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Numerical and experimental study on airborne disinfection by negative ions in air duct flow

Pei Zhou\textsuperscript{a,b}, Yi Yang\textsuperscript{c}, Gongsheng Huang\textsuperscript{b}, Alvin C.K. Lai\textsuperscript{b,d,*}

\textsuperscript{a} School of Civil Engineering, Hefei University of Technology, Hefei, Anhui, China
\textsuperscript{b} Department of Architectural and Civil Engineering, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong SAR, China
\textsuperscript{c} College of Engineering, Guangdong Ocean University, Zhanjiang, Guangdong, China
\textsuperscript{d} City University of Hong Kong Shenzhen Research Institute, Shenzhen, China

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A B S T R A C T

In this paper, we develop a mathematical model that aims (1) to predict the distribution of negative ions generated by an air ionizer installed in a ventilation duct and (2) to predict the efficiency with which it inactivates bacteria. The transportation equation for the negative ions was resolved combined with the bulk air velocity and the electric field.

The bacteria distribution was solved numerically by integrating the susceptibility constant, which was acquired from the experiments. Two types of bacteria (Serratia marcescens, Staphylococcus epidermidis) were aerosolized and released into a 9-m ventilation duct system. Inactivation efficiencies were calculated for inlet velocities from 2 to 6.5 m/s and for various ion intensities. The efficiencies for S. marcescens and S. epidermidis were 31.53% (SD, 11.4%) and 12.17% (SD, 0.43%), respectively, with susceptibility constants of $8.67 \times 10^{-11}$ Colony-Forming Units (CFU)/ions and $2.72 \times 10^{-11}$ CFU/ions, respectively. The modeling results matched those of the experiments well. The pressure penalty at the maximum velocity (6.5 m/s) was only 9 Pa. The results show that the use of negative ions has great potential to enhance indoor air quality by reducing airborne microorganisms in ventilation systems.

1. Introduction

According to the US Environmental Protection Agency, indoor air quality (IAQ) is one of the five most urgent environmental risks to public health \cite{1}. Heating, ventilation, and air conditioning (HVAC) systems play a vital role in ensuring the indoor air quality inside such environments. Outbreaks of severe infectious diseases, from severe acute respiratory syndrome in 2003 to avian influenza and Middle East respiratory syndrome in recent years, indicate the importance of effective disinfection in ventilation systems to prevent extensive infections inside a building \cite{2,3}. Ductwork systems provide a breeding ground for the potential reproduction and transmission of microorganisms \cite{4}. Such microorganisms can survive and propagate throughout the entire building through sophisticated, interconnected ventilation duct systems, which may lead to cross-infection of the occupants.

Conventional solutions for improvement of indoor microorganism levels are filtration or dilution. Commonly used medium-grade filters (minimum efficiency reporting value (MERV) of 8–10) are not effective in removal of small bacteria and viruses. In addition, filters can support active microbial growth if sufficient nutrients are present \cite{5}. Energy considerations generally prevent the use of high-efficiency particulate air (HEPA) filters in commercial buildings.

Thus, to balance energy consumption and IAQ, in addition to physical removal approaches such as filtration and dilution, chemical/biological-based approaches for inactivation of airborne microorganisms have recently been developed and applied in HVAC systems. An alternative method using air ionizers for disinfection was developed in recent years. Park et al. \cite{6} demonstrated the feasibility of the air ion disinfection approach for the reduction of aerosol particles in HVAC systems and found that this approach can be used to control IAQ. They showed that it is feasible to remove bioaerosols with a low-efficiency HVAC filter enhanced by continuous emission of unipolar air ions. Lee et al. \cite{7–9} conducted similar experiments to determine the disinfection performance of air ions against aerosolized bacteria. Unipolar and bipolar ionizers were installed in a duct flow to evaluate the disinfection efficacy with different numbers of ionizers and the polarity effect.

