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A Review of Air Ionization with Negative Ions for Aerosol Removal and Inactivation of Airborne Microorganisms in Confined Spaces †

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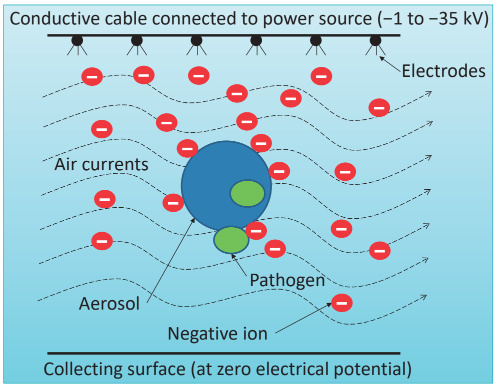
A comprehensive literature review was conducted to summarize and analyze the mechanisms and applications of air ionization for aerosol removal and inactivation of airborne microorganisms in confined spaces. This review focuses on engineered ionization systems (ionizers) that generate negative ions through corona discharge. Numerous studies have proven that air ionization is effective in removing aerosols and inactivating airborne microorganisms in confined spaces. Multiple physical, chemical, and biological processes may be involved in air ionization, including corona discharge and ion generation, attachment of ions to aerosol particles, transport of ions and aerosols in the air, electrostatic drift, deposition of aerosol particles on surfaces, and inactivation of biological agents if air ionization is used to prevent the spread of airborne pathogens. Each of these processes, as well as their interactions, is extremely complex, and only a limited number of studies have explored the interplays of these processes or attempted to integrate them into models that quantify the fundamental behavior of air ionization.

Keywords: aerosol, air ionization, negative ions, airborne microorganism, biocidal effect



1. Introduction

Aerosols—consisting of liquid or solid particles suspended in air—may be emitted from human activities, such as industry processing and material handling, or generated by natural phenomena, such as volcanic eruptions and wind blowing over dry soil. Aerosols in the atmosphere can have impacts on climate, weather, health, and ecosystems. This review focuses on aerosols in confined spaces (e.g., rooms), which are one of the major sources of indoor air pollution. The sizes of the aerosols range from nanometers to micrometers. Fine aerosols (less than 10 µm in diameter) can remain airborne for very long periods of time, which when inhaled may directly irritate the human or animal respiratory systems, penetrate deep into the lungs, or even enter the bloodstream. Aerosols, if laden with pathogens, serve as carriers for airborne disease transmission. Various methods have been used for removing aerosols from air, such as mechanical filtration, and among these methods, air ionization has gained increasing research attention because of its effectiveness and relatively low costs. Furthermore, air ionization not only physically removes aerosols from air (through electrostatic drift) but also biologically by inactivating pathogens attached to aerosols. While much research has shown that air ionization is effective in reducing aerosols in the air or inactivating biological agents attached to aerosols (bioaerosols), the physical and biological processes involved in air ionization have not been fully explored.

Air ions are formed when a gaseous (air) molecule receives sufficiently high energy to eject an electron. Air ions naturally exist in the environment and are generated by various natural and artificial energy sources, such as cosmic rays and corona discharge by lightning or power transmission lines. This review focuses on the air ionization achieved by engineered devices, commonly known as ionizers, that produce air ions through corona discharge.

Two physical configurations of ionization are common for removing aerosols from air: air ionization (or space charge) and electrostatic precipitator (ESP). In air ionization, ions are generated in a space (e.g., a room) and become attached to aerosol particles, creating charged aerosols; the charged aerosols are then attracted to and deposited on oppositely charged surfaces (or zero electrical potential if the ions are negative). In ESP, gas (air) laden with aerosols is drawn into an enclosure in which electrodes and grounded plates are used to ionize the air and

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collect charged aerosols. Electrostatic precipitators are generally considered a “filtration” system that removes aerosols when air flows through them. Accordingly, this review emphasizes air ionization specifically within confined spaces.

Aerosol removal and pathogen inactivation by air ionization involve simultaneous processes of air ion generation, air movement, aerosol movement, ion transport, ion and aerosol deposition, and biocidal effects on pathogens. The objective of this paper is to review, summarize, and analyze research advancements in air ionization by engineered systems for indoor air quality improvement; specifically, aerosol removal and inactivation of airborne disease pathogens by negative ions in ventilated and unventilated spaces.

