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Effect of Nonthermal Plasma Technology on Reducing Airborne Contaminants in an Indoor Setting

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A variety of air cleaning technologies have been used to reduce airborne contaminants consisting of particulates and gaseous pollutants in an indoor environment over the past several decades. Air cleaning technologies have the potential of assisting low-cost fibrous media to clean contaminated indoor air and reduce building ventilation rates to conserve energy. Air cleaning technologies including plasma air ionization, photocatalytic oxidation, sorption, ultraviolet, electrostatic precipitator, high-efficiency particulate air (HEPA), activated carbon, etc. are employed to reduce, capture, or eliminate airborne contaminants. The plasma air ionization method generally turns electrically neutral air into negative or bipolarized air ions by applying an electric charge to the indoor air to produce a clean indoor air environment. There are two types of plasma ionization: nonthermal ionization and thermal plasma ionization. Nonthermal plasma ionization includes dielectric barrier discharge (DBD) and needlepoint bipolar ionization (NBI). A growing body of recent evidence has presented the potential of using bipolar air ionization to remove airborne particles and gaseous pollutants, and to decrease bacterial deposition on surfaces, inactivate airborne bacteria, viruses, and fungi. Meanwhile, NBI is where the ions are emitted into the airflow by needles or carbon brushes or other needlepoint-type emitters while DBD bipolar ionization uses a sealed cathode tube to create a plasma discharge which will then emit ions into the airflow. The present work particularly studies the effect of DBD bipolar ionizer-assisted minimum efficiency reporting value (MERV) filter technology on reducing airborne contaminants including particulates and toxic gases.
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Keywords: indoor air quality, nonthermal plasma technology, bipolar air ionization, air cleaning technologies

1 Introduction

Indoor air quality is an indispensable measure for ensuring a clean indoor environment in sustaining occupant health, comfort, and productivity and is generally measured by the concentrations of particulate matter (PM) and gaseous pollutants. Particulate matter, also known as particulate pollution, is a mixture of solid particles and liquid droplets found in the air [1]. The size of particulate matter ranges from submicrons to microns (μm) in particle diameter. Examples of particulate matter include dust, smoke, dirt, pollens, molds, viruses, fungi, droplets, etc. that suspend in the indoor or outdoor air and generally come from two sources: inhalable particles (PM_{10}) with particle diameters that are 10 μm and smaller and fine inhalable particles ($PM_{2.5}$) with diameters that are 2.5 μm and smaller. Inhalable particles can be detrimental and risky to human health because the matter can get into the lungs and even the bloodstream of a human. Furthermore, gaseous pollutants generally comprise of volatile organic compounds (VOCs), which are organic chemical compounds emitted as gases from certain solids or liquids [2], and non-VOCs such as carbon dioxide emitted by humans. VOCs are highly volatile, mobile, and transportable over long distances [3]. VOCs vaporize easily under normal conditions due to their high vapor pressure or low boiling point in the environment and VOCs can be emitted from outdoor and indoor sources including wildfire, agricultural waste combustion, fossil fuels burning, automobile exhaust, new building materials and furnishings, office equipment, personal hygiene products, paint, etc. Unfortunately, VOCs are highly toxic, and they pose short- and long-term adverse effects to human health when there is a large concentration of or exposure of time to the VOCs by humans.

A variety of air cleaning technologies have been used to reduce airborne contaminants consisting of particulates and gaseous pollutants in an indoor environment over the past several decades. Air treatment technologies have the potential of reducing building ventilation rates to conserve energy. Air cleaning technologies including plasma, photocatalytic oxidation, sorption, ultraviolet, electrostatic precipitator (ESP), high-efficiency particulate air (HEPA), activated carbon, etc. are employed to reduce, capture, or eliminate airborne contaminants [4–8]. There are two types of plasma ionization: nonthermal and thermal plasma ionization. Plasma exists when electrons in molecules are heated to extremely high temperatures and the energized electrons leave the molecule orbits. A nonthermal plasma is basically a plasma that happens at room temperature when the molecules are introduced with a strong electrical field. Nonthermal plasma ionization is primarily used for indoor applications owing to its low ionization intensity and thus, it becomes the focus of the present work. Nonthermal plasma is generated by a strong electric field to create a neutral gas discharge and release electrons, and in turn generate ions and photons, which can generally agglomerate smaller particles and decompose VOCs [9]. Similarly, nonthermal plasma can be generated when electrons are released at high energy with the gaseous atoms and molecules remaining neutral in the atmospheric pressure. The high-energy electrons will then increase the ionization potential of those neutrally charged atoms and molecules to make negative and/or positive ions. Dielectric barrier discharge (DBD) bipolar ionization is a type of nonthermal plasma application. DBD produces highly nonequilibrium, controlled plasmas at atmospheric pressure and can effectively generate atoms, radicals, and energized species with energetic electrons at moderate gas temperatures [10]. The DBD is generally composed of two electrodes, which are separated

