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Factors affecting real-world applications of HEPA purifiers in improving indoor air quality

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With modern populations spending ∼90% of their time indoors, particulate matter (PM), a significant component of indoor air quality (IAQ), is of serious concern within indoor environments. High-efficiency particulate air (HEPA) filter technologies are commonly used to remove PM. Although their performance is well defined within a laboratory setting, many aspects of their real-world use remain poorly understood. This study investigated (i) the impact of air change rate on air purifier effectiveness, and how this influences energy-efficiency and other gaseous components of indoor air quality, and (ii) the relative effectiveness of operating single and multiple air purifiers within a multi-room residence. Measurements of air change and PM concentrations made in an Asian mega-city apartment, were used alongside air purifier performance data and external PM measurements to create a box model to simulate air purifier performance under different scenarios. Increasing air change rate inhibited the performance of air purifiers by acting as a source of outdoor PM into the indoor environment. Although sealing indoor environments is recommended to maximize the removal of PM, this permits the accumulation of gaseous components of IAQ and reduces energy efficiency. Use of multiple air purifiers in a multi-room residence reduces PM at a greater rate than use of a single more powerful air purifier. Moreover, use of multiple air purifiers is more energy-efficient, although the maintenance and upfront costs are likely to be greater.

Environmental significance

Although the performance of HEPA type purifiers is well documented within laboratory and chamber settings, little is known about their performance within real-world dwellings. Understanding the performance of HEPA type purifiers in the real-world can improve recommendations for their use and allow owners to further reduce their in-dwelling particulate matter (PM) exposures. This research shows that decreasing air exchange rate, can increase the PM removal efficiency of purifiers, however, this may lead to increased accumulation of gaseous components of indoor air quality and reduced energy efficiency. And additionally, use of multiple purifiers in a multi-room residence may increase PM removal efficiency and purifier energy efficiency, however, this will be at the expense of greater upfront and maintenance costs.

1 Introduction

It is well established that modern populations spend ∼90% of their time indoors, with indoor air pollution being a large risk factor to human health.[1,2] Particulate Matter (PM), the sum of all liquid and solid particles suspended in air, is a major determinant of indoor air quality (IAQ)[3] and is associated with a range of adverse health effects including myocardial infarction, stroke, heart failure, asthma, chronic obstructive pulmonary disease (COPD) and lung cancer.[4]

Rapid reductions of ambient (outdoor) PM concentrations are being observed in China. For example, a ∼30% drop in population-weighted annual mean $PM_{2.5}$ concentrations was reported between 2013 and 2017.[5] However, PM is still of concern given that in 2017, 73% of 338 Chinese cities failed to meet China's national air quality standards for $PM_{2.5}$ and PM_{10}.[6] Moreover, 66–87% of total exposure to $PM_{2.5}$ of outdoor origin occurs within indoor environments. This exposure contributed up to three-quarters of total premature mortalities in urban China in 2015.[7]

Indoor PM originates from indoor sources or penetrates inwards from outdoors. Typical indoor sources of PM include cooking, smoking, cleaning and burning incense or candles.[8] When ambient PM concentrations are low, indoor sources are the main determinant of indoor PM concentration, and because of the confined nature of indoor environments, these concentrations can be raised to several orders of magnitude higher

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than ambient concentrations.[3] However, in the absence of indoor PM sources, indoor concentrations correlate strongly with outdoor concentrations.[9,10] Therefore, in Chinese mega-cities where ambient pollution is often severe, the impact of outdoor sources on indoor PM is of concern. Although PM is especially important within a health context, a holistic view of IAQ must also consider gaseous components, for example, carbon dioxide, VOCs, nitrogen dioxide, and sulfur dioxide.[11]

Air change rates (h^{-1}) are a measure of how many times the air within a room is replaced within an hour. Air change can be an important control on indoor PM; for example, when ambient concentrations are lower than indoor concentrations, air change can reduce indoor PM; conversely, when ambient concentrations are higher than indoor concentrations, air change can increase indoor concentrations.[12] In more economically developed countries, reducing air change rates to improve the energy efficiency of buildings is becoming increasingly common. However, this has implications for IAQ, allowing some pollutants to accumulate to much higher concentrations.[3] Conversely, in areas with high ambient concentrations, such as Chinese mega-cities, reducing air change rates by sealing indoor environments can be beneficial to IAQ.[3]

High-efficiency particulate air (HEPA) type air purifiers, hereon referred to as APs, are valuable for reducing PM concentrations within indoor environments.[13] It is well established that the use of HEPA APs is associated with considerable reductions in PM concentration.[14–17] These reductions are associated with modest improvements in health outcomes.[18] Health improvements are most consistently observed within homes in Asian mega-cities, likely due to significant rates of ambient PM ingress, and therefore more significant reductions in PM.[16] Air purifiers are soon to become the fifth largest-selling home appliance in China, with sales of APs increasing from 112 million units in 2011 to 982 million in 2017.[19] With the burgeoning domestic use of APs in China likely to further increase, understanding their real-world performance is essential.

Research into APs removal of PM under controlled conditions is extensive, and intervention studies are improving the understanding of APs effects on health.[18] However, recommendations on how APs should be operated in real-world conditions are not clearly defined.[13,18] Therefore, it is necessary to better understand how technical (*e.g.*, runtimes, noise, maintenance, filter changes) and practical aspects (*e.g.*, AP positioning, the quantity of APs, air change rates) of APs impact their effectiveness.

Within existing literature, air change is often considered a removal mechanism of PM.[20] However, this is the perspective of more developed countries, where indoor concentrations typically exceed ambient concentrations.[10] In megacities with high levels of ambient PM pollution, where APs are most commonly used, ambient PM concentrations often exceed indoor concentrations, making air change a source of PM, rather than a sink.[21] Therefore, it is necessary to understand the effect of air change on AP performance and PM removal; to assess the advantages and disadvantages of decreasing air change in Chinese residences, and the implications of this on the gaseous components of IAQ.