There is an important parameter characterizes the susceptibility of bacteria disinfected with this kind of chemical/biological approach. It is often denoted as the susceptibility constant, $Z$, and its value depends...
primarily on complex biological characteristics of the airborne bacteria and the environmental conditions. Without knowing \( Z \), it is not possible to predict the disinfection performance. Our group previously measured \( Z \) for a few bacteria under UV-C irradiation \([10]\).

The disinfection mechanism of bacteria by air ions is usually summarized as a generated electrostatic force. Fletcher et al. proposed that unrecoverable electroporation plays a role in the disinfection effect of air ions \([11,12]\). Mendis et al. \([13]\) proposed and modeled an electrophysical mechanism that involves the electrostatic disruption of a cell membrane. Digel et al. \([14]\) explained the antimicrobial action of ions as a chemical modification of the surface proteins of bacteria. It is clear that the inactivation mechanism against microorganisms by air ions is still controversial.

There are a few experimental studies with air ionizers that aim to disinfect different types of bacteria, very few numerical studies were reported as well. Noakes et al. \([15]\) and Fletcher et al. \([12]\) developed a two-dimensional (2D) model to simulate the performance of negative ionizers in ventilated rooms, in which the electric field and ion balance equations were treated as user scalars and solved by a commercial computational fluid dynamics (CFD) tool. Mayya \([16]\) developed a detailed mathematical model of air ions by considering the electric field, particle charging, ion transport, and wall loss. However, none of

**Nomenclature**

- \( A \): Cross section area of the duct, \( m^2 \)
- \( C_i \): the concentration of bacteria, \( \text{CFU/m}^3 \)
- \( \text{CFU}_{\text{down}} \): the colony forming units of bacteria at downstream
- \( C_{\text{on}} \): the concentration of airborne after exposed to the negative ions
- \( d \): the distance between the ionizer and sampling point, m
- \( D_p \): Brownian diffusion coefficient for ion, \( m^2/s \)
- \( I \): the total ion current, \( A \)
- \( N_{\text{ion}} \): the number of negative ions reaching single bacteria, ions/CFU
- \( Q_{\text{capture}} \): the flow rate when the bacteria was captured, \( m^3/s \)
- \( S_i \): Source term, \( \text{CFU}/(\text{m}^3\text{s}) \)
- \( S_{\text{ion}} \): Source term of bacteria removed by negative ions, \( \text{CFU}/(\text{m}^3\text{s}) \)
- \( t_{\text{capture}} \): bacteria capturing time, s
- \( u \): inlet velocity, \( m/s \)
- \( \nu_d \): deposition velocity, \( m/s \)
- \( Z \): the susceptibility constant, \( \text{CFU/ions} \)
- \( \Phi \): potential difference, V
- \( \epsilon_0 \): the permittivity of free space, \( C^2/Nm^2 \)
- \( \mu \): dynamic viscosity, \( \text{N} \cdot \text{s/m}^2 \)
- \( \nu_t \): turbulent viscosity, \( m^2/s \)
- \( A_w \): the normal vector area of the cell face, \( m^2 \)
- \( \text{CFU}_{\text{up}} \): the colony forming units of bacteria at upstream
- \( C_0 \): the initial concentration of airborne, \( \text{CFU/m}^3 \)
- \( C_{\text{off}} \): the initial concentration of airborne microorganisms
- \( D_i \): Brownian diffusion coefficient for bacteria, \( m^2/s \)
- \( e \): elementary charge, C
- \( E \): the electrical field, \( \text{V/m} \)
- \( n \): number of negative ions, ions/\( \text{m}^3 \)
- \( p \): Pressure, Pa
- \( Q_{\text{exposure}} \): the flow rate when the bacteria was exposed to the ions, \( m^3/s \)
- \( S_d \): Source term of bacteria deposition onto walls, \( \text{CFU}/(\text{m}^3\text{s}) \)
- \( t \): Time, s
- \( t_{\text{exposure}} \): the ion exposure time, s
- \( V_{\text{cell}} \): cell volume, \( m^3 \)
- \( \nu_{s,i} \): particle settling velocity, \( m/s \)
- \( Z_i \): elaboration constant, \( m^2/J \)
- \( \rho \): air density, \( \text{kg/m}^3 \)
- \( \nu_p \): particle eddy diffusivity, \( m^2/s \)
- \( \mu_p \): ion mobility, \( m^2/\text{Vs} \)
- \( \eta \): disinfection efficacy, %
these studies modeled the disinfection of bacteria. In Ref. [17], a semi-empirical formula based on experiment results was applied to simulate the distribution of the bacteria *Escherichia coli*. However, the susceptibility constant was not measured; it was only determined by a trial-and-error approach.

