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Inactivation of airborne bacteria by cold plasma in air duct flow

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ABSTRACT

This paper developed a numerical model for predicting bacteria inactivation by cold plasma tube. The bulk air velocity, ion mobility, electric field and ion diffusion were considered in the model to obtain the distribution of negative ions. The sink term appeared in the model was determined by a semi-empirical approach through experiment. A 9-m long, 200 mm square duct was used for carrying out experiments. Negative ion concentration along the duct and inactivation rate of *E. coli* was measured. Based on the inactivation rate, the sink term was estimated and fed to the model. Three different device installation scenarios were investigated: single plasma unit, two plasma tubes arranged in horizontal and finally two plasma arranged in vertical orientations. The simulation results were agreed well with site measurement of ion intensities as well as pathogen inactivation experiments, an application of cold plasma in a single hospital ward was discussed. The developed model can be applied to advanced disinfection technologies in HVAC systems, besides, the method for modeling the bacteria can be expanded to other microorganisms. Limitations of the model are also discussed.

1. Introduction

The airborne transmission of infectious disease in microenvironments influences public health and has received more and more attention from the general public. Recent modeling studies further showed that there is a potential infection risk of indoor airborne transmission of diseases in high-rise hospitals [1,2] and office [3] through HVAC systems. To reduce this risk of infection, engineering control strategies should be implemented. Medium-grade filters are not effective for removing small bacteria and viruses. For many general premises, it is not economically-feasible to apply high ventilation rates or using High Efficiency Particulate Air (HEPA) filters [4]. In respect of the health associations of airborne pathogens, there is a huge demand for efficient disinfection technologies for HVAC systems [3]. UV-C is an effective inactivation means but emission of byproduct ozone must be considered as potential health effects [5,6]. Therefore, development and application of new technologies for effective disinfection of airborne pathogens at lower costs and with sustainability in energy resources for general use to provide cleaner environments are needed. Recently, cold plasma disinfection units for in-duct applications have become available commercially [7]. Dielectric Barrier Discharge (DBD) is one of plasma technology and commonly introduced into fundamental researches such as air purification application, DBD plasma units consist of 2 electrodes, at least one of which is covered with the dielectric layer. Normally, the dielectric layer is placed in the current path between 2 electrodes. At least one insulting layer between electrodes is needed to produce non-equilibrium atmospheric pressure discharge [8,9]. Previous experimental studies of cold plasma predominately focused on inactivation of medical devices placed on agar plates or well plates with plasma jets [10,11] and disinfection rate over 90% within a few seconds of plasma treatment was found [12]. Instead of single type of inactivation species, like ozone, UV-C, the disinfection mechanisms of cold plasmas on airborne microorganisms are associated with the presence of charged particles, ions, oxygen species and oxygen-containing radicals, UV-C, vacuum ultraviolet (VUV), and localized, periodic and short-term heating of microorganisms, as well as synergistically combined effects of these factors [13,14]. In literature cold plasma disinfection on airborne pathogens is scarcely reported. Terrier et al. investigated cold plasma disinfection effects on respiratory viruses under tube flow conditions resembling a practical ventilation system with a "reasonable" airstream velocity of 0.9 m/s [15]. However, the duct size had not been mentioned.

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Nomenclature

A	disinfection constant, m^3/ions
t	time, s
C_i	the concentration of bacteria
u	velocity, m/s
CFU_{down}	the colony forming units of bacteria at downstream
$v_{s,i}$	particle settling velocity, m/s
CFU_{up}	the colony forming units of bacteria at upstream
Z_i	elaboration constant, m^2/J
D_i	Brownian diffusion coefficient for bacteria, m^2/s
Φ	potential difference, V
D_p	Brownian diffusion coefficient for ion, m^2/s
ρ	air density, kg/m^3
e	elementary charge, C
ε_0	the permittivity of free space, C^2/Nm^2
E	the electrical field, V/m
ε_p	particle eddy diffusivity, m^2/s
E_p	negative ion intensity, ions/m^3
μ	dynamic viscosity, Ns/m^2
n	number of negative ions, ions/m^3
μ_p	ion mobility, m^2/Vs
p	Pressure, Pa
ν_t	turbulent viscosity, m^2/s
S_i	Source term
η	disinfection efficacy

It can be seen that multiple active species are presented and this makes modeling extremely difficult. Among all these species, ions are relatively easy to measure. Thus instead of measuring all reactive species, the authors selected only negative ions to study in this work. They were considered since previous experimental results reported that cell membrane of bacteria was ruptured and torn when it exposed to surroundings ions [16–19]. Previous studies have shown that this process can remove fine particles [20] and airborne microbes effectively in indoor environments [21,22]. It has been used in one hospital, which successfully reduced tuberculosis transmission among guinea pigs [23].

Although experimental studies have shown decent disinfection efficiency by negative air ions (NAI), very few numerical studies were reported. Noakes et al. [24] and Fletcher et al. [25] developed a 2D model to simulate the performance of negative ionizers in ventilated rooms which the electric field, ion balance equations were treated as user scalars and solved by a CFD tool Fluent. Mayya [26] developed a detailed mathematical model accounting for the electric field, particle charging, ion transport and wall loss. He solved the equations analytically and applied for a cubical ventilated room. To model airborne bacteria, additional "phase" must be considered. Bacteria can be treated as particles and can be modeled with the Eulerian or Lagrangian approach [27]. The particle motion and concentration will be influenced by ventilation systems and the particle properties, thus, it is crucial to consider airflow pattern, particle dispersion, gravitational settling and deposition loss. Lai and Nazaroff [28] developed a "three-layer model" (drift flux model) to model particle loss. In literature airborne pathogen inactivation rate by UV has been studied for different types of bacteria. Concepts such as UV dose and exposure time have been utilized to model microorganisms' response to UVGI [5,29–33]. However, the literature listed above either studying the modeling of DBD from the perspective of analytical solutions or modeling the deposition and dispersion for particles only. None of them combined NAI transportation as well as microorganism inactivation. Besides, very few studies utilizing plasma air ionization equipment in ventilation ducts especially when inside velocity larger than 2 m/s for removing bacteria in HVAC system.