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by insulated material gap spacing. One of the electrodes is covered with a dielectric material [11]. Electron energy released by the DBD ionizer will be used to disassociate the gas molecules and, thereby, to create ions [11].

A growing body of recent evidence has presented the potential of using a nonthermal plasma air cleaning technology, such as unipolar or DBD bipolar air ionization, to remove airborne particles and gaseous pollutants, and to decrease bacterial deposition on surfaces, inactivate airborne bacteria, viruses, and fungi [12–20]. Hobbs et al. [12] reported that a bipolar ionizer suppressed and mitigated particle generation in a clean room environment. Gabbay et al. [13] used a corona discharge ionizing generator to investigate the effect of ions on the microbial air pollution of a dental clinic. Microbial air levels in the dental clinic were significantly reduced with the generator by 40–50%. The data suggested that the ionizing generator can be used to reduce microbial air pollution within the dental clinic, thus reducing the environmental hazard of infections to the staff. Byeon et al. [6] measured the size distributions of bimodal submicron aerosol particles and estimated the collection efficiency of the particles for a hybrid two-stage ESP composed of a DBD charger as the particle charger and an ESP as the charged particle collector. The particle collection efficiencies increased as alternating current applied voltage increased at a fixed frequency and flowrate. Lee et al. [14] evaluated the continuous emission of unipolar ions to determine their ability to remove fine and ultrafine particles from indoor air environments. The study concluded that ionic air purifiers, which can produce unipolar ions, can be efficient in controlling fine and ultrafine aerosol pollutants in indoor air environments. Furthermore, Sherali [15] reported that there was a high concentration rate of aerosol decay with a bipolar ionization unit compared with that of without ionization.

Hyun et al. [16] conducted laboratory tests involving the filtration and inactivation of a bacteriophage MS2 virus using a carbon-fiber ionizer installed upstream of a medium filter. The overall filtration efficiency increased when the ionizer was on and the antiviral efficiency with bipolar ions was higher than that with unipolar ions, but the electric field was not effective for inactivation. Gast et al. [17] applied negative air ionization for reducing experimental airborne transmission of *Salmonella enteritidis* to chicks. Air ionization imparted a negative charge to airborne dust particles and thereby caused them to be attracted to ground surfaces. Reducing airborne dust levels through air ionization offered a powerful tool for restricting the opportunities for Salmonella infections to spread extensively throughout poultry flocks.

Zeng et al. [18] conducted experiments to evaluate the gas and particle removal effectiveness and potential for byproduct formation resulting from the operation of a commercially available in-duct bipolar ionization device. Both the chamber and field tests suggested that the use of the tested bipolar ionization unit led to a decrease in xylenes but an increase in oxygenated VOCs (e.g., acetone and ethanol) and toluene. Kim et al. [19] reviewed and compared various principles and approaches employed in air ionization techniques as a control technology for reducing off-gas emissions of volatile organic compounds. Air ionization techniques were used extensively to remove odors and VOCs from air flows, and the feasibility was demonstrated in sensitive manufacturing operations. The future of air ionization will be brightened by continuing efforts to improve their cost-effectiveness and minimize the production of by-products. Van Durme et al. [20] investigated the effect of catalyst and humidity on both ozone and toluene removal using hybrid plasma catalyst technology. Toluene is a type of VOCs. The tested plasma technology is nonthermal, which is a direct current corona discharge. Ozone removal strongly correlated with the active compound of the tested catalysts whereas the effect of humidity on ozone abatement was negligible for the tested catalysts. Toluene removal efficiency was 90% and 39% at 39% and 74% relative humidity, respectively. Park et al. [11] conducted a lab-scale test of a ventilation system including a DBD ionizer and a UV-photocatalyst filter for simultaneous removal of gaseous and particulate contaminants. The percentage reduction of PM 2.5 was approximately 79.5%. The UV-photocatalyst filter was used to enhance the decomposition of VOC gaseous species, such as formaldehyde (HCHO), benzene, toluene, and xylene (BTX), into carbon dioxide and water vapor products. Both HCHO and BTX were reported to be completely removed in the test [6]. Wu and Lee [21] carried out studies on the removal of VOCs by negative air ions (NAIs). Three species of VOCs—chloroform, toluene, and 1,5-hexadiene—were selected to react with NAI at relative humidities of 0%, 25%, and 70%. The reaction rate constantly declined as the relative humidity increased in the reaction between toluene and NAI, but such a relationship was not evident in the reaction between 1,5-hexadiene and NAI. In addition, Chen et al. [22] degraded formaldehyde by a soft-sliding-electrification-induced air ionization method.

