Use of Plasma Technology for Air Disinfection in Buildings

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Abstract

Since the 1970s, research in indoor air quality evolved from preventing occupational diseases in the industrial workplace to improving the air quality of indoor environments to cure the 'sick building syndrome', which is exacerbated by energy conservation through reducing the amount of outside air supply. Biological contaminants are of particular concerns and an effective IAQ disinfection system is vital for preventing the spread of airborne diseases.

The effectiveness of an air disinfection system depends on the disinfection capability of the air sterilization device and the air circulation design of the system. This article describes methods to determine and cross compare disinfection capability of air sterilization devices and provide examples of how to design a best fit disinfection system in buildings.

Introduction

In recent years, outbreaks of airborne diseases (such as Severe Acute Respiratory Syndrome (SARS), Avian Influenza and Swine Flu) over the world caused thousands of death [1, 2] and raised governments and public concerns. Transmission of infectious diseases through inhalation of airborne bacteria and fungal spores is a public health problem that poses substantial risks to health care workers and the public.

The pandemic outbreak of SARS, which caused thousands of death [2], highlighted the fast and wide spread of airborne virus and the needs to prevent and control the spread of the virus in indoor environment [3]. The risk of major pandemics is serious as reflected in the World Health Organization (WHO) announcement that while the H1N1 influenza virus has moved into the post-pandemic period, localized outbreaks of various magnitudes are likely to continue. [4]

A number of technologies, such as HEPA filter [5], UV [6], Ozone Generator [7, 8], Ionizer [8] and Ion Cluster Technology [9], are available to tackle indoor air quality (IAQ) problems, However, most of these technologies (and devices based on these technologies) are not sufficiently effective to stop the spread of airborne diseases.

Over the years, plasma technology has been developed for use in many kinds of applications, such as plasma display panel [10], surface modification (thin film processing: etching) [11], chemical reaction (generation of radicals) [12] and plasma health care (tissue texturing, sterilization) [13]. Recently, it has also been successfully developed for air disinfection. A number of studies have shown that plasma has high sterilization power [14, 15, 16] and is suitable for air disinfection [17, 18].

Plasma Generation

Plasma denotes the '4th state of matter', a state beyond the gas state, in which a significant portion (or all) of the gas particles are ionized. In other words, plasma is a mixture composed of freely moving ions, electrons, and neutral gas. Ionization can be induced thermally or excited by electromagnetic field [19]. While plasma is electrically neutral, it is conducting. For many situations, the conductivity of a plasma may be treated as infinite. The conducting property leads to wide range of plasma applications.

Air Disinfection Efficacy Rate

The ability of a device to perform disinfection is often presented in terms of disinfection efficacy. However, disinfection efficacy itself contains no information on how long it takes to attain the level of efficacy. Air sterilization requires destruction of pathogens within a short time. (A sick person introduces germs into the air every second as he breathes). Thus, if the destruction rate is lower than the generation rate, germs will be accumulated inside a room to ruin the air quality. The time element (i.e., disinfection speed) is necessary to reflect the ability of a device to provide air disinfection.

The efficacy of a disinfection device is obtained by comparing the Total Bacteria Count (TBC) in terms of the number of colonies forming unit (CFU) of the sampled air with treatment (Testing Sample) and without treatment (Control Sample), i.e.,

$$\textit{Disinfecting Efficiency } \xi = \left(1 - \frac{CFU \text{ of the Testing Sample}}{CFU \text{ of the Control Sample}}\right) \times 100\%$$

There are two common methods to determine the disinfection efficacy, static measurement and dynamic measurement as depicted in the figure below.