This paper aims to develop a numerical methodology based on disinfection performance of the cold plasma technique to estimate the distribution of bacteria in a ventilation duct. A full-size, experimental ventilation ductwork was designed and set up to measure one-pass inactivation efficacies of a cold plasma installation under various practical environmental conditions. *Escherichia coli* (ATCC 10536) was selected in this paper as a testing bacteria. The airflow, electrical field, and negative ion distribution were obtained by the Eulerian approach. A novel semi-empirical numerical expression based on experiment results was formulated and applied to simulate the distribution of bacteria. Drift-flux model was considered for bacteria transportation equation. In addition, three different installation scenarios have been

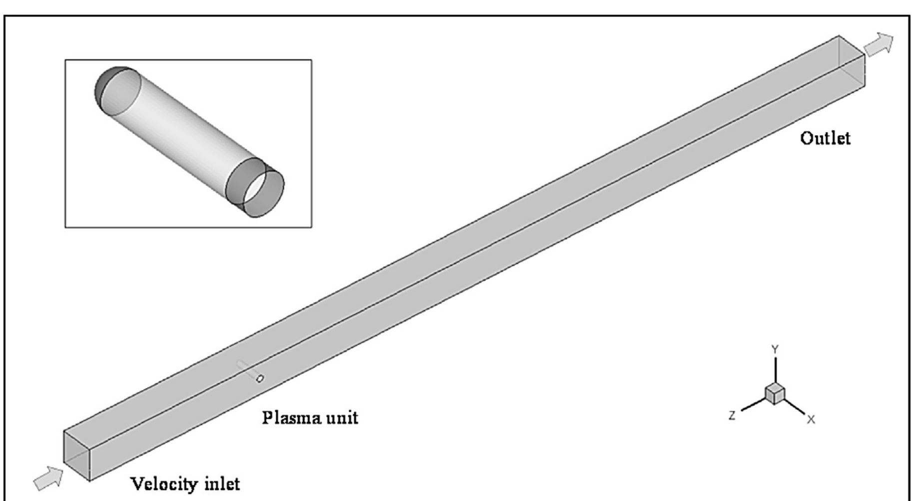
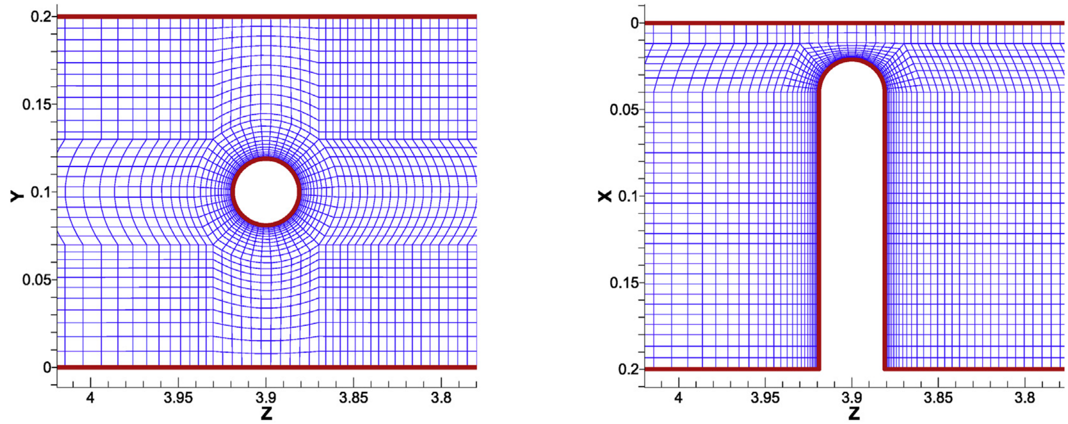
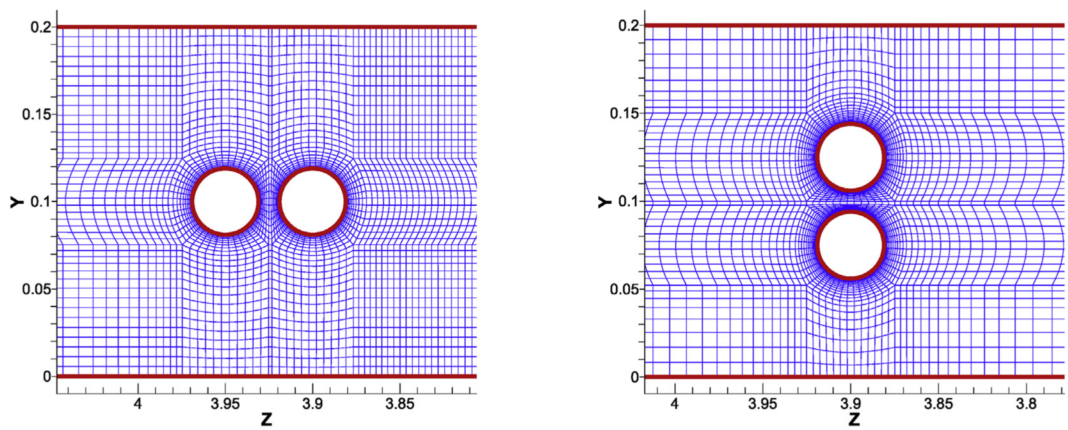


Fig. 1. Configuration of the plasma unit in a ventilation duct system.



(a). One plasma unit and grid display on the surface of the plasma



(b). Two plasma units and grid display on the surface of the plasma (horizontal and vertical)

Fig. 2. The detailed plasma unit and grid display.

investigated experimentally and numerically: one plasma unit, two horizontal and two vertical plasma units, an application of cold plasma in a single hospital ward was discussed as well. Conclusions are illustrated in the last section.

2. Methodologies

2.1. Modeling the negative ions and transport of microorganisms

The model assumes that all ions carry a single negative charge and can be modeled as a scalar concentration in air. Positive ions are not included in the model. To simulate the ion concentration, the potential (Eq. (1)) and electrical field (Eq. (2)) are governed by Poisson and Gauss's equations respectively. The negative ion concentration (Eq. (3)) then can be solved by the scalar transport equation as well.

$$\nabla^2\varphi = -\frac{e}{\varepsilon_0}n(x,y,z) \tag{1}$$

Table 1
Boundary condition setup.

