laboratory. Two Teflon coated fans located within the reactor gently mixed the air during filling and throughout the duration of each experiment. The Teflon reactor was not a fixed volume or shape like a stainless-steel chamber, and so there was some variation in the reactor volume between experiments. This is addressed in more detail later. Given that the air was purged entirely from the reactor before it was refilled, no additional cleaning was required between test runs. A TSI SMPS (Scanning Mobility Particle Sizer) consisting of a Differential Mobility Analyzer (DMA - classifier model 3080) and Condensation Particle Counter (CPC - model 3775) was used to measure the total particle number concentration (PNC) and particle size distribution (PSD) between 18-514nm in 94 size bins, with a full scan completed once every minute. Once the Teflon reactor was filled with ambient air, the AP was started. Experiments were repeated a minimum of four times for each AP, at each of three fan speeds (low, medium and high). A new HEPA air filter was used for each AP for the duration of the repeats, therefore, filter loading had a minimal effect on performance given that a single filter was used for no more than 24 hours in total (filters are rated for roughly ~1-2 years of regular use).

Clean air delivery rate

CADR was calculated using the equation $CADR = V(Dm - Dn)$ where V is the volume of Teflon reactor in ft^3, Dm is the particle number decay rate when the AP is active and Dn is the natural particle number decay rate in the reactor when the AP is inactive (AHAM, 2002). Dm and Dn are first-order loss rates (min^{-1}), the decay constants of an exponential decay in particulate number concentrations, as measured by the SMPS. Initial total particle number concentrations within the reactor varied between $8x10^4$ – $2x10^5$ #/cm^3, depending on the ambient conditions at the time.

If a decay series met either of the following criteria, then it was excluded; (a) if the decay series contained less than 9 points, meaning that the minimum test duration was less than 9 minutes (AHAM, 2002), and (b) if greater than 30% of values in the decay series exceeded their previous values.

Criteria (a) was responsible for identifying failed decay series on the largest AP at the highest fan speed, with the AP cleaning the reactor too quickly (<10 minutes), making calculations of decay rate and therefore CADR unreliable. Criteria (b) was mainly used to identify failures on the smallest AP at the lowest fan speed, with some decay series being difficult to identify amongst variability caused by mixing. Failure to meet these criteria is illustrated in Table 2.

Calculating natural decay rate was essential to determine how much particle removal was due to the AP and how much was due to other processes including agglomeration, wall loss and deposition. Natural Decay rates in the Teflon reactor were calculated with an AP present, but not actively running, using the SMPS for each of the 94 size bins from 18-514nm. In this way, both the measured decay rate and natural decay rate were specific to the particle size. The decay rates were measured five times within a single day, see Figure 2.