To model airborne bacteria, an additional “phase” must be considered in which the bacteria can be treated as particles and modeled by either the Eulerian or Lagrangian approach [18]. Eulerian approach has been applied previously by the present authors and the others for modeling disinfection of bacteria [19,20], thus in this paper Eulerian approach was adopted.

The literature listed above carried out experimental studies or modeled the particles separately. None of them combined modeling of ion transport and measurement of inactivation. Thus, the accuracy of the modeling could not be validated experimentally. Moreover, many studies used negative ionizers in very small tubes or at low velocities [9]. The results therefore may not be applicable for practical ventilation systems. Thus, this paper provides a mathematical model of negative ion systems. Therefore, this paper provides a mathematical model of negative ion statistical systems. Thus, this paper provides a mathematical model of negative ion distribution and susceptibility constants for two bacteria were also determined. Safety concern on ozone emission is also discussed.

2. Methods

2.1. Study design

The detailed experimental setup can be found elsewhere [21], and thus only a brief description is reported here. The designed ductwork was 9 m long and made of 200 mm × 200 mm modular galvanized steel. Fig. 1 includes a picture and a schematic of the test bed.

First, the emission system plays an important role in generating and delivering the bacteria. In this study, it consisted of a compressor and a nebulizer (24 jet, Collision Nebulizer, BGI). The pretreated filtered air was first compressed into the nebulizer, which was used to aerosolize the test bacteria (*S. marcescens* and *S. epidermidis*).

Second, the aerosolized bacteria were delivered to the inlet of a centrifugal fan inside a tailor-made plastic box. The plastic box was equipped with a HEPA filter to prevent contaminated air from entering the ducting from the laboratory. The fan speed was adjusted between 1.5 and 6.5 m/s with a switch. The bacteria were pushed through the duct system (0.95, 1.30, 1.65, 2.55, 2.90, 3.45, and 4.5 m from the ductwork inlet). Because it was impossible to directly contact the surface of the ion generator to obtain the real “emission rate,” which is required as a boundary condition setup for the ionizer, the air ion counter was placed 5 cm downstream from the ionizer to obtain the maximum ion concentration for the purpose of determining the ionizer’s boundary conditions. The air ion counter was carefully placed in the center of the duct, and the sampling opening was placed perpendicular to the airflow.

2.2. Procedure

2.2.1. Preparation of bacteria

The operation mainly consisted of three procedures: the preparation of test bacteria, the measurement of negative ions, and the sampling of the bacteria to calculate the inactivation efficacy. The Gram-negative bacteria *S. marcescens* (ATCC 6911) and Gram-positive bacteria *S. epidermidis* (ATCC 12228) were selected to test the disinfection efficiency of the negative ionizer. The pathogens were atomized and aerosolized by the nebulizer with an inlet pressure of 275.8 kPa.

