Cold plasma disinfection efficacy against different airborne bacteria in ventilation duct

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Abstract

Conventional solutions for improving indoor microorganism levels are better filtration or increasing dilution. Filters with minimum efficiency reporting value (MERV) ratings from 6 to 9, are often considered as medium-grade filters used frequently in ventilation duct systems, and are effective for removing super micron particles but not for small bacteria and viruses less than 1 micrometer in size. An alternative engineering approach cold plasma technology was tested in this study.

A 9 m long, 200 mm square duct was designed and set up to measure one-pass disinfection efficacies of a cold plasma installation under various practical environmental conditions. Five types of microorganisms, Escherichia coli, Pseudomonas alcaligenes, Staphylococcus epidermidis, Micrococcus luteus and Serratia marcescens, were chosen and tests were conducted at four airstream velocities, ranging from 2 to 7 m/s, and two different relative humidity (R.H.) levels. The inactivation efficacies for the first three types of bacteria varied from 20% to 70%. It is interesting to note that the inactivation efficacy increased with velocity. No detectable inactivation effect was found for Micrococcus luteus and Serratia marcescens. The inactivation efficacy at 90% R.H. dropped to 10% of the value measured at 55% R.H. When compared with data from systems using conventional fibrous filters, the pressure drop measured across the plasma unit was very small. Our experiments showed that cold plasma technology has high potential to be used as an energy-efficient method for

disinfection. Limitations of application are also discussed.

Keywords: cold plasma; inactivation; air conditional system; airborne pathogens; in-duct devices; indoor air quality

INTRODUCTION

Airborne transmitted pathogen infection can cause various diseases of significant morbidity and mortality. In highly crowded and indoor enclosed environments such as healthcare facilities, large shopping malls, commercial buildings, and public buildings, indoor pathogens shed from human may be transmitted and dispersed through HVAC systems, and may lead to cross-infections.

The minimum efficiency reporting value (MERV) is a standard index, with ratings from 1 to 16, used to rate the effectiveness of air filters for particles in the range of 0.3 μm to 10 μm in size. Filters with MERV ratings from 6 to 9, are often considered as medium-grade filters used frequently in ventilation duct systems, and are effective for removing supermicron particles but not for small bacteria and viruses less than 1 micrometer in size (Lu et al., 2009).

For many general premises, it is not economical to use high efficiency particulate air (HEPA) filters (Parham and Brent, 2013). Therefore, development and application of new technologies for effective disinfection of airborne pathogens for general use, at lower costs and with sustainability in energy resources are needed to provide cleaner and healthier environments. Active “in-duct” system is one of the few technologies for disinfection of airborne pathogens used in ventilation systems. They have been available on the market and utilized for several decades. Due to their low pressure drop characteristics, UVGI and corona-type pin ionizers are the two most popular installations.

Gas plasma, the fourth state of matter, is formed when a gas is ionized. Only until recently, advancement in plasma source technology allows the generation of plasma in near ambient pressure and temperature. It is called cold plasma or atmospheric pressure plasma and is

generated by applying a modulated electric field through a pair of electrodes to air molecules. For in-duct applications, one or multiple tube-like plasma generators are inserted into a ventilation duct. The advantages of such systems include high air flow handling rates, very low maintenance cost and low running cost. Hence they are suitable for use in existing buildings, requiring only minimal renovation work.

Our study aims to evaluate the disinfection effectiveness of cold plasma units on airborne pathogens commonly found in hospitals that has implications for practical applications, and identify the effects of airstream velocity and R.H. on the disinfection effectiveness. Pressure drops across the unit were also measured and compared with those across conventional filters. The disinfection performance of the plasma unit was characterized by the one-pass disinfection efficacy. This will facilitate cross comparison with the conventional filter approach.

MATERIALS AND METHODS

Organisms of biosafety level one of different sizes, as surrogates of those commonly found in bioaerosols, were selected (Versalovic et al., 2011): gram positive cocci - *Micrococcus luteus* (~ 1 μm) (ATCC 4698) and *Staphylococcus epidermidis* (~1 μm) (ATCC 12228), and gram negative bacilli - *Escherichia coli* (~1×3 μm) (ATCC 10536), *Serratia marcescens* (0.5×3 μm) (ATCC 6911), and *Pseudomonas alcaligenes* (~0.7×3 μm) (ATCC 14909).

The parameters were chosen with respect to commonly encountered practical situations. Four speed settings: 2.0, 3.5, 5.0 and 7.0 m/s were selected from within the range of airstream velocities commonly used in air conditioning systems. The Reynolds numbers were between

26,500 and 92,700, corresponding to turbulent flow.