2. General processes of air ionization by corona discharge for aerosol removal

When a strong electric field is created by applying a voltage around a conductor, a conductive region is formed in which air is ionized (corona discharge) (Goldman et al., 1985). When air molecules are ionized, both positive and negative ions are created. Ionization devices are categorized based on whether they produce one (unipolar) or two (bipolar) types of ions, which can be negative or positive; bipolar air ionizers are supplied with alternating electrical current, while unipolar devices are supplied with direct current that produce positive or negative ions based on the voltage supplied (Daniels, 2002). If the applied voltage is negative, the positive ions are attracted to the negative electrodes while the negative ions are “expelled” into the air. This type of system is termed negative air ionization (NAI), which is the focus of this review. NAI systems are commonly used for removing aerosols from the air because negative ions are known to have health and psychological benefits on humans (Goldstein, 2002; Pino and Ragione, 2013). Some air ionizers rely on the electric fields generated by the charges to distribute ions in the space (room), and others generate ions in an enclosed case and use fans or compressed air to move the ions from the ionizer to the space (room) where aerosols need to be removed. The first design is frequently used in large spaces (industrial application), while the second design is often used for small spaces such as households (residential application). This paper focuses on the first design, which typically consists of a high-voltage power supply, an array of needle electrodes to produce corona discharge, and a collecting plate(s) (or surfaces in the space such as interior surfaces of walls) (**Fig. 1**). When a negative voltage in the range of –1 to –35 kV is applied to the needle electrodes, a strong electric field around the tip of each needle electrode is formed. Air near the needle tips is ionized and the generated negative ions are accelerated by the electric field, gaining high energy and velocity, and knock electrons off surrounding

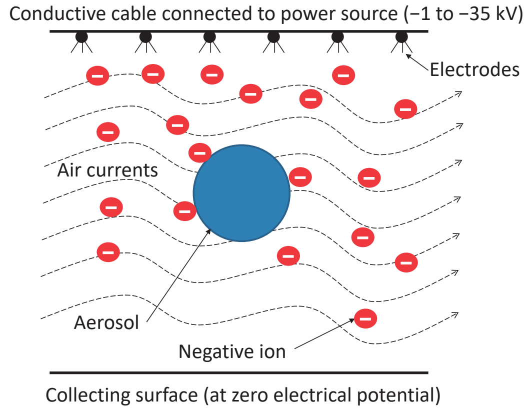

Fig. 1 Illustration of air ionization for aerosol removal.

air molecules to create more ions in the air, resulting in a cloud of air ions. The primary negative ions are superoxide (O^{-2}), which are more stable than other ions (Luts and Salm, 1994). Ions in the air collide with and attach to aerosol particles, making the aerosols negatively charged. The charged aerosols are attracted to and deposited on grounded surfaces (electrostatic drift), thus being removed from the air (**Fig. 1**). Although Brownian diffusion and gravitational sedimentation might have some effect on the movement of charged aerosol particles in the air, the electrostatic drift is the dominant force that drives the particles to grounded surfaces, particularly for small particles less than 0.005–1.0 μm (McMurry and Rader, 1985). Essien (2020) compared the changes in aerosol concentration in a chamber with NAI to natural decay (without NAI). He observed that 90 % of the aerosols were removed from the chamber in 175 s of ionization, while the aerosol concentration decreased to less than 1 % in the chamber without NAI for aerosols with an average size of 0.5 μm. This observation clearly showed the dominant role of the electrostatic drift in aerosol removal.

Many studies have shown that air ionization is effective in removing aerosols in confined spaces (indoor environment). Grabarczyk (2001) reported that a whole-room “ion shower” air ionizer was able to reduce aerosol concentrations by two orders of magnitude in an unventilated room within one hour for 0.3 to 2.5 μm aerosols. In a similar study, Grinshpun et al. (2005) evaluated five air ionizers to determine their efficiency in reducing the aerosol concentration in confined spaces. They reported that the more powerful of the two wearable ionizers removed 100 % of aerosols (0.3–3 μm) after 1.5 hours of uninterrupted operation. The most efficient stationary unit removed 100 % of aerosols (0.3–3 μm) within 12 minutes. Pushpawela et al. (2017) evaluated an ionizer for removing ultrafine particles in several conditions, including an unventilated chamber, an unventilated room, and three ventilated rooms. The chamber was filled with two different types of aerosols at concentrations of 5×10^3 and 7×10^4 particles/cm^3, respectively. In both cases, 70 % removal efficiency was obtained in 15 minutes of ionization. They observed that the aerosol removal efficiency decreased as the room size increased and was more effective in unventilated rooms than in ventilated rooms. Romay et al. (2024) conducted tests to determine the effect of air ionization on the deposition of aerosol particles on the walls in a room with and without ventilation. They reported that unipolar ions enhanced the deposition of aerosols on the interior surfaces of the room by a factor of two in rooms without ventilation, and that ionization was more effective in rooms with poor ventilation.

