

Effect of Ionizers on Indoor Air Quality and Performance of Air Cleaning Systems

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ABSTRACT

Corona ionizers are used to enhance the effectiveness of indoor air cleaners, remove odors, and to promote inactivation of viruses attached to airborne particles. However, there is limited experimental evidence of the effectiveness of ions in indoor air quality, and many commercial products have ambiguous or misleading performance statements. This study measured the effect of corona generated ions on particle wall deposition and on the performance of air cleaning systems. The experiments measured the indoor particle concentration decay of a polydisperse NaCl aerosol as a function of time for a variety of indoor room conditions including: (1) zero ventilation in the room, (2) HVAC system (100% outdoor air) at fixed flow rate, (3) Indoor air cleaners at different flow settings. For the zero-ventilation case, unipolar ions enhance wall particle deposition by a factor of 2, while bipolar ions do not enhance particle wall deposition. For the HVAC system and indoor air cleaners, the aerosol decay rates in the room increased by 10 to 30%, depending on the operating conditions. Ion and ozone concentrations were also measured in the room. This work demonstrates that unipolar ions can help improve indoor air quality, particularly in poorly ventilated environments, and have a measurable modest enhancement of the performance of air cleaning systems.

Keywords: Corona ionizer, Particle wall deposition, HVAC filtration, Indoor air cleaner, Filtration enhancement, Ozone generation

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1 INTRODUCTION

Exposure to PM_{2.5} pollution, both outdoors and indoors, is a health risk that has been linked to increased mortality and morbidity, mostly from cardiovascular and respiratory conditions (Pope *et al.*, 2018; Pope III, 2002). In addition to this, the recent COVID-19 pandemic has forced the world to find ways to improve indoor air quality in health care facilities (Ding *et al.*, 2020), industrial environments (Herstein *et al.*, 2021), commercial buildings (Navaratnam *et al.*, 2022), and residential homes (Zhao *et al.*, 2020), to reduce the probability of airborne transmission of viruses. Improved ventilation and air filtration systems have been proposed by several professional associations for HVAC (Guo *et al.*, 2021). The addition of virus inactivation technologies such as air ionization, ultraviolet germicidal irradiation, nanoparticle filter coatings, heat inactivation, and chemical disinfectants has been recently reviewed (Berry *et al.*, 2022). The use of air ionizers to improve indoor air quality has been proposed and implemented in portable air cleaners. In many of these devices, a corona ionizer is added to charge the particles and enhance the air cleaning performance (Lee *et al.*, 2004). Air ionization promotes additional wall particle deposition in the room (Hammad Ud Din *et al.*, 2020), and also enhances the filtration efficiency in conventional and electret filters by electrostatic mechanisms (Shi and Ekberg, 2015). A drawback of corona ionizers is the production of ozone in the corona discharge region. Ozone is a powerful oxidant that is harmful to breathe and produces inflammation and damage to the airways. For this reason, there are specific requirements limiting the ozone emission concentration to less than 50 ppb for commercial air cleaning devices sold in California (AB 2276). Although ionizers are being used and promoted worldwide in air



cleaning applications, their effectiveness in indoor environments is not well established, and some of their claims do not have sufficient science-based evidence (e.g., “simply plug the ionizer and replace bulky, expensive air purifiers with a simple, filterless, plug-in device”, <https://www.amazon.com/Clarifion-Negative-Generator-Filterless-Pollutants>; “the device emits positive and negative ions that treat the air, reducing certain bacteria and viruses in the coil and living space”, <https://www.nucalgon.com/products/iwave-air-ionization-systems/iwave-m-air-ionization-system/>).

The use of negative air ions to enhance the removal of submicron aerosol particles in indoor environments has been researched extensively. It is known that the negative ion-induced enhanced deposition to walls and surfaces is affected by many factors, including particle size and composition (Wu *et al.*, 2015), physical properties (i.e., surface roughness, electrical resistivity) of the walls and surfaces (Wu *et al.*, 2006; Yu *et al.*, 2017a), air movement and turbulence intensity (Lai and Nazaroff, 2000; Yu *et al.*, 2017b), relative humidity of the indoor air (Yu, 2012), as well as the room size and corresponding ion concentration distribution within the room (Lee *et al.*, 2004). Most of the literature available is based on experiments performed in relatively small chambers with well controlled parameters, and typically with very low air exchange rates, so that the effect of the different controlled parameters on the particle wall deposition could be elucidated using scientific physical principles. While this approach is ideal to compare experimental results with theoretical predictions, it is not directly applicable to real indoor environments with much larger room dimensions, complex air flow patterns, higher air exchange rates, particles of different sizes (i.e., polydisperse), and non-uniform ion concentrations. This study provides further experimental evidence of the effect of unipolar (for both positive and negative air ions), and bipolar corona ionizers on the particle deposition of a polydisperse submicron aerosol to the walls of an unoccupied office room, and on the performance of the HVAC filtration system and of two commercial portable air cleaners. The effect of the ionizers on the polydisperse aerosol decay rates in the room was carefully measured both for particle mass and number concentrations for several operating conditions of the air conditioning system or of the portable indoor air cleaners, showing that unipolar ionizers of either negative or positive polarity, have a consistent and quantifiable effect on the aerosol decay rates, while the bipolar ionizer did not affect the natural aerosol decay rate measured without the ionizers.

2 METHODOLOGY

The study was conducted in an unoccupied office room at the University of Minnesota, Mechanical Engineering building. The room (Fig. 1) has a total volume of 57.1 m³, a floor area of 20.8 m², and a ceiling height of 2.74 m. The walls and ceiling of the room are painted drywall (pressed gypsum) surfaces, and the floor is carpeted. The room has 2 air supply vents and 2 air return vents, with 100% outdoor air supplied to the room by the central HVAC system, and with a MERV 8 prefilter and a MERV 15 filter on the supply side. The HVAC system could be fully controlled from zero to a maximum of 6.5 m³ min⁻¹ (230 CFM) total air flow. The room air flow rate is normally controlled by the temperature setpoint in the room, but this automatic control based on temperature was bypassed during the experiments, so that the supply and return air flow rate conditions were accurately controlled to a constant value for each test.

The unipolar ionizer is a 5-point, 60-mm bar with 5 stainless steel micro-needle electrodes (Migro model ion12d, purchased from EBay.com), designed for operation at -7.5 kV and with a rated ion output of 12 billion ions per second, recommended for a room of 20 m², and with a power use of less than 1 W. The bipolar ionizer is a model iWave-M (Nu-Calgon 4900-35, St. Louis, MO) 45-cm flexible bar, with 8 carbon brush electrodes, for operation at +2.5/-2.5 kV, a rated ion concentration of 3.5×10^7 ions/cc per ft, under 5W power consumption, designed for use with a mini-split air conditioner of up to 45 m³ min⁻¹ (1600 CFM), and certified to pass an ozone chamber test (UL 867).