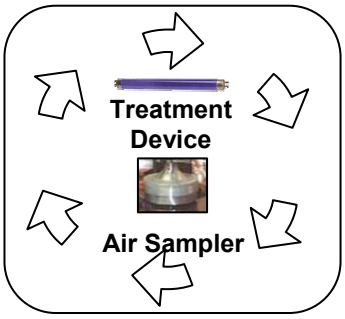

Fig. 1a: Static Measurement Method

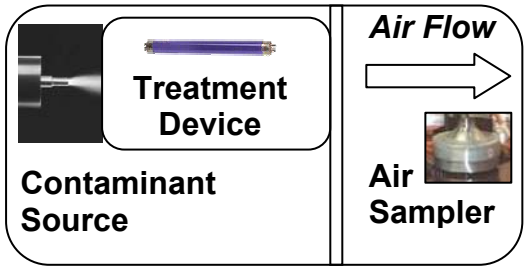

Fig. 1b: Dynamic Measurement Method

a. Static Measurement

After a certain amount of selected contaminants is injected in an enclosure, the air within the enclosure is circulated continuously through a treatment device. Air samples are taken at the beginning and after a period of time. Disinfection efficacy is obtained by comparing the CFU of these air samples.

b. Dynamic Measurement

In a dynamic measurement, contaminants are continuously injected to the air stream passing through a treatment device. Disinfection efficacy is obtained by comparing the air sampled upstream of the treatment device (i.e. air entering the device) and downstream of the device.

When the 'time' element is taken into consideration, both approaches can yield the disinfection efficacy rate. In the static measurement, the time behaviour of the contaminants (assuming a simple model of a uniform distribution of the contaminants within the enclosure) is given by:

$\frac{\partial n}{\partial t} = -\alpha n$ which gives $n = n_0 e^{-\alpha t}$

where n is the density of the contaminant, n_o the initial density of the contaminant (after injection and before treatment) and α the disinfection efficacy rate. In terms of the treatment time (Δt) and the efficacy ξ= 1 - n / n_0 , the disinfection efficacy rate is

$\alpha = -\ln(n / n_0) / \Delta t = -\ln(1 - \xi) / \Delta t$.

In the dynamic measurement, the behaviour of the contaminants (assuming a steady state one-dimensional flow for the contaminated air passing through the treatment device) is given by:

$u \frac{\partial n}{\partial x} = -\alpha n$ which gives $n = n_0 e^{-\alpha x / u}$,

where u is the air flow velocity. Therefore, the disinfection efficacy rate is $\alpha = -\ln(n / n_0) u / \Delta x$, where Δx is the length of the treatment devices through which air is treated. In terms of the treatment time (also known as residence time) $\Delta t = u / \Delta x$, the disinfection efficacy rate is

$\alpha = -\ln(n / n_0) / \Delta t = -\ln(1 - \xi) / \Delta t$.

Air Sterilization Effectiveness (Effect of ACH)

The removal of germs from contaminated air in an indoor environment depends on both the capability of an air sterilization device and the circulation of the air through the device. The terms often used for quantifying air circulation (e.g., in air conditioning system design) is the "Air Change per Hour" or ACH. It is a measure of the number of times air in a room will circulate through the disinfection system in an hour. The higher the ACH, the higher the air flow rate.

The desirable value of ACH depends on the type of usage of an indoor environment [20, 21]. General speaking, a higher ACH is required for an indoor environment, with i) more people in it; ii) presence of potential sources of contaminant (e.g. sick persons with infectious disease); and iii) occupants demanding cleaner environment (e.g. old persons, patients).

The design of an air disinfection system will therefore need to consider the disinfection rate of the device in conjunction with the size and usage of an indoor environment. The design principles can be demonstrated in a simple one-dimensional model, where the density of a contaminant (e.g. bacteria) varies along the length of a room having a cross-section area of A (i.e. height x width). As depicted in Figure 2 below, air flows (as

indicated by the arrows) from one side of the room to the other, then passes through a disinfection device and returns to the room.