In the present work, the effect of a DBD bipolar ionization device (AtmosAir Solutions FC-400) on the possibility of enhancing a minimum efficiency reporting value (MERV) filter to mitigate airborne contaminants that comprise of particulate matter and gaseous pollutants will be studied and reported. The present work does not study the reduction of microbes. The primary objective of the present work is to investigate if a low-cost MERV filter (e.g., MERV 13) when combined with the DBD bipolar ionizer can approximately reach the particulate removal efficiency of a HEPA filter with the dual purposes of conserving energy due to high pressure drop across a HEPA filter and reducing electrical power cost for sustainability. Furthermore, a HEPA filter is not optimal as a room air filter because of its high particulate removal efficiency, which is associated with higher electrical power cost and noise [23]. The secondary objective is to study the percentage reductions of gaseous pollutants including total volatile organic compounds, formaldehyde, and carbon dioxide gas concentrations due to the DBD bipolar ionization.

2 Materials and Methods

2.1 Experimental Methodology. A stand-alone unoccupied prop house built by the construction program of Fresno City College is used as the test chamber. Figure 1 demonstrates the setup of the present air cleaning test in a prop house. The components of the test setup include both supply and return air flexible/rigid ducts, one indoor air quality sensor, one source injector, one total volatile organic compounds (TVOCs) sensor, one mechanical air filter compartment, one dielectric bipolar ionization technology mounting station, and an air-handling unit. The tightly sealed L-shaped indoor test space enclosed by a thick boundary is shown in Fig. 1. Both Carrier Opticlean and air-handling units are located at the bottom right of the prop house, which is the garage space. The HEPA filter is installed inside the Carrier Opticlean negative air machine unit whereas the combined DBD bipolar ionization and MERV filtration system is placed inside the air-handling unit. There is one small room of the house located approximately toward the bottom center of Fig. 1, which is completely sealed and enclosed, and it is not part of the test study. Additionally, the non-filled and filled arrows indicate the directions of return and supply air in Fig. 1, respectively. The emission source is woodchip-based smoke. The TVOC sensor measures the TVOC concentrations in terms of percentages (%) whereas the indoor air quality sensor records the particle concentrations in count/cm^3, $PM_{2.5}$ and PM_{10} in $\mu g/m^3$, formaldehyde in mg/m^3, and carbon dioxide concentrations in parts per million (ppm). The airflow is maintained with a 100% return air by shutting off the outside air damper of the economizer from the air-handling unit in Fig. 1.

The floor area and the overall volume of the prop house are approximately 37 m^2 and 90 m^3, respectively. The prop house includes a central air conditioning system, and the system uses 100% recirculated air with tightly sealed ductwork. The central air conditioning fan is operated in all experiments. The indoor air cleaning test configuration varies between one of the in-duct MERV filters (e.g., MERV 8 and MERV 13) installed one at a time and with an in-duct DBD bipolar ionization device (AtmosAir