Ion concentrations in the room were measured at several locations using air ion counters (Model AIC2, AlphaLab Inc., Salt Lake City, UT) configured for either positive or negative ion measurements. For the bipolar ionizer two ion counters were used to simultaneously measure positive and

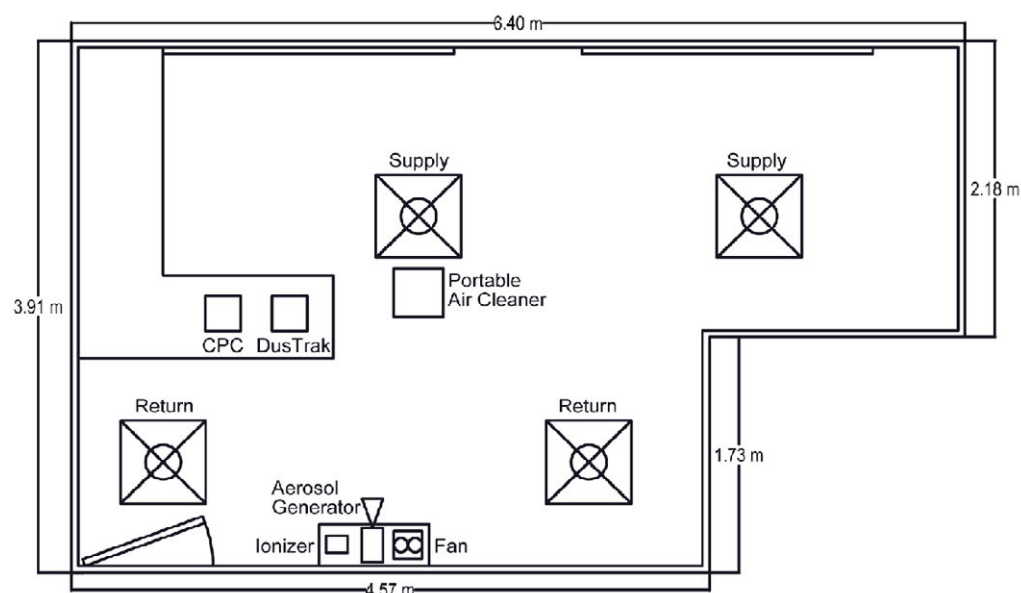


Fig. 1. Floor plan of office room used for the experiments.

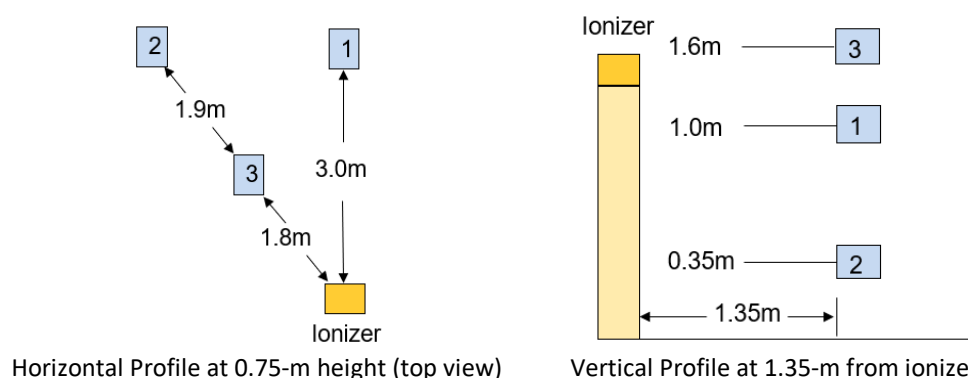


Fig. 2. Schematic diagram of unipolar ion concentration measurements. 1, 2, and 3 are the ion counters.

negative ions at the same location. The HVAC system was operating at normal conditions during these measurements. The ion counters were zeroed and self-calibrated before they were used. Fig. 2 shows the locations for the horizontal and vertical unipolar ion profile measurements.

Air flow rates at the two air supply vents and the two return vents were measured with a capture hood (TSI Alnor EBT731 Capture Hood, Shoreview, MN). Tests were conducted at only one flow setting of $4.8 \text{ m}^3 \text{ min}^{-1}$ (170CFM) when the central air conditioning system was used. In all the other tests, the air supply and return vents were fully closed to measure the natural decay of the room, or to measure the performance of the portable air cleaners. Ozone concentrations were measured with an ozone monitor (2B Technologies model 202, Boulder, CO) with the air vents closed to determine ozone formation by the tested corona ionizers.

The total number concentration of particles larger than 2.5-nm was measured by an ultrafine condensation particle counter (TSI Model 3756 CPC, Shoreview, MN) operating at 1.5 L min^{-1} sampling flow rate and counting in the single particle mode. Total aerosol mass concentration was also measured by a DustTrak aerosol photometer (TSI model 8530, Shoreview, MN) set with the default calibration factor of 1.0. No corrections were made to the mass concentration values since the decay measurements require only to determine the exponential decay rate.

For the particle decay experiments, a NaCl polydisperse aerosol was generated by atomizing a 2% w/v aqueous solution with a TSI 3079A portable aerosol generator. The NaCl had a count



mean diameter of 68-nm and a geometric standard deviation of 1.95, measured with a scanning mobility particle sizer. This polydisperse aerosol is representative of submicron particles in the 30 to 300-nm size range typically encountered in indoor environments, and includes the ultrafine fraction (i.e., < 100-nm) associated with greater adverse health effects (Morawska *et al.*, 2013). The NaCl aerosol was dried with a diffusion dryer and charge conditioned to a Boltzmann charge distribution with a Po²¹⁰ neutralizer (Liu *et al.*, 1986). The NaCl aerosol was released to the room at a height of 1.6-m for about 30 minutes with all the air vents fully closed. A small circulating fan was used to promote turbulent mixing in the room for all the experiments, particularly important when measuring the natural aerosol decay in the room without ventilation. The total number concentration reached up to about 80,000 cm⁻³, measured by the CPC, and up to an indicated mass concentration of about 0.50 mg m⁻³, measured by the DustTrak aerosol photometer. The described aerosol decay rate test closely follows the methodology of the ANSI/AHAM AC-1-2020 standard for measuring the performance of portable household electric room air cleaners with smoke particles. However, in our study NaCl particles were used instead of cigarette smoke since the experiments were done in a real office room where smoking is not allowed. We also used other aerosol measuring instruments not listed in the standard.

For the air cleaner experiments, two portable air cleaners were selected. The first one is a PuraShield® air cleaner (model CPUM-500-4), equipped with a single HEPA filter cartridge with 4 layers of filtration rated at 99.99%, and with 3 flow settings of 1.33, 3.54 and 7.08 m³ min⁻¹. No CADR (Clean Air Delivery Rate per AHAM AC-1, 2020 standard) is specified by the manufacturer. The second one is a Braun SensorAir™ air purifier (model BFD104W), equipped with iFD® (intense field dielectric) technology, with a washable iFD® filtration element, internal ionizer, and an odor and VOC final filter. This air cleaner has 4 flow rate settings (1–4), an internal air quality sensor, and a specified CADR of 5.49 m³ min⁻¹ (194 CFM), applicable to the highest flow setting for cigarette smoke particles.

The aerosol decay experiments were made with each ionizer turned OFF and turned ON (at specific voltage conditions), and with flow rate conditions specified for each experiment. Table 1 summarizes all the tests conducted for this study. Tests were replicated one time to verify the repeatability of each experiment. For the experiments with the indoor air cleaners, the particle

Table 1. Summary of tests conducted for this study.

