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Efficiency of ionizers in removing airborne particles in indoor environments

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ABSTRACT

Air ionizers are increasingly being used to clean indoor environments of particle pollution. We tested the efficiency of a small negative ion generator (Aironic AH-202) in removing ultrafine particles from indoor environments. A high-flow air filter fitted with a HEPA filter was used to compare the removal efficiencies. We estimated the percentage of particles removed when the ionizer was operated within a closed chamber of volume 1 m^3, in a closed unventilated room of volume 20 m^3 and in three force-ventilated rooms of volume 32, 45 and 132 m^3. The closed chamber studies were conducted with ambient particles and with smoke at particle number concentrations of 5×10^3 and 7×10^4 cm^{-3}, respectively. In both cases, 70% of the particles were removed by the ionizer in 15 min. In general, the particle removal efficiency of both the ionizer and the air filter decreased as the room size increased. Both devices were also more effective in unventilated rooms than in ventilated rooms. The most important finding in this study was that, while the air filter was more effective than the ionizer in the two small rooms, the ionizer was clearly more effective than the air filter in the three largest rooms. We conclude that air ionizers are more suited than high-flow air filters in removing ultrafine particles from rooms larger than about 25 m^3. The investigation also showed that small ions produced by the ionizer, placed in one room, were carried through the air conditioning system into other rooms, effectively removing particles from the air in these rooms in the process.

1. Introduction

Air ions are naturally formed in the atmosphere by ionization of neutral air molecules or atoms by cosmic rays from space and natural radioactivity on the earth. Ionization results in free electrons and positively charged simple molecules or atoms (positive ions). The free electrons instantaneously attach to neutral molecules or atoms, forming negative ions. Negative air ions are generally O_2^- molecules with an excess of electrons and positive air ions are generally N_2^+,O_2^+, N^+ and O^+ molecules with a deficiency of electrons. Positive ions occur in high concentrations in both indoor and outdoor polluted environments such as industrial and highly populated areas. Ions of both signs are naturally found in large numbers near the coastline, in the mountains, in forests [1] and near waterfalls [2].

Outdoor air pollutants are mainly produced from motor vehicle emissions, industrial emissions and construction activities. The reported indoor sources of air pollutants include smoking [3], candle burning [4], cooking [5], vacuum cleaning [6] and from modern appliances such as printers, copy machines, LD monitors, TV sets and mobile phones [7]. At the same time, the high level of indoor air pollutants has become an important concern because people spend most of their time (> 80%) indoors [8].

Ions can be artificially generated by electrical devices such as air ionizers (also known as ion generators), ozone generators and electrostatic precipitators. Most of these devices produce ions using “corona discharge” produced through a high-voltage. When these ions are released into the atmosphere, they soon attach to airborne particles, leading to the removal of particles from the air in two mechanisms. Firstly, it results in an enhancement of the aggregation process as charged particles are increasingly attracted to neutral particles due to image forces. Larger particles settle faster than smaller particles. Secondly, charged particles have a greater mobility than neutral particles and are transported and deposited more effectively on nearby surfaces due to image charges.

A number of studies have demonstrated that air ionizers are efficient at various levels in removing aerosol particles from indoor environment [9–14]. These studies have found a significant reduction in concentrations of airborne particles due to the presence of ions. For example, Grabarczyk [10] used corona ionizers in a 50 m^3 unventilated, unoccupied room and found that the particle number concentrations (PNC) reduced by up to two orders of magnitude after 2 h, for the size range 0.3–2.5 μm. Lee et al. [11] tested corona ionizers in a 24.3 m^3