Furthermore, it is unknown how effective a single AP is in reducing PM spatially throughout a residence, given the barriers to mixing presented by walls, doors, and furniture. Conversely, the benefits of having multiple APs deployed throughout a residence are also poorly defined.[13]

Therefore, this investigation aims to determine (i) how air change affects the efficiency of AP use and the implications of this on a holistic view of IAQ and energy-efficiency and (ii) how effective single and multiple APs scenarios are in reducing PM in a multi-room residence. This is investigated in a multi-room residence in Guangzhou China and is applied in a broader context using modelling.

2 Methodology

2 1 Description of the study location and approach

The investigations were conducted in a typical residential apartment located within the Guangzhou Institute of Geochemistry's Campus, in Guangzhou, China. The layout of the apartment is illustrated in Fig. 1. The two-bedroom, third story, seventy-five square meter non-occupied apartment was lightly furnished, with furniture and flooring being mostly wooden, typical for a residential apartment in south China. The area under investigation was forty-five square meters, and represents a smaller section of the whole apartment. This needed to be of an appropriate size to be cleaned by the largest AP alone (less than fifty-three square meters). There were no potent indoor sources of pollution during the study duration.

The investigation consisted of two experiments. Experiment 1 aimed to determine how air change rates affect the effectiveness of APs in removing PM from indoor air. This is designed to inform whether inhabitants should aim to reduce air changes in indoor environments when using an AP, but also considers the effect this will have on the gaseous components of IAQ. Experiment 1 uses a combination of measurement and modelling components.

Experiment 2 aimed to determine how effectively a single AP can clean an apartment of an appropriate size given barriers to mixing like walls, doors and furniture, and how this compared to operating multiple APs throughout the apartment.

2.2 Instrumentation and measurements

PM size-resolved number concentrations from 18–514 nm were measured in the residence using a TSI SMPS (classifier model 3082, CPC model 3775) with a full scan completed every minute. For both experiments, the SMPS was located in Room A and sampled air from three locations, namely, Room A, Room B and Room C. Sampling throughout the apartment was necessary to understand the spatial distributions of PM in the residence. The PM loss rates of the TSI conductive tubing taking samples from the rooms to the SMPS unit were accounted for by sampling air from the same room with each of the three lengths of hose, and then calculating the difference between measurements made by the longer hoses *vs.* having no hose. During the experiments, the SMPS inlet hose was switched at 5 minute intervals, to sample from different locations throughout the apartment. An

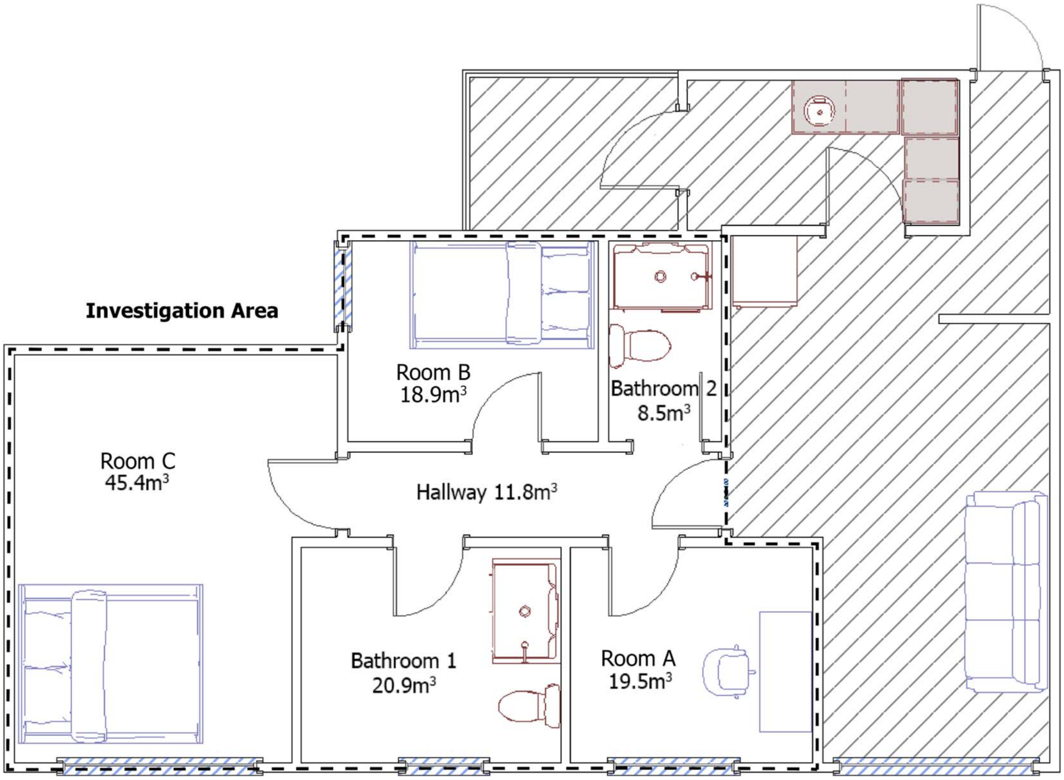

Fig. 1 Floor plan of the investigation apartment; a two-bedroom, third story, seventy-five square meter apartment in Guangzhou, China. The investigation area (contained within the dotted line) marks the section of the apartment used within these experiments and the room height was 2.8 meters.

example time series, showing how it is divided into multiple rooms, is illustrated in Fig. 2. AP performance was measured as total particle number decay rate, with greater decay rates being associated with more removal of PM and improved AP performance. Fig. 2(b) illustrates how the particle number decay rates were calculated, in order to represent AP performance.