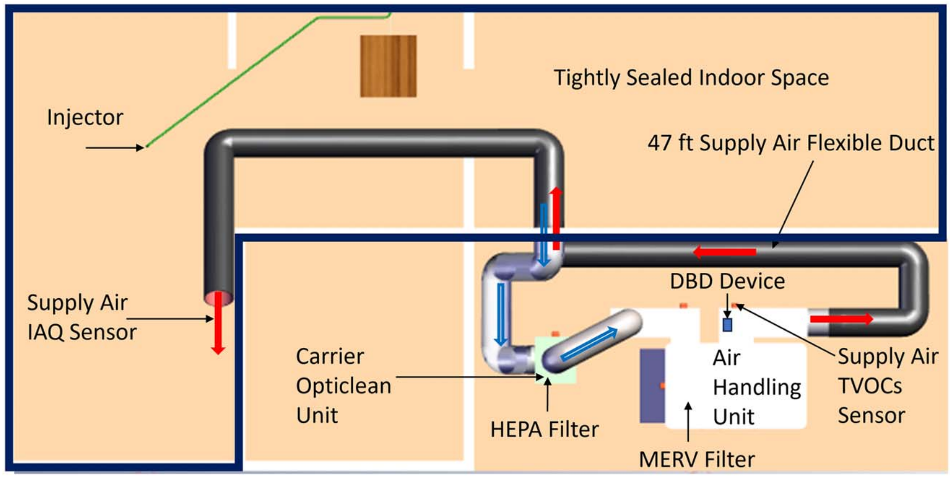

Fig. 1 Setup of the air cleaning test experiment. Non-filled and filled arrows represent return and supply air directions.

Solutions FC-400) either on or off. The in-duct DBD bipolar ionization device uses a sealed cathode tube to create a plasma discharge which will emit ions into the airflow. Indoor air cleaning experiments are carried out to test the effect of DBD bipolar ionization-assisted MERV filter on particulate matter removal efficiency, percent reductions of TVOCs, and decay of formaldehyde and carbon dioxide gas concentrations. The particulate matter removal efficiency will be compared with that of the HEPA filter alone. The prop house is equipped with instruments to monitor indoor particle and gaseous concentrations. The indoor air quality instrumentation system is composed of one TVOC sensor (BELIMO) and one indoor air quality sensor (TSI Q-Trak XP) mounted at the supply air duct location. The indoor air quality sensor measures the particle concentrations, particulate matter (e.g., $PM_{2.5}$ and PM_{10}), carbon dioxide, and formaldehyde concentrations at the supply air location. Each indoor air cleaning configuration test lasts approximately 1 h. All data are logged over a 1-min time resolution during the 1-h test duration. Each test configuration is repeated multiple times, and a general timeline of a test configuration is reported in this section. Source (e.g., woodchip-based smoke) injection system is triggered after 10-min baseline data collection and runs for approximately 5 min. Then, the air conditioning system fan and DBD bipolar ionizer if used are turned on for 30 minutes. Lastly, both the fan and the DBD bipolar ionization device will be turned off and the indoor environment will be left to settle down during the last 15 min of the test duration. All data are then collected and averaged from the repeated measurements at the supply air duct during the last 15-min steady state of each test when both fan and DBD bipolar ionization air cleaning device if used are turned off. The supply air velocity is 6.6 m/s that is measured by a hotwire anemometer (TSI). The supply air duct diameter is 36 cm. The average outdoor air temperature and relative humidity are measured at 90 °F and 20%, respectively. The ion count is measured by an air ion counter (AlphaLab Inc.). While the baseline average ion reading is 0.3×10^3 ions/cm^3 without ionization, the average ion count is 2.5×10^3 ions/cm^3 when the DBD bipolar ionization device is operated. The average ozone level is measured to be 0.003 parts per million (ppm) with ionization operated, which is well below the Environmental Protection Agency (EPA) standard of 0.075 ppm [24]. Additionally, Kang et al. [25] detected nitrogen oxides and peroxides from their nonthermal DBD plasma study. However, those by-products are not detected in the present study.

3 Results and Discussion

3.1 Particulate Matter Study. Figure 2 compares the average $PM_{2.5}$ removal efficiency of the MERV 13 filter assisted with and without DBD bipolar ionization and a stand-alone HEPA filter. The removal efficiency is determined using the following equation:

$$\text{Removal efficiency} = \frac{m_i - m_f}{m_i} \times 100\% \qquad (1)$$

where m_i and m_f represent the measured initial and final mass density of $PM_{2.5}$ in μg/m^3 during the air cleaning test period. A full mechanical recirculation system using MERV 13 filter assisted with DBD bipolar ionization technology shows significant improvement in the average $PM_{2.5}$ removal efficiency (97%) when compared with the MERV 13 filter alone without ionization (85%). The $PM_{2.5}$ removal efficiency of the HEPA filter is found to be 99.7% in the present study. According to the strict definition of a HEPA filter, it is at least 99.97% efficient at removing 0.3-μm particles [26], and it has greater efficiency for smaller and larger particles. Results show that the DBD bipolar ionization enhances the $PM_{2.5}$ removal efficiency of the MERV 13 filter to be approximately comparable to that of the HEPA filter alone. Figure 3