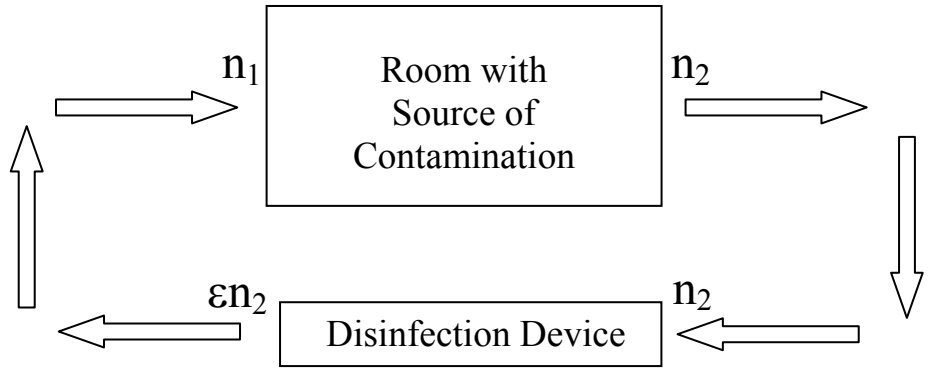

Figure 2: Configuration of the One-dimensional Model

a. One-dimensional Model of Room with Contamination Source

Assuming a steady state one-dimensional flow, the behaviour of the contaminant density (e.g. bacteria counts per unit volume) is described by:

$$u\frac{\partial n}{\partial x} = S - \alpha n$$

where n is the contaminant density
u the air flow velocity in the room
S the source of contaminant (generation per unit volume per second)
α the natural decay rate of the contaminant

The solution of the differential equation with the contaminant density being n_1 at the starting point of the room ($x = 0$) is:

$$n = \frac{S}{\alpha}\left(1 - e^{-\alpha x/u}\right) + n_1 e^{-\alpha x/u}$$

At the other side of the room, the contaminant density denoted by n_2 is

$$n_2 = \frac{S}{\alpha}\left(1 - e^{-\alpha \Delta x/u}\right) + n_1 e^{-\alpha \Delta x/u}$$

where Δx is the length of the room.

After passing through the disinfection device, the contaminant density is reduced to εn_2 where ε represents the single-pass reduction ratio of the device and therefore $1-\varepsilon$ the single-pass disinfection efficacy of the device. The air, having been disinfected, circulates back to the room. In a steady state $n_1 = \varepsilon n_2$ and n_2 can be written as:

$$n_2 = \frac{S}{\alpha}\frac{(1 - e^{-\alpha \Delta x/u})}{(1 - \varepsilon e^{-\alpha \Delta x/u})} = \frac{S}{\alpha}\frac{(1 - e^{-\alpha V/W})}{(1 - \varepsilon e^{-\alpha V/W})}$$

$$= \frac{S}{\alpha}\frac{(1 - e^{-\alpha/\eta})}{(1 - \varepsilon e^{-\alpha/\eta})}$$

where V is the volume of the room;
W the air volume flow rate; and
$\eta = W/V$ the air change rate (such as ACH)

Natural Decay of Contaminant

In the absence of contamination sources (for example, outside the operating hours of the room) and air circulation flow, the contaminant density (assuming no spatial variation) can be described by

$$\frac{\partial n}{\partial t} = -\alpha n$$

The contaminant density during the non-operating hours of a room will follow an exponential decay from the steady state concentration (n_0) generated during the operation hours, i.e.,

$$n = n_0 e^{-\alpha t}$$

For instance, if the natural decay time is $1/\alpha = 2$ hours, the contaminant concentration in the room after 6 hours of non-operating period will be reduced naturally to $n/n_0 = e^{-3} = 0.05$

b. One-dimensional Model of the Disinfection Device

Inside the disinfection device, there is no source of contaminant. The behaviour of the contaminant density is described by:

$$u'\frac{\partial n'}{\partial x'} = -\alpha' n'$$

where n' is the contaminant density inside the disinfection device
x' the distance along the disinfection device
u' the air flow velocity in the disinfection device
α' the disinfection efficacy rate of the disinfection device

The solution of the equation, with the contaminant density being n_2 at the device entrance ($x' = 0$), is:

$$n' = n_2 e^{-\alpha' x'/u'}$$

At the disinfection device outlet, the contaminant density is reduced to

$$\varepsilon n_2 = n_2 e^{-\alpha' \Delta x'/u'} = n_2 e^{-\alpha' \Delta t'}$$

i.e. $$\varepsilon = e^{-\alpha' \Delta x'/u'} = e^{-\alpha' \Delta t'}$$

where $\Delta x'$ is the length of the disinfection device and
$\Delta t'$ the residence time of the air staying inside the disinfection device

The above analysis shows that the single-pass reduction ratio ε is governed by the device disinfection rate and 'residence' time of air passing through the device.