Several important factors influence the effectiveness of aerosol removal by NAI, including aerosol generation, the charge of individual aerosol particles (the number of ions attached to a particle), which is dependent on the concentrations of ions and aerosol particles in the air; the strength of the electric field, air currents (airflow patterns), aerosol particle properties, and the deposition (collecting) surface properties.

2.1 Electrodes for ion generation by corona discharge

Negative air ions may be generated using various engineered systems (artificially) through corona discharges, thermionic electron emission, photoexcitation, and the Lenard effect. Most air ionizers for aerosol removal use electrodes to generate ions through the corona discharge. The geometry and material of the electrodes play a crucial role in producing ions in terms of quantity and stability. Needle-shaped electrodes are widely used in industrial and residential ionizers for aerosol removal. The needle electrodes may be made of various materials, including stainless steel and tungsten. Although simple and effective, needle electrodes have some shortcomings, including complicated circuitry for producing high voltage, cumbersome size, and potential safety concerns (Guo et al., 2021). Another concern of using metallic needle electrodes is ozone generation (Bálek et al., 2007).

Carbon fiber electrodes are increasingly used in air ionizers due to their high efficiency and low ozone generation. Carbon fiber electrodes can generate high concentrations of ions at relatively low operating voltages (<5 kV), producing a minimum amount of ozone (Radalj et al., 2024). A strong electric field can form around the tip of the carbon fiber at relatively low voltages, generating large quantities of ions due to the carbon fiber's relatively small radii of curvature (Kim et al., 2017). A carbon electrode may consist of a bundle of carbon fibers (carbon brush), with each fiber having a diameter of a few micrometers. The carbon fiber-based ionizers were shown to be effective in charging fine and ultrafine particles of 20–200 nm (Han et al., 2008).

2.2 Ion concentration

Negative ions naturally exist in the air at concentrations of approximately 10^8–10^9 ions/m^3. Romay et al. (2024) reported that ionizers produce ion concentrations 20 to 200 times higher than the background level. Hartmann and Kriegel (2022) compiled a list of ionization studies published in the literature, which showed a wide range of ion concentrations used for air ionization: from 5×10^7 to 2×10^{19} ions/m^3. Of the 20 cases they reviewed, 20 % had ion concentrations lower than 10^9 ions/m^3, 65 % between 10^9 and 10^{13} ions/m^3, and 15 % higher than 10^{13} ions/m^3. It has been demonstrated that ion concentrations greater than 5×10^{10} ions/m^3 are effective for reducing airborne dust and have a lethal effect on airborne bacteria (Mitchell and King, 1994). The experimental results reported by Fletcher et al. (2008) indicated that a minimum ion concentration of 10^{10} ions/m^3 was necessary for any significant effects on aerosol concentration in a ventilated space. Based on a chamber experiment, Essien (2020) reported that a low ion concentration of 3×10^{10} ions/m^3 did not produce any significant reduction in aerosol concentration and infectivity of reovirus carried by aerosols, while the reduction was significant at a high concentration of 2.4×10^{13} ions/m^3. It seems that the majority of air ionizers operate in the ion concentration range from 10^9 to 10^{13} ions/m^3, but a clearly defined minimum threshold of ion concentration for NAI to operate effectively does not exist. Generally speaking, the effectiveness of NAI increases with ion concentration. However, if the concentration becomes too high, an electrostatic shield on the deposition (collecting) surfaces may form, which prohibits the deposition of charged particles, particularly when the materials of the aerosol collecting surface have low electrical conductivity (Lee et al., 2004).

In a space with NAI, the ion distribution is generally not uniform; the ion concentration decreases with the distance from the ion generator. In essence, there is an effective operating range for an ionizer within a given space, which is the region where the ion concentration is notably higher than the background concentration in the space (Karim et al. 2023). This range is affected not only by the ionizer itself but also by other factors such as air currents, temperature, and humidity. Karim et al. (2023) reported that an ionizer's effective operating range increased with air velocity (to their maximum tested value of 4.5 m/s) but decreased with temperature and humidity (to their minimum tested values of 25 °C and 60 %, respectively).