The system was tested at two R.H. levels, 50-60% and 85-90% (represented as low and high R.H. respectively), to simulate the substantial variations of relative humidity conditions throughout the year in many Southeast Asian countries. The former is typical of indoor air-conditioned condition while the latter is typical of the outdoor air for summer months in those countries.

A 9-m long, 200 mm × 200 mm modular galvanized steel ductwork system was designed and fabricated. The sizes and airflow characteristics were resembled to practical scenarios. Figure 1 shows the schematic of the experimental setup. The ductwork was housed in an air-conditioned laboratory. The room temperature and the R.H. were maintained at stable conditions of 23°C ± 2°C and 55% ± 5% respectively. The ductwork consisted of 5 major galvanized steel modules and a tempered-glass section. The length of module ranged from 800 to 1200 mm. The pathogens were atomized and aerosolized by a 24-jet nebulizer (Collision Nebulizer, BGI) with inlet pressure 275.8 kPa.

A cold plasma unit of 4 W was used for the study (102C, Plasma Air International). Two single-stage viable Andersen cascade impactors (N6, Thermo Scientific) were used to sample the airborne microbial concentration, one upstream at location "A" (~54 cm from the plasma unit) and the other downstream at location "B" (~ 29 cm from the plasma unit). Each sampler was connected to a pump and the sampling volume was adjusted to 28.3 lpm.

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.

A multi-functional IAQ meter (9555, Velocicalc, TSI) incorporating a portable thermal anemometer (±3%) was used to measure the airstream velocity in the duct.

To evaluate the additional pressure drop due to the plasma unit, an IAQ meter (9555, TSI), which could be used as a digital manometer (±1Pa), was used to measure differential static pressure upstream and downstream across the unit. The measuring locations "C" and "D" are shown in Figure 1.

The R.H. was measured by an electronic hydrometer (SK-L200TH, SATO) with accuracy (±2%) at location "C". As ozone would possibly generate and had been a concern as a harmful by-product, O_3 was measured with a gas monitor (Series 500, Aeroqual) at location "X" (±10%).

PROCEDURE

For each type of microorganism tested, at each relative humidity condition, the experiment was performed in at least quintuplicate. The speed of the fan was gradually increased and the anemometer reading was monitored until airstream velocity reached 2.0 m/s. The plasma unit was warmed up for 30 minutes prior to the start of the experiment. The microorganisms were nebulized and fed to the buffer chamber for 10 minutes before sampling. The two pumps were switched on simultaneously. The sampling time was set to 106s, corresponding to total sampled air volume of 50L. It was chosen to avoid the upstream CFU counts overloading the impactor and too few the downstream counts after passing through the unit. The procedure was repeated at velocities 3.0, 5.0 and 7.0 m/s respectively.

Under low R.H. condition, no special treatment was taken for the bacteria-laden airstream. Filtered air-conditioned air was drawn from the laboratory and mixed with airborne bacteria generated by the 24-jet collision nebulizer. Under high R.H. condition, an additional six-jet collision nebulizer (BGI), placed inside the buffer chamber and filled with deionized water, was used to increase the humidity of the airstream (Fig. 1). To stabilize the airstream R.H., the nebulizer was operated for at least 10 minutes before the experiment started.

The inactivation efficacy of the cold plasma unit is defined as

$$\eta = 1 - \frac{\mathrm{CFU}_{down}}{\mathrm{CFU}_{up}} \quad (1)$$

where $\mathrm{CFU}_{\mathrm{down}}$ and $\mathrm{CFU}_{\mathrm{up}}$ are the colony forming units measured at the downstream and upstream positions respectively.

RESULTS

Pressure Drop

The results of the pressure drop against airstream velocity are shown in Fig. 2. The pressure drop readings were 2.6 to 7.2 Pa for velocities at 3.7 and 6.5 m/s respectively.

Effects of the Pathogens

The inactivation efficiencies of the cold plasma unit, η, for the 5 types of bacteria measured at 7 m/s are shown in Fig. 3. It is noted that cold plasma is effective for *E. coli*, *Staphylococcus epidermidis* and *Pseudomonas alcaligenes*.

Hence, only those three types of bacteria that responded to the cold plasma inactivation were chosen for further investigation.

Ion Concentration

The level of negative ion concentration measured at position X was found to increase with increased airstream velocity (Fig. 4). The first five data points (1.3, 2, 3, 3.5, 4 m/s) were utilized to formulate a best linear-fitted line shown in the figure. Consistent with the stated specification of the negative ion counter, high correlation between the ion intensity and the airstream velocity was observed up to 4m/s ($R^2 = 0.97$).