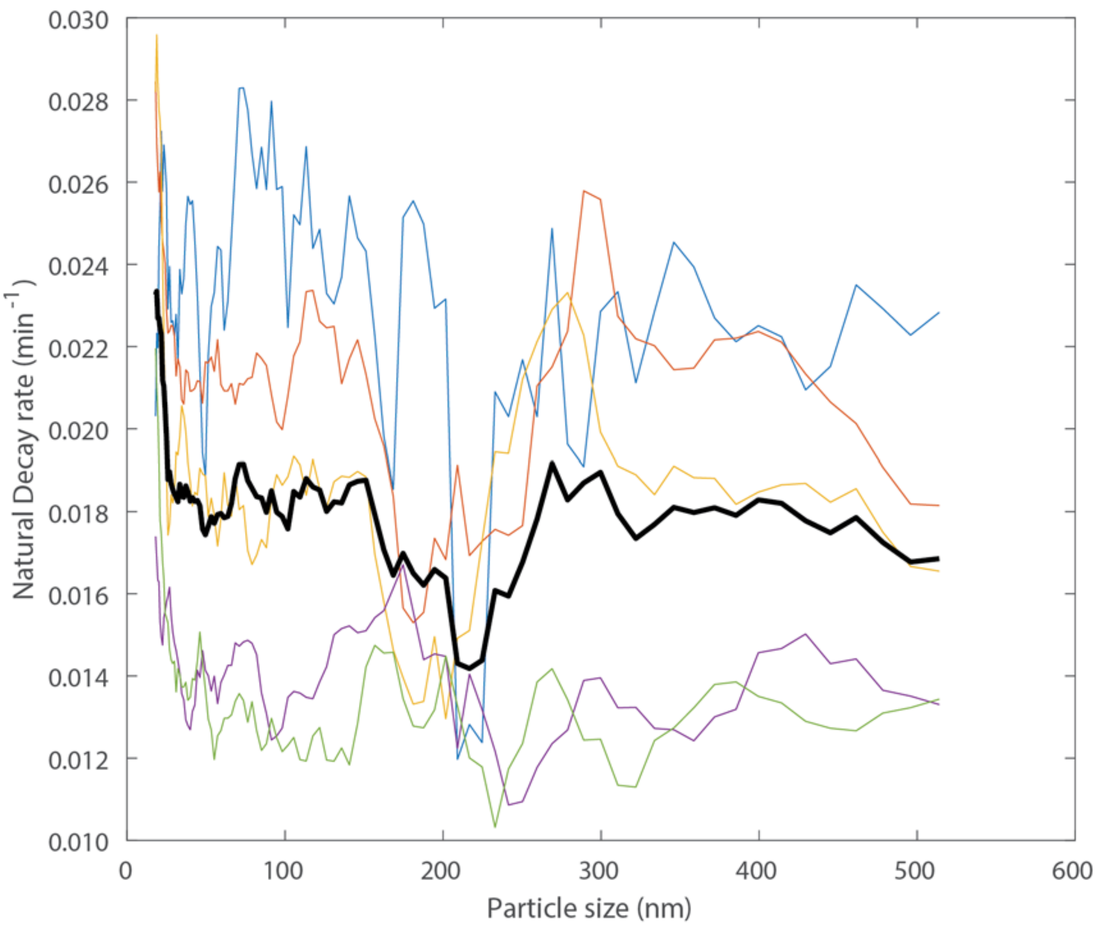

Figure 2. Natural decay rate (min^{-1}) in Teflon reactor without use of APs, n=5. Solid black line represents the average natural decay rate (min^{-1}).

Given that the Teflon reactor was inflated using ambient air, the reactor was not a fixed volume at the start of every experiment. The minimum and maximum volumes for the reactor at the fixed roof height were therefore calculated using the trace gas injection method (Mazzeo, 2012). The minimum and maximum volumes were 24.5 m^3 and 27.2 m^3 respectively, however, the reactor was inflated to an intermediate volume between the minimum and maximum volume. A volume of 25.9 m^3 (the midpoint between maximum and minimum volumes) was therefore used in the calculations.

In comparable chamber studies, high concentrations of tobacco smoke, vehicle exhaust, sodium chloride or pollen were released into the chamber and mixed (Mølgaard et al., 2014; Peck et al., 2016; Sultan et al., 2011; Waring et al., 2008). In this experiment, the reactor was filled with much lower particle concentrations in ambient air. The challenges associated with this investigation were likely larger than that of comparable chamber studies; given the nature of using ambient air, which varies temporally in composition, humidity and temperature. Furthermore, given that the reactor needed to be inflated to an approximate size, this limited the ability to use a fixed volume of air. However, measuring ambient air (with complex compositions) under real world conditions is likely more indicative of real-world performance than laboratory tests utilizing standardized particle types.

