Numerical simulation for bioaerosol removal of applying negative ionizers in a ventilated room

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Abstract
Airborne particles contain a variety of living materials such as viruses, bacteria and fungi especially in healthcare facilities and hospital wards, exposure to these contaminants may have high risk of infection, in order to reduce the risk of cross-infection, Corona discharge based on unipolar ionizer was proposed for removing aerosol particles in indoor environments, however, very few studies were conducted in ventilation ducts and particularly where the negative ionizer should be installed, thus the objective of this paper is to study the disinfection effect for bioaerosols when the negative ionizers were mounted in the duct system. Three different scenarios for ionizer installation were studied: one negative ionizer was installed near the inlet; one negative ionizer was installed near the return vent and two negative ionizers were both installed at inlet and return vent. A mathematical model was developed to solve the distribution of negative ions as well as the bacteria numerically. The potential, electrical field, negative ion and bacteria concentration were implemented into FLUENT as user scalars and coupled with air movement. The results showed the specific bacteria were removed when the negative ionizer was installed inside the duct system. The negative ionizers both installed near the inlet and outlet gave better distribution of negative ions as well as disinfection efficiency compared with other cases. Thus for real application, it is recommended the negative ionizer should be installed both inside the inlet and the outlet.

Keywords - numerical simulation, bioaerosol removal, negative ionizer, ventilation

1. Introduction

Indoor air contaminants pose serious threats to human health and one of them is airborne microorganisms including viruses, bacteria and fungi. For healthcare facilities or hospital wards, exposure to these contaminants may lead to infection. Previous studies have shown that building air conditioning or ventilation systems can transport the contaminants throughout interior spaces [1, 2]. To reduce the risk of cross-infection indoors, current technologies include high efficiency particulate air (HEPA) filters and ultraviolet disinfection are commonly used and implemented into HVAC systems. However high initial and operation costs of HEPA may not suitable for general purpose buildings and high UV dose may lead to emission of byproduct ozone [3, 4]. Corona discharge based on unipolar ionizer is another means for removing
aerosol particles in indoor environments. The negative ions were emitted from ionizer and migrated with bulk air in the indoor environment. Due to the electric field generated by the space charge, particle charging and electro-migration are the main mechanisms responsible for particle removal. Previous experimental results reported that cell membrane of bacteria was ruptured and torn when it exposed to surroundings with negative ions [5, 6, 7]. Unipolar and bipolar ionizers were installed in a duct flow to evaluate the antibacterial efficacy with different number of ionizers and NCPs [8].

The particles motion and concentration will be influenced by ventilation systems and the particle properties, thus it is crucial to consider airflow pattern, particle dispersion, settling and deposition. Lai and Nazaroff [9] developed a three-layer model (drift flux model) to simulate the particle loss. In the presence of air ions, the particles (contaminants) can be removed due to the wall loss, ventilation effect and the interaction with negative ions.

Mayya [10] developed the detailed a mathematical model accounting for electric field, particle charging, ion transport and wall loss. He solved the equations analytically for a cubical ventilated room. In another study a 2D model has been used to simulate the performance of negative ionizers in ventilated rooms which the electric field, ion balance equations were treated as user scalars and they were solved by a CFD tool Fluent [11]. In terms of bioaerosols, specific bacteria can be treated as particles and can be modelled with Eulerian method or Lagrangian method [12].

In the literature there were very few studies utilizing negative ion systems in ventilation ducts. A practical application of negative ionizers for ventilation systems was highlighted and emphasized in this paper. The objective of this paper is to explore the disinfection effect for bioaerosols when the negative ionizers were installed in a duct system. A typical hospital ward with ductwork connected was selected to conduct this study, three different configurations for ionizer installation were studied in this paper: one negative ionizer was installed near the air supply inlet (denoted as case 1); one negative ionizer was installed near the air return outlet (case 2) and two negative ionizers were both installed at inlet and return vents (case 3). The rest of this paper is organized as follows: The methodology including the model description and the boundary conditions set up were first introduced, followed by simulation results and discussion, the conclusion part was illustrated in the last section.