Influence of Airstream Velocity

The inactivation efficacy of *E. coli*, *Staphylococcus epidermidis* and *Pseudomonas alcaligenes* increased with increased airstream velocities, as shown in Fig. 5a to 5c. When the airstream velocity was increased from 2 m/s to 7m/s, the mean ± SD of inactivation efficacy for *E. coli*, *Staphylococcus epidermidis* and *Pseudomonas alcaligenes* increased from 31.1 ± 10.2 % to 72.2 ± 11.9 %, 19.1 ± 10.9 % to 66.3 ± 25.3 %, and 34.4 ± 11.3 % to 56.4 ± 11.0 % respectively.

That the inactivation efficacy increased with airstream velocities appears to be counterintuitive. It seems that this could not be explained based on a simple linear combination of an increase in number of negative ions and a decrease in residence time associated with increased airstream velocities.

Effects of Relative Humidity

E. coli and *Staphylococcus epidermidis*, as the two types of microorganisms most susceptible to disinfection by the cold plasma unit according to our findings above, were chosen for further experiments at two different levels of relative humidity with airstream velocity 7 m/s.

The levels of negative ion concentration and the results are shown in Table 1. When the relative humidity was increased from 52% to 81%, the inactivation efficacy for *E. coli* and the negative ion concentration decreased by 87% and 92% respectively. Similarly, the inactivation efficacy for *Staphylococcus epidermidis* and negative ion concentration decreased by 58% and 90% respectively when the relative humidity was increased from 62% to 81%. The inactivation efficacy for *Staphylococcus epidermidis* was less affected by the increased relative humidity as compared to the effects observed for *E. coli.*

DISCUSSION

There are a number of factors affecting the selection of in-duct filtration devices, including running costs, initial costs, expected performance, volumetric airflow rates, airstream velocities, contaminant levels, safety of operation and the nature of sources, and so on. In this work we focused on the pressure drops, the airstream velocities and the inactivation efficacies.

MERV is a standard used to rate the effectiveness of air filters for particles in the size range of 0.3 μm 10 μm. In this size range, the filtration efficiencies are inversely correlated with particle sizes (Zuraimi and Tham, 2009): for the same filter, the lowest efficiency would be found at 0.3 μm. If a fibrous filter is used to reduce airborne microorganism level, MERV 16 is suggested and seemed to be effective (Parham and Brent, 2013). However, the disinfection efficacies for cold plasma are not related to the sizes of the bacteria, instead they depend solely on the susceptibility of the particular microorganism to plasma. If the pollutants for a particular indoor environment include both particles and microorganisms, the conventional filtration-based approach is more suitable as it can reduce pollutant concentration, regardless of their nature. However, if microorganisms are the only concern, cold plasma devices are

more energy-efficient for removing those targeted microorganisms. A very low pressure drops of 3-7 Pa had been measured for the cold plasma units in our study as compared to MERV 11 filter with a corresponding mean initial pressure drop of over 20 Pa (Zaatari et al., 2014), if the disinfection efficacy for cold plasma is assumed to be 50% for bacteria size ranging from 0.3 to 1 μm. Inferring from the current results, it can be seen that cold plasma technology is more energy efficient than that of conventional fibrous methods.

The most important feature for cold plasma installation is the emission of multiple reactive species, most of which have been confirmed to have disinfection capabilities. However, determination and identification of their reactive species require expensive instruments, such as optical emission spectroscopy (Fricke et al., 2012). In this work we have demonstrated that the disinfection efficacy for the cold plasma installation on certain types of microorganisms can be estimated by simply measuring the negative ion level.

CONCLUSIONS

In this work, an in-duct cold plasma device was tested in a full-scale ventilation duct. Five different bacteria were selected and three of them, *E. coli*, *Staphylococcus epidermidis*, *Pseudomonas alcaligenes*, showed significant susceptibility to cold plasma while the other two showed negligible susceptibility. Initial finding on disinfection efficacy which ranges from 20 to 70%, is encouraging. The disinfection efficacy increases with the level of negative ion concentration and the airstream velocity in the air duct system, and decreased with increased level of relative humidity.

Finally, before cold plasma can be applied widely, it would be desirable to further investigate three main aspects; the disinfection mechanisms of cold plasma on various pathogens, the disinfection efficacy on pathogens and finally the energy implication.

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Caption of the Figure and Table

Figure 1. Schematic of the experimental set-up.