Items	Numerical method
Supply air inlet	Velocity inlet: 2.0 m/s, 3.5 m/s, 5.0 m/s
Outlet	Outflow
Turbulence model	RNG k-ε model, Standard wall functions
Numerical schemes	Upwind second-order difference scheme; SIMPLEC algorithm
	UDS0, 1, 2 QUICK algorithm
Mesh type and number of grids	Hexahedral-structured, 0.5, 0.7 and 0.75million for one, two vertical and two horizontal
Plasma tube	Velocity inlet: 0.5 m/s, Ionizer generation rate: 3.02×10^{12}ions/m^3
Residuals of convergence	Continuity momentum turbulent kinetic 10^{-4}; UDS0, 1, 2 10^{-5}
Walls	UDS 0 and UDS 1 specific value = 0
	UDS 2 specific flux = 0

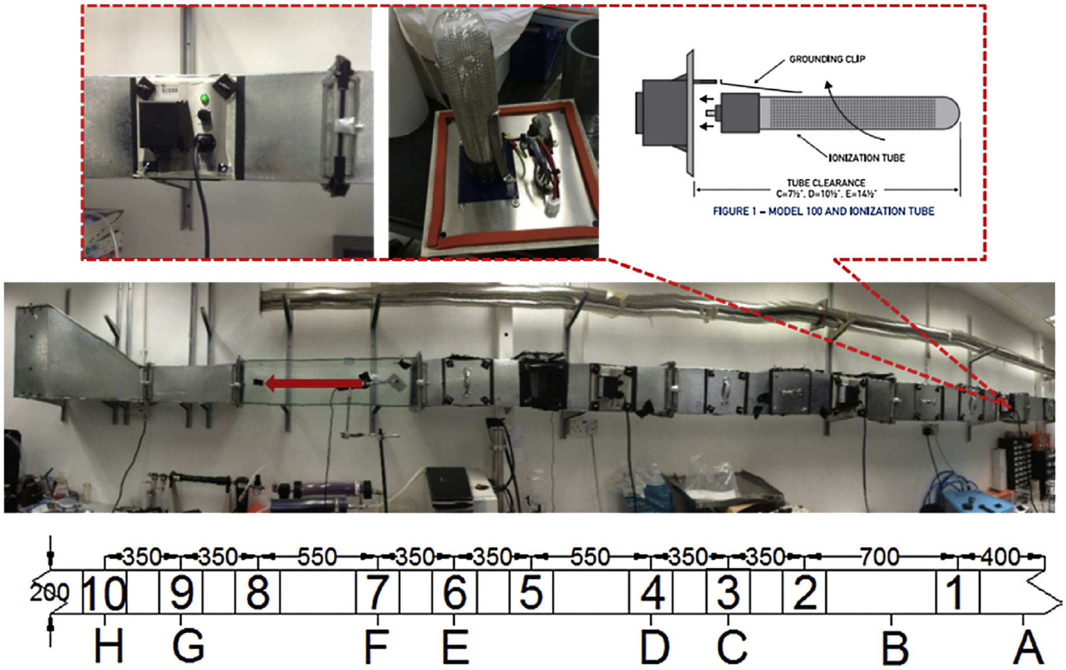


Fig. 3. The schematic picture of ductwork system and plasma unit installation.

$$\vec{E} = -\nabla\varphi = -\left(\frac{\partial\varphi}{\partial x}\vec{i} + \frac{\partial\varphi}{\partial y}\vec{j} + \frac{\partial\varphi}{\partial z}\vec{k}\right) \quad (2)$$

$$\frac{dn}{dt} + \left(\vec{u} + \mu_P \cdot E\right)\nabla n = D_p \nabla^2 n \quad (3)$$

where Φ is the potential of the plasma unit, V; e is elementary charge, 1.6 × 10^{-19}C; ε_0 is permittivity of free space, 8.854 × 10^{-12} C^2/Nm^2; E is electric field, V/m; n is the number of negative ions, ions/m^3, u is air flow velocity in ventilation duct, m/s; μ_p is ion mobility, 1.35 × 10^{-4} m^2/Vs; D_p represents the ion diffusion coefficients, 3.5 × 10^{-6} m^2/s, the values can be found in Refs. [24,26].

The electrical force will impact on the charged particles in duct flow, which consequently influence the uncharged particles, this effect can be simulated by adding a source term on momentum, see Eq. (4), ρ is the density of air, kg/m^3; μ is dynamic viscosity, Ns/m^2; P is pressure, Pa.

$$\rho\frac{Du}{Dt} = -\nabla p + \nabla\cdot(\mu\nabla u) - en(x,y,z)\nabla\varphi \quad (4)$$

The governing equation for the bacteria concentration can be written as:

$$\frac{\partial C_i}{\partial t} + \nabla\cdot\left[\left(\vec{u} + v_{s,i}\right)C_i = \nabla\cdot\left[(D_i + \varepsilon_p)\nabla C_i\right] + S_i\right. \quad (5)$$

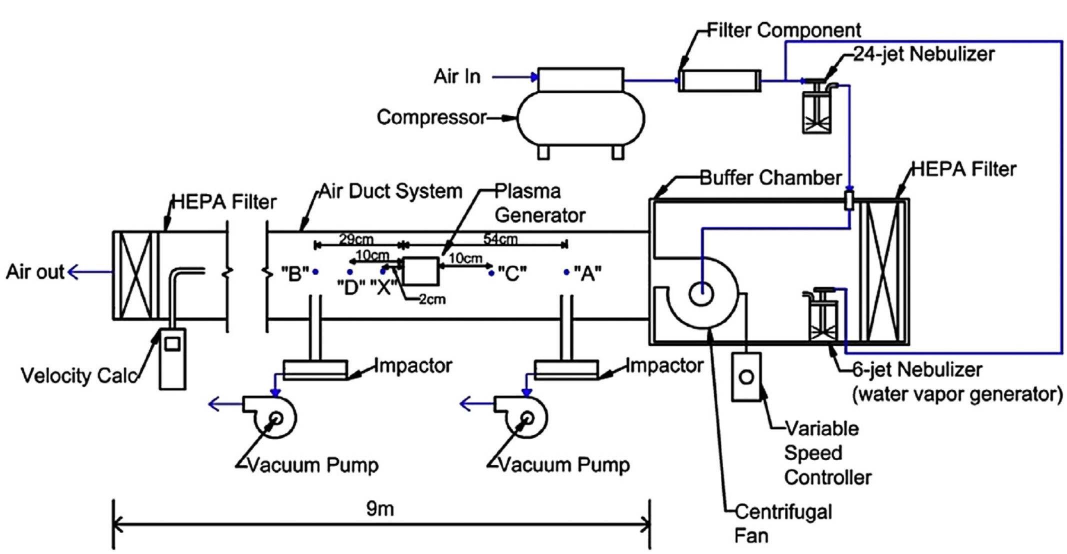


Fig. 4. Schematic diagram of experimental set-up.

$$S_i = -Z_i E_p C_i \tag{6}$$

where C_i is the particle concentration of particle size is group i, $v_{s,i}$ is the particle settling velocity, m/s; ε_p is the particle eddy diffusivity, m^2/s, for small particles it is assumed that $\varepsilon_p/v_t = 1$, where v_t is the fluid turbulent viscosity; D_i is the Brownian diffusion coefficient, m^2/s; the settling velocity and Brownian diffusion coefficient can be calculated in Ref. [34]. Eq. (6) was retrieved from Refs. [30,35,36] for modeling disinfection of airborne using UVGI sources, the similar method can be applied to simulate the bacteria respond to the ion intensities. S_i is the source term; Z_i is the disinfection susceptibility due to UV sources, m^2/J. It is noted that the natural decay for bacteria was not considered in this model, the drift flux model [27,28,37] was applied to modeling bacteria dispersion and deposition onto internal wall surface due to the gravity, Brownian, and turbulent diffusion. It is assumed that the diameter for *E-coli* is 1.0×10^{-6} m with density 1400 kg/m^3.