Air cleaning mode	Flow rate setting	Ionizer condition	Ionizer voltage (kV)
N/A	0 m ³ min ⁻¹ (vents closed)	OFF	OFF
N/A	0 m ³ min ⁻¹ (vents closed)	ON	Unipolar, +7.5 kV
N/A	0 m ³ min ⁻¹ (vents closed)	ON	Unipolar, –7.5 kV
N/A	0 m ³ min ⁻¹ (vents closed)	ON	Bipolar, –2.5 kV/+2.5 kV
N/A	0 m ³ min ⁻¹ (vents closed)	ON	Bipolar, –3.5 kV/+3.5 kV
Central Air (100% outdoor air with MERV8 and 15 filtration)	4.81 m ³ min ⁻¹ (supply and return air balanced)	OFF	Unipolar, +7.5 kV
Central Air (100% outdoor air with MERV 8 and 15 filtration)	4.81 m ³ min ⁻¹ (supply and return air balanced)	ON	Unipolar, –7.5 kV
Central Air (100% outdoor air with MERV 8 and 15 filtration)	4.81 m ³ min ⁻¹ (supply and return air balanced)	ON	Bipolar, –2.5 kV/+2.5 kV
PuraShield® Air Cleaner	High Flow (7.08 m ³ min ⁻¹)	OFF	OFF
PuraShield® Air Cleaner	Mid Flow (3.54 m ³ min ⁻¹)	OFF	OFF
PuraShield® Air Cleaner	Low Flow (1.33 m ³ min ⁻¹)	OFF	OFF
PuraShield® Air Cleaner	High Flow (7.08 m ³ min ⁻¹)	ON	Unipolar, +7.5 kV
PuraShield® Air Cleaner	High Flow (7.08 m ³ min ⁻¹)	ON	Unipolar, –7.5 kV
PuraShield® Air Cleaner	High Flow (7.08 m ³ min ⁻¹)	ON	Unipolar, –5.0 kV
PuraShield® Air Cleaner	High Flow (7.08 m ³ min ⁻¹)	ON	Unipolar, –10.0k V
Braun SensorAir™ Air Purifier	High Flow (level 4)	OFF	OFF
Braun SensorAir™ Air Purifier	Mid Flow (level 2)	OFF	OFF
Braun SensorAir™ Air Purifier	High Flow (level 4)	ON	Unipolar, –7.5 kV
Braun SensorAir™ Air Purifier	Mid Flow (level 2)	ON	Unipolar, –7.5 kV



number concentration decay was used instead of the mass concentration decay. This was done to better match the measurement of the CADR as specified in the ANSI/AHAM standard for room air cleaners. The natural room decay rate experiments were repeated for each set of experiments to account for any small changes in the particle wall deposition due to fluctuations in the environmental thermal conditions of temperature and relative humidity in the room.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Ion Concentrations

Fig. 3 shows the unipolar horizontal ion concentration profiles at three locations in the room, directly across the ionizer (3.0-m) and at two positions diagonal to the ionizer (at 1.8-m and 3.7-m from the ionizer). The background ion concentrations for both positive and negative ions is about

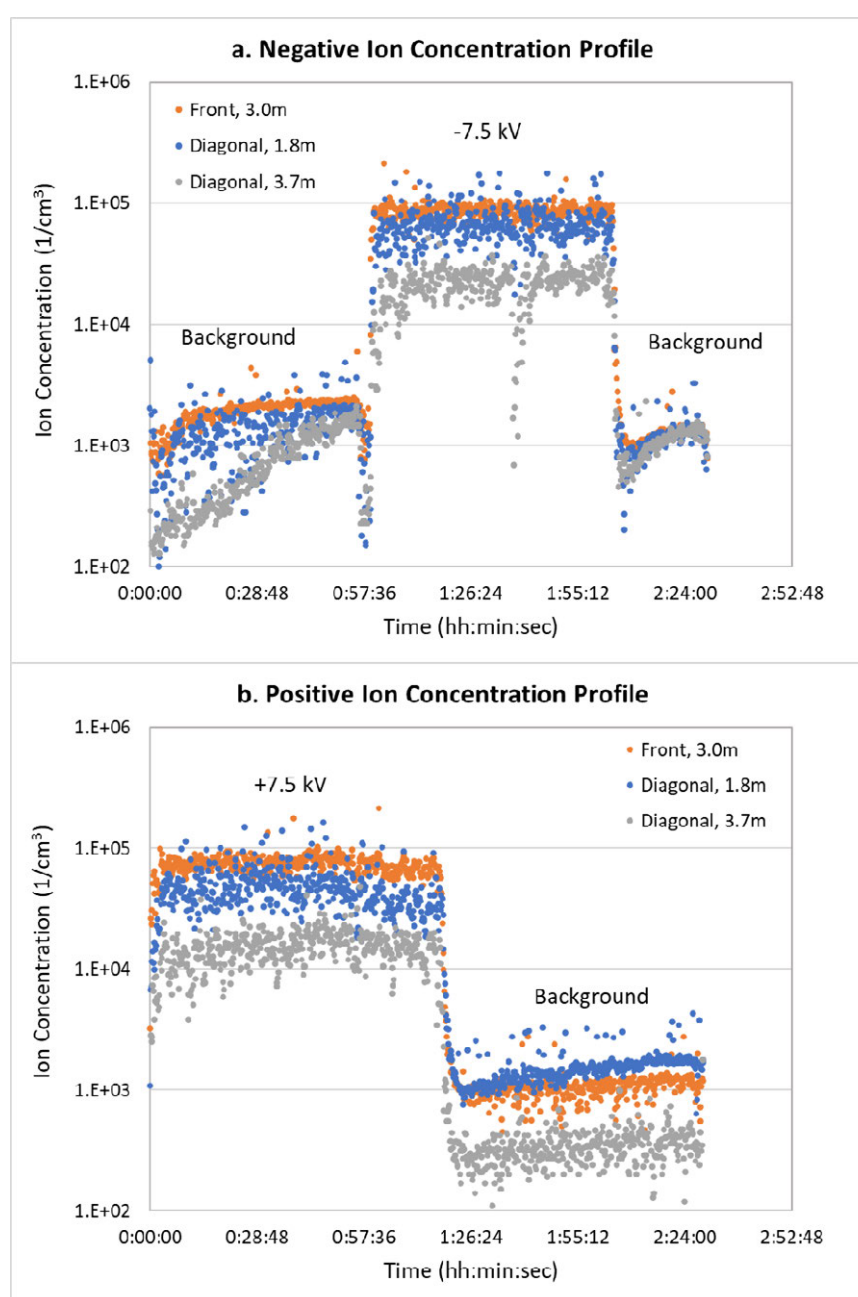


Fig. 3. Horizontal unipolar concentration profiles (a. negative; b. positive).



1,000 ions cm^{-3} . The ion concentrations with the unipolar ionizer at 7.5 kV vary from 1.5×10^4 to 8.7×10^4 ions cm^{-3} , depending on the specific location. The highest concentration is directly across the ionizer. Negative ion concentrations are a little higher than positive ion concentrations for the same high voltage magnitude. In all cases, these ion concentrations are 20 to 90 times higher than background ion concentrations. Fig. 4 shows the vertical unipolar ion concentration profiles at heights of 0.35-m, 1.05-m and 1.60-m, at a distance of 1.35-m directly across the ionizer. The ion concentrations are lower near the floor level. However, in all cases the ion concentrations are 20 to 200 times higher than background ion concentrations. Therefore, unipolar ions spread throughout the room (Khandare *et al.*, 2019), and remain relatively stable and at relatively high concentrations when the ionizer is turned ON. However, the ion concentrations are not uniform, and decrease in magnitude as the distance from the ionizer increases.