Figure 2. Pressure drop across the plasma unit. Error bars denote the standard deviation of repeated samples.

Figure 3. The inactivation efficacy of cold plasma for the 5 tested microorganisms at air velocity of 7 m/s.

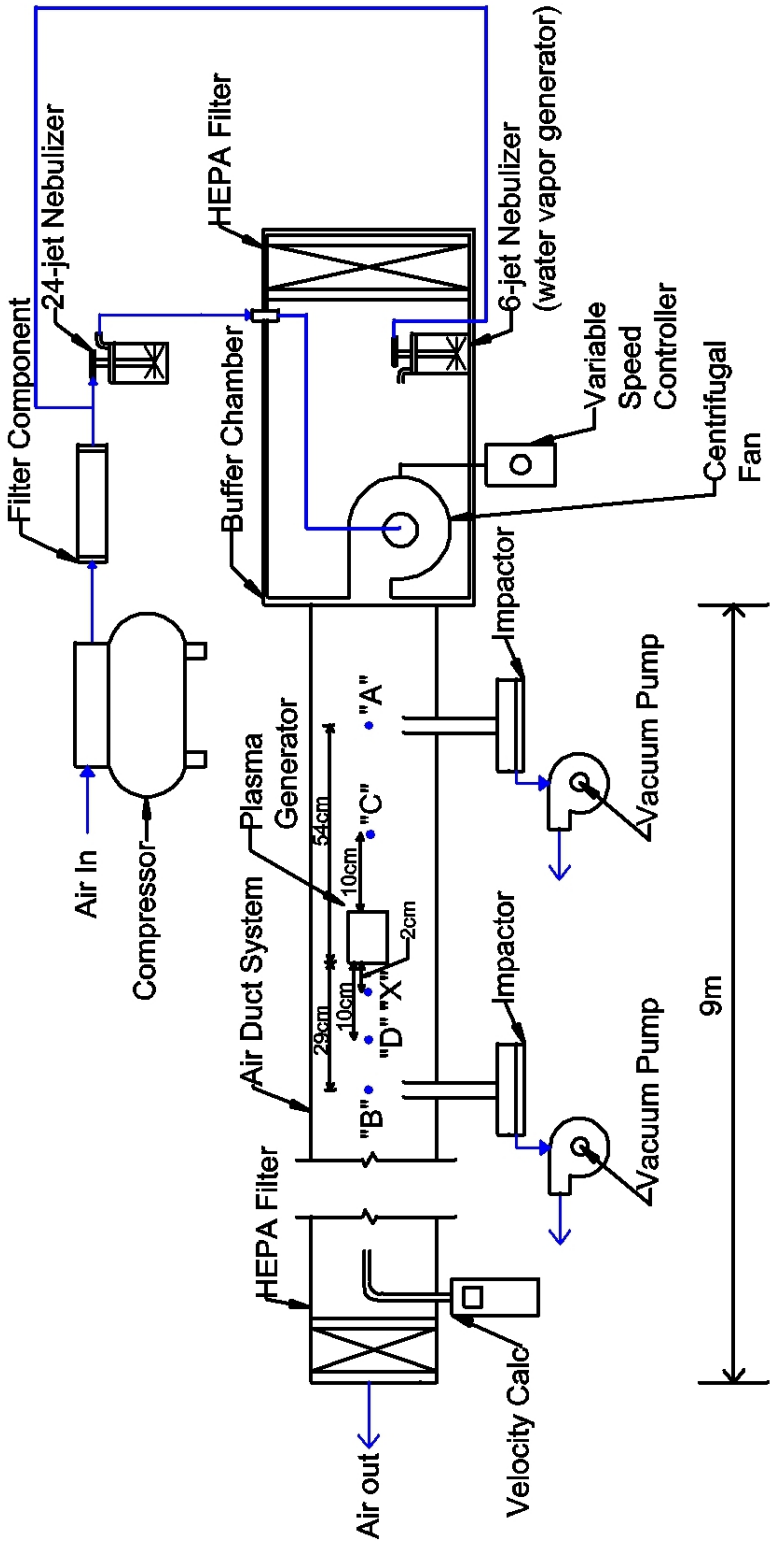
Figure 4. Correlation between the negative ion concentration and airstream velocity.

Figure 5. The inactivation efficacy of cold plasma at various air velocities for a) *E. coli*, b) *Staphylococcus epidermidis*, and c) *Pseudomonas alcaligenes*. Error bars denote the standard deviation of repeated samples.

