Performance of in-duct bipolar ionization devices on pollutant removal and potential byproduct formation in indoor environments

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SUMMARY
The COVID-19 pandemic has highlighted the importance of indoor air quality (IAQ) since SARS-CoV-2 may be transmitted through virus-laden aerosols in poorly ventilated spaces. Multiple air cleaning technologies have been developed to mitigate airborne transmission risk and improve IAQ. In-duct bipolar ionization technology is an air cleaning technology that can generate ions for inactivating airborne pathogens and increasing particle deposition and removal while without significant byproducts generated. Many commercial in-duct ionization systems have been developed but their practical performance on pollutant removal and potential formation of byproducts have not been investigated comprehensively. The results in this study showed that the in-duct bipolar ionization technology can significantly improve the particle removal efficiency of the regular filter, while no significant ozone and ion were released to the indoor air.

KEYWORDS
Ionization, COVID-19, particulate matter, VOCs, air cleaning.

1 INTRODUCTION

Indoor air quality (IAQ) has become an increasing concern today, particularly during the COVID-19 pandemic as it can be transmitted through airborne route (Bueno de Mesquita et al. 2021; Greenhalgh et al. 2021; Morawska and Milton 2020; Shen et al. 2021). Many air cleaning technologies have been developed to address indoor air quality issues (Zhang et al. 2022). Main air cleaning technologies include filtration, sorption, ionization, oxidation, and ultraviolet germicidal irradiation (UVGI). Air ionization is an air cleaning technology that introduces ions to indoor air, which has the potential for particle and bioaerosol removal (Hyun et al. 2017; Nunayon et al. 2019; Pushpawela et al. 2017; U.S. EPA 2022), and also affects the formation and removal of some volatile organic compounds (VOCs), although the efficiency is likely insignificant (Zeng et al. 2021). Other gaseous byproducts such as ozone and nitrogen oxides (NO_x) may also be generated in the air ionization process. High levels of ions in indoor air may also have adverse effects on human health (Dong et al. 2019; Liu et al. 2021).

Bipolar ionizers generate both positive and negative ions and have been implemented in HVAC ducts and standalone air cleaners (Carrier Global 2021; Global Plasma Solutions 2021). The application of in-duct bipolar ionization devices has the benefits for enhanced particle removal and minimal operation and maintenance costs. It has been recommended by some experts as a possible mitigation strategy to against COVID-19 (Berry et al. 2022). However, there is still a research gap of adequate research evidence on the efficacy and safety of using air ionization technologies to address IAQ issues (Zeng et al. 2021). This paper studied the performance of two types of in-duct ionization systems in particle removal and byproduct generation. Decay tests were conducted in a full-scale chamber with the office scenario.

2 METHODOLOGIES

Two different in-duct bipolar ionization devices were studied. Ionizer A (I-A) was mounted on a regular MERV 8 filter with 34 groups of positive/negative needlepoints. The unit was tested for a few times under normal conditions before the current study. The other one, ionizer B (I-B), was a portable in-duct bipolar ionizer with 6 groups of positive/negative needlepoints. The ionizer was design to ionize the in-duct air. Both ionizers were installed inside a blower system (Healthway 1200SC). Ionizer A was installed at the outlet of the blower duct, and the ionizer was on the upstream of the filter. Ionizer B was installed 0.25m upstream of the filter. The operating airflow rate of the blower in this study was controlled at 505 m^3/h. Both ionizers can be controlled independently. Full-scale chamber tests were performed in the Building Energy and Environmental System Laboratory (BEESL) at Syracuse University (Figure 1). A full-scale single office was built inside the full-scale environmental chamber with carpet floor, painted gypsum wallboards for walls and ceiling, a wooden table with a laptop, a manikin wearing soiled t-shirt, two workstation partitions, a blower with duct that simulates the air handling unit, and two mixing fans on the corners. The room size was 3.5×3.0×2.7m (29.1m^3).

Figure 1. Chamber testing configurations and blower settings.