Fig. 5 shows the bipolar ion concentrations measured at 1.5-m directly across from the bipolar carbon brush ionizer, and at a height of 1.6-m. Simultaneous positive and negative ion concentrations were measured at 2.5/–2.5 kV and at 3.0/–3.0 kV. Higher voltages resulted in arcing across the brush electrodes. At 2.5/–2.5 kV the ion concentrations were 20 times higher than ambient levels and with a near balanced condition. At 3.0/–3.0 kV, the concentrations increased but the ions were not balanced (i.e., positive ions had more than double concentration). Fig. 6 shows the same measurements made at the corner of the room (3.7-m diagonally from ionizer and at 0.75-m

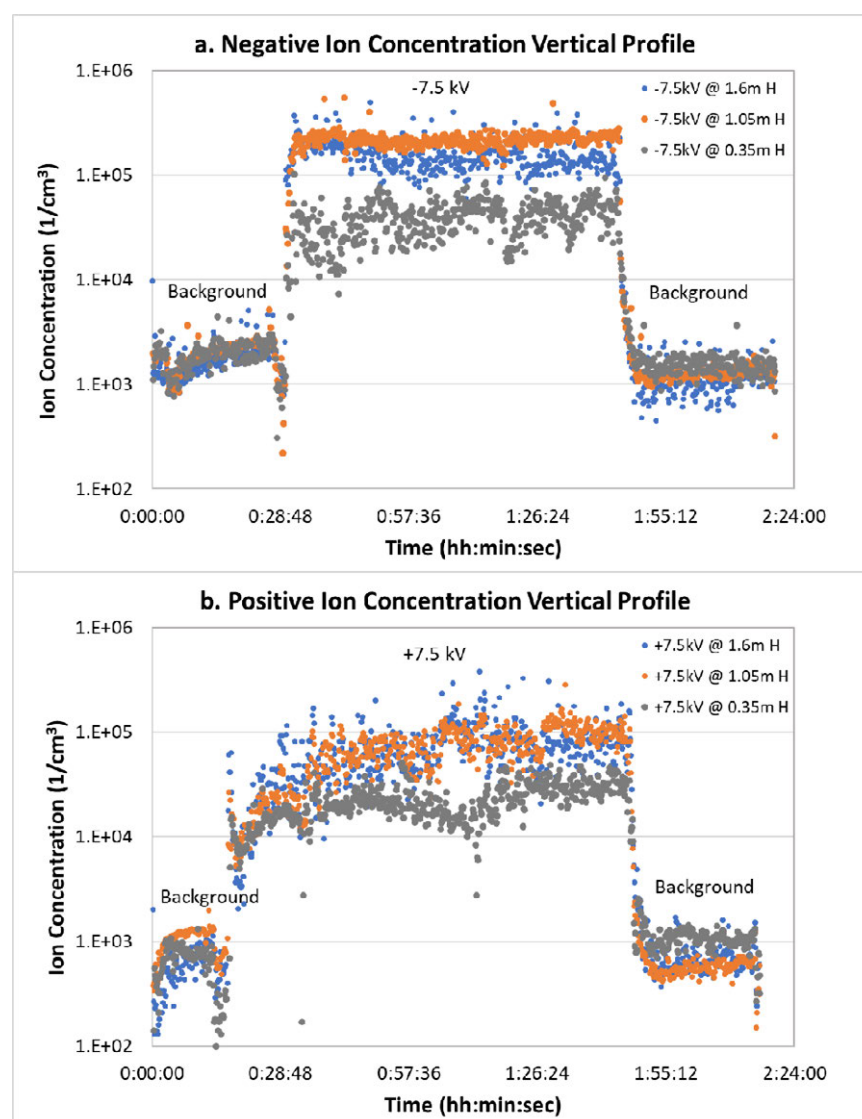


Fig. 4. Vertical unipolar ion concentration profiles (a. negative; b. positive).

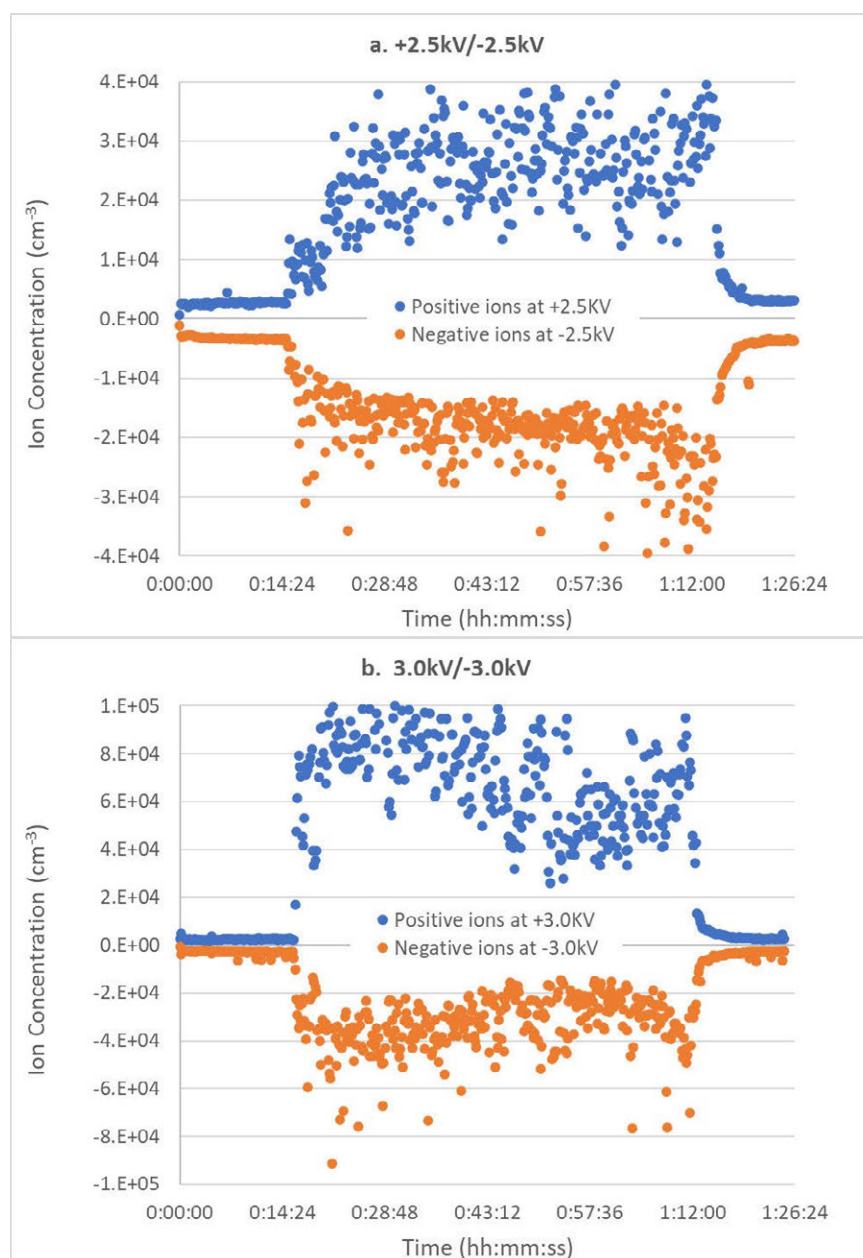


Fig. 5. Bipolar ion concentration profiles at 1.5 m across from ionizer (a. +2.5 kV/–2.5 kV; b. +3.0 kV/–3.0 kV).

height). In this case, there was no ion balance at 2.5/–2.5 kV, but nearly balanced ion concentrations at 3.0/–3.0 kV. From these measurements, the bipolar ion concentrations are lower than those measured for the unipolar ionizer. This is probably due to ion-ion recombination and to the lower operating voltages for this particular ionizer. The ion bipolar balance is also not uniform in the room.

3.2 Ozone Concentrations

The ozone concentration was measured at a central location inside the room with the unipolar corona ionizer turned OFF to determine the natural background ozone concentrations. With the HVAC vents open, the indoor ozone concentrations followed the typical diurnal cycle characteristics of outdoor ozone as shown in Fig. S1, with concentrations that varied approximately between 5 and 20 ppb. With the air vents closed the indoor ozone concentrations were always below 5 ppb.