Using particle number measurements, as opposed to mass measurements, allowed this investigation to quantify the APs effectiveness in reducing particle number concentrations, which are associated with smaller sized particles and ultra-fine particles, which are considered to be of greater health importance.[22,23] This size range is particularly relevant, as it contains the 200–250 nm size fraction, which is considered the most difficult for purifiers to remove effectively.[13,24]

Three popular HEPA type APs on the Chinese market were used for these experiments, these are referred to as 'AP large', 'AP medium' and 'AP small' and are described in detail in Lowther *et al.* (2020).[13] The HEPA filters had been used previously in Lowther *et al.* (2020),[13] but only for several hours under ambient conditions, so filter loading was minimal.

The measurements for Experiment 1 and 2 were conducted in May and June of 2019.

2.3 Experiment 1

The effect of air change on AP performance is largely unknown within the context of mega-cities with higher levels of ambient PM. Therefore, this investigation measures the effect of different air change conditions on the performance of three air purifiers within a real-world indoor environment. Modelling was conducted to give a better understanding of how changes to air change rate might be important when considering a holistic view of IAQ.

Three ventilation scenarios were selected to test in each room: sealed (windows, doors and air conditioning closed); air conditioning on, and windows open. These ventilation scenarios were selected as they were available for each of the measurement rooms. Air change rates were quantified for each of the three rooms and for each of the ventilation conditions using the CO_2 decay method.[25] Briefly, CO_2 was released from portable canisters and was mixed using fans, then, CO_2 decay was measured using a portable air quality monitoring system.[26] The room was unoccupied during the experiment, to reduce any impact of CO_2 generated by human metabolism. Air change rates displayed within Table 1 represent the average of three decays for each of the nine scenarios.

During these experiments, every room was ventilated until indoor PM concentrations matched ambient PM concentrations. Then, the desired ventilation condition was set up and finally, the AP was activated. Once particle concentrations had reached equilibrium, the air purifier was switched off, the room was ventilated, and the next repeat began. The point of equilibrium was determined between the competition of two processes, *i.e.* ventilation, the source of PM and the AP, the sink of PM.

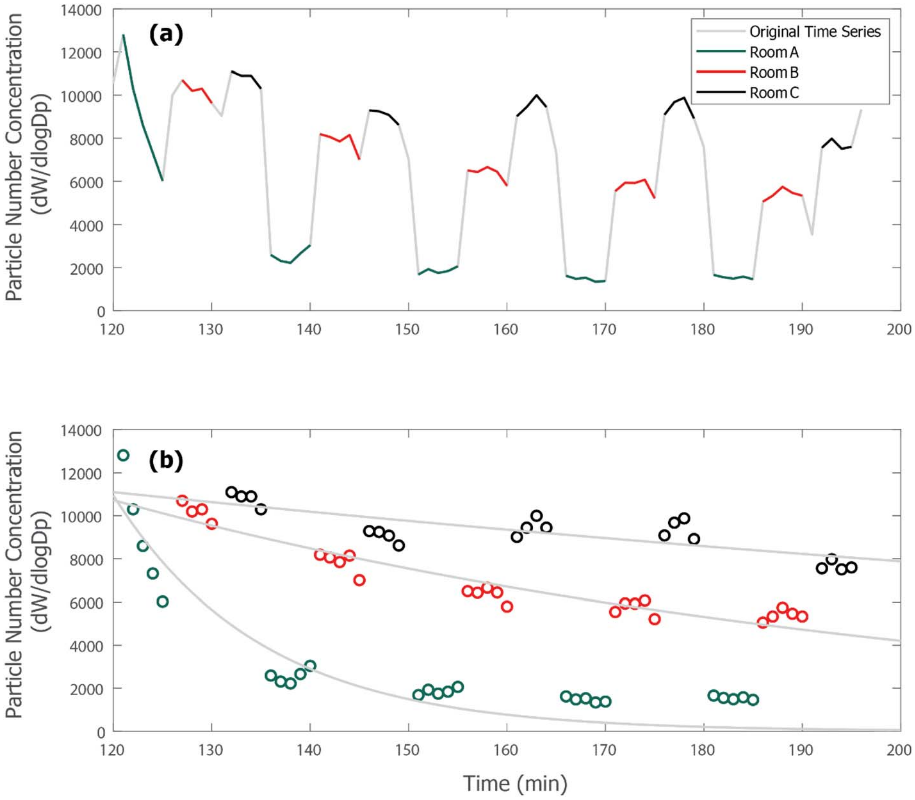

Fig. 2 Measuring particulate matter decay across three rooms with a HEPA purifier active by switching the inlet hose on the SMPS at five-minute intervals. (a) Shows an example time-series and how this varies for three rooms and (b) shows an example exponential fit from which a rate of decay can be calculated.

2.4 Experiment 2

Although commercially available APs are given a recommended room size,[27] when considering the barriers to mixing which are present within most multi-room residences, it is largely unknown to what degree they can reduce PM throughout the dwelling. Therefore, this study assessed the advantages and disadvantages of operating single and multiple APs within a multi-room residence.

For the single AP scenario, AP large was operated on its maximum fan speed and was placed in Room A. At maximum fan speed, this AP is rated to clean a 53 m^2 area and was therefore suitable for use within the 45 m^2 investigation area. For the multiple AP scenario, Room A, Room B and Room C contained the small, medium and large APs respectively, each running on their lowest fan speed. The Clean Air Delivery Rate (CADR) of the two scenarios was chosen to be roughly equivalent with the single AP and multiple AP scenarios outputting 316 and 301 $ft^3\ min^{-1}$ (537 and 511 $m^3\ hour^{-1}$) respectively.[13] The multiple AP scenario is more energy-efficient, consuming 43.5 W compared to 69.7 W for the single AP scenario.[13]

Before the experiments, the investigation area was ventilated with air from outdoors until indoor PM concentrations matched outdoor concentrations. Next, the investigation area was sealed, with windows closed and air conditioning turned off, to minimize infiltration of outdoor PM. During these experiments, doors within the investigation area remained open, to facilitate mixing between rooms.