2.3 Ion attachment to the aerosol particles

Ion attachment to aerosols in the atmosphere has been studied extensively (e.g., Hinds, 1999; Wright et al., 2023). The number of charges acquired by an aerosol particle by diffusion charging is a complex process that depends on the physics of the ion–particle interactions and the duration of the particle in the space (Noakes et al., 2007). A widely used approach is to relate the ion–aerosol attachment coefficient to the flux of ions calculated from the diffusion-mobility equation (Hoppel and Frick, 1986), but difficulties arise when the aerosol particles are small (in the order of the ionic mean free path). Quantifying the ion–aerosol attachment requires the solution of a system of balance equations. Noakes et al. (2007) used the charging equations presented by Harrison (1992) to estimate the number of charges acquired by the particles due to diffusion charging in the ion field. Essien (2020) developed a model to predict the number of ions attached to an aerosol particle and observed that the number of attached ions on a particle increased with residence time in a nonlinear fashion under steady-state conditions at an ion concentration of 2.4×10^{13} ions/m^3. Specifically, ions rapidly attached to aerosol particles at the initial stage, followed by a slower attachment rate over time.

2.4 Airflow

Airflow (air currents) in the space where ionization is applied affects two important processes: the ion concentration distribution (ion movement) and the movement of charged aerosol particles toward the collecting surfaces. Ultimately, these processes dictate the aerosol removal efficiency of ionization. The ion movement in the immediate vicinity of the ionizer is driven by the electric field near the electrodes (ionic wind), while the ion movement (distribution) beyond the immediate vicinity of the ionizer is affected by air currents (airflow patterns) (Mitchell, 1997). For areas not in the immediate vicinity of the ion generator, significant improvements in the distribution of air ions could be achieved with simple air-moving devices like fans. Karim et al. (2023) reported that the ionizer's effective operating range increased with air velocity. However, the effective precipitation of aerosol particles requires that the electrostatic drift velocity of the charged particles be significantly higher than that of the sedimentation and airflow (Grabarczyk, 2001). If the space is ventilated, the ventilation air may remove the ions from the space, thus reducing the ion concentration in the space. La et al. (2019) conducted an experiment to study the effect of the ventilation rate on the ion concentration in a chamber and reported that an airflow rate of 136 m^3/h resulted in fewer ions in the chambers than 34 m^3/h, and consequently, the aerosol removal efficiency of ionization decreased with an increase in the ventilation rate. Heo et al. (2022) also reported that the biological inactivation efficiency of ionization decreased as the airflow velocity increased, and they attributed this decrease in inactivation efficiency to the reduction of the contact time of bioaerosols exposed to ions.

The effect of ventilation (airflow) on aerosol removal varies with the aerosol concentration. Based on numerical modeling, Noakes et al. (2007) reported that the aerosol particles were removed from the air in a ventilated space mainly by ventilation air when the aerosol concentration was low (<10^9 particles/m^3), regardless of the ion concentration. However, at higher aerosol concentrations, the electrical deposition became more important; specifically, the removal rate increased by an order of magnitude with each tenfold increase in the aerosol concentration.

2.5 Aerosol particle properties

Generally, the efficiency of any aerosol removal technology increases with the particle size. Hofer and Nicolai (2007) reported that the reduction by ionization in total suspended particulate matter (PM) was much greater than the reduction of PM_{10} and $PM_{2.5}$ because the ions were more readily attached to the larger particles. However, their data did not show an obvious difference between PM_{10} and $PM_{2.5}$. La et al. (2019) conducted a chamber experiment with an NAI ionizer that generated ion concentrations of 5.6×10^{12} to 1.5×10^{13} ions/m^3 and observed that the aerosol removal efficiency increased with the aerosol particle size. Specifically, the removal efficiency increased sharply from about 70 % at an aerodynamic diameter of 0.25 µm to 95 % at about 0.6 µm, and then increased slowly to about 100 % at 6 µm (La et al. 2019).

The aerosol type (or materials that form aerosols) may also affect the ionization removal efficiency. Sawant et al. (2012) used air ionization to remove fog, vehicle smoke, and dhoop smoke (incense smoke) in a glass container and reported that the rate of aerosol removal by NAI was the fastest for fog, reaching approximately 100 % removal at about 150 s. In comparison, the 100 % removal took about 300 s for the vehicle smoke, while it took 350 s to reach about 93 % of the removal of dhoop smoke. Grinshpun et al. (2005) measured the removal efficiency of NAI for three different aerosolized materials: polydisperse NaCl particles, monodisperse polystyrene latex, and Pseudomonas fluorescens cells, and they did not observe any significant differences among the three materials.