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chamber and found that particle removal efficiency was 97% for 0.1 μm particles and 95% for 1 μm particles, after 30 min. Grinshpun et al. [12] tested commercially available ionic air cleaners in a 2.6 m^3 chamber and found that the most powerful unit showed a particle removal efficiency of 90% within 5–6 min and 100% within 10–12 min for particle sizes between 0.3 and 3 μm. Both those studies concluded that the particle removal efficiency was not significantly affected by the particle size, while it increased with increasing ion emission rate. Wu et al. [13] studied the influence of the wall surface material on the removal of particles with negative air ions in an indoor environment. They used different wall surface materials such as stainless steel, wood, polyvinyl chloride (PVC), wallpaper and cement paint as the inner surface of a chamber and concluded that the removal of particles from the air was more efficient when the walls were of wood and PVC than of any other materials. Further, Shiue et al. [14], studied particle removal efficiency by measuring PNC at different heights and distances from the negative ion source in a closed chamber. They observed the highest particle removal efficiency at a height of 60 cm from the floor. They also found that particle removal efficiency decreased with increase in distance from the negative ion source due to limited horizontal diffusion of ions. Sawant et al. [15] used corona discharge to test the possibility of reducing the concentration of fog and smoke in a 72 cm^3 closed unventilated glass container. They found that a particle removal efficiency of 93–97% in the chamber within 6 min. This study demonstrated that it is possible to reduce the concentration of fog and smoke to a significant degree using negative air ions resulting in improved visibility in a closed chamber.

These studies clearly demonstrated that ionizers were efficient in reducing aerosol particles in indoor environments. However, most of these studies were conducted in closed chambers and not in real life environments. In this study, in addition to a closed chamber, we estimated the particle removal efficiency by a small negative ion generator (Aironic AH-202) in a number of different indoor environments such as unventilated and ventilated rooms, also investigating the effect of room size.

2. Methods

2.1. Instrumentation

2.1.1. Ionizer (negative ion generator)

A small commercially available negative ion generator (Aironic AH-202) was used to ionize air molecules. This device is mains powered, contains four corona needles and emits approximately 1×10^6 negative ions s^{-1}.

2.1.2. Air filter

An air filter fitted with a HEPA filter, provided by Healthway (New York, USA) was tested in this study. The filter has three settings: high mode (air flow rate-5660 l/min), medium mode (air flow rate-3540 l/min) and low mode (air flow rate-2400 l/min). The estimated particle removal efficiency by this device (based on the specifications reported by the manufacturer) is 99.99% at of all particles as small as 0.007 μm in size.

2.1.3. P-trak ultrafine particle number monitor

A TSI model 8525 P-Trak ultrafine particle monitor was used to measure the number concentration of particles in the size range 0.02–1 μm in real-time. The P-trak uses high-grade ethyl alcohol as its working liquid in the condensation particle counting technique to count ultrafine particles by means of laser scattering and detection. Data is stored on the instrument and later downloaded to a computer using the software provided. This instrument has a measurement range of 0–500,000 particles per cm^{-3}. The time resolution was set to 1 s.

2.1.4. Scanning mobility particle sizer (SMPS)

A scanning mobility particle sizer (SMPS), consisting of a TSI 3936 differential mobility analyser and a TSI 3781 condensation particle counter, was used to determine the particle size distribution in the range 10–400 nm.

2.2. Experimental methods

The experiments were carried out in a range of different indoor environments at the Garden Point campus of the Queensland University of Technology in Brisbane. The indoor environments were chosen to represent different volumes and ventilation systems. The experiments in each environment were repeated three times.

2.2.1. Chamber experiments

These experiments were conducted with ambient air in a closed chamber of volume 1 m^3. The initial PNC in the chamber was about 5×10^3 cm^{-3}. The P-track was placed at a height of 30 cm above the floor while the ionizer was placed on the floor of the chamber with its power switch accessible from outside to control its operation time. In each experiment, before the ionizer or the air filter was turned on, the conditions were allowed to reach an equilibrium state with the P-trak readings steady for at least 5 min. At that time, the ionizer or the air filter was turned on for a fixed period, as required, while the PNC was continuously monitored. Throughout this study, the air filter was used in the high mode setting. Particle size distribution was measured by the SMPS, in order to determine any changes in particle size during the particle charging process.