Solutions without Disinfection

In the absence of a disinfection device (i.e., there is no device to reduce contaminant density or when the disinfection function of the device is switched off), $\varepsilon = 1$ and the steady state concentration of the contaminant is

$$n_0 = \frac{S}{\alpha}$$

This reflects the balance between contamination generation (represented by the source term S) and the natural decay of the contaminant in the room (represented by the natural decay rate α).

Solutions with Disinfection

According to the one-dimensional analysis above, the steady state performance of a disinfection system is given by:

$$\frac{n_2}{n_0} = \frac{(1-e^{-\alpha/\eta})}{(1-\varepsilon e^{-\alpha/\eta})}$$

with n_2 being the contaminant density in the presence of disinfection (i.e., with disinfection device operating) and n_0 the contaminant density in the absence of disinfection (i.e., prior to disinfection device in operation).

For a perfect disinfection device, the single-pass disinfection efficacy is 100% (i.e., $\varepsilon = 0$). In this case, the contaminant density reduction at the 'exit' end of the room is

$$n_2 / n_0 = 1 - e^{-\alpha/\eta}$$

This is the lowest contaminant density achievable in the presence of contaminant source. For example, if the natural decay time is 2 hour (i.e., $\alpha = 0.00014\ s^{-1}$) and the number of Air Change per Hour is 6 (i.e., air change rate $\eta = 0.00167\ s^{-1}$), the contaminant density reduction is $n_2 / n_0 = 0.08$ (or equivalently the removal ratio is $1 - n_2 / n_0 = 0.92$). This is the best attainable with the given natural decay and ACH parameters. Under these conditions, a perfect disinfection device can reduce the contaminant density in the room to 8% of the original level (i.e. 92% of the contaminant is eliminated). Figure 3 below shows the variation of the contaminant density ratio n_2 / n_0 against the disinfection ability of a device expressed in terms of ε, the single-pass reduction ratio of the device.