2.5 Model development

The laboratory-determined performance of APs, room volumes and measured air change rates were supplemented with externally sourced data to develop a box model of how PM is affected by APs and air exchange. These values are displayed in Table 1. The model accounted for two processes: PM removal by the AP, and PM exchange with the outdoors. The model simulated the behaviour of an independent room and therefore did not account for air change between rooms. The box model is described by the following equations.

$$M = C_{t-1} \times \exp(-\text{CADR} \times \Delta t/V)\ \text{(PM removed by AP)} \quad (1)$$

$$C_t = M + (A - C_t) \times \exp(\text{ach} \times \Delta t)\ \text{(PM exchanged with outdoors)} \quad (2)$$

where M = model output, C_t = concentration at time t, C_{t-1} = concentration at previous time step $t - 1$, V = room volume (ft^3), CADR = clean air delivery rate ($ft^3\ min^{-1}$), Δt = time step (min), A = particle concentration of ambient air and ach = air exchange rate (min^{-1}).

A simpler model using source terms and ventilation rates (outlined in Table 1) were used to model gaseous components of IAQ, as seen in Fig. 7 and 8.

Table 1 Model parameters and their respective sources

Model parameters		
Parameter	Value	Source
Air change (ach) parameters (h^{-1})		
5th percentile of annual infiltration rate of 294 Chinese residences	0.08	Hou 2019 (ref. 28)
25th percentile of annual infiltration rate of 294 Chinese residences	0.22	Hou 2019 (ref. 28)
50th percentile of annual infiltration rate of 294 Chinese residences	0.34	Hou 2019 (ref. 28)
75th percentile of annual infiltration rate of 294 Chinese residences	0.56	Hou 2019 (ref. 28)
95th percentile of annual infiltration rate of 294 Chinese residences	1.12	Hou 2019 (ref. 28)
Room A (AC on)	0.55	Measured
Room A (sealed)	0.30	Measured
Room A (window open)	1.64	Measured
Room B (AC on)	2.30	Measured
Room B (sealed)	0.40	Measured
Room B (window open)	1.68	Measured
Room C (AC on)	2.22	Measured
Room C (sealed)	3.04	Measured
Room C (window open + AC)	8.31	Measured
Room C (window open)	6.10	Measured
CO_2 model parameters		
Average apartment size	39 m^2	Chinese bureau of statistics 2019 (ref. 29)
Model bedroom size	15 m^2	N/A
Model kitchen and living room size	7.5 m^2	N/A
Breathed volume	6 L min^{-1}	Carroll 2007 (ref. 30)
CO_2 concentration in exhaled air	38 000 ppm	CO_2 meter (ref. 31)
Cooking model parameters		
PM generation rate	$24.7 \times 10^{10}\ s^{-1}$	Zhao 2018 (ref. 32)
Total VOC (TVOC) generation rate	2.14 mg m^{-3} min^{-1}	Zhao 2014 (ref. 33)
Other parameters		
Air purifier CADRs	Various	Lowther 2020 (ref. 13)
Outdoor background PM concentration	$1.0092 \times 10^4\ cm^{-3}$	Measured
Indoor background PM concentration	$6.614 \times 10^3\ cm^{-3}$	Measured

3 Results and discussion

3.1 Study location background information

The effect of air change on AP performance is a function of the PM concentrations in the ambient air penetrating inwards. Therefore, it is necessary to understand the likely concentrations and composition of PM in ambient air outside the apartment and its variability. In the presence of no dominant indoor sources, the average indoor concentration was 6900 cm^{-3} compared to 11 500 cm^{-3} outdoors, (see Fig. 3). Guangzhou ambient $PM_{2.5}$ in the wet season (when this campaign was conducted) is typically composed of organic aerosol (49%), sulphate (20%), nitrate (17%), ammonium (13%) and chloride (1%).[34] Key sources of emissions of $PM_{2.5}$ in Guangzhou in the wet season can be attributed to vehicular (37%), industrial (32%), power generation (12%) and residential (7%) sectors with a further 12% from indistinguishable sources.[35]

It is important to note that the majority of $PM_{2.5}$ is generated by vehicular sources, which predominantly generate particles <500 nm.[36]

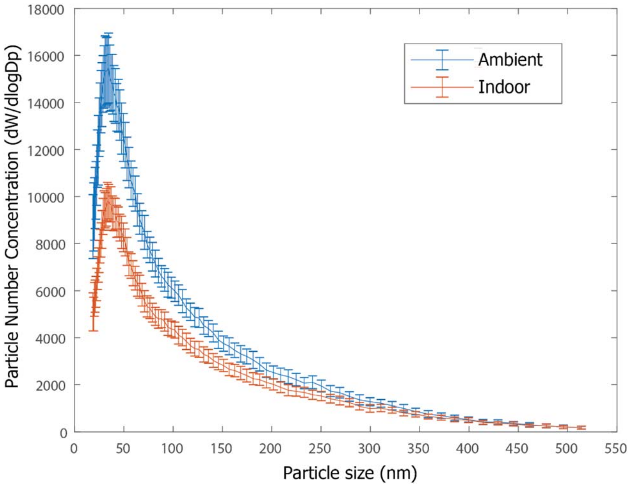

Fig. 3 PM size distributions of ambient and indoor air from 18–514 nm collected by a TSI SMPS, over 12 hours (2 hours per day), with the measurement between ambient and indoor switched every 20 minutes, on six days of the sampling campaign. d*W*/dlog Dp units display particle size distributions normalised to one decade of particle size.