In order to study the effect at high PNC values, the experiment was repeated with a controlled quantity of smoke introduced into the chamber by inserting a lighted match into the chamber for a very short time of less than 1 s. After a few minutes, this gave a mean PNC of about 7×10^4 cm^{-3}. The ionizer was turned on and left on for a period of 25 min.

2.2.2. Unventilated room

These experiments were conducted in a closed unventilated room of volume 20 m^3. The ionizer and P-trak were placed approximately 1.5 m apart. In each experiment, the ionizer or the air filter was turned on after it was observed that the P-trak recorded an approximately constant PNC reading for 5 min. Next, the ionizer or the air filter was turned on for a period of 15 min. When the ionizer or the air filter was turned off, the P-trak continued recording for another 10–15 min. Air filter was used in its high mode setting. The vertical distribution of PNC was also investigated by placing the P-trak at different levels in the room.

2.2.3. Ventilated rooms

These experiments were conducted in three ventilated rooms of volume 30 m^3, 45 m^3 and 130 m^3. The ionizer or the air filter and the P-trak particle monitor were placed at the same level, approximately 1.5 m apart. In each experiment, after ensuring that the PNC was steady, the ionizer or the air filter was turned on for a period of 15 min, after which, the P-trak continued recording for another 10–15 min. The air filter was used at the high mode setting during all experiments. The air flow rate through the ventilated rooms was approximately 30 l s^{-1}.

2.2.4. Ventilated system

A further set of experiments were conducted with the ionizer and the P-trak particle counter in different rooms. The rooms were physically separated from each other but connected via the central air conditioner ventilation system. In this system, air was circulated through a HEPA filter and temperature control system and approximately 20% of air from outside the building was filtered and mixed with the circulating air on each cycle. This meant that 80% of the air in the building was being filtered and recirculated. The aim was to investigate if ions

were able to penetrate through the HEPA filter and air conditioning system and be carried through from one room into another. In order to do this, the ionizer was placed in the large ventilated room of volume 130 m^3 and the P-track in each of the other two small ventilated rooms of volume 30 m^3 and 45 m^3. The initial PNC was recorded for 15 min in the smaller room and then, the ionizer in the large ventilated room was turned on for a period of 10 min while the measurements were continued.

2.3. Analysis

2.3.1. Theory

When an ionizer is turned on, an electric field is created about the corona needles of the ionizer, which ionizes the air in the room. These ions can collide with water vapour molecules in the air, producing small ions. These small ions then attach to airborne particles.

The deposition velocity of airborne particles due to gravitational settling can be expressed as

$$v_g = \frac{gd^2\rho}{18\eta} \tag{1}$$

where g is the gravitational constant, d is the particle diameter, ρ is the density of particle, and η is the viscosity of the air[16]. Here, we can see that deposition velocity is proportional to the square of the particle diameter d. However, for the particles smaller than 1.0 μm, the equation (1) will be more accurate if it is multiplied by the slip correction factor C_c. Therefore, the slip-corrected form of the deposition velocity due to gravitational settling can be expressed as

$$v_g = \frac{gd^2\rho C_c}{18\eta} \tag{2}$$

The drift velocity of charged particles is given by

$$v_e = \mu E = \frac{nqEC_c}{3\pi\eta d} \tag{3}$$

where μ is the particle mobility, n is the number of charge, q is charge of an electron, E is the intensity of the electric field, η is the viscosity of the air and d is the particle diameter [16]. The slip correction factor, C_c is in the form of

$$C_c = 1 + \frac{\lambda}{d}\left(2.34 + 1.05\exp\left(-0.39\,\frac{\lambda}{d}\right)\right) \tag{4}$$

where λ is the mean free path in the air and d is the particle diameter [16]. Here, we can see that drift velocity is inversely proportional to particle diameter d. That is, smaller particles will experience higher speeds.