In order to precede the modeling, the approach adopted in this paper was retrospective. Eq. (6) can be simply replaced by Eq. (7) in terms of negative ions, here A and n are corresponding to Z_i and E_p respectively.

$$S_i = -AnC_i \tag{7}$$

A is a constant depends on the microorganism and its value was determined by a trial-and-error approach, m^3/ions; n is the number of negative ions, ions/m^3. For a pre-defined airflow velocity and cold plasma configuration and installation, A is related to η (disinfection efficacy). An initial value of A was chosen and modeled disinfection efficacy was evaluated. The value was compared with the experimental result; if these two values were not matched (±5%), a new set of A was tried.

It must be emphasized here that the model proposed for the source term was semi-empirical; not analytical nor theoretical. Here the term A deserves elaboration. Unlike filtration by mechanical mechanisms like fibrous filters of which the filtration efficacy can be predicted (or modeled) by knowing the bacteria size, while disinfection susceptibility by cold plasma tubes, negative ionizers or UV irradiation cannot be predicted theoretically. A depends on how a particular microorganism and other environmental factors like relative humidity, temperature, etc. This parameter cannot be predicted or modeled.

2.2. Configuration of the model

A 3D model was constructed in ANSYS ICEM and imported into FLUENT to simulate the negative ions distribution as well as the air flow pattern. The detailed geometry of this ventilation duct is shown in Fig. 1. The dimension of the ventilation duct is 0.2 m × 0.2 m × 5.0 m, the diameter of the plasma unit is 0.03804 m and 0.18 m long, which located in 1.1 m after the velocity inlet, with relative coordinate 3.9 m in the 3D model. The negative ions were emitted from the middle cylindrical surface as shown in the figure.

Three configurations of plasma units were installed into the ventilation duct system: one plasma unit, two vertical plasma units and two horizontal plasma units. Fig. 2a and b give the partial

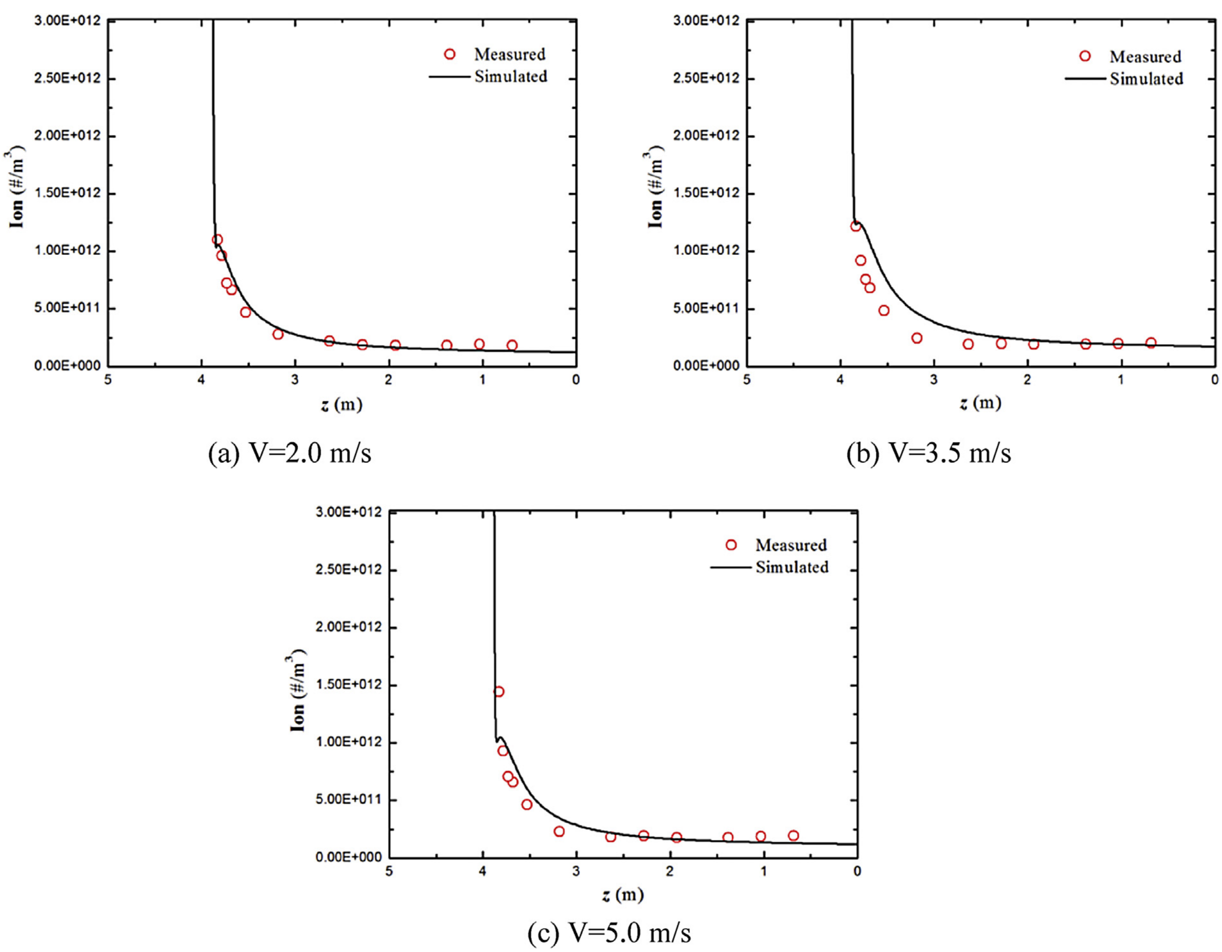


Fig. 5. The comparison concentration of negative ions between simulation and measurement with different inlet velocities.