3. Results and discussion

Air purifier performance statistics

Air Purifier	Fan Speed	CADR (ft^3min^{-1}) Statistics								Electrical Power Draw (W)	Energy efficiency (CADR/W)	Noise (dB)	Noise rating (CADR/dB)
		Min	Max	Mean (s.d.)	Coefficient of Variation (%)	Median	N	R	S				
AP(Large)	High	130	440	316 (58)	18	330	6	564	64	60.5	5.2	51.4	6.1
	Medium	123	346	251 (35)	14	251	6	564	7	35.0	7.2	44.2	5.7
	Low	58	279	151 (36)	24	152	6	564	1	20.0	7.6	34.5	4.4
AP(Medium)	High	130	288	230 (23)	10	232	4	376	1	36.3	6.3	49.9	4.6
	Medium	75	221	154 (25)	17	161	4	376	1	16.1	9.6	40.2	3.8
	Low	57	112	95 (10)	11	98	4	376	2	6.9	13.8	N/A	N/A
AP(Small)	High	25.9	327	172 (52)	31	160	7	658	4	61.5	2.8	47.0	3.7
	Medium	98	308	155 (29)	19	156	5	470	1	45.2	3.4	37.3	4.2
	Low	34	79	55 (10)	18	56	4	376	23	16.6	3.3	34.5	2.3

Table 2. Air Purifier Statistics, R is the number of repeats, N is the number of decay series measured (R multiplied by the number of size bins = 94), S is the number of runs that failed to meet the selection criteria. The CADR values presented were averaged over the 94 size bins from 18-514 nm.

Our results show that larger APs and higher fan speeds generate larger average CADRs than smaller APs and lower fan speeds, as expected. This aligned with electrical power draw, which also increased with increasing AP size and fan speed. The coefficients of variation measured over 18-514nm were comparable to those of Waring et al. (2008), who measured 16% and 14% for the two HEPA APs tested. Table 2 also shows that the APs were most noise and energy efficient when running on their lowest fan speeds. On lower fan speeds AP (Medium) was substantially more energy efficient than AP (Large) or AP (Small).