Further, the maximal drift velocity of the particle is approximately equal to

$$v_e = \mu E = E^2\varepsilon_0\left(\frac{3\varepsilon_r}{2+\varepsilon_r}\right)\left(\frac{1+\frac{2\lambda}{d}}{3\eta}\right)d \tag{5}$$

where μ is the mobility of the particle, E is the intensity of the electric field, ε_0 is the permittivity of the air, ε_r is the relative permittivity of the particle [10].

When $v_e >> v_g$, the mechanism of the removal of particles from the air is dominated by electrical forces rather than by gravitational settling. Using equations (2) and (5), this condition gives

$$E \gg \sqrt{\left(\frac{2+\varepsilon_r}{3\varepsilon_r}\right)\frac{gdp}{6\varepsilon_0}} \tag{6}$$

This expression shows that the electric field E required to remove particles increases in proportion to the square root of the diameter of the particles. Smaller particles have a higher electrical mobility and are more likely to meet the condition for removal. Therefore, it is expected that the ionizer will preferentially cause smaller particles to be removed, thus increasing the average particle size.

2.3.2. Percentage of particles removed

The percentage of particles removed was defined as the percentage decrease in PNC with respect to the background count, of ionizer or air filter in each indoor environment. It was calculated using the equation

$$\text{Percentage removed} = \left(\frac{C_0 - C_t}{C_0}\right) \times 100\ \%$$

where C_0 is the initial PNC (t = 0) and C_t is the PNC at time t. C_0 was measured when the ionizer or air filter was turned off (ie. natural decay) and C_t was measured with the ionizer or air filter turned on. We defined the particle removal efficiency (ε_t) as the percentage of particles removed in a period of 15 min.

3. Results and discussion

Over the course of the entire study, the room temperature ranged from 20–23 °C, the relative humidity from 67–78% and the atmospheric pressure from 1005–1026 hPa. However, the maximum variation of these three parameters during the course of any given experiment was of the order of 0.5 °C, 1% and 1 hPa, respectively. Thus, the environmental conditions remained relatively stable over the course of each experiment.

3.1. Chamber experiments with ambient air

Fig. 1(a) shows the percentage of particles removed and the PNC as a function of time with the ionizer operating in the closed chamber. The initial PNC in the chamber was about 5000 cm^{-3}. The ionizer was turned on for a period of 10 min. The PNC dropped to approximately 50% at the end of the first 5 min and by 70% at the end of the 10 min period of continuous operation. Thereafter, the PNC stabilized at about 1500 cm^{-3}. Fig. 1(b) shows the results of the experiment repeated with the air filter at high flow, instead of the ionizer. In this case, almost 80% of the particles were removed within the first 30 s, and all of the particles in the chamber were removed in 2 min.

Fig. 2 shows the typical particle number size distributions obtained by the SMPS at three stages of these experiments - before, 10 min after and 20 min after the ionizer was turned on. The background concentration did not change by more than about 10% in the course of time when the ionizer was not activated. It can be seen that the ionizer was efficient at removing particles in the entire size range 10–400 nm. This is in contradiction to Grabarczyk [10] who reported that only particles larger than 0.3 μm could be efficiently removed by corona ionizers. Although it is not obvious in Fig. 2, we found that the count median diameter (CMD) of the particle size distributions increased significantly when the ionizer was turned on. From an initial CMD of 76 nm, it increased to 87 nm at the end of the 10 min period of operation. This is a result of two physical processes that cannot be experimentally separated. First, smaller charged particles have a higher mobility than larger charged particles, and therefore, they migrate towards and are deposited on the walls of the chamber more effectively than the larger particles. Secondly, particles attach to charged particles more readily than to neutral particles. Operating the ionizer results in more charged particles and enhanced coagulation, thus increasing the CMD of the particles.