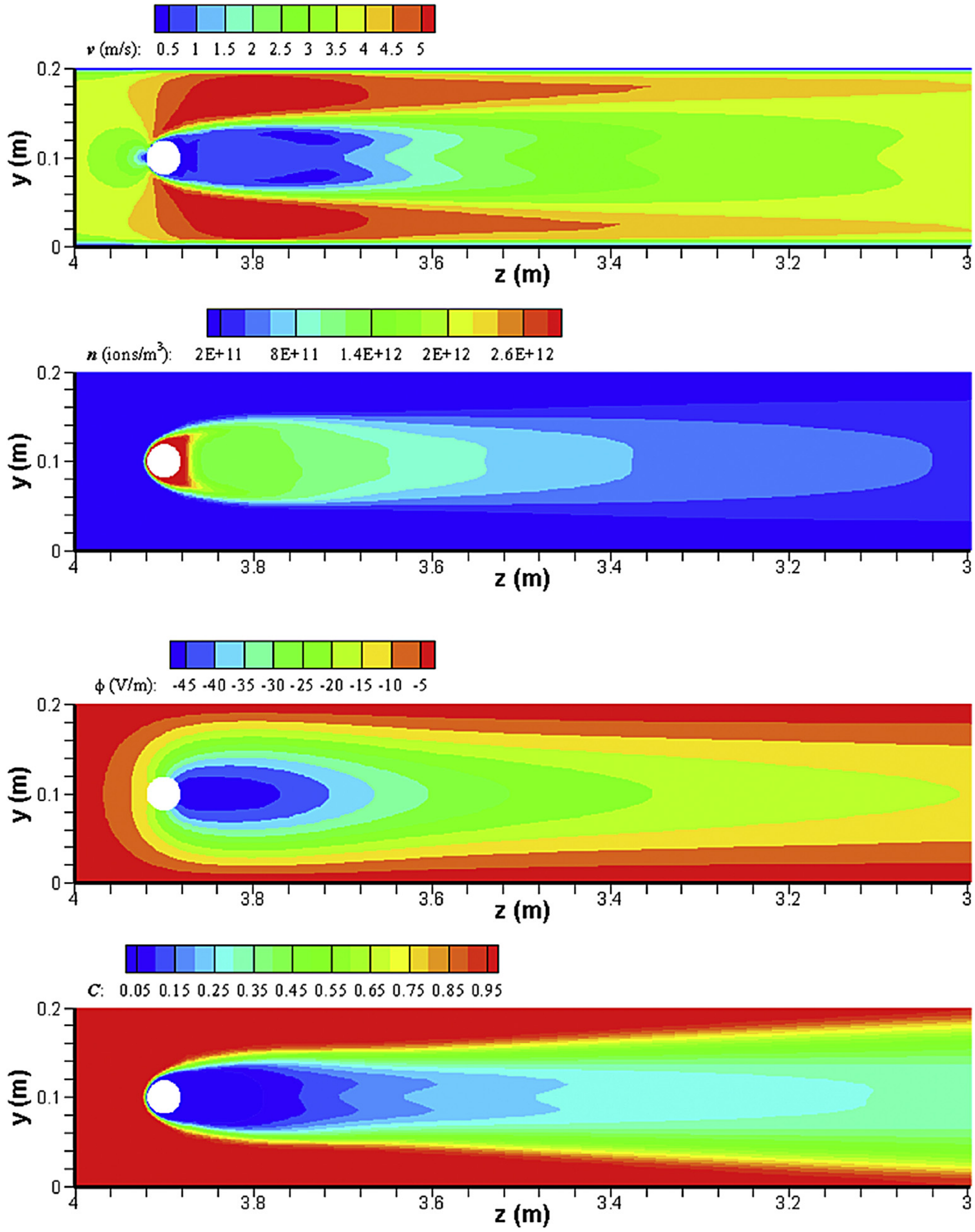


Fig. 6. The contour of velocity, negative ions, potential and bacteria for air velocity 3.5 m/s.

enlarged cross-section view of tubes and the structured grid also shown in the figure.

2.3. Boundary conditions setup

The detailed boundary conditions are summarized in Table 1. It is noted that in this model, the energy equation was not activated since there was no heat source in duct and the temperature was controlled within 23 ± 2 °C in experiment phase, and relative humidity was set to 55 ± 5%, thus the influence of temperature and relative humidity were insignificant in this model. The potential, the negative ion and bacteria concentration were implemented into Fluent and treated as UDS0, UDS1 and UDS2 respectively (User Define Scalars). The negative ionizer was treated as a velocity inlet and "emitted" negative ions into the duct system at a constant speed of 0.5 m/s. It should be noted that the boundary condition of the negative ion was determined by the in-situ measurement results. The airflow field will be solved firstly, followed by an electrical field, the negative ion and bacteria transportation equations are seems converged when the residuals reached to 10^{-5}. The transient simulation will be conducted with the time step 0.1 s.

3. Experiment setup

Detail experimental design can be found elsewhere [7] and only brief description is reported here. A 9-m long, 200 mm × 200 mm modular galvanized steel ductwork system was designed and fabricated. Fig. 3 shows the picture and schematic of the experimental setup. A cold plasma air ionization equipment of 4 W (102C, Plasma Air International) was installed at ductwork module No. 2 as shown in Fig 3. The plasma tube was composed of metal barbed wire based on a dielectric barrier discharge mechanism. The upstream of the ductwork was connected with a mixing chamber and a centrifugal fan. A negative ion counter with measuring range up to 1.99×10^8 ions/cc (Air Ion Counter, AlphaLab) was used to measure the emission. Referring to the manufacturer's specifications, one important limitation of the counter was that the airstream velocity must be less than 4 m/s. The number of negative ions was measured at different locations in downstream of the duct system with different inlet velocities. The ion counter was carefully put into the middle of the duct through the pre-designed windows and faced directly to the plasma tube during the measurement.

The pathogens were atomized and aerosolized by a 24-jet nebulizer (Collision Nebulizer, BGI) with inlet pressure 275.8 kPa. Two single-stage viable Andersen cascade impactors (N6, Thermo Scientific) were used to sample the airborne microbial concentration, see Fig. 4. Each sampler was connected to a pump and the sampling flow rate was adjusted to 28.3 l/min. The sampling time was set to 106 s with a corresponding total sampled air volume of 50 L. Gram-negative bacilli *Escherichia coli* (ATCC 10536) was selected in this study to test the disinfection efficiency of the cold plasma tube. The test bacterium can be found in dust and on inanimate surfaces of hospital environments or formations of biofilms, and have potential clinical relevance in the transmission of nosocomial pathogens [39]. For the experiments, the effective inactivation of *E. coli* occurred within the distance of 0–40 cm from the induction coil reported by Liu [40], thus, the disinfection efficacy was calculated from location “A” and “C” as shown in Fig. 3, the disinfection efficiency can be defined as:

$$\eta = 1 - \frac{CFU_{down}}{CFU_{up}} \tag{8}$$

where CFU_{up} and CFU_{down} are the colony forming units of *E. coli* from location “A” and “C”, “A” is before contacting to the plasma unit, and “C” is 35 cm far away from the plasma unit after the bacteria was exposed to the negative ions. At least 10 samples of *E. coli* were prepared before inoculated and atomized into ductwork system at a certain inlet velocity. For modeling, the disinfection efficacy was evaluated by calculating the average concentration of the planes of “A” and “C.”