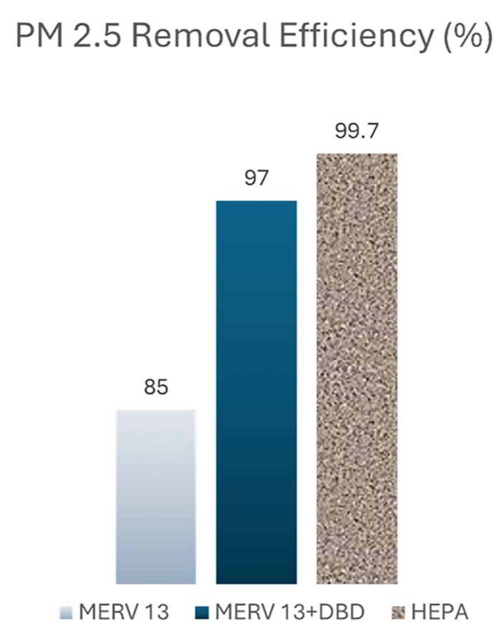

Fig. 2 Comparison of the $PM_{2.5}$ removal efficiency of MERV 13 filter assisted with and without DBD bipolar ionization and a stand-alone HEPA filter

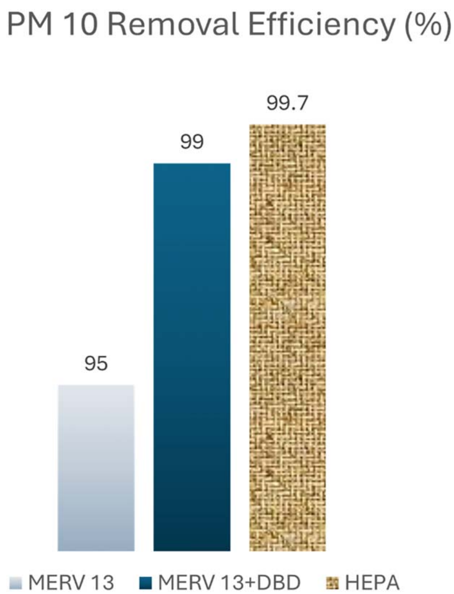

Fig. 3 Comparison of the PM_{10} removal efficiency of MERV 13 filter assisted with and without DBD bipolar ionization and a stand-alone HEPA filter

compares the average PM_{10} removal efficiency of the MERV 13 filter assisted with and without DBD bipolar ionization and the HEPA filter alone. The removal efficiency of PM_{10} is calculated similarly using Eq. (1). The MERV 13 filter assisted with DBD bipolar ionization technology improves the PM_{10} removal efficiency (99%) compared with the MERV 13 filter alone without ionization (95%). In addition, Fig. 4 shows concentrations of submicron and micron particle diameters at the controlled case and several air cleaning test configurations with a MERV 13 filter. A controlled case is when neither a fibrous filter nor a DBD bipolar ionizer is used. The MERV 13 filter with the in-duct DBD bipolar ionizer operated demonstrates a comparable reduction in concentrations of submicron and micron particle diameters to the HEPA filter alone. A significant percent reduction (95%) in the concentration of 0.3-μm particle diameter between MERV 13 filter with DBD bipolar ionizer operating and a controlled case can be seen in Fig. 4. Ions from the DBD ionization induce an agglomeration effect on particulate they encounter. Ions are distributed to space via air-handling equipment with the expectation of agglomerating smaller particles into larger particles. This amalgamation of smaller particles into larger particles increases the effectiveness of the filters present in the heating, ventilating, and air conditioning (HVAC) system (larger particles are more easily captured by filters) as well as results in large particles falling out of the air they were previously suspended in. This agglomeration phenomenon increases the effectiveness of the physical air filters installed in the air-handling unit. The larger the particle is, the more easily it is captured by the filter and thus, not returned out into space. Figure 5 presents that the DBD bipolar ionization augments both the particulate matter 2.5 and 10 μm (μm) removal efficiency to be in the upper 80% when an in-duct MERV 8 filter was used. Similarly, Fig. 5 shows a general reduction in particulate concentration when DBD bipolar ionization is activated with a MERV 8 filter compared with a MERV 8 filter with ionization off or in a controlled experiment without using any MERV filter or bipolar ionization.