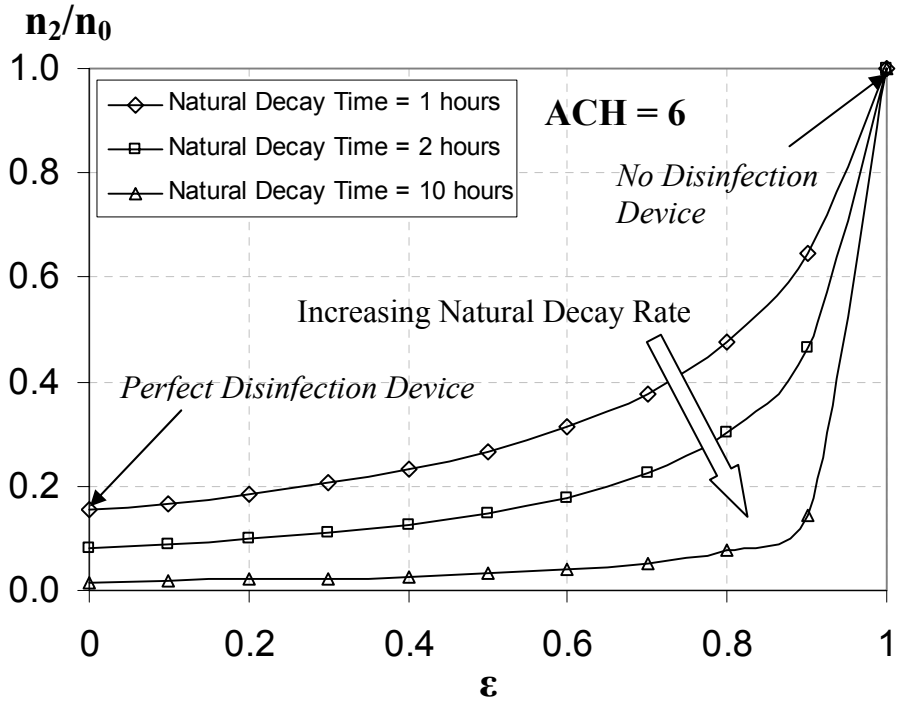

Figure 3: Effect of Device Single-pass Reduction Ratio (ε) on Room Contaminant Density n_2 / n_0

A disinfection UV lamp typical can achieve 95% efficacy with an exposure time of some 5 minutes for the more vulnerable types of bacteria (and much longer for the tougher micro-organisms such as spores), which translates to $\alpha' = 0.01\, s^{-1}$ [see, for example, 22 and therein]. Taking a disinfection rate of a UV disinfection system as $\alpha' = 0.1\, s^{-1}$ and a residence time of air passing through the device $\Delta t' = 16\ ms$, the single-pass reduction ratio ε is

$$\varepsilon = e^{-0.0016} = 0.99$$

Plasma technology has a much higher disinfection efficacy rate. Our measurements showed that plasma technology can achieve over 95% efficacy within 16 ms. This translates to a disinfection efficacy rate of 180 s^{-1}. Taking a reference design of the plasma disinfection device with $\alpha' = 100\, s^{-1}$ and $\Delta t' = 16\ ms$, the single-pass reduction ratio ε is

$$\varepsilon = e^{-1.6} = 0.20$$

The effect of ACH value on the performance of a air disinfection system (in terms of n_2 / n_0) is shown in Figure 4, assuming different natural decay times from 1 hour to 10 hour.

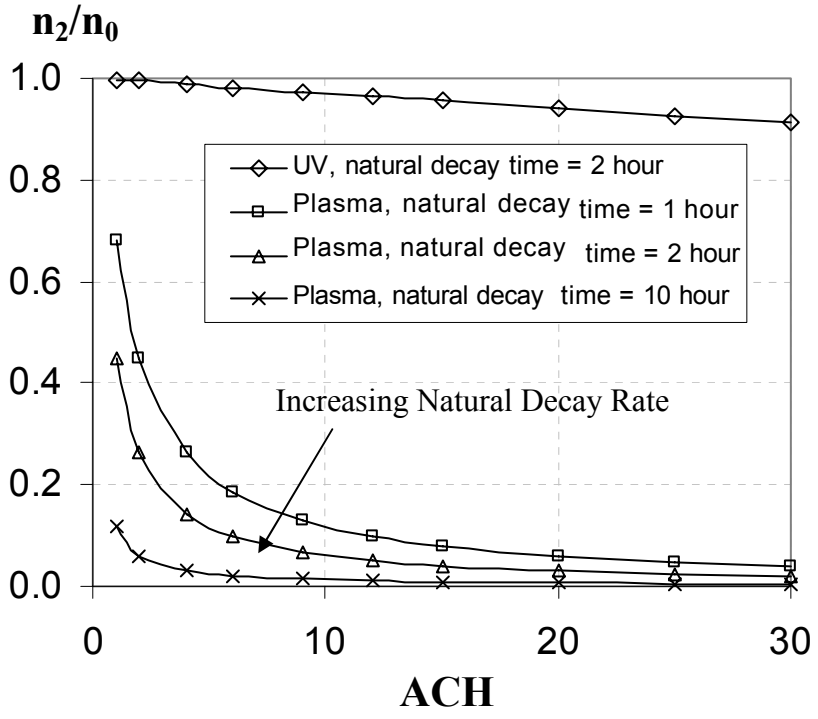

Figure 4: Effect of Air Change Rate (ACH) on Room Contaminant Density n_2 / n_0

The plot shows an 'exponential' drop of n_2 / n_0 with ACH, which is more discernable in the cases of plasma disinfection system. For the plasma cases, contaminant reduction at level of $n_2 / n_0 < 0.2$ is obtainable with ACH > 6. A higher ACH will lead to better disinfection effectiveness (i.e. lower n_2 / n_0). Since a higher ACH value will cause higher power consumption in air circulation, a disinfection system should be designed with

carefully selected ACH values to balance the required disinfection effectiveness against the power consumption.