2.6 Collecting surface material

When NAI is used in a confined space (room), charged aerosol particles may be deposited on many surfaces of different materials, such as walls, ceilings, furniture, and equipment in the room. Few studies have evaluated the effect of surface materials on aerosol deposition/removal by NAI. Wu et al. (2006) conducted an experiment to compare the removal efficiencies of NAI for five surface materials: stainless steel, wood, PVC (polyvinyl chloride), wallpaper, and cement paint. Using artificially generated solid NaCl particles of 30 and 300 nm at an ion concentration of $3–5 \times 10^9$ ions/m^3, they determined the effective cleaning rates (ECR) as an indicator of removal efficiency for each of the five surface materials. Their results showed that the surface materials had a significant effect on the ECR.

Specifically, the ECR was ranked in the following order for the 300 nm aerosols: wood > PVC > wallpaper > stainless steel > cement paint. It is interesting to note that the ECR order for the 30 nm aerosol followed a slightly different order: wood > PVC > cement paint > wallpaper > stainless steel. They reported that the ECR was related to the surface resistivity and electrical conductivity, and the roughness of the cement paint surface might also have affected the ECR. Tanaka and Zhang (1996) found that the aerosol removal efficiency of NAI in a swine building was affected by dust accumulation on the walls.

2.7 Ozone generation

Ozone, as an air pollutant, is a byproduct of corona discharge when generating ions. The National Ambient Air Quality Standards (NAAQS) established by the US Environmental Protection Agency set an ozone concentration limit of 70 ppb (8-hour average) in the ambient air. An ozone concentration of less than 50 ppb is required for commercial air cleaning devices sold in California, USA (Romay et al., 2024). Hence, a critical focus of air ionization research and technology development has been on reducing ozone production.

Ozone generation by ionizers is dependent on several factors, including the electrode geometry and material, operating voltage, and polarity of the corona discharge, as well as the ambient conditions such as temperature and humidity (Kim et al., 2017; Qian, 2021). Yasumoto et al. (2010) reported that ozone concentrations increased with increasing discharge current and decreased with decreasing electrode thickness in an ESP. While the study of Yasumoto et al. (2010) showed that the thinner electrode wire (0.1–0.2 mm) generated less ozone, the low mechanical strength of thin wires (<0.1 mm) may limit their applications because they break easily. Zukeran et al. (2023) designed a knife-edge electrode that produced a similarly low level of ozone as thin wires, but with improved mechanical strength. Furthermore, in comparison with metallic electrodes, carbon fiber electrodes produce significantly less ozone. Han et al. (2008) reported that minimal ozone (<4 ppb) was generated by the carbon fiber electrodes when the applied voltages were less than –4 kV (i.e., less negative).

3. Numerical modeling of air ionization in confined spaces

Air ionization involves multiple physical and biological processes, including corona discharge, electric field due to space charge, electrostatic drift, ion movement, ion–aerosol attachment, transport of aerosols by air current, deposition of aerosol particles on surfaces, and inactivation of biological agents if air ionization is used to prevent the spread of airborne pathogens. Many studies have been reported in the literature on individual processes, but few studies have attempted to integrate the processes and explore the interplays of these processes. Integrating multiple processes in a model requires solving the coupled equations that govern different processes, which is mathematically challenging. Advances in the processing power of computers, along with advanced numerical methods, present an opportunity for using numerical techniques to model air ionization processes. A comprehensive numerical model should be based on the integration of multiple (sub)models, such as ion generation, airflow, aerosol transport, ion transport, ion–aerosol attachment, electrostatic field, and aerosol deposition (**Fig. 2**).