2.2.2. Concentration measurement of negative ions

The ion generation probe of the negative ion generator was inserted inside the ductwork through an 8-mm-diameter circular opening. The ion intensity was regulated by setting the input voltages (6–12 V). In this experiment, only one air velocity was tested: 3 m/s. The number of negative ions was measured at different locations downstream of the duct system (0.95, 1.30, 1.65, 2.55, 2.90, 3.45, and 4.5 m from the ductwork inlet). Because it was impossible to directly contact the surface of the ion generator to obtain the real “emission rate,” which is required as a boundary condition setup for the ionizer, the air ion counter was placed 5 cm downstream from the ionizer to obtain the maximum ion concentration for the purpose of determining the ionizer’s boundary conditions. The ion counter was carefully placed in the center of the duct, and the sampling opening was placed perpendicular to the airflow.

2.2.3. Inactivation of bacteria

For bacteria disinfection experiments, a variable speed-controlled fan was used to deliver filtered air mixed with bacteria. The steady air stream was controlled at speeds of 3.0, 4.0, 5.0, 6.0, and 6.5 m/s by monitoring the fully developed speed at a point 4 m downstream of the fan. Each impactor was connected to a vacuum pump, and the sampling flow rate was set to 28.3 L/min. The sampling time was set to 106 s with an equal total sampled air volume of 50 L. For each velocity, each bacteria was repeated at least 10 times. The disinfection efficacy was calculated by the following equation:

$$\eta = 1 - \frac{\text{CFU}_{\text{down}}}{\text{CFU}_{\text{up}}}$$

where *CFU*<sub>down</sub> and *CFU*<sub>up</sub> are the colony-forming units (CFUs) of bacteria from the upstream and downstream regions of the ionizer, respectively, as shown in Fig. 1. After cultivating both *S. epidermidis* and *S. marcescens* for 24 h, the CFUs were counted and the disinfection efficacy was calculated.

2.3. Modeling the negative ions and transport of microorganisms

The modeling in this study was done by a commercial CFD tool, ANSYS-FLUENT. The potential difference, the electrical field, and the negative ions were treated as scalars in FLUENT. The governing equations are written as follows:

$$\nabla^2 \phi = - \frac{\nabla n(x, y, z)}{\varepsilon_0}$$

(2)

$$\vec{E} = -\nabla \phi = - \left( \frac{\partial \phi}{\partial x} \hat{i} + \frac{\partial \phi}{\partial y} \hat{j} + \frac{\partial \phi}{\partial z} \hat{k} \right)$$

(3)

$$\frac{dn}{dt} + (\vec{u} + \vec{v}_E) \nabla n = D_n \nabla^2 n$$

(4)

The potential, given in Eq. (2), and the electrical field, given in Eq. (3), are governed by Poisson and Gauss’s equations respectively. *n* is the potential of the plasma unit, *V*, *e* is the elementary charge,
The continuity equation for the bacteria concentration can be written as:

$$\frac{\partial C_i}{\partial t} + \nabla \cdot (\mathbf{v}_i C_i) = \nabla \cdot (D_i \mathbf{v}_i C_i) + S_i$$

(6)

where $C_i$ is the particle concentration of a particular particle size in group $i$, CFU/m³, $\mathbf{v}_i$ is the particle-settling velocity, m/s, $\varepsilon_i$ is the particle eddy diffusivity, m²/s; for small particles it is assumed that $\varepsilon_i/\nu_i = 1$, where $\nu_i$ is the turbulent viscosity. $D_i$ is the Brownian diffusion coefficient, m²/s. The settling velocity and Brownian diffusion coefficient can be calculated according to reference [22]. Eq. (7) was retrieved from Refs. [20,23,24] for modeling the disinfection of airborne bacteria using UVGI sources. In this study, it was adapted to simulate the bacteria “reacting” to the ion intensities. $S_i$ is the source term, which includes two parts: bacteria deposition onto walls, $S_d$, and bacteria disinfect by negative ions, $S_{ion}$.

$$S_d = -\sum \frac{\langle \nu \cdot A \rangle}{V_{cell}} C_i$$

(8)

$$S_{ion} = -\frac{\partial (C_i - C_{i0} e^{-a N_{ion}})}{\partial t} = -Z \frac{\partial N_{ion}}{\partial t} C_i$$