3.2 Total Volatile Organic Compounds Study. Volatile organic compounds are some of the most common air pollutants emitted from a variety of outdoor sources such as transportation and industrial processes, as well as from indoor sources such as household decorative materials, office printers, etc. [9]. The present study employs a TVOCs sensor (BELIMO) to measure the concentration of TVOCs in terms of percentage. The TVOCs percentage is defined as the ratio of the actual concentration of TVOCs and the maximum possible concentration of TVOCs. One hundred percent is equivalent to 1000 parts per billion (ppb) of TVOCs. DBD bipolar ionization is a nonthermal plasma technology that generates ions, which in turn decomposes toxic VOCs. Figure 6 shows trended TVOCs percentage data with DBD ionization test configuration. The result shows that the DBD bipolar ionization produces an average TVOCs percent reduction of about 40%. A fibrous filter has no effect on the mitigation of VOC concentrations, so their impact on the study is not included.

3.3 Formaldehyde and Carbon Dioxide Study. Both formaldehyde and carbon dioxide gas concentrations do not exhibit significant reductions due to the DBD ionization. Figure 7 shows a minor reduction in the trended concentration data of HCHO gas from the present study with DBD bipolar ionization in operation. The HCHO gas concentration peaks at the end of the source (smoke) injection to the studied indoor air space. However, the reduction in the concentration of HCHO gas is less significant compared with the peaked HCHO gas concentration. Similar findings are found in the work of Park et al. [11] in which the DBD ionization does not have much effect on the removal of HCHO. Figure 8 shows a trended profile of carbon dioxide concentrations with DBD bipolar ionization operating. Owing to oxygen having higher ionization energy than carbon, an insignificant decay of carbon dioxide concentrations was observed in the present study. Thus, DBD ionization does not mitigate carbon dioxide concentration.

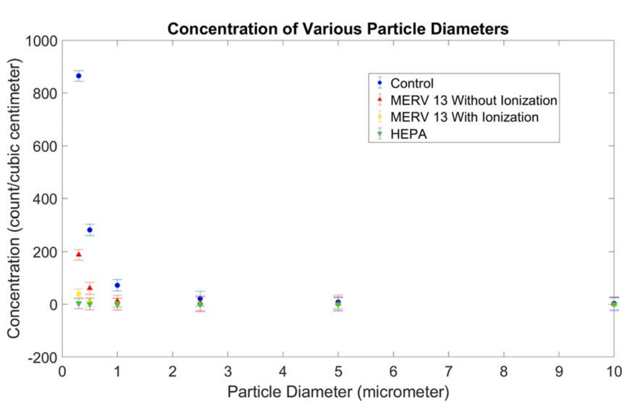

Fig. 4 Concentrations of submicron and micron particle diameters at the controlled case and several air cleaning test configurations with a MERV 13 filter

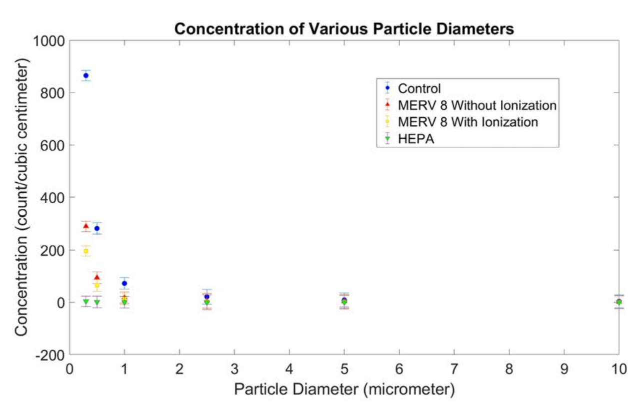

Fig. 5 Concentrations of submicron and micron particle diameters at the controlled case and several air cleaning test configurations with a MERV 8 filter