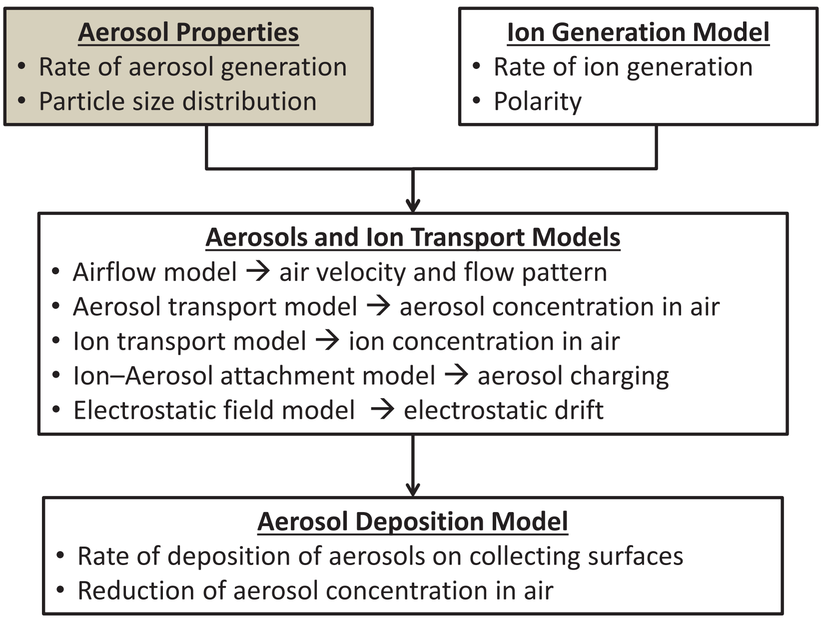

Fig. 2. Proposed framework of integrated numerical models for aerosol removal by air ionization.

Noakes et al. (2007) used a ventilation model and a CFD (computational fluid dynamics) model to simulate NAI processes in ventilated spaces. Their ventilation model was based on the balance equations of ions and aerosols in a ventilated space, taking into account both generation and removal mechanisms for ions and aerosols. The ion generation rate was simulated by the charging equations of Harrison (1992). The removal mechanisms included ventilation removal and ion–ion/ion–particle interactions, as well as diffusive and gravitational deposition at the walls and electrostatic deposition due to the ion-induced electric field. In their CFD model, the ion generation was treated as a point source with a constant generation rate at the location where the ionizer was placed. All ions were assumed to carry a single negative charge and modeled as scalar concentration in air. Gauss's law was employed to simulate the electric field generated by the space charge due to ions. A scalar transport equation was used to predict the steady-state distribution of the negative ions in the ventilated space. The electrophoretic force acting on the charged aerosol particles was calculated from the particle charge and the electric field strength and then used to calculate the momentum change, which was included in the momentum equations as a source term in the CFD model.

Essien (2020) developed an integrated model to simulate air ionization in a chamber. The model consisted of several sub-models that each simulated a specific process, including airflow, electric field, ion drift, aerosol charging (ion–aerosol attachment), and aerosol transport. The model did not simulate ion generation by corona discharge; rather, unipolar (negatively charged) ions were simply "released" into the chamber as a point source at a constant rate. Similarly, aerosol particles were treated as monodispersed spherical particles in the separate phase, using a Lagrangian approach under distinct random walk. The integrated model was implemented in a commercial CFD software package (ANSYS FLUENT) to perform the simulations. The model output included the spatial distributions of air velocity, ion concentration, aerosol concentration, electric field intensity, and ion–aerosol attachment (number of ions attached to an aerosol particle) at predefined time steps. Ultimately, the aerosol removal efficiency was calculated from the change in the aerosol concentration in a given time interval.

Ren et al. (2023) used an integrated numerical model to assess the layout strategy of ionizers in a classroom with natural ventilation to improve aerosol removal efficiency and reduce the risk of infection by aerosolized pathogens. A CFD model was used to simulate the distributions of aerosol particles and negative ions in the room. Poisson's equation and Gauss's law were used as the governing equations for the electric potential and electric fields, respectively, which were then used in the scalar transport equation for ion concentration. The effect of the electrostatic force acting on the charged aerosol particles was treated as the source term in the momentum equation in the CFD model.

4. Biocidal effects of air ionization

Aerosols are carriers of many airborne disease pathogens, such as SARS-CoV-2, which may be emitted in aerosol form during normal breathing, talking, coughing, or sneezing by infected individuals (Jarvis, 2020). Aerosols of biological origin or with biological agents (such as pathogens) attached to them are commonly known as bioaerosols. Besides the physical removal of bioaerosols from air through the electrostatic force by air ionization, many studies have reported the biocidal effects of ions, but the physical and biological mechanisms involved in the biocidal effects of ionization are still poorly understood (Fletcher, 2007).