Table 1. The influence of relative humidity on inactivation efficacy.

Supplementary Information:

Micrographs of the scanning electron microscopic analysis of *E. coli* after 15s exposure to a) air and b) cold plasma.



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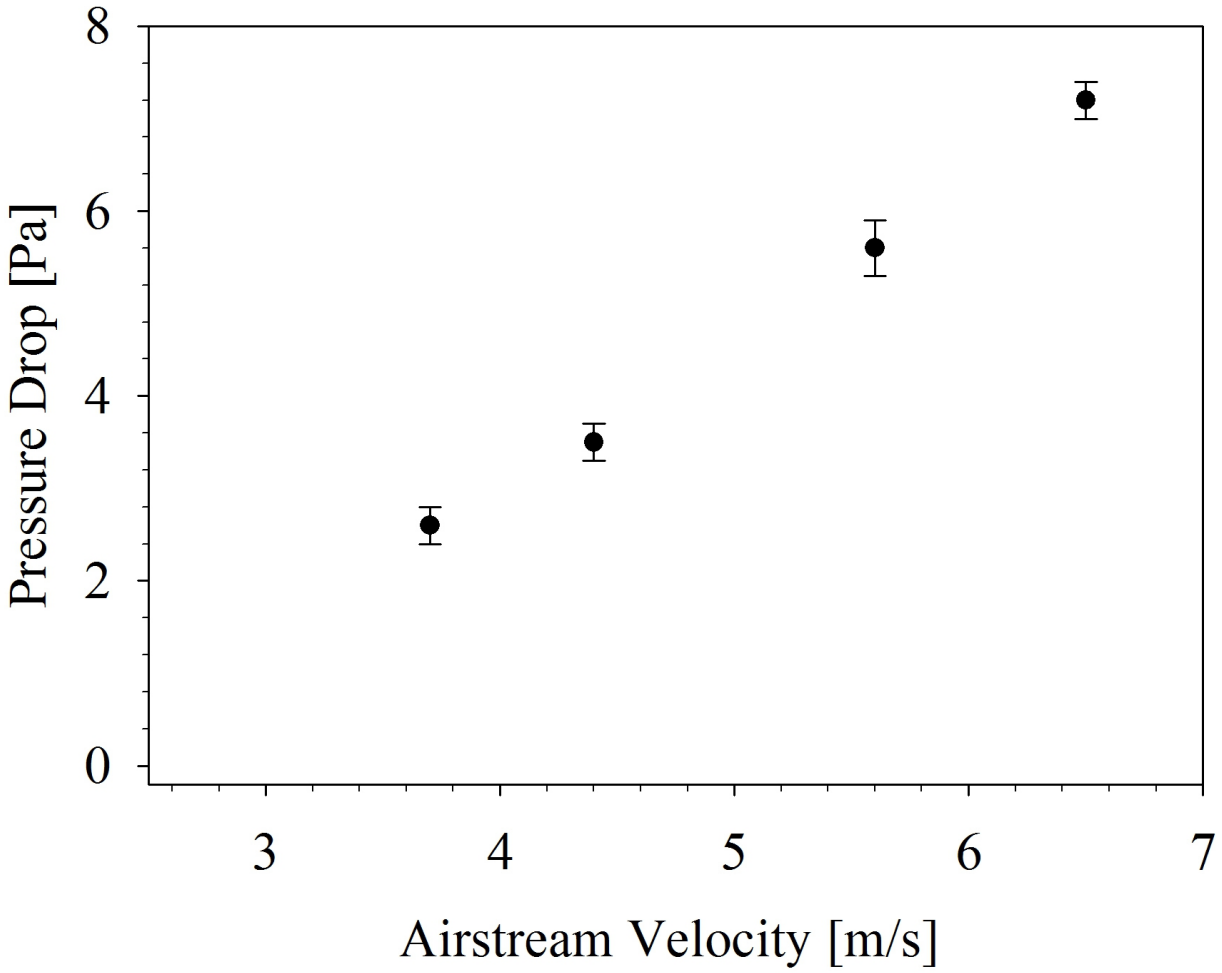
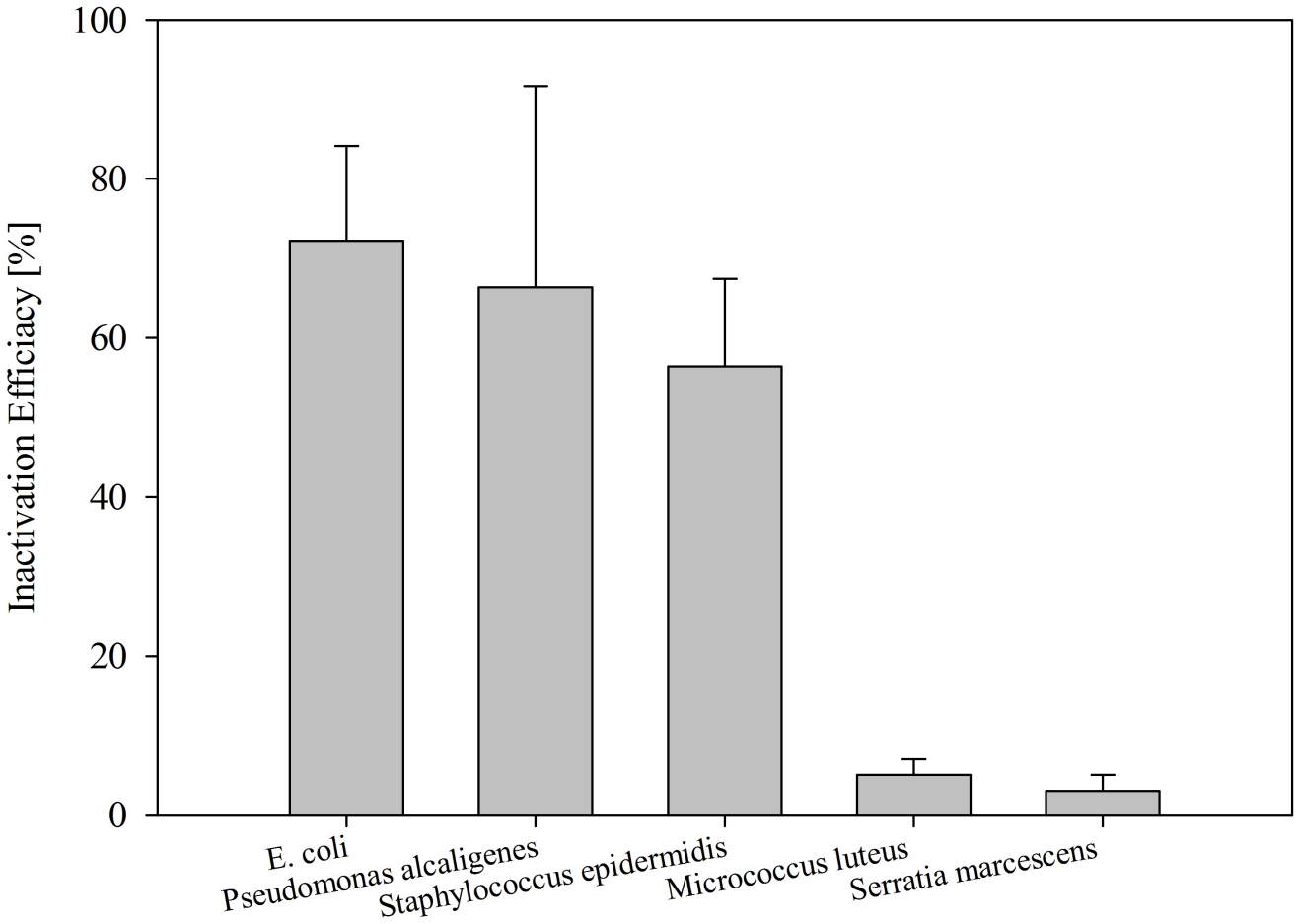