Air purifier removal efficiency with particle size

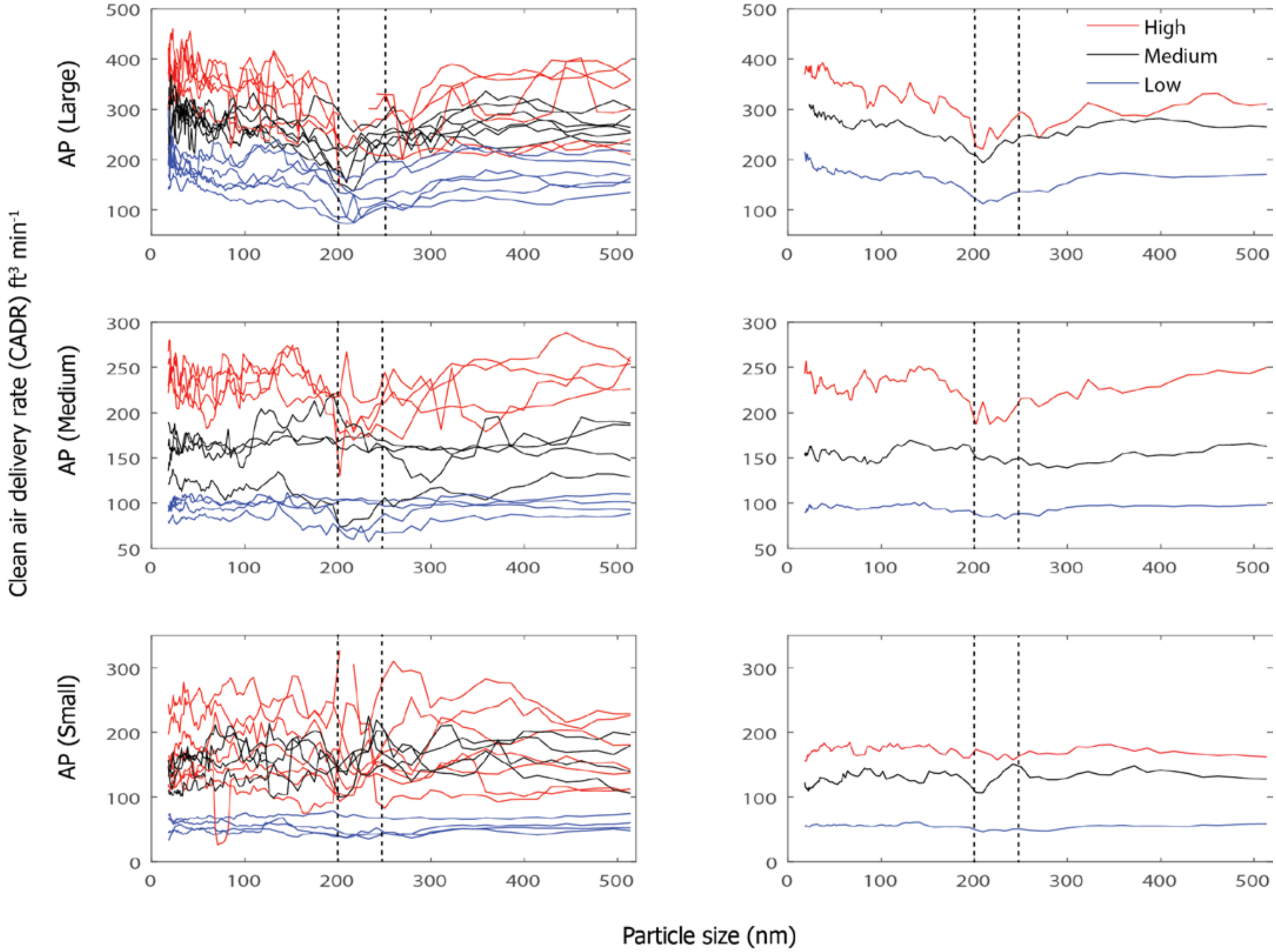

Figure 3. CADR as a function of particle size for three APs and for three fan speeds. Each line on the left plots represents a single AP decay series whilst the lines on the right plots show the average for each fan speed.

Figure 3 shows that AP (Large), (Medium) and (Small) are all effective at removing UFPs from ambient air. Each AP showed a distinctive removal profile which was consistent across the fan speeds, most likely attributed to the design of the HEPA filter and sealing. These profiles, although distinct, share some common themes. Generally, the APs performed least well between ~200-250nm, which is consistent with the understanding of the removal processes of HEPA filters (Kowalski et al., 1999; Stafford and Ettinger, 1972). This can be seen more clearly in Figure 4.