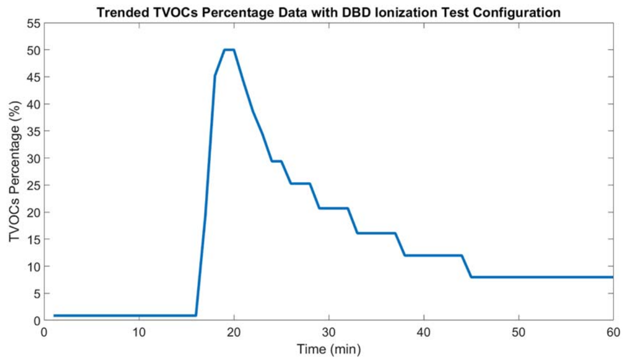

Fig. 6 Trended TVOCs percentage data with DBD ionization test configuration

3.4 Effect of Air Velocity. Figure 9 presents the effect of air velocity on ion concentration with a MERV 13 filter including DBD bipolar ionization. Three air velocities of 3.3 m/s, 6.6 m/s, and 9.5 m/s are reported. The findings show that higher air velocity leads to a greater ion count, which also indicates better air quality as evidenced by the results demonstrated in Fig. 10. At 0.3-μm particle diameter, the percent reduction of particle concentration from the lowest to the highest air velocity is found to be 73%.

3.5 Energy Evaluation Study. The power consumptions of the combined DBD ionization and MERV 13 filtration system and stand-alone HEPA filtration are evaluated and compared. Power consumption is determined using the following equation:

$$\text{Power} = \frac{Q \times \Delta P}{\eta} \tag{2}$$

where Q, ΔP, and η refer to the volumetric airflow rate, airflow resistance in terms of pressure drop across a filter, and combined motor and blower efficiency, respectively. Equation (2) will add the DBD bipolar ionization power in the case of ionization. In the present study, the supply air velocity is measured at 6.6 m/s and the supply air duct diameter is 36 cm. The measured flow resistances of MERV 13 and HEPA filters are 224 Pa and 398 Pa, respectively. The combined motor and blower efficiency is rated at 65%. In addition, the power consumption of the in-duct DBD bipolar ionization device (AtmosAir Solutions FC-400) is 7.68 W. Thus, the power consumptions of the combined DBD ionization and MERV 13 filtration system and stand-alone HEPA filtration are 238.68 W and 411 W, respectively. This finding shows that the HEPA filter uses 42% more power than the combined DBD ionization and MERV 13 filtration system.

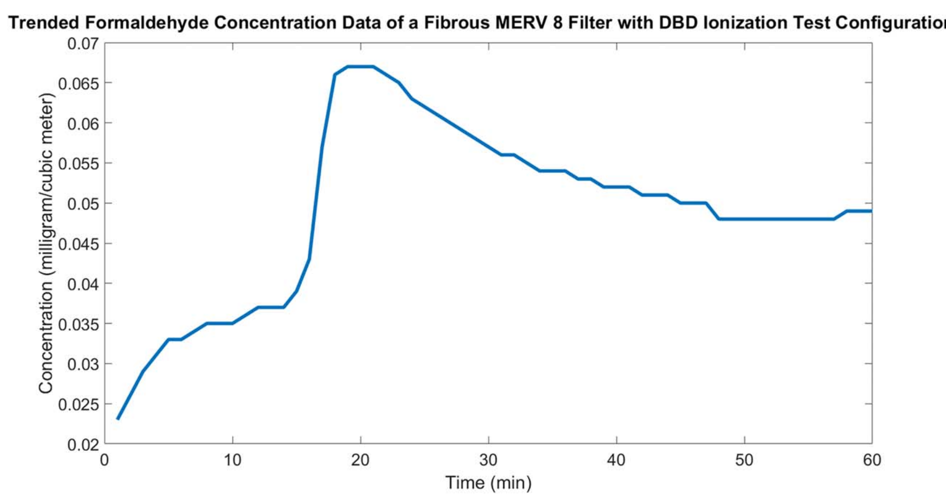

Fig. 7 Trended formaldehyde concentration data with DBD ionization test configuration