3.2. Chamber experiments with smoke

While the above study shows how particles in the air are removed by an ionizer and a commercial air filter, an interesting aspect of the study was to investigate the efficiency of these two devices in a high PNC environment. This was achieved by injecting a controlled amount

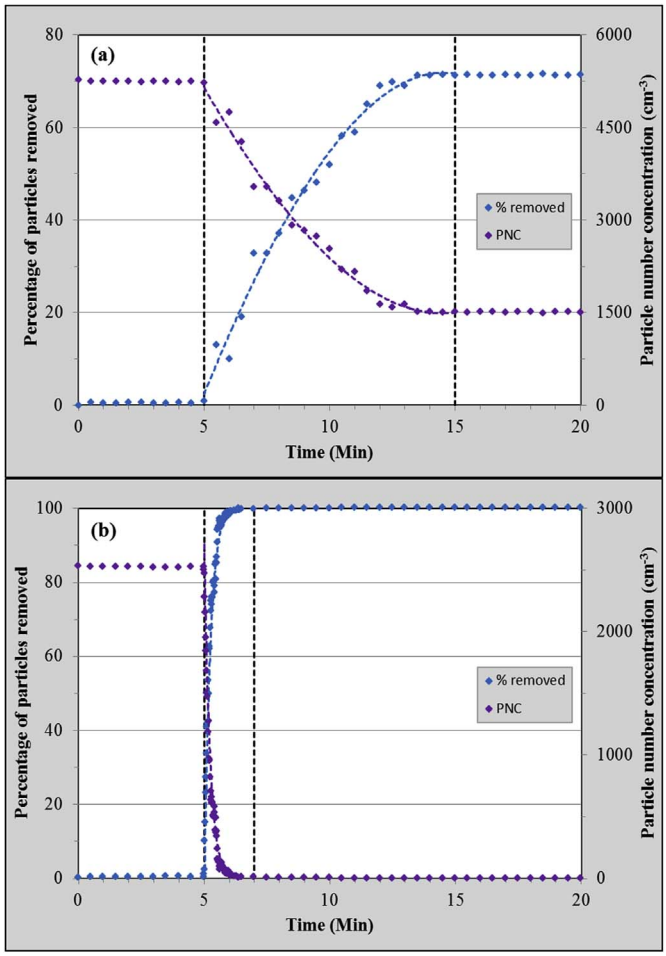

Fig. 1. Percentage of particles removed in the closed chamber using (a) the ionizer (b) the air filter (in blue) and PNC (in purple). In (a), the ionizer was turned on at 5 min and off at 15 min as shown by the two broken lines. In (b), the air filter was turned on at 5 min and off at 7 min as shown by the two broken lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

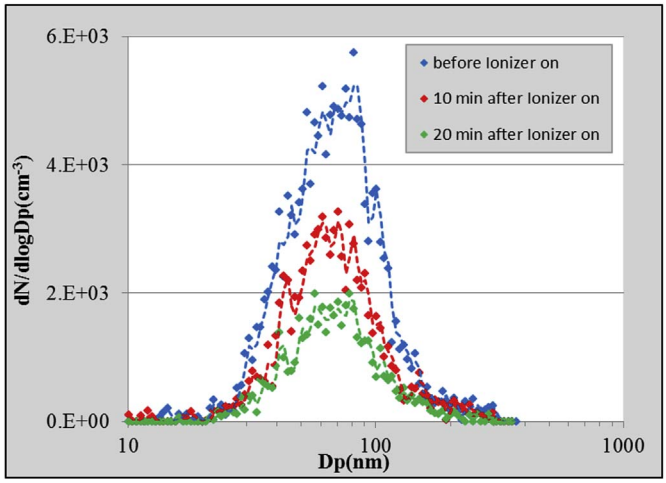

Fig. 2. Typical size distribution before the ionizer was turned on (in blue), 10 min after it was turned on (in red) and 20 min after it was turned on (in green). Initial PNC = 5000 cm^{-3}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

of smoke into the chamber. Fig. 3 shows the percentage of particles removed and the PNC as a function of time with the ionizer operating in the closed chamber after the introduction of smoke. After introducing