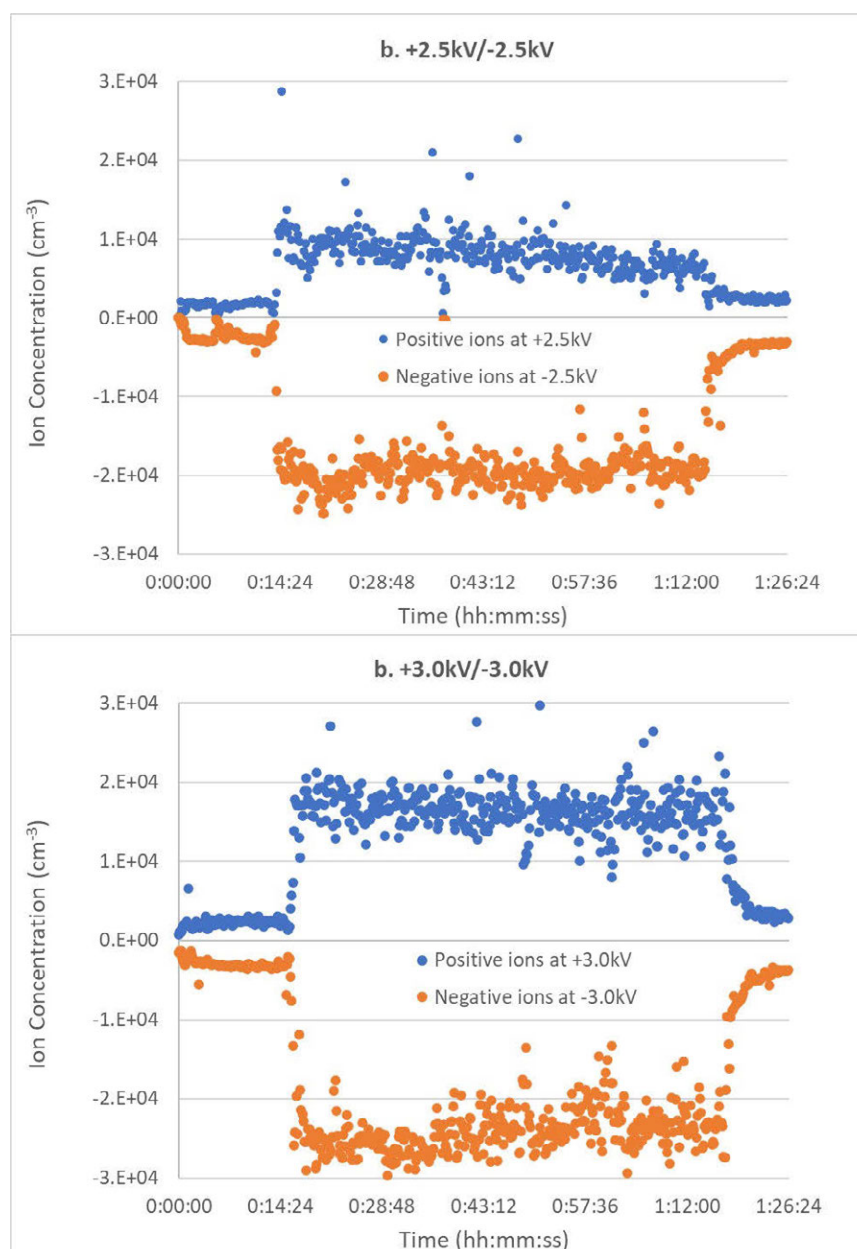


Fig. 6. Bipolar ion concentration profiles at corner of the room (a. +2.5 kV/–2.5 kV; b. +3.0 kV/–3.0 kV).

When the unipolar ionizer was operated at either –10.0 kV or +10.0 kV, the ozone concentrations did not increase inside the room, as shown in Fig. 7. This was an unexpected finding, which is probably due to the low corona currents associated with corona discharges with electrodes facing the open indoor environment, resulting in very low ozone generation.

3.3 Aerosol Decay without Ventilation in the Room

Fig. 8 shows the aerosol mass concentration decay in the room with all the air vents fully closed. The lowest decay curve is for the room without ionizer, and this curve represents the natural decay due to particles depositing on the walls and floor of the room. Nearly the same decay curve was measured for the bipolar ionizer operating at 2.5/–2.5 kV. This indicates that bipolar ions do not enhance particle deposition to the walls, and this is consistent with aerosol particles that have an equilibrium Boltzmann charge distribution that is attained when particles are exposed

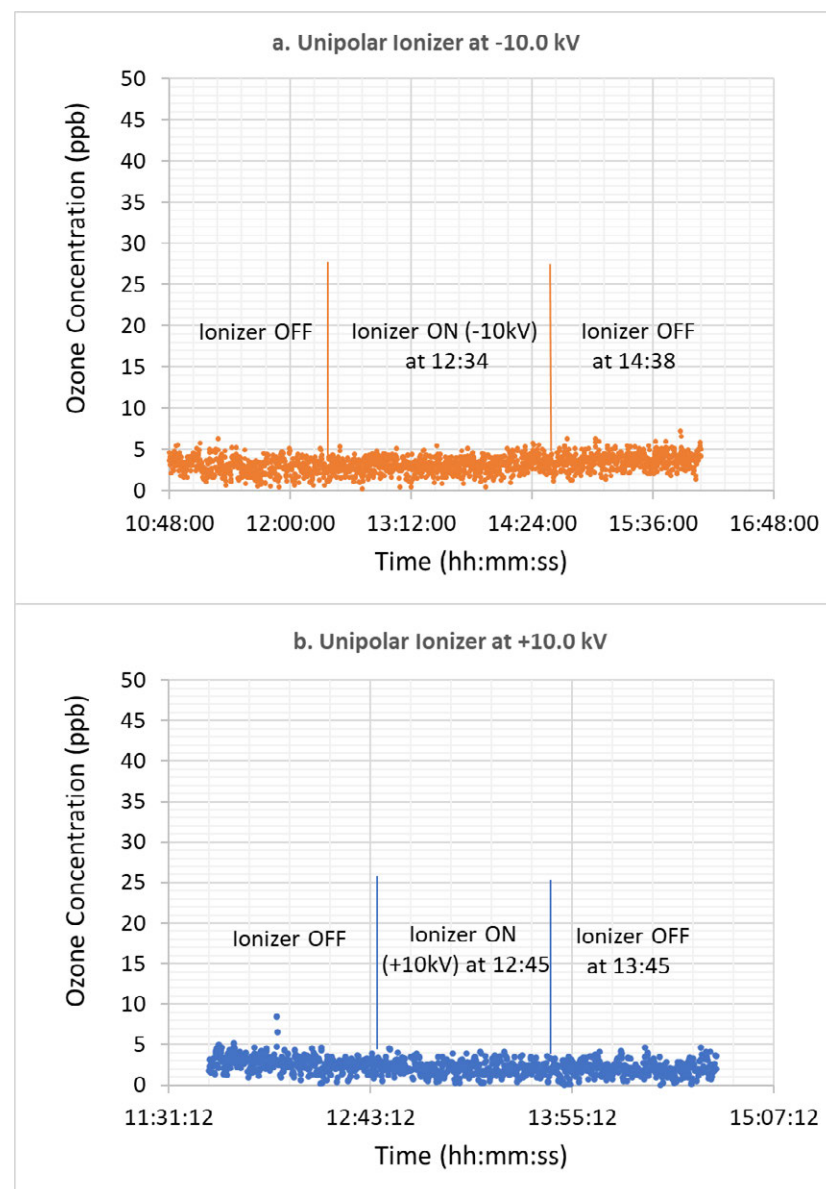


Fig. 7. Ozone concentrations for unipolar ionizer with vents closed (a. -10.0 kV; b. $+10.0$ kV).

to a balanced concentration of bipolar ions. On the other hand, when the unipolar ionizer is turned on, either for positive or negative voltage (i.e., $+7.5$ kV or -7.5 kV), the aerosol decay rates are 2.0 and 2.3 times larger for positive and negative ions respectively. This is due to the unipolar particle charging experienced by the aerosol particles (Pui *et al.*, 1988), and the faster deposition to the walls by electrostatic mechanisms (Grinshpun *et al.*, 2005; Lee *et al.*, 2004). The enhanced wall loss due to unipolar charging results in a 50% aerosol mass concentration reduction in 40 and 35-min for positive and negative ions respectively, compared with 80-min without the unipolar ionizer.