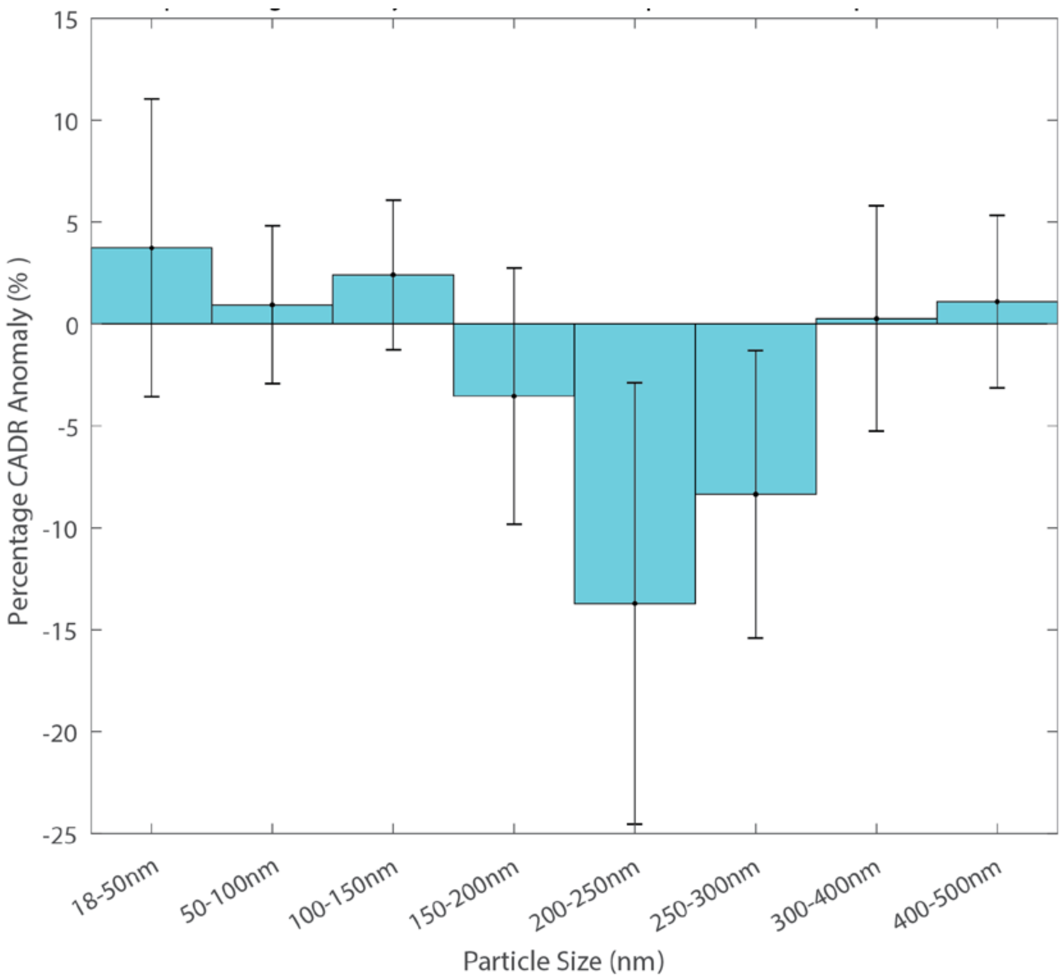

Figure 4. Percentage change in CADR relative to mean CADR for particle sizes between 18-500nm averaged over all tested air purifiers and fan speeds. Each value is the average value for the size bin. Percentage anomaly was calculated for the average of each of the APs for each given fan speed (n=9) and was divided into size bins. The standard deviation was calculated across the 9 arrays and is shown with the error bars indicating one standard deviation.

Figure 4 is consistent with the typical performance of a HEPA filter (minimum efficiency 200-300nm) (Kowalski et al., 1999; Stafford and Ettinger, 1972), and aligns with the understanding that diffusion primarily removes the smallest particles and that interception, inertial impaction and sieving primarily remove the largest particles, with particles in the intermediate size range (~100-400nm) least efficiently removed. However, this is contrary to the findings of Peck et al. (2016) who observed peak performance between 100-700nm and Sultan et al. (2011), Waring et al. (2008) and Lee et al. (2015) who observed lowest performance for particles <100nm and consistent performance above this. In Sultan et al. (2011) and Waring et al. (2008), these unexpected performances were attributed to non-uniform mixing in the chamber, with air flows short circuiting the APs and isolated flows forming due to particle size and flow dynamics. However, our results, based on the use of a Teflon reactor, may be more reliable than those generated in stainless-steel chambers, as our reactor was specifically designed to mix uniformly and reduce particle deposition. In addition, given that the Teflon reactor is more rounded than a stainless-steel chamber, this will promote mixing, reducing the likelihood of isolated flow-pathways forming. Waring et al. (2008) also attributed lower performances for UFPs due to particles within the APs bypassing the filter medium. Differences between our measurements and those of Waring et al. (2008) could be due to AP housing and filters being designed to be sealed more tightly during the past 10 years, in order to force particles through the filter medium. Alternatively, the subset of APs selected in this study could be especially well sealed; this may be linked to the bias towards selecting APs that were popular on the Chinese market and were therefore likely effective.