3.2 Experiment 1

Generally, increased air change rate is associated with decreasing particle decay rate and therefore decreased AP performance, as seen in Fig. 4. For each of the three rooms, the performance of APs is least effective under the window open ventilation scenario. It should be noted that some of the measured air change rates appear unusual, particularly the greater air change in Room C when sealed than with the AC on and the greater air change in Room B with AC on than with the window open. These experiments were conducted in an urban megacity context where ambient PM often exceeds indoor PM, and hence increasing air change can act as an additional source of PM and reduce the effectiveness of air purification.

Particle decays when the AP was operated under the different ventilation conditions are shown in Fig. 5. Both the modelled and measured outputs show that increasing air change rate decreases the rate of net particulate removal (and therefore the APs performance). In addition, the air change rate appears to determine the equilibrium particle number concentration achieved. Therefore, at lower air change rates, the AP performs more efficiently, and a lower equilibrium concentration is reached. The model appears consistent with what was measured and this would indicate that our understanding of processes within the indoor environment is reasonable.

Fig. 6 shows how the decay of PM due to AP use changes under different ventilation conditions when indoor PM concentrations are initially greater than outdoor concentrations (*i.e.* when a dominant indoor source of PM is present). Fig. 6 demonstrates that when indoor PM concentrations exceed ambient PM concentrations, as is the case initially, then air change acts as a sink of PM, removing PM from the indoor environment. Conversely, when indoor PM concentration is less than ambient PM concentration, air change inhibits the performance of the air purifier, leading to decreased particle decay rates and increased equilibrium PM concentration, as for the measurements shown in Fig. 6. Looking at total PM exposure (area under the curve) for each of the ventilation scenarios in Fig. 6, it seems that when PM is of concern, and when there are limited indoor sources of PM, sealing the environment is the best strategy for reducing exposure. Although sealing the environment initially removes PM at a slower rate (when ambient PM > indoor PM), this effect is small compared to the benefits of increased removal rate and decreased equilibrium concentration when indoor PM > ambient PM. If indoor and ambient PM concentrations could be quantified in real-time, as may be possible in a future smart home,[37] ventilation could be automatically controlled to maximise the removal efficiency of PM. However, until then it

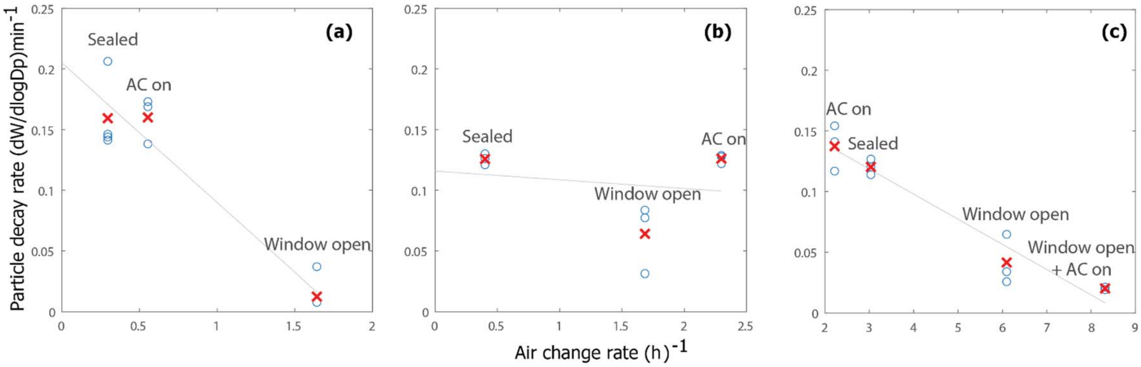

Fig. 4 The measured relationships between air change and particle decay rates for three rooms under the different ventilation scenarios; (a) Room A, (b) Room B and (c) Room C. The blue circles and red cross represent the repeats and the mean respectively.

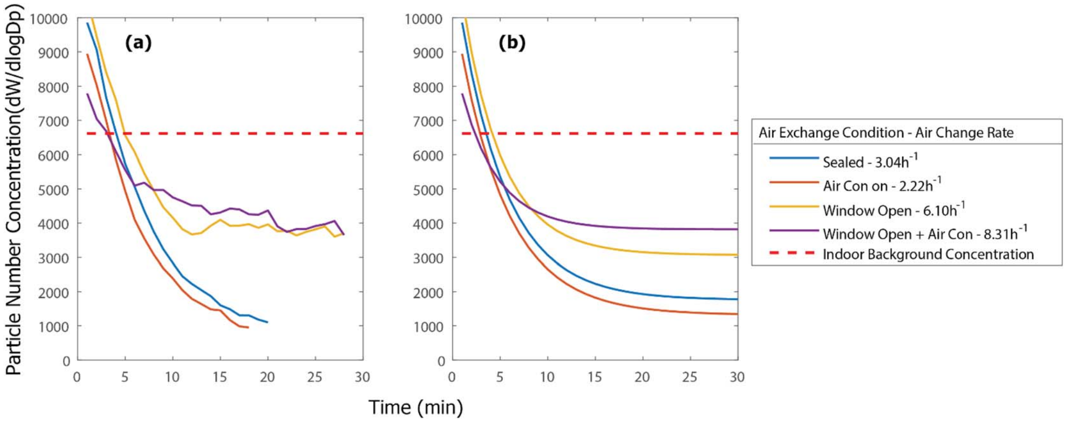

Fig. 5 (a) Measured and (b) modelled total particle number decays when an air purifier is active in Room C under four ventilation conditions.

