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One-pass antibacterial efficacy of bipolar air ions against aerosolized *Staphylococcus epidermidis* in a duct flow

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ABSTRACT

While heating, ventilating, and air-conditioning (HVAC) systems can provide healthy and comfortable indoor environments, virtually any part of an HVAC system can support active microbial growth if sufficient nutrients are present. In this study, we introduced a methodology to enhance the one-pass antibacterial performance of air ions against aerosolized bacteria in a ventilation duct flow. *Staphylococcus epidermidis* (*S. epidermidis*) was aerosolized, mixed with the duct flow, and exposed to air ions generated by carbon fiber ionizers installed inside the duct. The *S. epidermidis* was then sampled at the exit of the duct and incubated to evaluate their cultivability as functions of the ion exposure time, ion concentration, and ion polarity. When the ionizers produced bipolar air ions for 2 s, a high antibacterial efficiency of 85% was obtained when four ionizers were positioned both at the top and bottom walls of the duct in a configuration in which there were three changes in ion polarity (one positive ionizer, one negative ionizer, one positive ionizer, and one negative ionizer in series along the flow direction). When the ion exposure time was decreased to 0.2 s, an antibacterial efficiency of 50% was realized by applying a configuration with seven changes in ion polarity. By using a scanning electron microscope (SEM), cell contraction of *S. epidermidis* caused by the bipolar ion treatment was observed.

1. Introduction

Bioaerosols are airborne particles of biological origin and include a variety of living materials such as viruses, bacteria, and fungi. Bioaerosols are omnipresent in human surroundings. Exposure to bioaerosols in indoor environments is potentially associated with a wide range of adverse health problems including infectious diseases, acute toxic effects, allergies, asthma, inflammatory lung diseases, and cancer (Ji et al., 2007; Main, 2003; Xu et al., 2011).

Heating, ventilating, and air conditioning (HVAC) systems are essential to modern life when properly designed, installed, operated, and maintained. Even though HVAC systems can provide healthy and comfortable indoor environments, virtually any part of an HVAC system can support active microbial growth if sufficient nutrients are present (Batterman & Burge, 1995). Microorganisms growing in an HVAC system produce volatile organic compounds (VOCs) and aerosols. Research has demonstrated that air filters in HVAC systems may be colonized by bacteria and fungi (Kemp et al., 1995; Maus et al., 2001;

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Möritz et al., 2001; Noris et al., 2011). This colonization inevitably leads to a loss of filtration and potential filter deterioration with the eventual release of microorganisms (Ahearn et al., 1997; Simmons & Crow, 1995).

Under normal operating conditions, ventilation ducts within HVAC systems can also be contaminated with dust particles and serve as reservoirs for microorganisms to proliferate (Zuraimi, 2010). Air velocities can affect the re-suspension of microbials from the duct surface and thus, enable the microbes to re-enter the airstream. Emissions from biologically-contaminated HVAC systems including ducts have resulted in indoor air pollution problems with adverse health effects. Ventilation duct cleaning (DC) has been commercially advocated to remove pollutant sources inside HVAC systems. However, after cleaning, the duct can be recontaminated through deposition or in the case of microbials, regrowth (Brosseau et al., 2000; Zuraimi, 2010). Accordingly, there is growing interest in developing alternative methods for the removal of bioaerosols from HVAC systems.