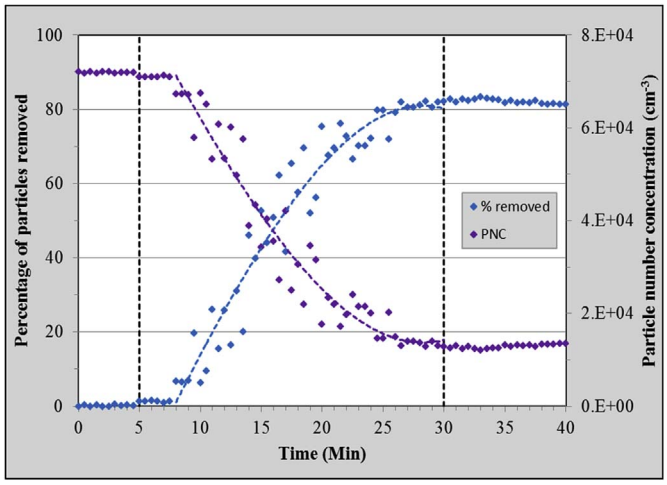

Fig. 3. Percentage of smoke particles removed by the ionizer (in blue) and PNC (in purple) in the closed chamber. The ionizer was turned on at time 5 min and off at 30 min as indicated by the two broken lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the smoke, the initial PNC was about 7×10^4 cm^{-3}. When the ionizer was turned on, the PNC began to decrease slowly. After a period of about 25 min, the concentration reached a steady value of about 1.3×10^4 cm^{-3}. The particle removal efficiency was highest soon after the ionizer was turned on and then decreased in time. The high number of ions emitted in the relatively small volume removed a considerable number of airborne particles by the same two mechanisms described in the previous section. 20% of the smoke particles were removed in the first 5 min, and 80% within a period of about 20 min.

3.3. Unventilated room

The experiments in the unventilated room demonstrated that the ionizer caused a vertical PNC gradient. At the same level as the ionizer, the PNC decreased from 2700 cm^{-3} to 1750 cm^{-3} (removed 35% of particles) in 5 min and to 1500 cm^{-3} (removed 45% of particles) after 15 min. At a level 1 m above that of the ionizer, the PNC decreased from 2700 cm^{-3} to 2400 cm^{-3} (removed 11% of particles) in 5 min and to 2000 cm^{-3} (removed 25% of particles) after 10 min. This behaviour is in agreement with the findings of Shiue et al. [14] and indicated that the position of the ionizer is an important factor in particle removal.

When the air filter was turned on at its high mode setting, the PNC in the room decreased from 6500 cm^{-3} to 3200 cm^{-3} (removed 50% of particles) in 5 min and from to 2500 cm^{-3} (removed 60% of particles) after 15 min. These results show that, with the filter turned on, the particle removal efficiency with the air filter was significantly higher than that with the ionizer in the closed unventilated room. Fig. 4 shows the corresponding percentages of particles as a function of time for the air filter, and the ionizer, at the same vertical level.

3.4. Ventilated rooms

As expected, with the ionizer turned on, the particle removal efficiencies in the ventilated rooms were lower than that in the unventilated room. The mean percentages of particles removed in a period of 15 min in the small ventilated room, medium ventilated room and the large ventilated room were 40%, 30% and 22% respectively (Fig. 5). The removal efficiency with the air filter was also tested in the same rooms. The mean percentages of particles removed by the air filter in 15 min in the small ventilated room, medium ventilated room and the large ventilated room were 25%, 10% and 6% respectively (Fig. 5). These values are all smaller than the corresponding values observed in the small unventilated room. However, an interesting observation is