Given that the lowest removal efficiencies were observed within this 200-300nm range, it is worth considering the real-world importance of this size fraction. Firstly, these particles are relevant in a health context. Particles of <300nm can penetrate into the alveolar region of the lungs (Heyder, 2004) and pass into the circulation system, with particles <200nm being found in the brain (Maher et al., 2016) and it is thought that particles <240nm can cross the placental barrier, potentially impacting upon fetuses (Wick et al., 2010). Secondly, because the removal properties of building shells are similar to those of a HEPA filter, the particle size that most effectively penetrates cracks in building shells is ~200nm, similar to the 200-250nm for our HEPA APs (Hänninen et al., 2013; Liu and Nazaroff, 2001). Thirdly, the deposition velocity (m/s), the rate at which particles are deposited onto surfaces, is also lowest at ~200 nm which is consistent with the reactor deposition rates in this investigation (Lai, 2002). This means that particles within this size range can effectively penetrate building shells and will have longer airborne residence times, due to lower depositional velocities.

Particles within the 200-300nm size range are usually found at low concentrations in the atmosphere, typically falling between the Aitken (10-50 nm) and Accumulation (50-1000 nm) particle modes, subject to controls such as composition, humidity and turbulence. Irrespective, Cai et al. (2017) showed that there are still a significant number of particles found within this size range in Guangzhou, in fact, a second accumulation mode was observed with peak number concentrations within the 200-300nm range. Another investigation across 60 Hong Kong residences concluded that particles <400nm contributed the most to total particle mass (Chao et al., 2002). This is unusual, given that the smallest particles usually contribute the least to total mass measurements. The large concentrations of these particles in megacities could be attributed to secondary aerosols, vehicular and industrial emissions, which generate smaller sized particles (Zhang et al., 2018).

In summary, within Asian mega-cities, particles within the 200-300nm range are abundant in ambient air, can penetrate building shells effectively, can remain airborne for long periods, and are able to penetrate the deepest and most sensitive regions of the body. This means that the population are more likely to be exposed to particles of this size fraction than particles of other fractions in the indoor environment, which may have important health consequences. It is therefore important to note that HEPA APs currently are least efficient at removing this size fraction. It would be beneficial to design another filter media which could remove these 200-300nm particles without dramatically changing the pressure gradient across the filter medium.