4.1 Inactivation of microorganisms

Krueger and Reed (1976) reported that negative air ions at concentrations over 5×10^{10} ions/m^3 had a lethal effect on airborne bacteria and could speed up the decay process of microbial aerosols. Jiang et al. (2018) conducted a literature review of the effect of negative air ions on human health and summarized that negative air ions caused significant biological decay and growth inhibition/inactivation of bacteria, fungi, and viruses. Hagbom et al. (2015) conducted a study to determine the effect of ionization on the infectivity of *Canine Calicivirus* and observed that the reduction in infectivity was greater than 97 % after 40 minutes of ionization. Alonso et al. (2016) evaluated an NAI system for reducing airborne pathogens in pig barns and observed that the overall airborne pathogen reduction was between 0.5 and 1.9 logs. La et al. (2019) investigated the effectiveness of negative ionization in reducing PRRSV (porcine reproductive and respiratory syndrome virus) in a ventilated chamber and reported that the reduction rates ranged from 68 % to 96 %. In an experimental study, Comini et al. (2021) exposed both gram-positive and gram-negative bacteria to air ions and observed that bacterial viability could be reduced by 95 % by ionization. Essien (2020) conducted a chamber test to study the effect of NAI on Mammalian Reovirus (MRV). He reported that at an ion concentration of 2.4×10^{13} ions/m^3, the reduction in the virion concentration was greater than 1.0 log (90 %) after 90 s of ionization, and a 2.0 log reduction (99 %) was observed in the viral infectivity. This result indicated that ionization not only physically removed bioaerosols from air (reduction in virion concentration) but also inactivated viruses (greater reduction in viral infectivity).

Although many studies have proven that ionization is effective in inactivating microorganisms, few have explored the biological mechanisms of inactivation. In particular, the roles of the biological characteristics of microorganisms, such as morphology, cellular structures, and stages of the lifecycle, are poorly understood.

4.2 Reducing the infection risks for humans and animals

Mitchell and King (1994) conducted experiments to investigate the effectiveness of air ionization in reducing the airborne transmission of Newcastle viruses and found that airborne transmission was reduced by 6.6 % to 27.7 % by ionization. Gast et al. (1999) conducted a study to determine the effect of negative air ionization on the prevention of the airborne transmission of *Salmonella enteritidis*. One-week-old chicks were orally inoculated and housed in an upstream controlled environment room. Day-old chicks were kept downstream in controlled environment cabinets with negative ionizers installed. A negative control without ionizers downstream was also set up in different cabinets. At 3 and 8 days post-inoculation, *S. enteritidis* was found on the surface of 89.6 % of the downstream chicks from cabinets without negative air ionizers, but on only 39.6 % of the downstream chicks in the presence of the ionizers. Similarly, *S. enteritidis* was recovered from the ceca of 53.1 % of sampled downstream chicks in cabinets without ionizers, but from only 1.0 % of the ceca of chicks in cabinets in which ionizers were installed. Hagbom et al. (2015) used guinea pigs to study air ionization for reducing the airborne transmission of the influenza A virus and found that ionization prevented 100 % of guinea pigs from infection. A research team at the University of Leeds tested ionizers in hospital wards and found that the nosocomial agent *Acinetobacter* was completely eliminated from the air and infections were reduced to zero (McDowell, 2003). A similar observation was made by Kerr et al. (2006), who concluded that negative air ionization was promising in controlling nosocomial *Acinetobacter* infections and worthy of further investigation. Ren et al. (2023) used numerical simulations to compare the scenarios with and without ionization in a classroom and estimated that the infection risk could be reduced by 23 % on average when ionizers were placed at different locations in the room.

4.3 What inactivates airborne microorganisms, ions or ozone?

It is a known fact that ozone has strong biocidal effects. Given that ionizers may generate ozone as a byproduct of their operation, there is a debate in the research community on what causes the inactivation of microorganisms by ionization, namely, ions or ozone? For example, Fletcher et al. (2007) reported that ozone seemed to be responsible for the inactivation of most bacteria they tested, but both the electric field and air ions played a contributory role. On the contrary, Park et al. (2016) reported that the ions were mainly responsible for the biocidal effect on bacteria and that ozone had a negligible effect.

Fletcher et al. (2007) summarized that the biocidal effect of ionization involved three modes of action: electrodynamics (ions, electrons, and other ionizing radiation); electrostatics (electric charge/electric field); and electrochemical effects (ozone production). They conducted an experiment to quantify the contributions of these modes to the microbial mortality of seven bacterial species (*Staphylococcus aureus*, *Mycobacterium parafortuitum*, *Pseudomonas aeruginosa*, *Acinetobacter baumanii*, *Burkholderia cenocepacia*, *Bacillus subtilis*, and *Serratia marcescens*). The bacterial samples were inoculated on tryptone soya agar plates with approximately 300 colonies per plate. In the first set of tests, a thin mica sheet was placed between the ion source and the agar plates to prevent ions and ozone from reaching the bacterial samples while leaving the electric field unaltered. In the second set of tests, a grounded wire mesh was placed directly above the agar plates to prevent the exposure of the bacterial samples to ions and the electric field while allowing ozone to pass. Their results showed that, with the exception of *Mycobacterium parafortuitum*, the principal cause of cell death was ozone exposure, while electroporation played a secondary role. However, in the case of *Mycobacterium parafortuitum*, electroporation resulting from exposure to the electric field might be the principal cause of cell inactivation.