3.4 Aerosol Decay with Ventilation in the Room

Fig. 9 shows the mass concentration decays with fixed filtered outdoor air supply and return air flow rates of $4.8 \text{ m}^3 \text{ min}^{-1}$ (170CFM), and for the same cases described before, without and with the unipolar and bipolar ionizers. In these decay curves, we can clearly see the benefit of high efficiency filtration on the aerosol decay rates that are one order of magnitude higher than the decay rate without ventilation. Also, in this case, the unipolar ionizer enhances the mass

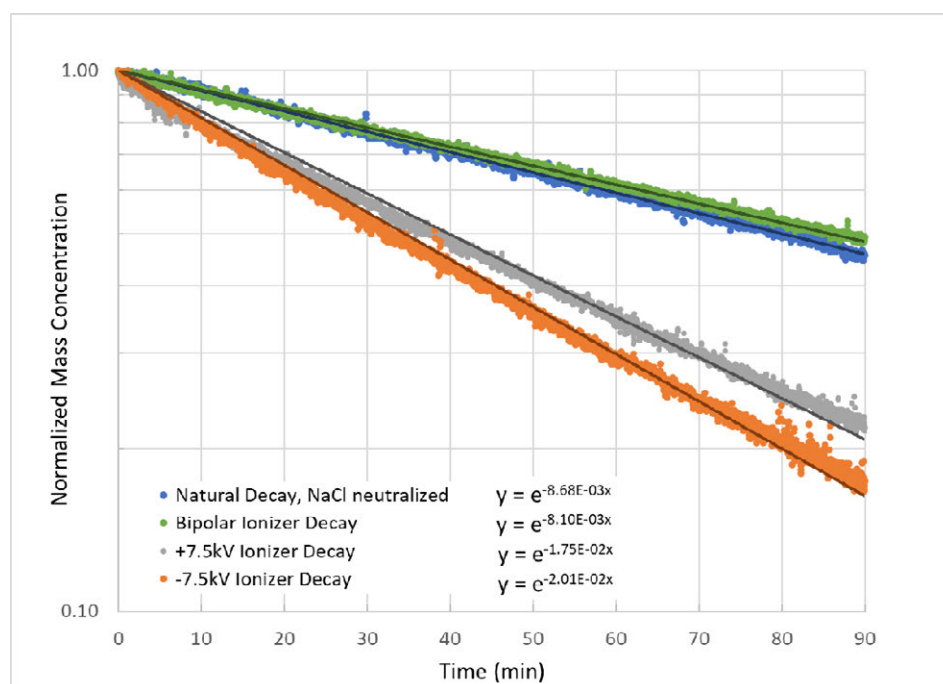


Fig. 8. Aerosol mass concentration decay without room ventilation.

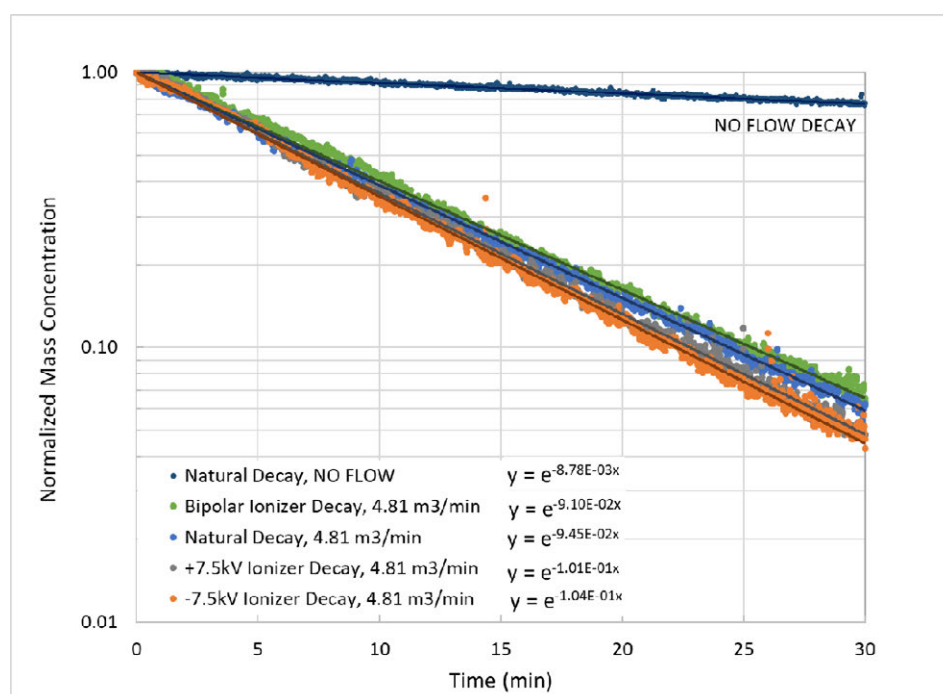


Fig. 9. Aerosol mass concentration decay with ventilation (100% filtered outdoor air).

concentration decay rates by only 6 to 10% for positive and negative unipolar ions respectively. In this case the enhancement is only from the additional particle wall deposition, since the return air with charged particles is not recirculated. The bipolar ionizer does not enhance the aerosol decay rates. Fig. S2 in the supplementary information shows the corresponding aerosol number concentration decay curves with a nearly identical trend and slightly higher decay rates due to the lower particle sizes detected by the CPC. Therefore, the same conclusions can be drawn using particle number concentrations.

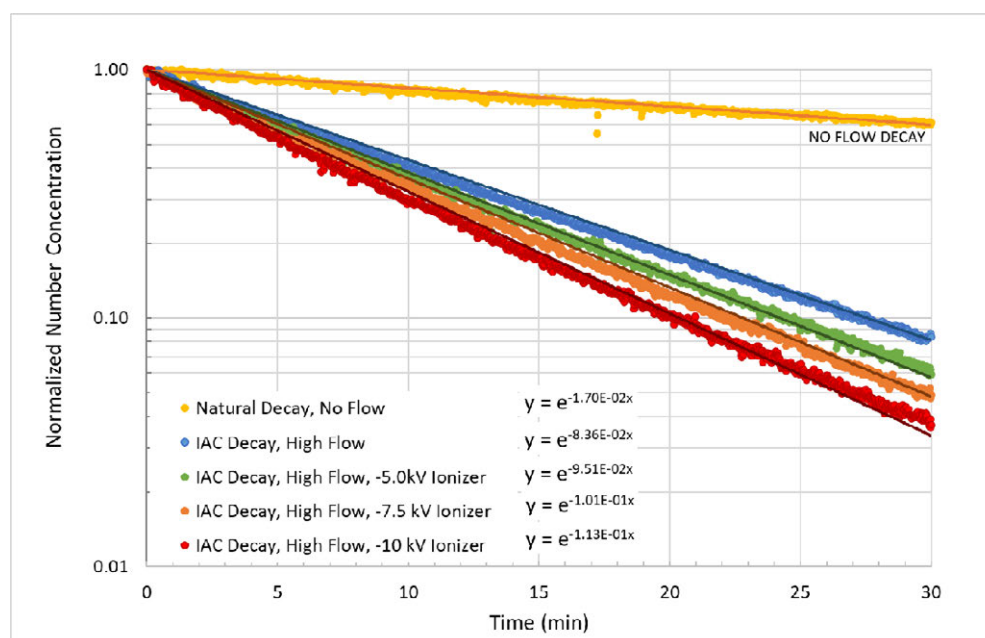


Fig. 10. Aerosol number concentration decay for PuraShield™ air cleaner.