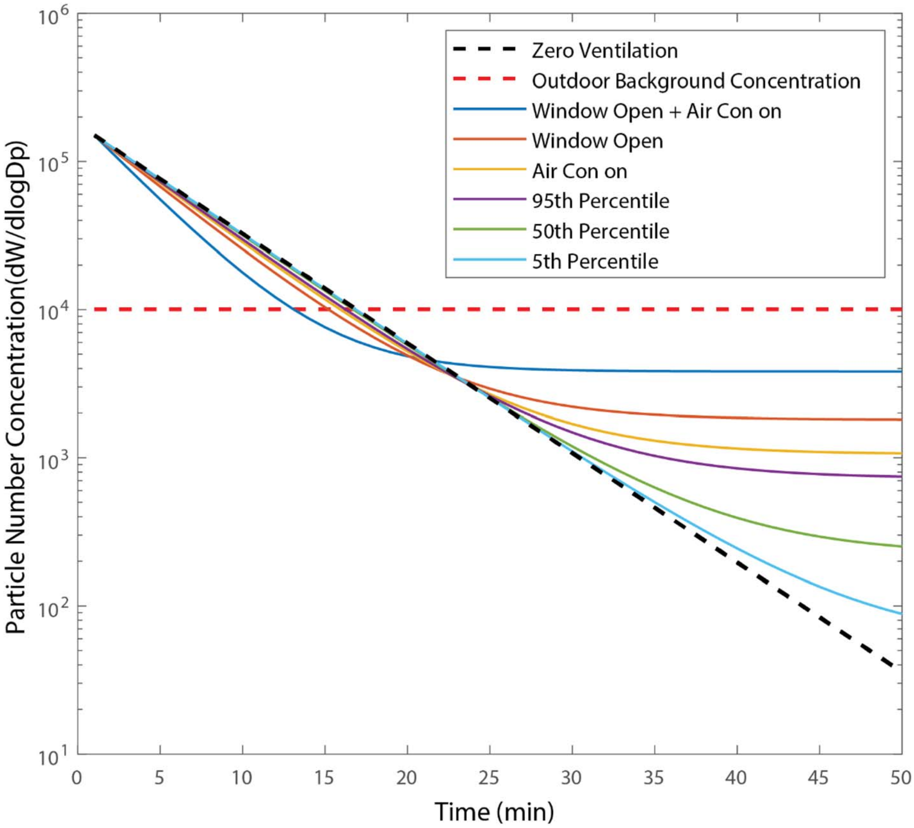

Fig. 6 Modelled total particle number decays when the large AP is active on medium fan speed in an average-sized Chinese bedroom under five ventilation conditions. The initial concentration is significantly greater than the ambient background to simulate a potent indoor PM source. The window open and air-con on, air change rates used were averages for measurements across the three rooms. The percentiles are of annual infiltration rate of 294 Chinese residences as in Hou *et al.*, 2019.[28]

is likely best to seal the environment and allow the AP to remove PM with limited inhibition.

When PM is of primary concern, and there are limited sources of indoor PM, sealing the environment and allowing the AP to reduce PM with minimal inhibition seems like the most logical strategy. However, this may not be coherent with a holistic view of IAQ. Therefore, it is also necessary to consider the effect of this sealing on the gaseous components of IAQ.

Fig. 7 considers the impact of sealing on the accumulation of CO_2 from breathing within a 'sealed' bedroom overnight. It demonstrates that by the end of the night, concentrations can be 4–10 times greater than the background. It is thought that CO_2 concentrations greater than $\sim$1000 ppm can affect concentration and comfort,[38] with the 8 hour time-weighted-average exposure limit value to CO_2 being 5000 ppm.[39] Within an average-sized Chinese bedroom with average air change, and a single occupant, CO_2 concentrations can reach $\sim$2000 ppm overnight.

Fig. 8 shows how different ventilation conditions will influence the removal of PM and total volatile organic compounds (TVOCs) after a cooking event. Regardless of the ventilation condition, PM is reduced to an acceptable level within $\sim$50 minutes. However, the ventilation condition does define the equilibrium concentration reached, as outlined in Fig. 4 and 5. TVOCs, a gaseous component of IAQ, which are therefore not removed by the AP are not reduced to acceptable levels within the 3 hour duration, regardless of the ventilation strategy. This demonstrates that although 'sealing' indoor environments can be beneficial for the removal of PM, this will have clear implications on the accumulation and decay of gaseous components of IAQ.

Increasing air change rate can be used to reduce transmission of airborne pathogens and improve air quality, whilst reducing air changes can also reduce ingress of outdoor air pollution and improve energy efficiency. There is therefore much discussion around the role of air change in both residential and commercial building types. Our findings are consistent with the existing literature which indicates that air exchange can act as both a source and sink of indoor air pollution.[12] With air change acting as a source of PM into indoor environments, in our studies we demonstrate that this will also affect the efficiency of APs in reducing PM concentrations within residences. Additionally, this effect is quite significant, with a 95th percentile air exchange room in China, having almost an order of magnitude greater PM number concentrations than a 5th percentile room (Fig. 6). It is therefore likely that rooms with HEPA purification, and lower air change rates,