Air Purifier performance for differing particulate matter types

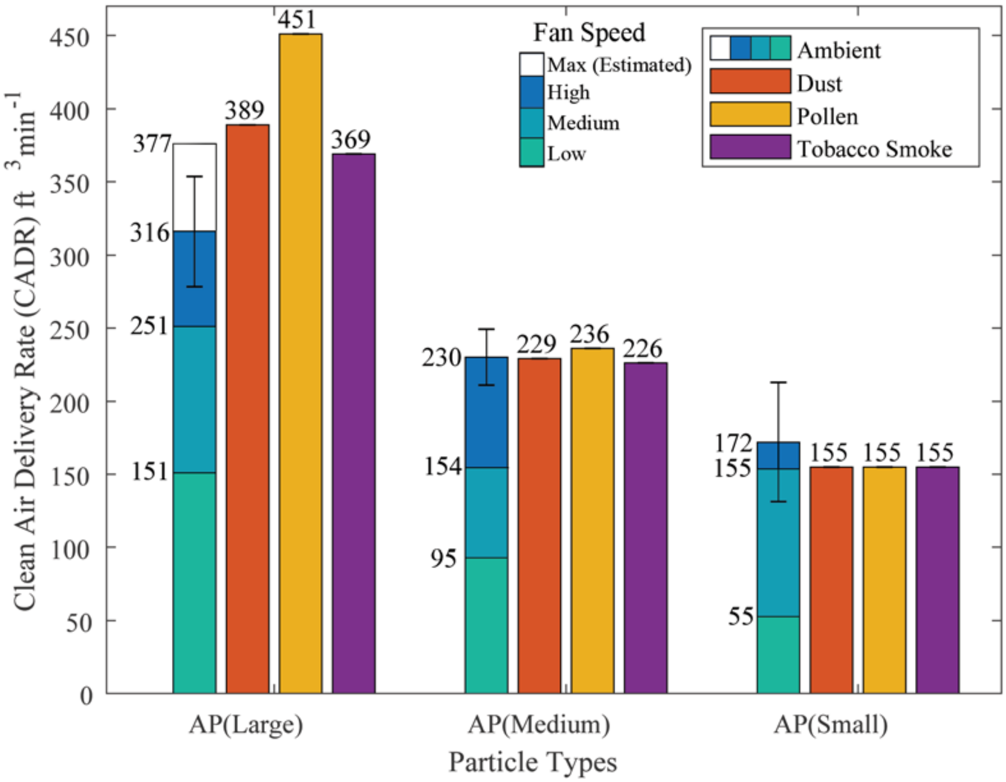

Figure 5. The CADR (ft^{3}min^{-1}) for different particle types for three APs. Ambient measurements collected in this study were compared against AHAM dust, pollen and tobacco smoke CADRs for the same APs. Error bars represent 95% confidence intervals around the means. For AP (Large), performance on maximum fan speed is estimated based on energy consumption ≈ fan rpm ≈ CADR Performance**.** Given that APs are only tested by AHAM at max speed, this should be used for comparison with AHAM measurements.

In this investigation, ambient particles, despite representing a smaller size fraction (18-514nm) than tobacco smoke (90-1000nm), dust (500-3000nm) and pollen (5000-11000nm), were removed with similar (or greater) efficiency than AHAM's standard particle types, as seen in Figure 5. Therefore, the AHAM standards appear indicative of how efficiently ambient air particles are removed by APs, and hence seem an appropriate proxy for "real world" AP performance.

Our results support Peck et al. (2016) who found that particles generated by diesel combustion were removed at a greater rate than AHAMs "standard" particle types. This similarity could be due to the strong influence of vehicular emissions (~20%) in ambient air in Guangzhou. Given the size of the diesel combustion generated particles used by Peck et al. (2016), and the ambient particles used in this experiment, we would expect them to be removed less efficiently than AHAM standard particle types. Peck et al. (2016) attributed this higher removal efficiency of diesel particles to differences in the measured size ranges between AHAM and those measured within their investigation. However, we hypothesize that this is likely due to smaller ambient and diesel particles having higher charge to mass ratios compared to tobacco, dust or pollen particles, which increases removal through the process of diffusion. As the filter media becomes more saturated with charged particles, this will more effectively remove particles with higher charge to mass ratios (Hanley et al., 1994).

Applying the relationship between particle size and AP removal efficiency as identified in Figure 5, we can estimate how efficiently different particle types commonly generated in indoor environments may be removed.