Particle decay (or “pull-down”) tests were performed to study the particle removal performance of tested ionizers. Particles were generated using an 8-jets nebulizer (BLAM, CH Technologies Inc) driven by purified filtered clean air supply, and injected into the chamber at the beginning of the test period and the injection stopped when the indoor particle concentration reach around 1000#/cm^3 and particles deposit naturally for a certain period of time before turned on the blower and ionizers. The air handling unit (AHU) of the chamber system was completely off over the test period, with only natural infiltration presented. The method has been widely used in other studies. A similar procedure was introduced in the ANSI/AHAM standard for portable electric room air cleaners (ANSI/AHAM 2020). The air supply was approximately 20 psi, which obtained an output volumetric flow rate of 18L/min. The salt solution for particle generating contained 0.05 mol sodium chloride (NaCl) and 0.004 mol anhydrous magnesium sulfate (MgSO4) in 0.5 L deionized (DI) water. Particle concentrations were measured using TSI Aerodynamic Particle Sizer 3321 (APS) spectrometer, which measures aerodynamic particle size from 0.5 to 20 µm. Ozone was monitored using the 2B Technologies Model 202 Ozone Monitor, which has a resolution of 0.1 ppb. Negative ions were monitored using air ion counter (Alphalab Inc, Model AIC2) with the maximum range of 2 million ions/cm^3 (accuracy: ±20% of reading). The airtightness of the chamber was measured through a CO2 decay test, monitored by the photoacoustic gas monitor (Lumasense Inc, Innova 1412i). All samples were monitored at the exhaust of the chamber.

Particle concentrations were monitored every 2 seconds. In this study, the data was processed to obtain the average concentration every 1 minute. Exponential regression was performed for time-sequential particle concentrations of decay tests (Eq. 1). The removal rates of filter (k_{filter}) and ionizer ($k_{ionizer}$) were estimated based on the regression results and the natural decay rate (k_n, the combined effect of infiltration k_{inf} and deposition k_{dep}) (Eq. 2). Clean air delivery rate ($CADR_{particle}$) and equivalent single-pass removal efficiency ($SPRE_{particle}$) in terms of particle removal was estimated based on the removal rate.

$$C_t = C_0 \cdot e^{-\lambda t} \tag{1}$$

$$\lambda = k_n + k_{filter} + k_{ionizer} = (\lambda_{inf} + k_{dep}) + k_{filter} + k_{ionizer} \tag{2}$$

3 RESULTS AND DISCUSSIONS

The infiltration rate of the tested chamber was around $0.01h^{-1}$ for decay tests (Figure 2). All detected indoor particles were below 2µm in size with a median diameter roughly between 0.7 and 0.8µm. The natural decay test illustrated that the natural decay rate of total particle concentrations (k_n), that is the combined effect of infiltration (λ_{inf}) and particle natural deposition (k_{dep}), was $0.22h^{-1}$ (R^2>0.99). The decay periods of other tests revealed a consistent distribution of natural decay rates, approximately $0.20\text{-}0.25h^{-1}$ (R^2>0.99 for all tests). The contribution of particle deposition merely was $0.19\text{-}0.24h^{-1}$. Figure 3 showed the examples of total particle concentration distributions over test period of MERV 8 filter test and ionizer A test.

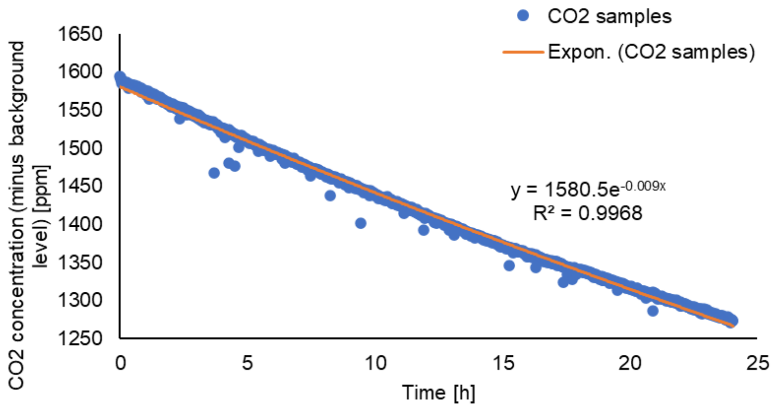

Figure 2. CO2 decay test for determining the infiltration rate (Nov 28th, 2021).