(9)

Eq. (8) and Eq. (9) have been used by the authors [10]. The summation term in Eq. (8) is the sum of all the faces of the immediate layer near the wall. The term $\mathbf{v}_i$ is the deposition velocity which was calculated by the three-layer model developed by Lai and Nazarrof [25], m/s. $A_{wall}$ is the normal vector area of the cell face, m², and $V_{cell}$ is the cell volume, m³. The drift flux model [18,26,27] was applied to model bacteria dispersion and deposition onto the internal wall surface due to gravity and Brownian and turbulent diffusion. The density of both bacteria was assumed to be 1400 kg/m³ [17]. It is noted that the natural decay of the bacteria was not considered in the model since the sampling point before and after ionizer is relatively short, only 1.2 m in this study. As the diameters for S. marcescens and S. epidermidis in this study were less than 1.0 μm, together with the velocity tested, the dimensionless relation time is in the order of $10^{-2}$, thus turbophoresis can be ignored without causing any significant error [28].

Eq. (9) can be used to describe the bacteria disinfected due to the presence of ions. $C_0$ is the initial concentration of airborne bacteria, which is equal to the upstream concentration, CFU/m³, $Z$ is the microorganism susceptibility constant under negative ions, CFU/ions, and $N_{ion}$ is the number of negative ions that reached a single bacteria, ions/CFU, which can be expressed by Eq. (10) [29].

$$N_{ion} = \frac{n \times t_{exposure} \times Q_{exposure}}{C_i \times t_{capture} \times Q_{capture}}$$

(10)

$t_{exposure}$ is the bacteria exposure time by ion and $t_{capture}$ is the bacteria capturing time. The term $t_{exposure}$ was calculated by using Eq. (11), where $d$ is the distance between the ionizer and the sampling point; in this study, $d$ was 0.9 m. The sampling time, $t_{capture}$ was 106 s in this case. $Q_{exposure}$ is the flow rate when the bacteria is exposed to the ions, which can be expressed by Eq. (12), m³/s. Here, $A$ refers to the cross area of the ductwork. $Q_{capture}$ is the sampling flow rate, which was 28.3 L/min.

$$t_{exposure} = \frac{d}{u}$$

(11)

$$Q_{exposure} = A \times u$$

(12)

It is noted that $t_{exposure}$ equals $t$ in Eq. (9) because the duct is filled with negative ions and the exposure time is approximately equivalent to the length of time that bacteria is exposed by the ions in the duct. Then, Eq. (9) can be rewritten as follows:

$$S_{ion} = -Z \frac{n \times Q_{exposure}}{C_i Q_{capture} t_{capture}} = -2.419 \times Z \times n$$

(13)

where the constant 2.419 was calculated by $Q_{exposure}/(Q_{capture} \times t_{capture})$. The key issue becomes how to obtain the constant Z. It can be determined by considering the surviving fraction of airborne microorganisms exposed to negative ions in a ventilated room [29]:

$$\ln(C_{aint}/C_{off}) = -Z \times N_{ion}$$

(14)

where $C_{off}$ is the initial concentration of airborne microorganisms, $C_{aint}$ is the average concentration of airborne microorganisms after being exposed to the negative ions. Z was determined experimentally by adjusting the ion intensity and the slope of the fitted line is the Z.

Fig. 2. Configuration of negative ionizer in a ventilated ductwork.
2.4. Configuration of the model

A three-dimensional (3D) model was constructed in ANSYS ICEM and imported into FLUENT to simulate the negative ion distribution as well as the air flow pattern. The detailed geometry of this ventilation duct is shown in Fig. 2. The dimensions of the ventilation duct were 0.2 m (W) × 0.2 (H) m × 4.5 m (L). The negative ionizer was located 0.6 m from the inlet, with a diameter of 5 mm and a length of 0.04 m. Its mesh is shown in the sub-graph of Fig. 2.