Figure 2. Pressure drop across the plasma unit. Error bars denote the standard deviation of repeated samples.



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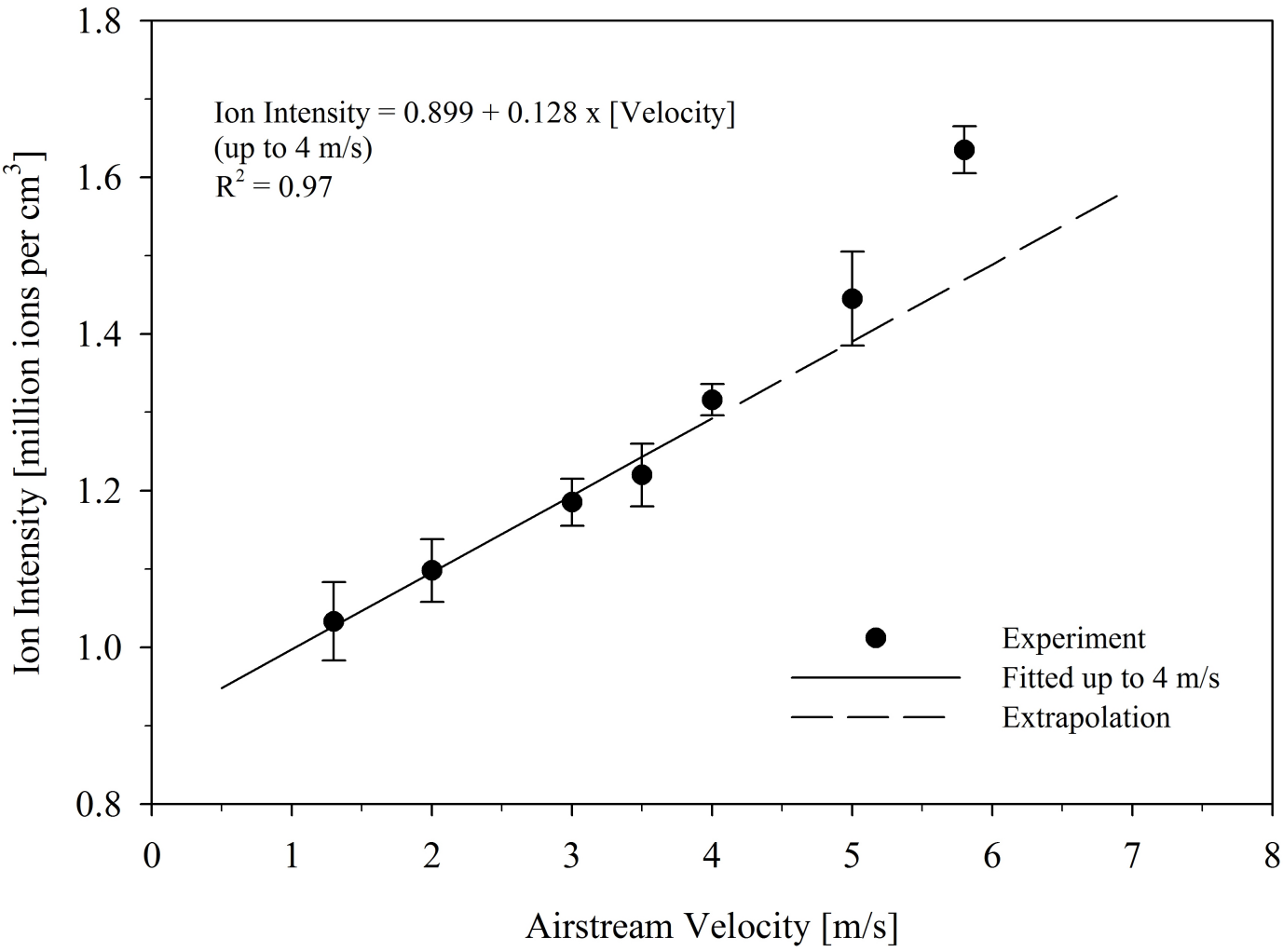
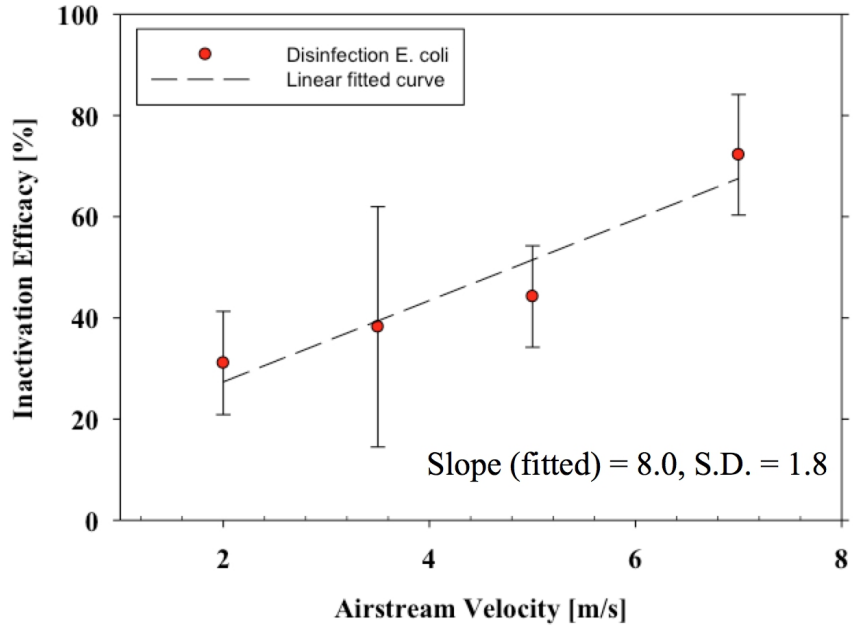
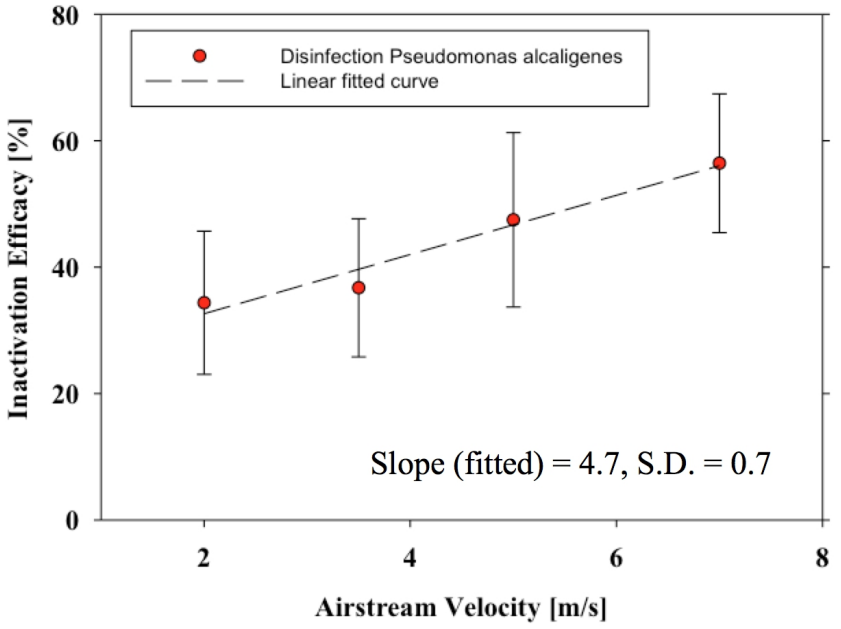