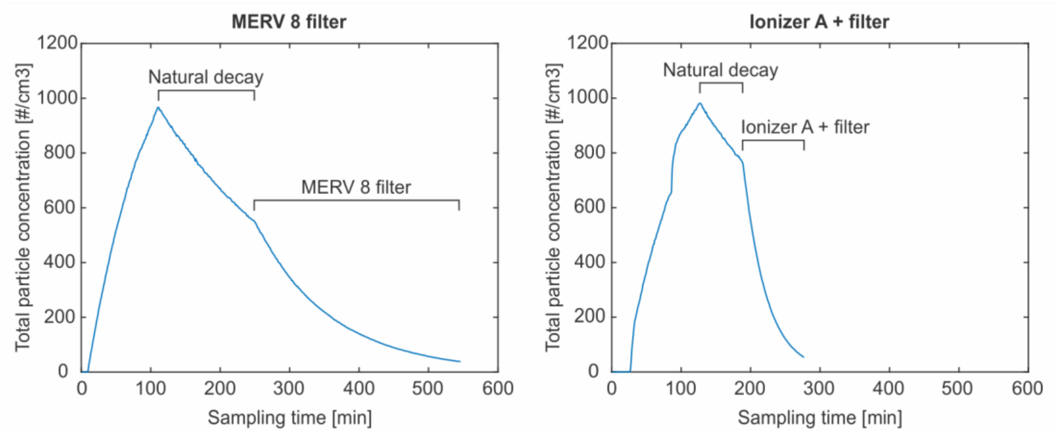

Figure 3. Total particle concentration distributions in MERV 8 filter test and ionizer A test.

Table 1 showed the removal rate, $CADR_{particle}$ and $SPRE_{particle}$ of each test under the given experimental conditions. The regular MERV 8 filter illustrated a relatively low equivalent $SPRE_{particle}$ on particle removal under current settings, around 1.7%, which was close to the lower bound of typical particle efficiencies tested by other studies (Alavy and Siegel 2020; Azimi et al. 2014; Shi et al. 2012; Shi and Ekberg 2015; Stephens and Siegel 2012). The combined use of ionizers and MERV 8 filter showed an increase on $CADR_{particle}$ by 30.4-37.5 m^3/h and filtration efficiency by around 6-7.4%, which was 3.6 to 4.5 times higher than the efficiency of the tested filter. The ionizers in this study can enhance the efficiency of the regular MERV 8 a lot.

Air ionization can generally remove particles from the air through two ways. One is the enhanced deposition of airborne particles to the indoor surfaces due to the aggregation of charged particles (increased particle size) and the attraction of charged particles by the surfaces. The other is the elevated particle filtration/capture by the charged filter as the generated ions attached on the filter. The aggregation of charged particles can also be filtered more readily by the filter. Based on the collected ion concentrations, most ions generated by the ionizer were trapped/captured by the filter when the filter was installed at the downstream of the ionizer. Therefore, the particle removal of using ionizer B individually ($CADR_{particle}$ of 19.44 m^3/h and $SPRE_{particle}$ of 3.8%) was only due to the enhanced deposition of charged particles (without the effect of enhanced filtration). It represented the maximum particle removal contribution through enhanced deposition. Considering the significant decrease of ion concentrations through the filter, the actual particle removal by enhanced deposition may contribute less at the scenarios with the filter installed and integrated with the ionizer. Therefore, based on the test results, the enhanced filtration by the charged filter likely dominated the particle removal for the integrated use of ionizer and filter, while the enhanced deposition from the air to indoor surfaces had less effects.

Table 1. Performance of different units during chamber tests.

Test conditions	Filter (MERV 8)	I-A + filter	I-B + filter	I-B (no filter installed)
Decay rate[a] [h^{-1}]	0.25	0.24	0.25	0.20
Removal rate [h^{-1}]	0.54 **0.29** (w/t decay)	1.82 **1.58 (w/t decay)**	1.59 **1.34 (w/t decay)**	0.87 **0.67** (w/t decay)
$CADR_{particle}$ [m3/h]	15.69 **8.53** (w/t decay)	52.96 **45.99 (w/t decay)**	46.32 **38.93 (w/t decay)**	25.28 **19.44** (w/t decay)
$SPRE_{particle}$ [%]	3.1 **1.7** (w/t decay)	10.5 **9.1 (w/t decay)**	9.2 **7.7 (w/t decay)**	5.0 **3.8** (w/t decay)

[a] Natural decay rate (k_n): the combined effect of infiltration (λ_{inf}) and particle natural deposition (k_{dep}).