3.5 Aerosol Decay with Indoor Air Cleaners and Zero Room Ventilation

Fig. 10 shows the aerosol number concentration decay of the PuraShield® air cleaner at the high flow setting of $7.08 \text{ m}^3 \text{ min}^{-1}$ (250CFM) with the ionizer turned OFF and with the unipolar ionizer turned ON at -5.0 kV , -7.5 kV , and -10.0 kV . It is clear that higher unipolar ionizer voltages lead to faster decay rates when compared to the decay rate with the ionizer turned OFF. The decay rates are 14%, 21%, and 35% higher at -5.0 kV , -7.5 kV , and -10.0 kV respectively. These higher decay rates are due to enhanced wall deposition and to higher filtration efficiency of the air cleaner filter element, both by the additional electrostatic deposition mechanism at play. The PuraShield® air cleaner only has mechanical air filtration and no ionizer built in, so the improved performance is due to the operation of the unipolar ionizer in the room. The improved decay rates translate directly in higher CADR values per the AHAM standard. It is worth to comment that this air cleaner has a lower CADR than expected at the high flow setting, so either the filter is not HEPA, or it has a significant internal bypass inside the unit. Fig. S3 in the supplementary materials shows the decay rates of the PuraShield® air cleaner without the ionizer at the 3 flow settings and the corresponding measured CADR calculated values and the corresponding effective air cleaning efficiencies.

Fig. 11 shows the aerosol number concentration decay of the Braun SensorAir™ air cleaner operated at the mid (i.e., 2) and high flow settings (i.e., 4), with and without the unipolar ionizer at -7.5 kV . It is worth noting that this air cleaner has an internal ionizer that charges the particles in the room, but the additional unipolar ionizer is still able to further enhance the aerosol decay rates by 7% and 18% at the high and mid flow settings respectively. For the Braun SensorAir™ air cleaner, the measured CADR at the high flow setting is $6.03 \text{ m}^3 \text{ min}^{-1}$ (213CFM), consistent with the value of $5.49 \text{ m}^3 \text{ min}^{-1}$ (194CFM) specified by the manufacturer for smoke aerosols.

3.6 Simple Analytical Model for Room Concentration Decay and Derived Empirical Parameters

Using the validated analytical model derived by Cao *et al.* (2021), the following equations can be used to predict the mass concentration of particles in the room:

$$M(t) = a \times e^{bt} + c \quad (1)$$

where coefficients a , b , and c are:

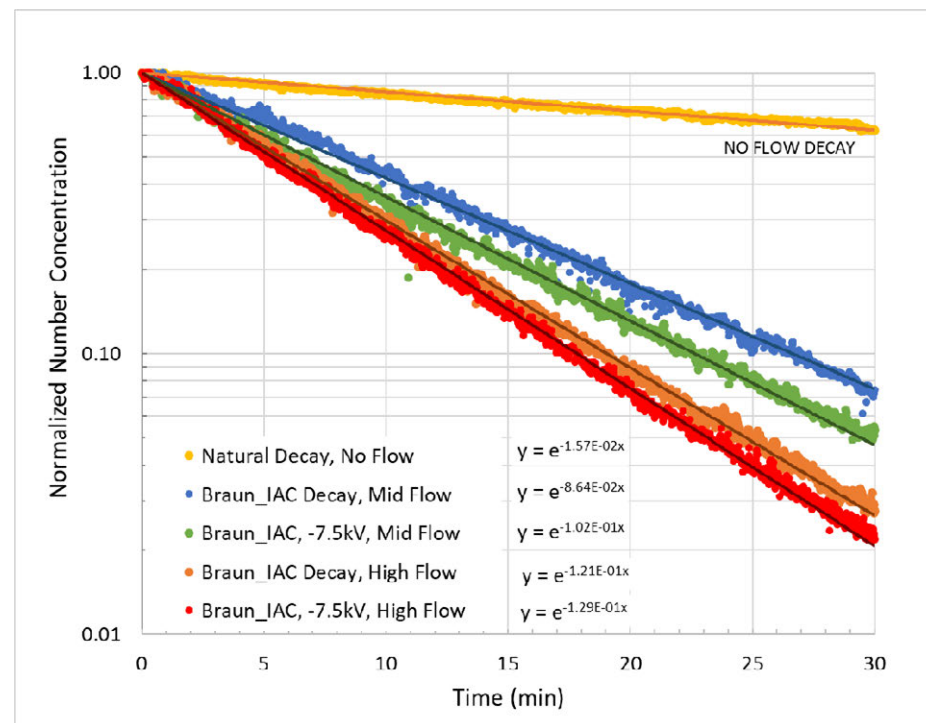


Fig. 11. Aerosol number concentration decay for Braun SensorAir™ air cleaner.

$$a = M_0 - \frac{S + Q_{AHU}(1 - \eta_{AHU})M_a}{Q_{AHU} + \eta_{IAC}Q_{IAC} + A_s(k_w + k_i)} \quad (2)$$

$$b = \frac{Q_{AHU} + \eta_{IAC}Q_{IAC} + A_s(k_w + k_i)}{V} \quad (3)$$

$$c = \frac{S + Q_{AHU}(1 - \eta_{AHU})M_a}{Q_{AHU} + \eta_{IAC}Q_{IAC} + A_s(k_w + k_i)} \quad (4)$$

A_s : Total surface area of the room (includes walls, floor, and ceiling) (97.15 m²)

V : total volume of the room (57.17 m³)

M_0 : Initial particle mass concentration in the classroom

M_a : Outdoor particle mass concentration (< 10 µg m⁻³)

η_{AHU} : AHU (air handling unit) filter efficiency (~0.94, MERV 8 + MERV 15 filters)

η_{IAC} : IAC (indoor air cleaner) filter efficiency

Q_{AHU} : flow rate of AHU (0 or 4.81 m³ min⁻¹)

Q_{IAC} : flow rate of IAC (0, 1.33, 3.54 or 7.08 m³ min⁻¹ for the PuraShield™ air cleaner)

k_w : Wall-loss coefficient (calculated from data)

k_i : Ion-wall-loss coefficient (calculated from data)

S : source term (zero when atomizer is off and no activity in the room)

For the case of natural decay rate in the room with no ventilation, Eq. (1) is simplified to:

$$M(t) = M_0 \times e^{bt} \quad (5)$$

$$\text{where } b = \frac{A_s(k_w + k_i)}{V} \quad (6)$$



Table 2. Particle wall loss coefficients for natural and ion-enhanced deposition.

Experimental condition	Measured mass decay constant ^a (s ⁻¹)	Wall loss coefficient (m s ⁻¹)
Natural decay (no ionizer)	1.48×10^{-4}	$k_w = 8.51 \pm 0.60 \times 10^{-5}$
Positive ion induced decay (+7.5 kV)	2.91×10^{-4}	$k_{ip} = 8.65 \pm 0.61 \times 10^{-5}$
Negative ion induced decay (-7.5 kV)	3.36×10^{-4}	$k_{in} = 11.2 \pm 0.8 \times 10^{-5}$

^a Decay constants calculated by linear regression analysis. Standard error for decay constants is $< 2\text{E-}7$.