Park et al. (2016) conducted an experiment in a sealed plastic chamber to differentiate the biocidal effect of ozone from that of ions on bacteria. Four bacterial species were tested: *Escherichia coli, Staphylococcus aureus, Bacillus subtilis*, and *Enterococcus faecalis*, and a low ozone emission ionizer was used to generate ions in the chamber. The first set of tests was performed with the ionizer operating in the normal mode. In the second set of tests, an ion capturer was used to remove ions generated by the ionizer, while the ozone generated by the ionizer remained the same as in the first set of tests (at a concentration of 35 ppb in the test chamber). They observed that the biocidal effect was dramatically reduced in the second set of tests in which ions were removed, indicating that the ozone generated by the ionizer had little biocidal effect. In other words, the ions generated by the ionizer were responsible for the biocidal effect.

The above review of two studies indicates that there is an agreement in the research community on the effectiveness of air ionization in removing airborne microorganisms, but there seems to be disagreement on the mechanisms of biocidal effects due to ozone or ions. In other words, the true mechanisms of the biocidal effects of ionization are not fully understood. It is often cited in the literature that the biocidal effect is due to "oxidative stress" (e.g., Comini et al., 2021), implying that the ozone causes the biocidal effects. However, the experiment by Fletcher et al. (2007) resulted in a 94.9 % reduction in the survival rate of *Mycobacterium parafortuitum* in the absence of ozone or negative ions, and they attributed this biocidal effect to electroporation. They noted that the ionization electrodes were only 25 mm from the test samples of bacteria in their experiment and this short distance could expose the bacteria to an electric field as high as 400 kV/m, while the onset of cell lysis generally takes place at 100 kV/m. This high electric field may occur in a negligible area near the electrodes, but not in the entire room. Therefore, the question remains whether ions can inactivate microorganisms in the entire room, and what the underlying mechanism might be. Essien (2020) hypothesized that the inactivation of the MRV virus was due to an ion-induced dipole torque acting on the virus capsid proteins. This hypothesis has yet to be verified. The magnitude of the dipole torque is dependent on two physical factors: the magnitudes of the electrostatic forces and distances between forces (or locations where forces act). This implies that the inactivation of microorganisms by dipole torques would be affected by the size and shape of different species of pathogens and the charge heterogeneity. Research is warranted to further explore the dipole torque mechanism.

Furthermore, corona discharge produces superoxide, which is a biocide that can inactivate or inhibit the growth of microorganisms. Few studies have explored the contribution of superoxide to the biocidal effects of air ionization.

5. Conclusions

Air ionization has been proven to be an effective technology for removing aerosols and inactivating airborne microorganisms in confined spaces. The most common type of engineered air ionization systems (ionizers) generates air ions through the corona discharge. A critical parameter of ionization is the ion concentration generated in the space. The concentration range reported in the literature spans from 10^9 to 10^{13} ions/m^3; however, a precise minimum threshold of ion concentration for ionization to operate effectively has not yet been clearly defined. Very high ion concentrations may negatively affect the performance of air ionization because an electrostatic shield may form on the collecting surfaces, inhibiting the deposition of charged particles, particularly if the collecting surfaces have low electrical conductivity. The effectiveness of air ionization is also influenced by other factors, including airflow, aerosol particle properties, and materials of the collecting surfaces.

Multiple physical, chemical, or biological processes may be involved in aerosol removal by ionization, including corona discharge and ion generation, attachment of ions to aerosol particles, transport of ions and aerosols in the air, electrostatic drift, deposition of aerosol particles on surfaces, and inactivation of biological agents, if air ionization is used to prevent the spread of airborne pathogens. Each of these processes, as well as their interactions, is extremely complex, and only a few studies can be found in the literature that have explored the interplays of these processes or attempted to integrate these processes into models that quantify the fundamental behavior of air ionization.

Although much research has shown that air ionization is effective in inactivating microorganisms, the mechanisms of inactivation remain poorly understood. Specifically, the contributions of ions and ozone (a byproduct of ion generation) to the biocidal effects of ionization are still under debate in the research community.

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