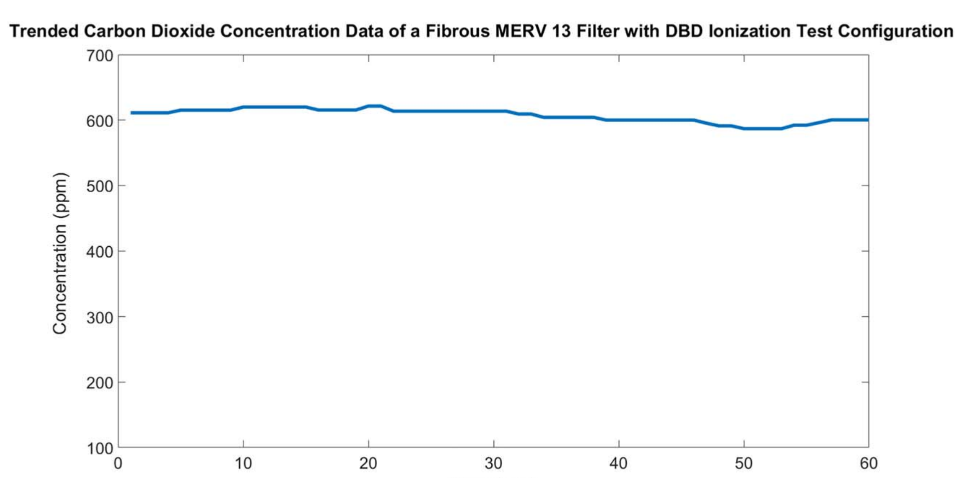

Fig. 8 Trended carbon dioxide concentration data with DBD ionization test configuration

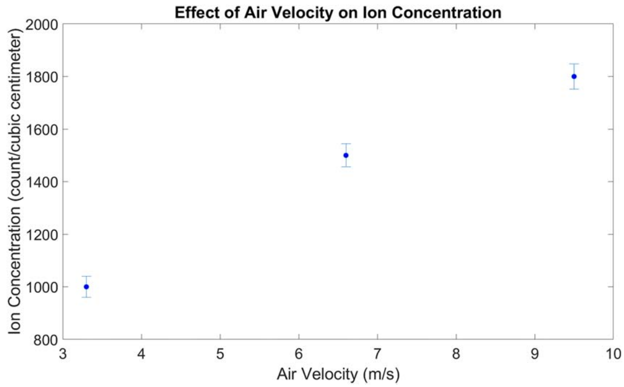

Fig. 9 Effect of air velocity on ion concentration

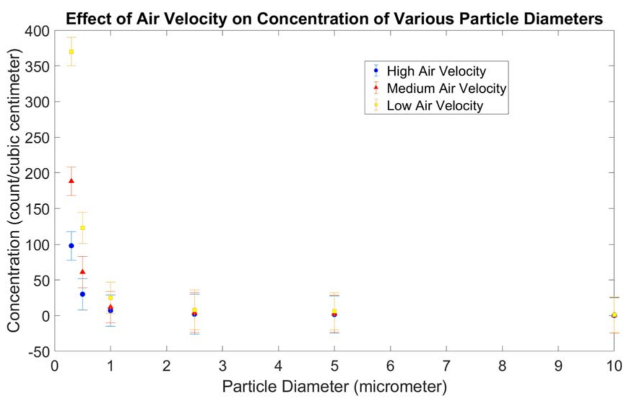

Fig. 10 Effect of air velocity on the concentration of submicron and micron particle diameters with a MERV 13 filter without ionization

4 Conclusions

In summary, the present work studied the effect of a nonthermal plasma technology, DBD bipolar ionization, on the possibility of augmenting a MERV filter to mitigate airborne contaminants that comprise of particulate matter and gaseous pollutants. Experimental results demonstrated that a low-cost MERV filter (e.g., MERV 13) when combined with the DBD bipolar ionizer can approximately attain the particulate removal efficiency of a HEPA filter alone (99.7%). HEPA filter is not optimal as a room air filter because of its high particulate removal efficiency, which is associated with higher electrical power cost and noise (Rudnick 2004). The present work shows that energy consumption due to high pressure drop across a HEPA filter can be conserved, and electrical power costs can be reduced for sustainability. The particulate removal efficiency of $PM_{2.5}$ was 97% when the MERV 13 filter was combined with the DBD bipolar ionization air cleaning device. A significant percent reduction of particulate concentration (95%) at 0.3-μm particle size was reported. In addition, a modest percentage reduction of total volatile organic compounds due to the DBD bipolar ionization also was reported. However, the present study observed only a minor reduction in the concentration of formaldehyde gas with an insignificant reduction in the concentration of carbon dioxide with DBD bipolar ionization operating.

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Conflict of Interest

There are no conflicts of interest.

Data Availability Statement

The datasets generated and supporting the findings of this article are obtainable from the corresponding author upon reasonable request.

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