2. Methods

2.1 Mathematical model: Modeling the negative ions and transport of microorganisms

The ionizer is an electrical device that uses high voltage but small current to ionize (electrically charge) air molecules, negative ions are particles with one or more extra electrons. It is assumed that in this model all ions carry a single negative charge and can be modeled as scalar concentration in air. The potential, electrical field and ion transportation equations are coupled each other, the potential (1) and electrical field (2) are governed by Poisson and Gauss’s equations respectively. The negative ion transport equation (3) can be solved combined with (1) and (2).
\[ \nabla^2 \phi = -\frac{e}{\varepsilon_0} n(x, y, z) \]  

(1)

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

(2)

\[ \frac{dn}{dt} + (\vec{u} + \mu_p \cdot E) \nabla n = D_p \nabla^2 n \]  

(3)

Where \( \Phi \) is the potential of the ionizer, \( e \) is elementary charge; \( \varepsilon_0 \) is permittivity of free space; \( E \) is electric field; \( n \) is the number of negative ions; \( u \) is air flow velocity in ventilation duct; \( \mu_p \) is ion mobility; \( D_p \) represents the ion diffusion coefficients, the specific values can be found in reference [10].

The removal mechanism for negative ionizer is particle charging and electromigration. The governing equation for the bacteria concentration can be written as:

\[ \frac{\partial C_i}{\partial t} + \nabla \cdot [(\vec{u} + v_{s,i})C_i] = \nabla \cdot [(D_i + \varepsilon_p) \nabla C_i] + S_i \]  

(4)

\[ S_i = -\zeta \cdot C_i \]  

(5)

Where \( C_i \) the particle concentration of particle size in group \( i \), \( v_{s,i} \) is the particle settling velocity, \( \varepsilon_{p,i} \) is the particle eddy diffusivity and \( D_i \) is the Brownian diffusion coefficient. \( S_i \) is the source term, \( \zeta \) is the disinfection rate, which is the function of negative ion concentration, type and property of bacteria, temperature, relative humidity and the time, it is noted that the disinfection efficiency is different in terms of different types of bacteria and it can be determined by sterilization experiments [13].

Equations (1) to (5) are closed equations for negative ions and bacteria concentrations. To resolve these equations, the air movement properties were predefined and this was obtained by solving Navier-Stokes equations to get the velocity field with transient simulation, then additional 200s was calculated after (1) to (5) were loaded in Fluent. The impacts of temperature to bacteria survival were neglected due to the small changes of temperature in air conditioning systems, so energy equation was not activated in this study.

### 2.2 Model description

A typical hospital ward (2.3m×2.25m×2.3m) with mixing ventilation was selected to conduct this study, as shown in Fig.1. The inlet and the return outlet were both located in ceiling level with dimension of 0.3m × 0.3m each. The negative ionizer was installed inside the duct system adjacent to the inlet or return vent depending on different scenarios. The ionizer was a tube with 0.038m of diameter and 0.2m long. The bacteria was released from the return vent and transported into the duct system and finally dispersed into indoor environment. The corresponding 3D model was established in ANSYS ICEM with duct system directly connected to the room.
2.3 Boundary setup

The potential, the negative ion and bacteria concentration were implemented into Fluent and treated as UDSs (User Define Scalars) compiled in C language as UDF (User Define Function). The electrical force generated by electrical field was added into the source term of the momentum terms. SIMPLE algorithm was used to couple pressure and velocity fields. The second-order upwind scheme was employed for convection term discretization and QUICK scheme for scalars.

The initial room condition was assumed to be filled up with bacteria with uniform concentration 1 (dimensionless). The same concentration was given at the boundary of the return air duct. The walls were assumed to be grounded with boundary conditions on the electric potential and ion concentration was given by $\Phi=0$ and $\partial n/\partial s=0$ respectively where $s$ is the normal to the walls of the domain. A drift flux model [12] was applied to simulate the deposition and dispersion of bacteria due to the gravity, Brownian and turbulent diffusion. The negative ionizer was treated as a velocity inlet and generated negative ions into the duct system at a constant speed of 0.5m/s. It should be noted that the boundary condition of the negative ion was determined by the in-situ measurement results and is not shown in this paper. The detailed boundary conditions are summarized in Table 1.