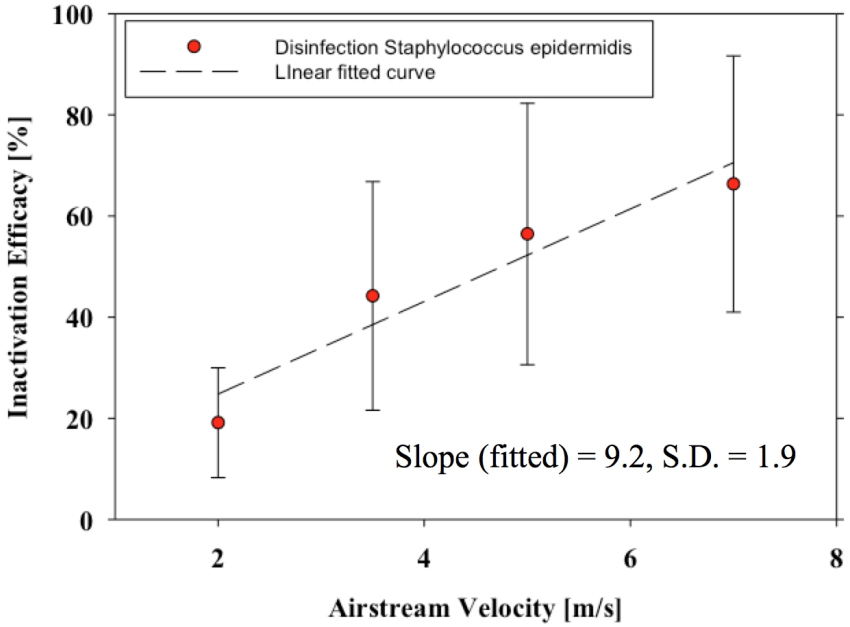
Figure 4. Correlation between the negative ion concentration and airstrea



(a)



(c)



(b)

Figure 5. The disinfection efficacy and disinfection efficacy normalized by ion intensity of cold plasma at various air velocities for a) *E. coli*, b) *Staphylococcus epidermidis*, and c) *Pseudomonas alcaligenes*. Error bars denote the standard deviation of repeated samples.

Microorganisms	Negative ion Concentration ($\times 10^6/cm^3$)	Relative humidity (%)	Inactivation efficacy (%)
E. coli	1.881	52	72.2
	0.150	81	9.2
Staphylococcus epidermidis	1.881	62	66.3
	0.180	81	27.7

Table 1. The influence of relative humidity on inactivation efficacy.