Electrical corona discharges have been used in the development for antimicrobial use. Air ions generated by corona discharges are known to damage cell membranes by physical and chemical processes. Mendis et al. (2000) reported that electrostatic disruption of a cell membrane can occur when the membrane acquires a sufficient electrostatic charge, causing the outward electrostatic stress to exceed its tensile strength. Noyce & Hughes (2002, 2003) investigated the bactericidal effects of both negative and positive ions generated by a DC electrical corona on stationary phase cells under nitrogen. Exposure to either negative or positive ions produced significant reductions in the *Escherichia coli* (*E. coli*) and *Pseudomonas veronii* (*P. veronii*) colony numbers. In those studies, the mechanism responsible for the death of the bacteria was electrostatic interactions with numerous charged groups in the cell wall. These previous studies showed that the bactericidal effect was due to the eventual electrostatic disruption of the cell membrane as a result of ionic accumulation on the cell membrane (Noyce & Hughes, 2002, 2003). To analyze the biological effects of electrically-generated negative air ion (ENI) exposure, Cai et al. (2008) focused on the brood size, lifespan, and presence of apoptotic cells in the germ line of *Caenorhabditis elegans* (*C. elegans*). They explained that reactive radical species have profound damaging effects on cells via diffusion to the cell surface and the production of secondary radicals (Cadet et al., 1999). Mainelis et al. (2002) reported that electrical charges of different magnitude and polarity imparted on airborne microbial cells by means of induction charging influence inactivation of *Pseudomonas fluorescens* bacteria. The electric charging affected the membrane potential of sensitive microorganisms so significantly that their cells, especially those that were already injured, became nonviable.

In addition to air ions, corona discharges can produce ozone which induces cell death among bacteria (Fletcher et al., 2007). However, inhalation of ozone has been demonstrated to cause extensive pulmonary changes in rats including epithelial injury and fibrosis, and has an adverse effect on respiratory functions in humans (Castillejos et al., 1992; Jakober & Phillips, 2008; Shargawi et al., 1999). An added concern with the introduction of ozone into modern indoor spaces is the possible health impact of secondary emissions from the reaction of ozone with chemicals such as terpenes, which can produce pollutants such as formaldehyde and ultrafine particles (Weschler, 2000; Jakober & Phillips, 2008). Ozone is one of the six criteria pollutants in USA and its concentration is regulated (US EPA, 2013).

Recently, some researchers have demonstrated that carbon fiber ionizers produce stable unipolar ions in sufficiently high concentrations with little ozone generation (Han et al., 2008, 2009; Kim et al., 2011; Park et al., 2009, 2010). Owing to the very small diameter of the carbon fibers, it is conceivable that the electric field at the tip of the carbon fibers can become high enough to generate corona discharge at a relatively low applied voltage compared to existing corona chargers where less oxidized material leads to a lower generation of ozone (Boelter & Davidson, 1997; Han et al., 2008, 2009).

Air ions generated by a carbon fiber ionizer have been found to provide effective antibacterial performance. Park et al. (2009) reported the installation of a carbon fiber ionizer in front of a fibrous medium filter to enhance the removal of submicron aerosol particles and bioaerosols. The antibacterial performance of the air ions was investigated after *E. coli* was deposited on the filter. Kim et al. (2011) confirmed the disruption of the cell membrane using scanning electron microscope (SEM) images when *E. coli* and *Staphylococcus epidermidis* (*S. epidermidis*) were exposed to air ions generated by carbon fiber ionizers. The SEM images indicated that the air ions broke up the cells and eroded or split the cell surfaces.

In all of the reports mentioned above, the antibacterial performance of air ions was studied in such a way that the air ions were applied to the bacteria placed on a surface such as a filter or agar plate. However, there is an increasing need to remove airborne bacteria when they are moving through ventilation ducts within an HVAC system. In this study, we introduced a methodology to enhance the one-pass antibacterial performance of air ions against aerosolized bacteria in a duct flow. For this purpose, *S. epidermidis* was aerosolized and mixed with the duct flow when they were exposed to air ions generated by ionizers installed inside the duct. The *S. epidermidis* was then sampled at the exit of the duct and incubated to evaluate their cultivability as functions of the ion exposure time (flow residence time), ion concentration, and ion polarity.

2. Materials and methods

Figure 1 shows a schematic of the experimental setup. The setup consisted of a particle generation system, test duct, sampling system, and air ionizer(s). The test duct made of acryl had a cross-sectional area of $0.04 \times 0.04\ m^2$ and a length of 1 m. The temperature and relative humidity of the test duct were 22.5 °C and 10%, respectively.