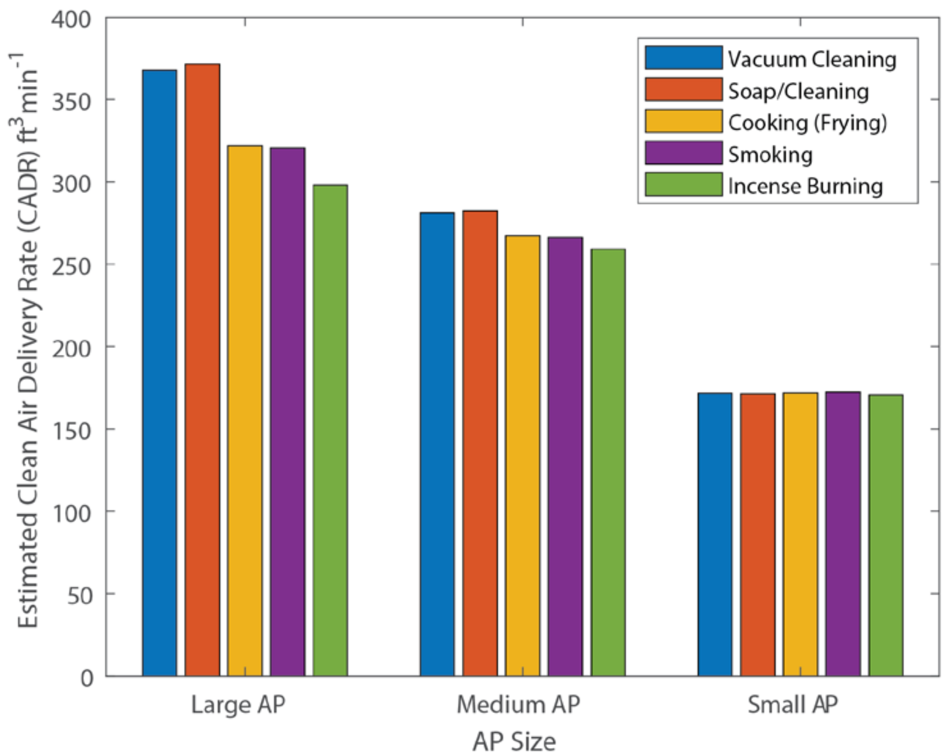

Figure 6. Estimated CADR values for different particle types for three APs running on high fan speed. The particle size distributions utilized to estimate CADR were adapted from Vu et al., (2017), assuming a log normal distribution of particle size generation. This estimation of CADR is based on particles being differentially removed based on particles size; it therefore does not account for other factors affecting removal, for example, particle shape, composition and electrostatic charges. Particle types are ordered in increasing mode particle size, with vacuum cleaning particles being the smallest and incense burning being the largest.

By applying PSDs for different particle types adapted from Vu et al. (2017), we can estimate CADR values for different particle types for each of our APs, as shown by Figure 6. For the largest AP, a 20% difference in CADR can be seen between the most and least efficiently removed particle types. The particle types with the lowest CADR scores were those with high particle number concentrations in the 200-250 nm range, where particles are least effectively removed. It is especially noteworthy that fry cooking, smoking and incense particles are removed less efficiently, given that these are common practices in Chinese households (Apte and Salvi, 2016).

Conclusions

Using the largest indoor smog chamber in China, this investigation aimed to determine (a) which particle sizes from ambient air were most and least efficiently removed by APs and explain how this may be important in a real world context and (b) whether ambient air particles were removed more or less effectively than AHAMs standard particle types.

This investigation found that although UFPs were effectively removed by each of the APs, a reduced removal efficiency was observed within the 200-250nm size range. This is important in a health context, with particles within that size range being present in significant concentrations in mega-cities (Cai et al., 2017), able to effectively penetrate the shells of buildings (Hänninen et al., 2013; Liu and Nazaroff, 2001), remain suspended (Lai, 2002), and penetrate into the deepest areas of the body (Heyder, 2004; Maher et al., 2016; Wick et al., 2010). Furthermore, this investigation found that ambient air particles were removed at a similar rate to AHAMs standard particle types, suggesting that these standards are representative of "real world" performance.

Further investigations should try to identify technologies which may improve the removal of 200-250 nm particles by HEPA filters without dramatically affecting the pressure drop. Additionally, it is necessary to understand the degree to which other properties of particles, apart from size, affect their removal rates.

This could be used to further identify key particle types that may be important within a health context and which are more difficult to remove through filtering. Furthermore, some aspects of HEPA AP use should be explored, for example, how factors like AP placement, number of APs, rate of air exchange and mixing may influence AP performance within a residential setting.

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