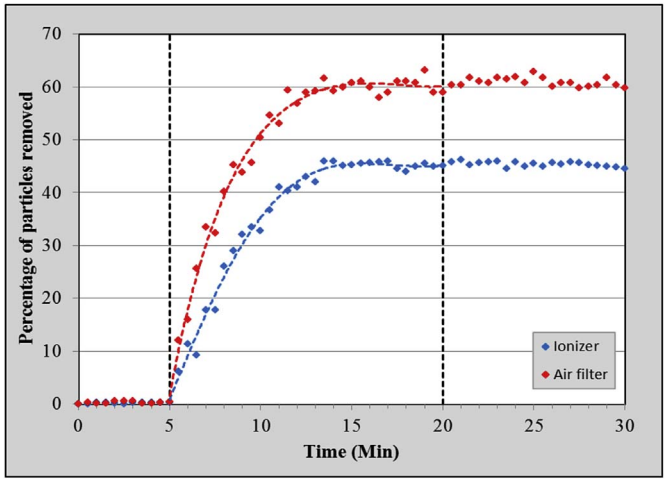

Fig. 4. Percentage of particles removed in a small unventilated room using the ionizer (in blue) and the air filter (in red). In each experiment, the device was turned on at time 5 min and off at 20 min as indicated by the two broken lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

that, in the larger ventilated rooms, the removal efficiency with the ionizer was clearly greater than with the high-flow air filter unit. To demonstrate this, in each room, we calculated the mean removal efficiency in the first 15 min after the ionizer or air filter was turned on. Fig. 6 shows the result. It was observed that, considering the uncertainties involved, while the air filter was significantly more efficient than the ionizer in the chamber and in the small room (to the left of the broken line), the ionizer was clearly more efficient than the air filter in the three larger rooms (to the right of the broken line). The threshold size of room is about 25 m^3 but this value is obviously specific to the ionizer used and air filter used in this study. In order to explain this observation, we hypothesize that, while the air filter loses some efficiency because it recycles the cleaned air from its proximity and does not access the peripherals of the room, the ions from the ionizer scatter throughout the room and is able to charge and remove a larger number of particles from the room. This effect will not be dominant in small rooms but will be more effective as the room size becomes larger.

3.5. Ventilated systems

All of the above experiments were conducted within a given space, either a chamber or a room. The last part of this study was designed to investigate whether ions produced in one room could be carried by the air conditioning system into other rooms and affect the PNCs in those rooms. When the ionizer was turned on for 10 min in the large ventilated room, the PNC was significantly decreased in both smaller rooms. The removal efficiencies in the two rooms were in the range 30–40%, which is of the same order as when the ionizer was in the same room. This is an interesting finding and shows that the ions are carried between rooms through the air conditioning system. No doubt, particles in the air conditioning unit are removed by the ions and the air that is expelled into the rooms have a lower PNC than when there was no ionizer in the other room. While the larger particles are trapped in the HEPA filters in the air conditioning unit, small ions are able to pass through the HEPA filters and reach other rooms. The air exchange rate could have an impact on the performance of removing particles in ventilated systems.

4. Conclusions

While confirming that air ionizers are able to remove ultrafine particles from indoor environments, the results of this study provide