Table 2 shows the calculated (exponential regression) wall loss coefficients for no ionizer and for unipolar positive and negative ions, using the decay curves shown in Fig. 8. The unipolar ionizer wall loss coefficients are as large as the natural wall loss coefficient, effectively doubling the wall deposition in the room.

For the case of aerosol room decay with the HVAC system operating at $4.81 \text{ m}^3 \text{ min}^{-1}$ Eq. (5) still applies, but the coefficient b has an additional term:

$$b = -\frac{Q_{AHU} + A_s(k_w + k_i)}{V} \quad (7)$$

Table 3 shows the empirical decay constants for the 3 cases tested, with the last three rows estimating the natural, positive and negative ion induced decays, showing good agreement with the values shown in Table 2. This agreement indicates that the ion enhanced wall deposition remains when the HVAC system is running.

For the case of aerosol room decay with the indoor air cleaner, Eq. (5) is still applicable with the coefficient b as:

$$b = -\frac{\eta_{IAC}Q_{IAC} + A_s(k_w + k_i)}{V} \quad (8)$$

Using the measured number concentration decay constants shown in Fig. S2 (ionizer OFF), and with the manufacturer's specified flow rates at the low, medium, and high flow settings (assuming 5% flow rate uncertainty), the effective efficiency of the PuraShield™ air cleaner can be calculated at each flow setting. The results are shown in Table 4 with overall efficiencies lower than 99%, which may be due to a significant internal bypass flow that does not get filtered, leading to lower-than-expected CADR values, considering the internal filter is rated as a HEPA filter. We tested another identical air cleaner and obtained equivalent results. Table 4 also shows the calculated CADR values for the PuraShield™ air cleaner at high flow, and with the ionizer at -5.0, -7.5, and -10.0 kV, showing a significant improvement of up to 42% in the CADR.

Using the measured decay constants shown in Fig. 11 for the Braun SensorAir® air cleaner, Table 5 shows the calculated CADR values at the 2 flow settings tested, without and with the additional unipolar ionizer turned ON. Since this air cleaner has an iFD® filter element which relies

Table 3. Mass concentration decay constants with ventilation.

Experimental condition	Measured mass decay constant ^a (s ⁻¹)
Mass decay with ventilation only ($4.81 \text{ m}^3 \text{ min}^{-1}$)	1.57×10^{-3}
Mass decay with ventilation and positive ions	1.69×10^{-3}
Mass decay with ventilation and negative ions	1.73×10^{-3}
HVAC system decay (Q_{AHU}/V)	$(1.40 \pm 0.13) \times 10^{-3}$
Natural decay (no ionizer)	$(1.72 \pm 0.13) \times 10^{-4}$
Positive ion induced decay (+7.5 kV)	$(2.80 \pm 0.13) \times 10^{-4}$
Negative ion induced decay (-7.5 kV)	$(3.30 \pm 0.13) \times 10^{-4}$

^a Decay constants calculated by linear regression analysis. Standard error for decay constants is $< 1\text{E-}6$.



Table 4. Performance of PuraShield™ air cleaner.

PuraShield™ flow setting	Measured number decay constant ^a (s ⁻¹)	Calculated efficiency of air cleaner (%)	Measured CADR (m ³ min ⁻¹)
Zero flow (natural decay)	0.285×10^{-3}	N/A	N/A
LOW (1.33 m ³ min ⁻¹)	0.600×10^{-3}	80 ± 5	1.06 ± 0.01
MID (3.54 m ³ min ⁻¹)	0.935×10^{-3}	63 ± 5	2.21 ± 0.01
HIGH (7.08 m ³ min ⁻¹)	1.41×10^{-3}	54 ± 5	3.85 ± 0.03
HIGH (7.08 m ³ min ⁻¹) and -5.0 kV	1.59×10^{-3}	63 ± 5	4.45 ± 0.03
HIGH (7.08 m ³ min ⁻¹) and -7.5 kV	1.68×10^{-3}	68 ± 5	4.79 ± 0.03
HIGH (7.08 m ³ min ⁻¹) and -10.0 kV	1.88×10^{-3}	77 ± 5	5.49 ± 0.03

^a Decay constants calculated by linear regression analysis. Standard error for decay constants is < 1E-6.

Table 5. Performance of Braun SensorAir® air cleaner without and with additional room ionizer.

Braun SensorAir® flow setting	Measured number decay constant ^a (s ⁻¹)	Measured CADR (m ³ min ⁻¹)
Zero flow (natural decay)	0.262×10^{-3}	N/A
HIGH flow (no ionizer)	2.02×10^{-3}	6.02 ± 0.03
HIGH flow (ionizer at -7.5 kV)	2.15×10^{-3}	6.48 ± 0.03
MID flow (no ionizer)	1.44×10^{-3}	4.04 ± 0.03
MID flow (ionizer at -7.5 kV)	1.70×10^{-3}	4.93 ± 0.03

^a Decay constants calculated by linear regression analysis. Standard error for decay constants is < 1E-6.

on electrostatic precipitation (<https://www.darwintechology.com/technologies/>) to remove the particles in the room, the use of the additional ionizer results in enhanced CADR values, particularly at the lower flow setting. This is due to the higher particle collection efficiency for charged particles, which is more efficient at lower flow rates, due to the additional particle residence time in the ifD® element. At the medium flow setting the CADR with the additional room ionizer is almost equivalent to the CADR at the high flow setting without the additional room ionizer, saving energy and reducing blower noise.

4 CONCLUSIONS

The use of simple unipolar ionizers (like the one used in this study) can enhance particle wall deposition to the interior surfaces of a room by a factor of two, leading to faster aerosol decay rates, particularly in rooms with poor ventilation rates. Bipolar ionizers, on the other hand, do not have a measurable effect on the aerosol decay rate, since both positive and negative ions tend to reduce the overall charge of the particles, and therefore do not enhance particle wall deposition.

Unipolar ionizers can also enhance the performance of indoor air cleaners, in particular those that rely on electrostatic precipitation (such as ifD® elements). This is due to the additional particle charging and the resulting increase in particle collection by coulombic forces. For air cleaners that rely on conventional air filters, unipolar ionizers have a smaller effect, but they can still enhance particle filtration by electrostatic mechanisms, and this effect will be larger for electret filters with built-in permanent charges in the media. The same conclusions can be drawn for recirculating HVAC systems with air filter elements. The corona ionizers tested did not increase the background ozone concentrations in the room, demonstrating that low current corona discharges can be safely used due to their very low ozone generation rate.

A limitation of the current experimental study is that the measurements were made in an unoccupied office room, with an artificially generated aerosol, and under well controlled ventilation conditions. In a real indoor environment, with ventilation and aerosol sources that vary with time, it would be very difficult to quantify the benefit of ionization on the performance of the filtration of the HVAC system or of the portable air cleaners. However, the mechanisms of enhanced wall



deposition and particle collection on air filters would still be the same for an indoor environment at realistic conditions, so the conclusions from this study should still be applicable. The results of this study could also vary somewhat with changes in parameters such as relative humidity, particle composition and size distribution, wall surface characteristics, and others. However, the conditions selected are representative of a typical indoor environment in many parts of the world, so the findings should still be valid and applicable.

While the use of unipolar ionizers combined with conventional filtration can improve particle collection performance, there are other potential benefits associated with the use of ionizers that should be investigated, such as the potential reduction of the viability of airborne microorganisms (Jiang *et al.*, 2018). The next phase of our work will quantify the effect of unipolar and bipolar ions on the viability of coronaviruses, a topic of great interest to continue address events like the COVID 19 pandemic with practical engineering-based solutions to improve indoor air quality and reduce the probability of airborne infections inside health care, industrial, commercial, and residential buildings.

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SUPPLEMENTARY MATERIAL

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