2.5. Boundary conditions setup

The specified boundary conditions are summarized in Table 1. Even though the disinfection tests were conducted at varied inlet speeds, only the air velocity at 3 m/s was simulated in this study. The potential and the negative ion and bacteria concentrations were implemented into FLUENT and treated as user-defined scalars, UDS0, UDS1, and UDS2, respectively. The negative ionizer was modeled as a velocity inlet and it “emitted” negative ions into the duct system at a constant speed of 0.5 m/s. The ionizer generation rate was determined by the equation: \( I/\mu \), where \( I \) is the total ion current (A) [16]. The emission strength was obtained by experiment. The initial concentration of bacteria from the inlet was set to 1.0 (dimensionless). The airflow field was solved first, followed by the electrical field. The negative ion and bacteria transport equations were converged when the residuals reached \( 10^{-5} \).

The transient simulation was conducted with a time step of 0.1 s. The mesh type was hexa-structured and grid-independent tests were performed with: 1,043,260, 1,522,460 and 1,985,420 grid cells, by comparison the distribution of negative ions in the leeward of the ionizer (x = 0.1 m, y = 0.6–4.5 m, z = 0.07 m), the discrepancy for these three types of cell numbers was no more than 5%, thus we selected 1,043,260 grid cells for further calculation to save computational time and resources. The maximum y+ is 54.9, which is sufficient the requirement of y+ for standard wall function.

3. Results and discussions

3.1. Air ions

Fig. 3 shows the profile of negative ions with measured data along the central line of the ionizer when the inlet velocity was 3.0 m/s. The measured maximum ion concentration was \( 2.24 \times 10^{11} \) ions/m³. It was expected that the ion level would decrease dramatically with increasing downstream distance because of the high ion mobility, which would lead to significant loss to the duct wall. The negative ion distribution predicted by the present model agrees well with the experimental results. The discrepancy between the modeling and experiment can be attributed to the limitation of the negative ion counter and misalignment of the ion counter directly facing the negative ionizer.

3.2. Disinfection experiment results

Fig. 4 shows the disinfection efficiency of \( S.\) epidermidis and \( S.\) marcescens at different inlet velocities. The inactivation of negative ions on bacteria performed better at lower inlet velocities. The highest disinfection efficiency decreased when the inlet velocity increased. For \( S.\) epidermidis, the disinfection efficiency gradually decreased to 9.5% and 7.7% when the inlet velocity was 5.0 m/s and 6.0 m/s, respectively. For \( S.\) marcescens, the disinfection effectiveness decreased to 17.1% at 4.0 m/s and 6.5 m/s. As the velocity increased, the dose (ion level multiplied by exposure time) received by the bacteria decreased, which reduced the disinfection efficiency.

Fig. 5 shows the disinfection efficacy of \( S.\) marcescens and \( S.\) epidermidis for voltages of 12 V and 6 V. The negative ion intensity at the sampling point for the two voltages was \( 4.54 \times 10^{10} \) ions/m³ for 12 V and \( 3.16 \times 10^{10} \) ions/m³ for 6 V. In the case of \( S.\) marcescens, the disinfection efficacy decreased from 31.5% to 20.7% with a standard deviation of ±11%. For \( S.\) epidermidis, the disinfection efficacy decreased from 11.9% (± 0.3%) to 5.8% (± 3.5%). These results were used to determine the susceptibility constant for each microorganism.

3.3. Determination of susceptibility constant

The method for calculating the susceptibility constant was illustrated in Section 2.3; it was determined by the relationship between the ion intensity and the inactivation efficacy. By plotting \( ln(C_{total}/\epsilon) \) against \( N_{ion} \) the linear-fitted slope is the susceptibility constant (Eq. (14)), as shown in Fig. 6. The constants for \( S.\) epidermidis and \( S.\) marcescens were 2.723e−11 and 8.676e−11 CFU/ions, respectively.