A multi-functional IAQ meter (9555, Velocicalc, TSI) incorporating a portable thermal anemometer (±3%) was used to measure the airstream velocity in the duct. A location was selected to better measure full developed velocity which was 4 m downstream of the fan. The measuring probe was inserted through an opening at the tempered-glass and adjusted at the central plane perpendicular to the flow direction. The steady airstream was controlled to 2.0 m/s, 3.5 m/s and 5.0 m/s for inactivation efficacy experiment respectively.

4. Results and discussion

4.1. One plasma unit

Fig. 5 shows the modeling results of negative ions with measured data at different inlet velocities along the central line (x = 0.1 m, y = 0.1 m, z = 0–3.88 m). Since it is impossible to directly contact the surface of the plasma unit to obtain the real “emission rate” which is required as a boundary condition for the negative ions, the negative ion meter was placed at 2 cm downstream from the plasma tube to obtain the possible maximum number of ion concentration. The measured maximum ion concentration was 1.097×10^{12} ions/m^3, 1.219×10^{12} ions/m^3, 1.444×10^{12} ions/m^3 for air velocity 2.0, 3.5 and 5.0 m/s respectively. It can be seen that negative ion concentration increases with velocity since charge drift equation was implemented. It was expected that the ion level decreased dramatically with downstream distance [38], the reason is due to the relatively small ion diffusion coefficient. 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 facing directly to the cold plasma tube.

Fig. 6 shows the detail distribution of velocity field, negative ion, potential difference, and bacteria in the downstream of the plasma unit. The inlet velocity, in this case, was 3.5 m/s. The potential difference, bacteria concentration, and distribution are governed by the negative ions, thus, the higher potential difference and lower bacteria at the rear of ionizer were clearly shown where the negative ions give a maximum magnitude. The bacteria were removed when the negative ions were presence in Fig. 6. However, the effect of gravitational settling and wall deposition is not shown clearly in this figure due to the diameter for the selected bacteria is only 1 μm, the impact of electric force on bacteria is not shown as the electric force is insignificant compared to momentum force. Thus, the measured disinfection efficiency only depends on the number of negative ions. It is noted that the bacteria is nearly zero at downstream very close to plasma tube. Two reasons can be attributed to this, first, the bacteria distribution at the rear of plasma tube is relatively small due to the effect of fluid flow around circular cylinder tube, the second reason is the largest number of negative ions occurs here resulting in nearly zero distribution of bacteria since the disinfection efficacy was assumed increasing linearly with negative ion concentration. The disinfection efficiency decreases when it is far away from the plasma tube because the number of negative ions decreases. The disinfection simulation is compared with experiment for different inlet velocities, as shown in Fig. 7. The experiment shows that the disinfection efficiency increases from 32% to 43% when the inlet velocity increases from 2 m/s to 5 m/s. The simulation results have a good agreement with the experiment result.

4.2. Two plasma units

Fig. 8 shows that when the plasma units are horizontal

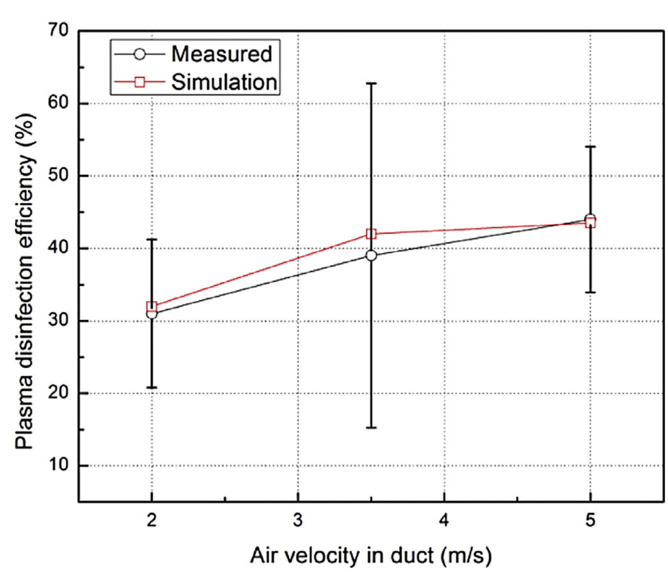


Fig. 7. The disinfection efficiency comparison for one plasma unit with different inlet velocities.

configured, the velocity field does not change too much compared with one plasma unit, even though the number of negative ions increases. However, it is interested to find that the number of negative ions was not doubled as we expected, the reason can be explained by the very close distance (50 mm) between the windward unit and leeward unit, the leeward unit "blocked" the diffusion of the negative ions generated from the windward unit, that's why the disinfection efficiency is lower than 2 vertical case. The disinfection effect in this case is only 31.6%. When the plasma units are vertically installed, the air flow is blocked by the two tubes and it becomes unstable and oscillates at the leeward of the plasma units which can be seen from the velocity field shown in Fig. 9. The disinfection efficiency for this case is 47%. The inactivation efficacy for 2 vertical plasma units is higher than 2 horizontal units mainly due to the ion concentration in cross section is larger than 2 horizontal units. Table 2 gives the disinfection efficiency comparison between experiment and simulation for different installation configurations (inlet velocity = 3.5 m/s). The 2 plasma units do not show any overwhelming inactivation effect compared with one plasma unit, in addition, the pressure drop should be cautious especially 2 vertical plasma units are installed.

4.3. An application of cold plasma in a single ward

The model developed in Section 2 was applied in this section to study disinfection efficacy of cold plasma technology in healthcare facilities and hospitals under practical scenarios. Thus, all the parameters selected were carefully chosen. A little ward was selected to conduct this study and the configuration for this room was shown in Fig. 10.