For the basic UV system with $\alpha' = 0.1\ s^{-1}$, the system performance also improves with ACH. However, contaminant reduction (n_2 / n_0) cannot reach values below 0.9 even with a high ACH value of 30. Such system will not be effective in sustaining a good indoor air quality.

The above analysis indicates that air disinfection system design should take into consideration of:

- Air disinfection efficacy capability of the disinfection device; and
- Air change rate to determine the overall effectiveness of the system to meet IAQ requirements.

Real Case Study

Following the analysis and design principles outlined above, an air sterilization system incorporating plasma technology was designed and installed at the two border-crossing rail stations in Hong Kong. Operation of the air sterilization units creates a sterilized zone at the passenger paths so that cross-contamination of pathogens carried by passengers leaving from and arriving in Hong Kong through the stations will be reduced. The air sterilization systems cover the lobbies and accessories rooms (including toilets and control rooms). There are about 50 air sterilization units (in the form of ceiling hideaway fan-coil units) installed at the two stations. The system was designed with a target ACH of 12.

The performance of the system was evaluated by measuring the Total Bacteria Count (TBC) of the air in the sterilization zones covered by the system. The measurement was conducted independently by a Hong Kong Laboratory Accreditation Scheme (HKOLAS) certified laboratory. Air samples were taken at the peak traffic hours when there were many passengers passing through the stations. One set of the measurements was obtained with the system switched OFF and another with the system ON. For the two stations together, there were 18 measurement locations in total for system performance evaluation. The measurements verified that the system performed better than the stipulated requirements and was able to improve air quality to meet good IAQ standard. Extracted below are some of the results from the measurements.

Sampling Location	**System-Off**	**System-On**	
	Airborne Bacteria (B_i) cfu/m^3	Airborne Bacteria (B_f) cfu/m^3	Bacterial Removal (β) %
Departure Hall Male Toilet	1500	200	86.7
Arrival Hall Male Toilet	4750	840	82.3
Arrival Concourse	2500	440	82.4
Station Control Room	110	20	81.8

Note: The bacterial removal rate (β) is calculated from $(B_i - B_f)/B_i$ x 100 %

Table 1: Extracted IAQ result of border-crossing rail stations in Hong Kong

These results show that the plasma disinfection system can achieve a good performance in improving the indoor air quality with a bacterial removal rate of better than 80% at these locations. The originally high level of biological contamination was reduced to an acceptable level in compliance with IAQ guidelines from Environmental Protection Department of Hong Kong Special Administrative Region Government [23]. In addition to destruct micro-organism, the air sterilization system was able to remove odour. While there was no quantitative measurement, staff familiar with the station noted the improvement particularly in the toilets.

Conclusion

Disinfection efficacy rate can and should be used as a universal parameter for assessing and comparing the capability of air sterilization technologies and devices. Efficacy alone is insufficient to reflect the disinfection capability because it does not take into account of the 'treatment time'. For the same disinfection efficacy outcome, a shorter treatment time means a higher disinfection efficacy rate and a more powerful disinfection. The performance of an air sterilization system depends critically on the disinfection efficacy rate.

The overall effectiveness of an air sterilization system also depends on the air change rate (or ACH). While a higher ACH yields a higher disinfection efficacy, the corresponding higher air flow rate results in more energy consumption in air circulation and air cooling/heating. With a properly chosen ACH value, the performance of the system can be optimized to balance between the desired disinfection performance and the energy consumption.

An air sterilization system incorporating plasma technology, designed following the principles discussed above, was able to improve air quality to an acceptable level in compliance with IAQ guidelines. The plasma air sterilization system can also remove odour, though further quantitative measurements are needed to quantify the odour removal performance.

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