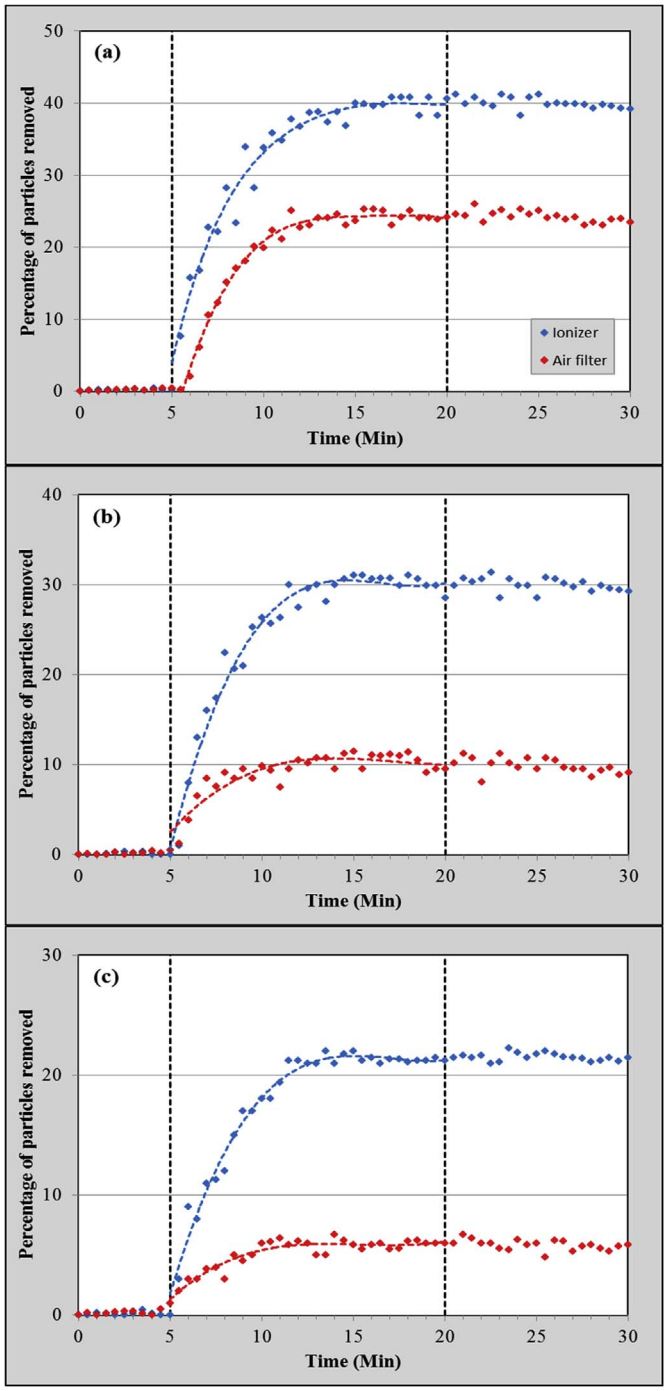

Fig. 5. Percentage of particles removed in three ventilated rooms of volumes (a) 32 m^3 (b) 45 m^3 (c) 132 m^3 using the ionizer (in blue) and the air filter (in red) separately. Each of the devices were turned on at 5 min and off at 20 min as indicated by the two broken lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

further information pertaining to room size and ventilation systems. With the ionizer used in this study, the particle removal efficiencies ranged from 70% in a small chamber (1 m^3) to 20% in a large room (130 m^3). The removal efficiencies in each of the rooms were compared with that due to a high-flow (5660 l min^{-1}) HEPA filter. While the particle removal efficiency was higher with the ionizer than with the filter in the chamber and the small room, the ionizer was more efficient at removing particles from the air in the three larger rooms (larger than 25 m^3). It was observed that the ionizer removed, not just the large particles but, ultrafine particles too of all sizes. When the ionizer was

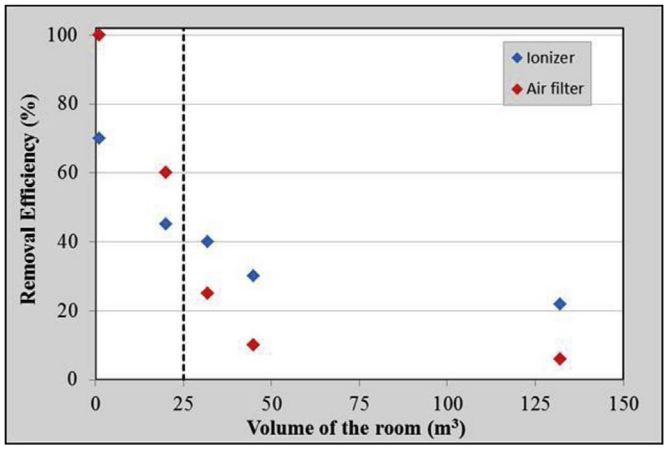

Fig. 6. The mean particle removal efficiencies due to the ionizer (in blue) and air filter (in red) as a function of room size. The uncertainties in the values ranged from 10% in the smallest room to 5% in the largest room. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

placed in one room, the air conditioning system carried small ions into other rooms and was consequently effective in removing a significant number of airborne particles in these other rooms.

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