3.4. Modeling results

The bacteria concentrations for both \( S.\) epidermidis and \( S.\) marcescens were determined when the susceptibility constant was fed back into the source term of the bacteria equation (Eq. (9)), as shown in Fig. 7. Compared to removal by disinfection, the effect of gravitational settling and wall deposition was only 0.02%, and thus these two effects could be ignored because the selected bacteria were only 1 μm in size. The measured disinfection efficiency depends on the constant susceptibility \( Z \) and the number of negative ions. The disinfection efficiency against \( S.\) marcescens was higher than that of \( S.\) epidermidis. The bacteria concentration was nearly zero downstream very close to the ionizer for two reasons: first, the bacteria distribution at the back of the ionizer was relatively low due to the effect of fluid flow around the cylindrical tube; and second, the largest number of negative ions occurred here, resulting in a distribution of bacteria near zero because the disinfection efficacy was assumed to increase linearly with negative ion concentration (when the velocity is the same). The disinfection efficiency decreased at distances far away from the ionizer because the number of negative ions decreased. The predicted concentration of bacteria (facet average at the sampling cut-plane) was 32.8% and 12.7% for \( S.\) epidermidis and \( S.\) marcescens, respectively, as compared to the experimental results, as shown in Table 2.

4. Conclusions and discussion

Reducing energy for air conditioning systems has a significant effect on global energy consumption. The fibrous filtration approach has been used since air conditioning systems were first introduced. It is of great interest to develop a non-filter-based solution for microorganisms. Inactivation of bacteria leads to harmless substances that pose no threat to humans. Air ions could be a potential approach, but such a method has not been studied systematically, even though the effect of negative ions has not been studied systematically, even though the effect of negative ions...
Ions on microorganisms has long been controversially disputed in many research areas [9,30].

In this study, the distribution of negative ions and their effects on bacteria were numerically and experimentally investigated in ventilation ductwork. Gram-positive *S. epidermidis* (ATCC 12228) and Gram-negative *S. marcescens* (ATCC 6911) microorganisms were selected to conduct the disinfection experiment. The disinfection efficiency at different inlet velocities was studied, and it was found to range from 8% to 16% and from 17% to 31% for *S. epidermidis* and *S. marcescens*, respectively. The pressure drop $\Delta P$ ranged from 1.84 Pa to 8.23 Pa, the ionizer inside the duct had a much lower pressure drop compared with HEPA filters.

In a previous work [11], the authors investigated mainly the air ion disinfection effect on those bacteria collected on the filter. For airborne inactivation by negative ions in air duct flow in our case, the susceptibility constant for *S. marcescens* and *S. epidermidis* was $8.676 \times 10^{-11}$ CFU/ions and $2.723 \times 10^{-11}$ CFU/ions, respectively. The $Z$ value of a bacteria is a major factor in a particular microorganism's vulnerability to disinfection. This parameter must be determined experimentally. This study measured $Z$ for the two bacteria. This parameter is needed to help engineers estimate the number of the ionizers required for the system and the bacteria concentration indoors. In the modeling part, the distribution of negative ions was simulated, and the results agreed well with the experimental data.

Regarding the safety issue, particular attention was paid on the ozone emission. It is a power oxidant and it has severe health impacts on human. Its generation is always an important concern for any mechanism involving high potential discharge. In this study, the measured ozone concentration was 68 ppb at 1.5 m/s. The emission rate was estimated to be 29 mg/h. This low emission rate would lead to indoor concentrations lower than 50 ppb [31].

The method proposed may thus play a pioneering role in the simulation of removal mechanisms for various bacteria, particularly in the HVAC field.

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Table 2
Comparison of inactivation experiment and simulation result.

|                | Measurement (%) | Predicted (Facet average Y = 1.5 m) |
|----------------|-----------------|-------------------------------------|
| *S. marcescens*| 31.53           | 32.6                                |
| *S. epidermidis*| 12.17           | 12.7                                |

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