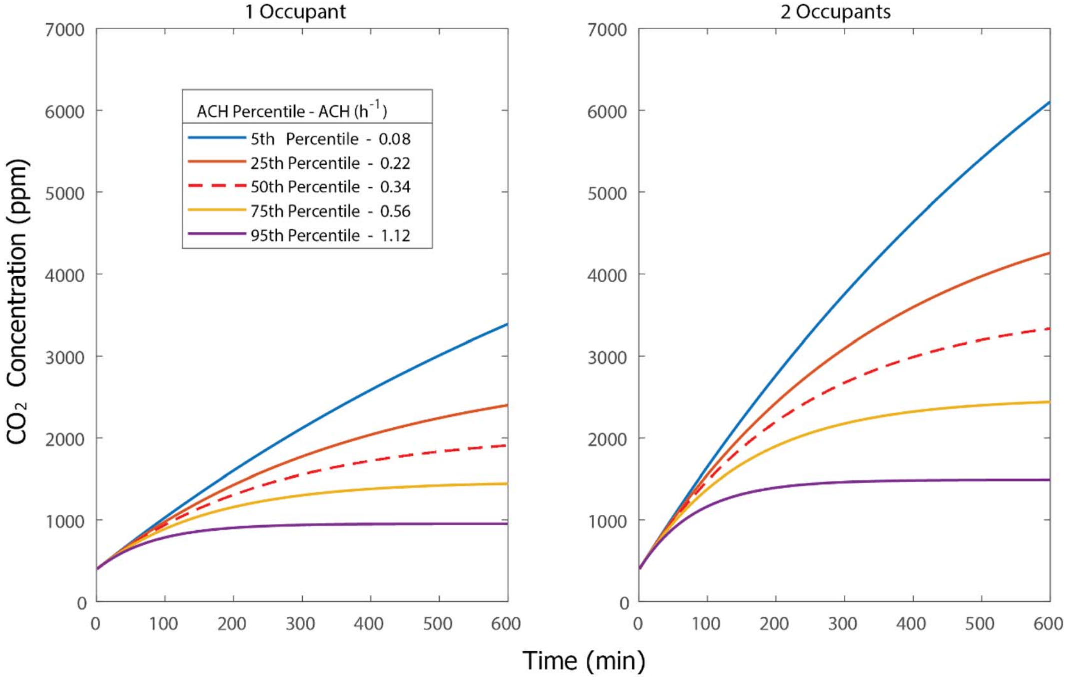

Fig. 7 Carbon dioxide accumulation from one and two occupants breathing in an average-sized Chinese bedroom over ten hours, for different air change conditions. The percentiles are of annual infiltration rate of 294 Chinese residences as in Hou *et al.*, 2019.[28]

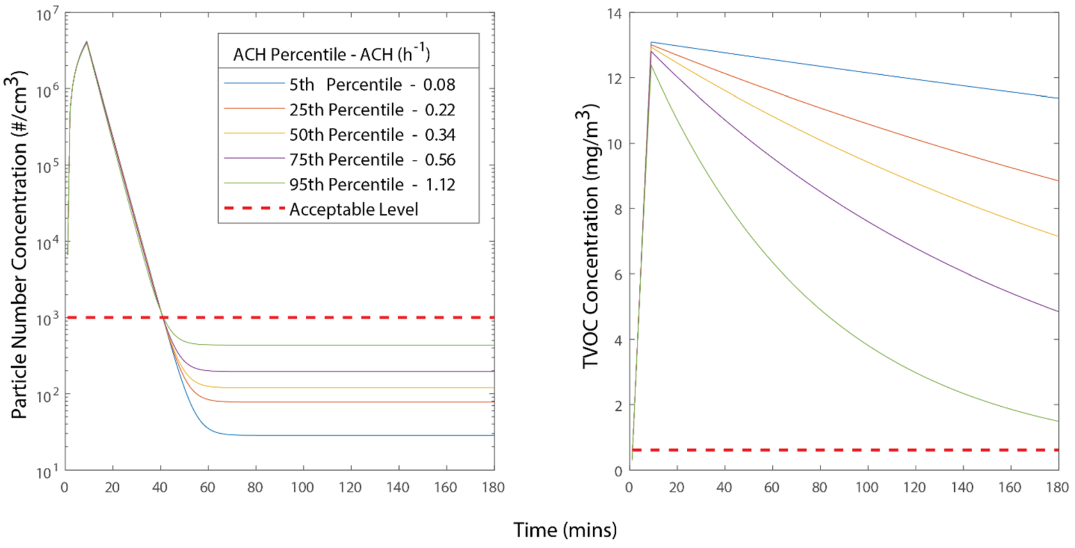

Fig. 8 Particle number concentration (cm^{-3}) and TVOC concentration (mg m^{-3}) over time for simulation of a ten-minute Chinese style stir-frying event in a 21 m^3 room; after the ten-minutes of cooking small AP is turned on at maximum fan speed. This is simulated for different air change conditions. The acceptable TVOC concentration is 0.6 mg m^{-3}.[40] The acceptable level of PNC is set as 10^3 cm^{-3}, defined as "relatively clean" by Lowther *et al.*[3] and Bo *et al.*[41]

will tend to have much lower PM concentrations than those with greater air change rates.

The modelling components of this investigation demonstrate that IAQ is a holistic issue, and that although reducing air exchange may be beneficial for reducing concentrations of some pollutants, it could potentially increase the concentrations of others. In the future, building management systems and residential systems could use a combination of indoor and outdoor air quality sensors (measuring multiple types of pollutants), to make intelligent and real-time decisions on how best to utilise ventilation and filtration, in order to minimise overall exposure to pollutants. However, an ethical dilemma (exacerbated by limited epidemiological evidence) that will need to be faced is how these devices can be used to support more holistic decision-making about exposures. For example, is it better to seal an environment and expose individuals to elevated levels of CO_2, or ventilate an environment and increase exposure to more ambient pollutants such as PM or NO_2? Overall, such systems should have their efficacy explored, as they are likely to lead to significant reductions in overall exposures to air pollutants from internal and external (ambient) sources.

In addition to air change rate, another important factor effecting AP performance within residences is the number of air purifiers used across a residential space. This is considered in Experiment 2.