In this study, ozone generations were detected after the ionizers were turned on. But the generation rates were very slight. The background ozone concentrations in the chamber were almost zero (0-0.1 ppb). The mean steady-state ozone concentrations of the ionization periods in three tests (ionizer A, ionizer B, and ionizer B without filter) were 1.2, 2.0, and 2.9 ppb, respectively, significantly lower than the WHO's recommended 50 ppb level. Our earlier ozone decay test illustrated that the ozone deposition rate in the same room setting was around $4.6h^{-1}$ (most ozone deposition occurred on building surfaces and human-related surfaces (Nazaroff and Weschler 2021; Shen and Gao 2018; Yao and Zhao 2018)). Therefore, it can be estimated that the ozone generation rates during the ionization in three tests were 0.33, 0.52, and 0.77mg/h for ionizer A, ionizer B, and ionizer B without filter, respectively. The generation rates were significantly lower than other ionization technologies (Guo et al. 2019). Therefore, in field tests, no significant ozone increase was monitored.

Besides, no significant ion increase was detected for the tests with the filter, while for the test without filter installed, significant ion increase was observed (Figure 4). Most ions generated by the ionizer were trapped/captured by the filter when they travelled through the filter along with the air flow. Some studies observed adverse health effects on cardiovascular system when people were exposed to high level of airborne negative ions (13×10^3 #/cm^3 and 60×10^3 #/cm^3) (Dong et al. 2019; Liu et al. 2021). Therefore, the high level of airborne ions of the ionization case without filter in this study (16.1×10^3 #/cm^3) was likely unfavorable for people's cardiovascular health and need to be removed/filtered. Therefore, it is highly recommended to use the ionizers at the upstream of the filter to maximize their performance and minimize the indoor ion concentration.

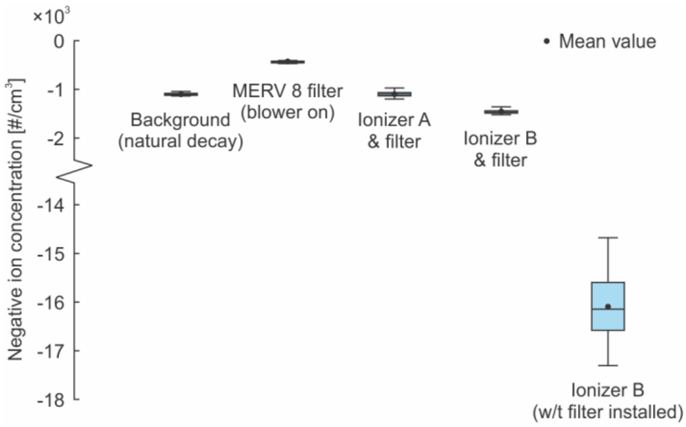

Figure 4. Steady-state negative ion concentration distributions of different cases (negative values indicated negative ions).

4 CONCLUSIONS

This study tested two different in-duct needlepoint bipolar ionizers in a full-scale office space built inside a well-controlled environmental chamber. Particle decay tests were conducted to evaluate their performance and potential secondary emissions such as ozone and negative ions. The results showed that the in-duct ionization systems can significantly increase the removal of particles while no significant ozone and ions were generated. The use of ionizer increased the $CADR_{particle}$ by around 30.4-37.5 m^3/h than a regular MERV 8 filter, which were 6.0-7.4% increases in $SPRE_{particle}$. Most ions generated by the ionizer were trapped/captured by the filter when the filter was installed at the downstream of the ionizer. The enhanced filtration by the charged filter likely dominated the particle removal for the integrated use of ionizer and filter, while the enhanced deposition from the air to indoor surfaces had less effects. The ozone generation rates during the ionization in three tests were 0.33, 0.52, and 0.77mg/h for ionizer A, ionizer B, and ionizer B without filter, respectively, which were significantly lower than other ionization technologies. The indoor ozone concentrations measured during the test periods were significantly lower than some recommended ozone levels. Therefore, the ozone generation of the tested ionizers were significantly below the concerned indoor ozone exposure level. Filter is highly recommended to be used at the downstream of the ionizer in air ducts as it can capture most air ions and maintain the indoor air ion concentration at a relatively lower level, below the level with potential health issues. Thus, in-duct needlepoint bipolar ionization technology is a potential approach for removing indoor particles and mitigating infectious risks.

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