<table>
<thead>
<tr>
<th>Ventilation Geometry</th>
<th>Mixing Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diffuser type</td>
<td>Inlet, Return, Grille 0.3×0.3</td>
</tr>
<tr>
<td>Air exhaust vent</td>
<td>Outlet, Grille 0.3×0.3</td>
</tr>
<tr>
<td>Air supply rate</td>
<td>ACH=3s⁻¹</td>
</tr>
</tbody>
</table>

Table 1. Boundary conditions for the simulation setup
<table>
<thead>
<tr>
<th>Negative ionizer geometry and generation rate</th>
<th>Diameter=0.038m; Generation rate: $3.02 \times 10^{12}$/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbulence model</td>
<td>RNG k-ε model</td>
</tr>
<tr>
<td>Numerical schemes</td>
<td>Upwind second-order difference scheme; UDS0-2 QUICK SIMPLE scheme</td>
</tr>
<tr>
<td>Mesh type and number of grids</td>
<td>Hexahedral-structured, 1.5 million</td>
</tr>
<tr>
<td>Residuals of convergence</td>
<td>Continuity momentum turbulent kinetic $10^{-4}$; UDS0-2 $10^{-4}$</td>
</tr>
<tr>
<td>Walls</td>
<td>UDS 0 and UDS 1 specific value=0; UDS 2 specific flux=0</td>
</tr>
<tr>
<td>Bacteria properties</td>
<td>$d_p=1.0 \times 10^{-6}$m, Density=1400kg/m$^3$</td>
</tr>
</tbody>
</table>

### 3. Results and Discussion

Fig.2 gives the velocity contours for case 1, case 2 and case 3 ($X=0.475$m, $Y=1.125$m). The air speed was accelerated from 0.25m/s to nearly 1m/s when it passed through the ionizer near the inlet. The airflow pattern was influenced by the ionizer installation inside the duct system while a little impact to the indoor air circulation and distribution.

![Case 1: inlet plasma unit installation](image1.png)  ![Case 2: return plasma unit installation](image2.png)
Case 3: inlet and return plasma units installation

Fig. 2 Contour of velocity for different installation configurations ($x = 0.475\text{m}$, $y = 1.125\text{m}$)

Fig. 3 gives the distribution of negative ions in different installation configurations. The negative ions were blow into the indoors through the duct work system and driven by the air movement. The ion concentration at the rear of plasma was exponential decreased with the distance from ionizer, plumbed to 20% of its initial value only 0.5m away from it in case 1, the average number of the negative ions in the room were $3.9 \times 10^{11} \text{#/m}^3$, $2.6 \times 10^{11} \text{#/m}^3$ and $4.7 \times 10^{11} \text{#/m}^3$ respectively. There was no negative ion distribution in duct system when ionizer unit was installed near the inlet in case 2. For case 3, when the ionizers were both mounted, the negative ions were filled up with the duct as well as the room.
Case 3: inlet and return plasma units installation

Fig. 3 Contour of negative ions for different installation configurations (x = 0.475m, y = 1.125m)

Case 1: inlet plasma unit installation

Case 2: return plasma unit installation

Case 3: inlet and return plasma units installation
Fig. 4 Contour of bacteria for different installation configurations ($x=0.475\text{m}, y=1.125\text{m}$)

The simulation results showed the bacteria were removed when negative ions were presence in Fig. 4. The removal efficiency depends on the number of negative ions. The most effective scenario is case 3 where the pollutants were totally removed after 200s. Case 2 was the worst one since the bacteria was not removed from the indoor space (the concentration was still 0.5 after 200s). In case 1, although the particle was removed from the indoor space, the duct system was still filled with bacteria. Fig. 5 also gives a clear picture to show the average bacteria concentration from outlet against with time for the 3 cases. The concentration of bacteria decreases with time from 1 to 0.4, 0.1 and 0 for case 1, case 2 and case 3 after 200s calculation. The case 3 is the best compared with case 1 and case 2 since the bacteria was removed from indoor space with the minimum time.

![Graph showing bacteria concentration over time for three cases](image)

Fig. 5 The relationship between bacteria concentration and time in 3 cases (outlet)

4. Conclusions

In order to reduce the risk of cross-infection in a ventilated room, 3 different scenarios of negative ionizer installation were configured and numerically simulated. The simulation results showed the bacteria was removed when the negative ionizer was installed inside the duct system. The deployment of ionizer has little impact to the air flow field. The disinfection effect for bioaerosol removal was highly related to the number of negative ions. The negative ionizers both implemented near the inlet and outlet gave better distribution of negative ions and thus highest disinfection efficiency for bacteria compared with other cases was obtained. Thus for practical application, it is recommended the negative ionizer should be installed both inside the inlet and the outlet.

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References