3.3 Experiment 2

Table 2 compares the effectiveness of single and multiple AP usage within a two-bedroom residence.

Under the single AP scenario, Room A was cleaned most efficiently, as this was where the AP was located. The reduction in PM decreased for Room B and Room C as the distance away from the AP increased. For the multiple AP scenario, where one AP was located in each room and was operated on the lowest fan speed, ~70–80% reductions in PM can be seen consistently across the three rooms. Therefore, not only is it more energy-efficient to run multiple APs on lower modes, than it is to run a larger AP on maximum fan speed, it also more efficient in removing PM. It should be noted that, although a single AP was able to reduce PM across the investigation area, this was with all the doors open, which often will not be the case in an occupied residence, especially whilst sleeping, when AP use is arguably most important. Under a scenario where all the doors were closed, the improvements from a multiple AP scenario would likely be significantly greater than from a single AP scenario. Even within typical Chinese residences which are comparatively small, a single AP is likely insufficient to clean the area it is rated for, given the barriers to mixing that are present within residences, *i.e.* walls, doors and furniture. Therefore, a better strategy would be to have APs located in any room where extended periods are spent. This would also be beneficial for energy consumption, being more efficient than running a single AP on greater fan speed. However, the upfront cost of multiple APs will be greater.

This research is consistent with the existing literature in highlighting the tangible reductions of PM concentrations associated with HEPA AP use.[14–17] In this investigation, reductions in the number concentrations of PM of between 30–80% (depending on the setup) were observed. Previous studies have reported reductions in PM concentrations of 50%, 63% and 30–70% respectively.[14–17] However, this is the first research to demonstrate that use of multiple APs around a residence may be more effective in removing particulate matter from indoor air than a single AP. Although less efficient, this investigation also shows that use of a single purifier within a residence can still provide significant reductions in PM concentrations in adjacent rooms. With populations spending approximately one third of their time sleeping, and 50–60% of their waking time at home,[42] wider adoption of HEPA technologies in many urban settings with elevated PM may be able to significantly reduce overall PM exposures, and improve overall population health. Given that exposure is a function of both the amount of time spent in an environment, and the concentration of pollution in that environment, it would be necessary to first understand where people spend time in their homes (which is relatively well documented[42]) and second, how pollutant concentrations vary in different rooms of any given home (which is much less certain). Further research into the second element of this could allow us to give better recommendations on where in the home,

Table 2 Particle decay rates and percentage particle reductions over two hours for the three measurement rooms for the single AP and multiple AP scenarios

	Single AP scenario				Multiple AP scenario			
	Decay rate min^{-1}				Decay rate min^{-1}			
	Repeat number				Repeat number			
	1	2	3	Mean	1	2	3	Mean
Room A	0.0272	0.0155	0.0291	0.0239	0.0311	0.0264	0.0248	0.0274
Room B	0.0108	0.0113	0.0143	0.0121	0.0318	0.0335	0.0297	0.0317
Room C	0.0045	0.0118	0.0046	0.0069	0.0219	0.0164	0.0187	0.0190

	Single AP scenario				Multiple AP scenario			
	Percentage reduction per hour				Percentage reduction per hour			
	Repeat number				Repeat number			
	1	2	3	Mean	1	2	3	Mean
Room A	80.4	60.5	82.5	74.5	84.5	79.5	77.4	80.4
Room B	47.8	49.2	57.7	51.6	85.2	86.6	83.2	85.0
Room C	23.5	50.6	24.0	32.7	73.2	62.6	67.4	67.7

residents should be prioritising use of HEPA APs. For the time being, it would seem sensible to recommend usage where most time is spent, *i.e.*, bedrooms and living rooms.

4 Conclusion

Using a combination of measurement and modelling, this investigation aimed to determine the effect of air change on AP effectiveness and the benefits of using single or multiple APs within a multi-room residence.

Firstly, increasing air change rate inhibited the effectiveness of AP use, by acting as a source of PM into the indoor environment. The rate of air change determined the equilibrium concentration reached in the indoor environment, once the sink of PM (AP) and source of PM (air change) became balanced. Conversely, when indoor PM > ambient PM, *i.e.* when there are strong sources of PM indoors, then air change can act as a sink of PM. However, this sink is negligible compared to the sink of the AP. Therefore, when PM is of major concern within the indoor environment, and when there are minimal indoor sources of PM, it seems logical to seal the environment as much as is possible, to minimize the inhibition of the AP. However, this allows for the accumulation of gaseous components of IAQ, which are not removed by the HEPA filter. Additionally, in contrast to many developing countries, where sealing of buildings is becoming increasingly prevalent as a method to improve energy efficiency,[3] in China, increasing natural ventilation is suggested to be beneficial to improving energy efficiency.[43] Therefore, there are many conflicting factors when suggesting an optimal air change rate. Future work could determine to what extent a "smart home", where concentrations of various pollutants can be measured in real-time, and where air change can be adjusted accordingly, can reduce exposures to PM.

Secondly, the use of multiple APs within a multi-room residence can reduce PM concentrations more than the use of a single AP on higher fan speed. Therefore, in a multi-room residence, it is beneficial to have APs located in any room where significant time is spent, and although the upfront and maintenance cost of APs is greater, utilizing multiple APs is also more energy-efficient than operating a single more powerful AP on higher fan speed.

This investigation used measured and modelled data to determine that increasing air change inhibits the performance of APs, and therefore, sealing is beneficial to reducing exposure to PM, although this conflicts with concentrations of gaseous components of PM and improving energy efficiency in Chinese buildings. Additionally, using multiple APs in a multi-room residence can reduce exposure to PM and have a lower energy consumption when compared to the use of a single AP.

Conflicts of interest

There are no conflicts of interest to declare.

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