The ward utilizing ceiling supply and ceiling return mixing type

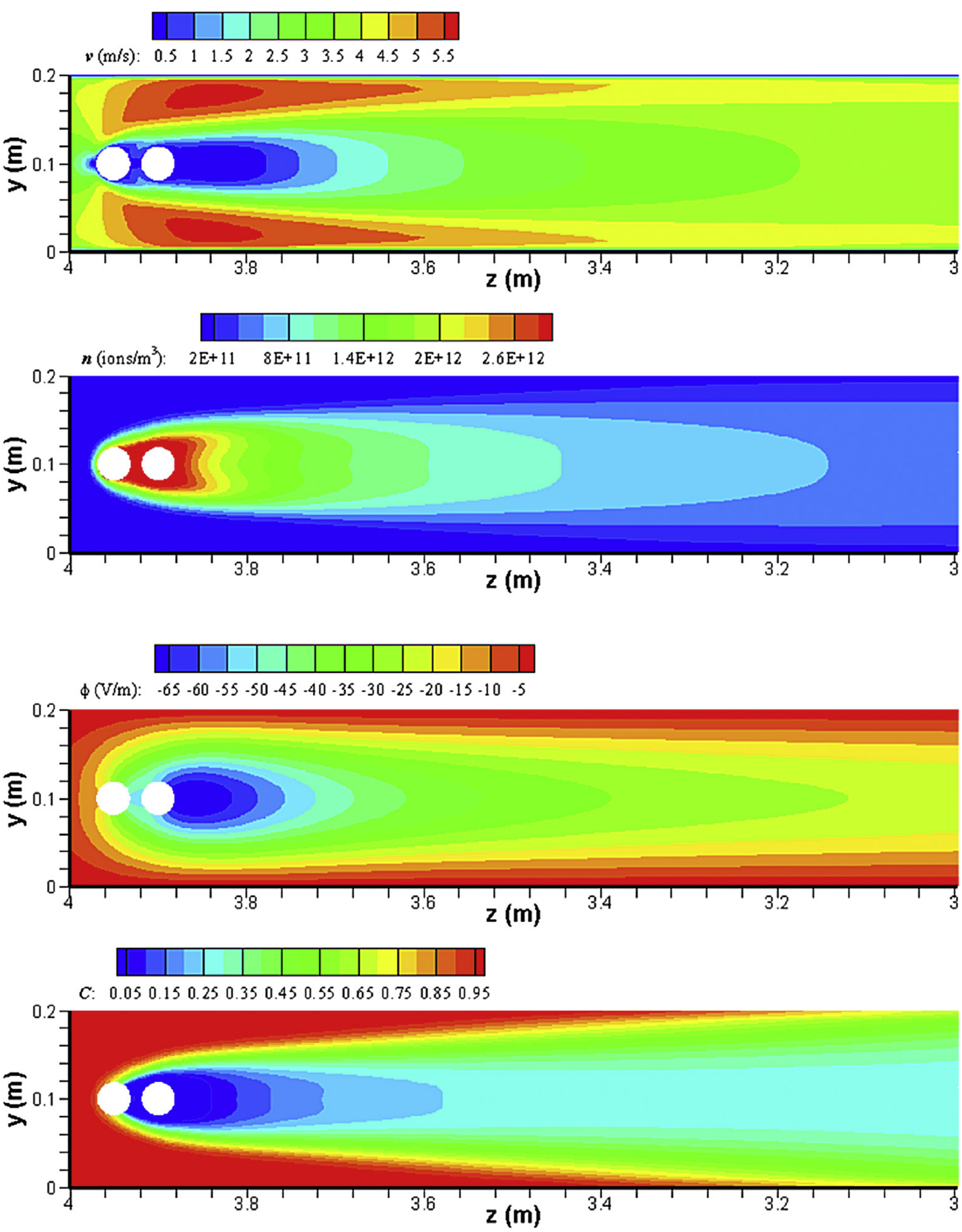


Fig. 8. The contour of velocity, negative ions, potential and bacteria for air velocity 3.5 m/s (2H).

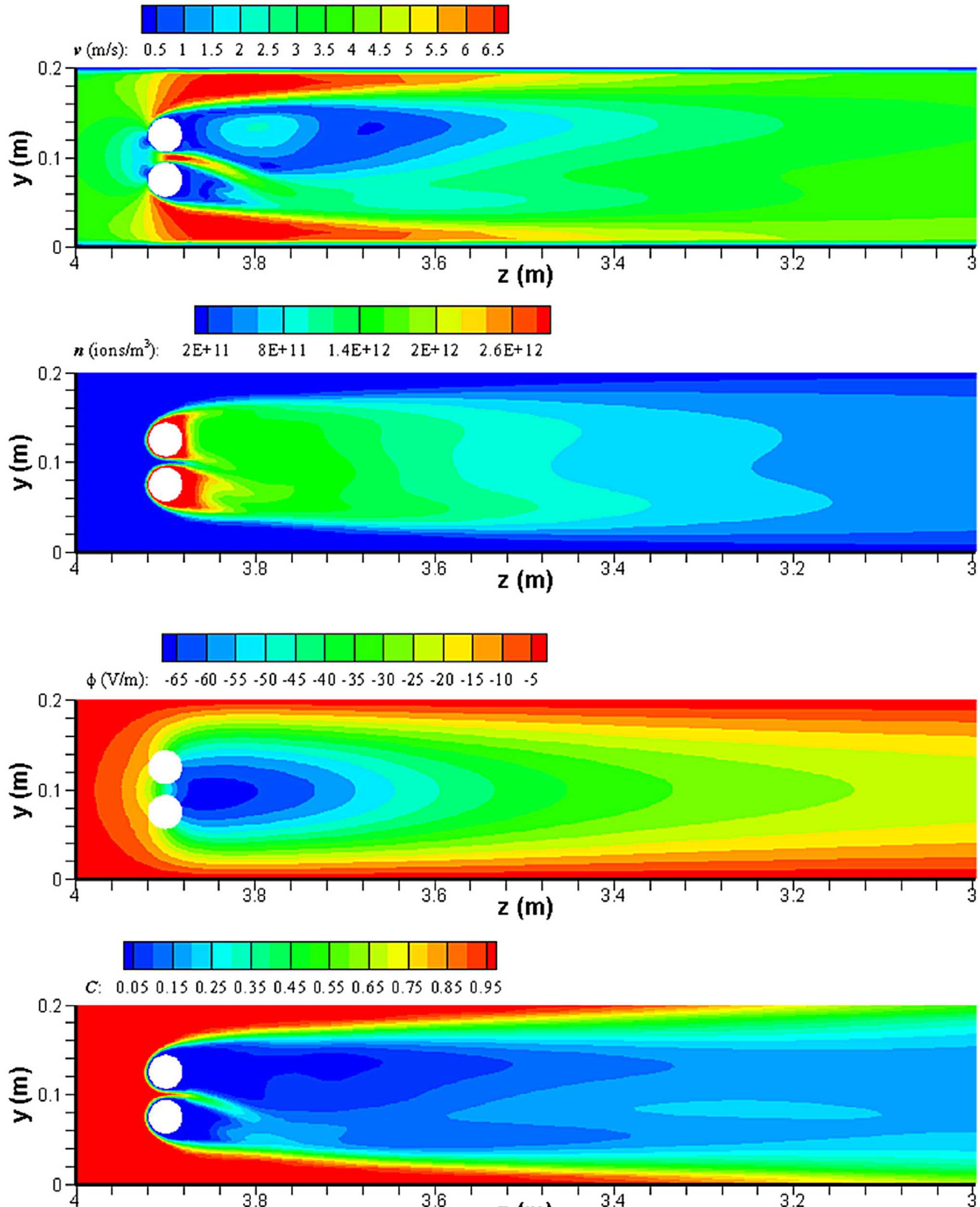


Fig. 9. The contour of velocity, negative ions, potential and bacteria for air velocity 3.5 m/s (2 V).

of ventilation. This system is very common in hospital wards, and in fact for most air-conditioned buildings. The dimensions for air inlet and the outlet was 0.3 m × 0.3 m. The outdoor airflow rate (fresh air) was 10% of total airflow rate. The bacteria were released from the return vent and transported to the duct system and finally dispersed into the ward. Three typical cases were studied in this section: one plasma unit installed near the air inlet (denoted as case 1); one plasma unit installed near the air return grille (case 2) and plasma units were both installed at the inlet and return grilles (case 3). The initial condition for bacteria was assumed to be unity in the return grille and the ward was considered filled with bacteria (the initial value was unity). Fig. 10 illustrates the three scenarios for the room. The ACH was 3 h^{-1}. The boundary conditions were similar to simulate the negative ions as well as bacteria in a ventilation duct system as described in Section 2. The hexahedral structured mesh was used and the number of grids was 1.5million. The transient simulation was conducted throughout the whole process with time step 0.1 s (another 200 s was calculated after the indoor airflow reached stable and constant).

Table 2
The disinfection efficiency for different configurations (3.5 m/s).

	One plasma unit	Two horizontal units	Two vertical units
Simulation	43%	31.6%	47%
Experiment	40%	28%	51%

Fig. 11 gives the average bacteria concentration from the outlet with time in different installation configurations. It is noted that the initial condition in duct and room was assumed filling with bacteria. The simulation results show that the bacteria are disinfected

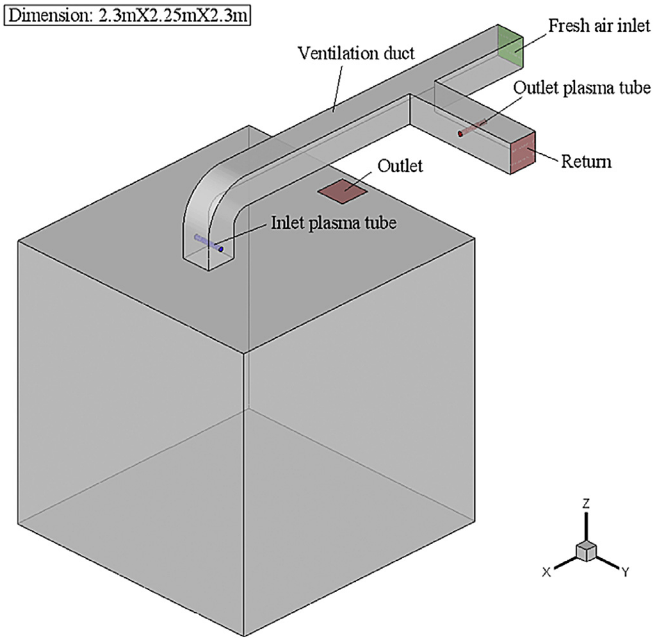


Fig. 10. Configuration of small ward.

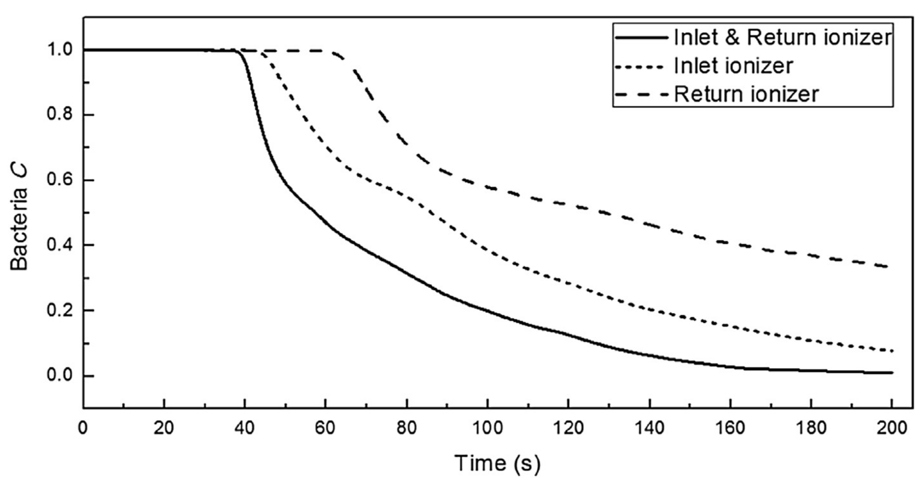


Fig. 11. The outlet concentration of bacteria against time in different installation configurations.

when negative ions are presence. The disinfection efficiency depends on the number of negative ions. The concentration of bacteria decreases with time from 1 to 0.4, 0.1 and 0 for case1, case 2 and case 3 after 200 s calculation. The case 3 is the best compared with case 1 and case 2 since the bacteria are disinfected from indoor space with minimum time.

5. Conclusions

This paper developed a numerical methodology based on disinfection performance of the cold plasma technique to estimate the distribution of bacteria in a ventilation duct. A full-size, experimental ventilation ductwork was designed and set up to measure one-pass inactivation efficacies of a cold plasma installation under various practical environmental conditions. The *Escherichia coli* (ATCC 10536) was selected as an inactivation sample in this paper to conduct the numerical simulation. The airflow, electrical field, and negative ion distribution were obtained with the Eulerian method, a novel semi-empirical formula based on experiment results were applied to simulate the distribution of bacteria. The impacts of electrical force and drift flux model were considered in momentum and bacteria transportation equation. The negative ion distribution predicted by the present model agrees well with the experimental results. The inactivation efficiency against *E. coli* ranges from 30% to 50%.

In addition, Tube installation arrangement for two tubes was also investigated: two horizontal and two vertical plasma units. It is observed that vertically arranged configuration give higher inactivation efficacy than that of horizontally arranged tubes. In real applications, it is recommended that the plasma tube should be deployed near both the inlet and return outlet for a better inactivation efficacy against airborne bacteria especially in hospitals.

In terms of modeling methodology, it is assumed that the disinfection mechanisms of plasma on airborne microorganisms are associated with the presence of negative ions, thus, the disinfection mechanism of microorganisms was simplified by considering the effect by negative ions only. A semi-empirical drift flux model was developed to model bacteria concentration in the presence of negative ions. The semi-empirical approach adopted here may expand to other airborne bacteria disinfection experiments.

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