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Evaluation of biological inactivation efficacy for in-duct pulsed xenon lamp

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A R T I C L E I N F O

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A B S T R A C T

In-duct pulsed xenon lamp can destroy the bioaerosols in the flowing airstream as it passes through. Current researches mostly focus on the food sterilization and surface sterilization. In this work, an in-duct pulsed xenon lamp sterilization experimental system was developed with stainless steel duct to model use in the HVAC (Heating, Ventilation and Air Conditioning) system. To study the effect of power supply parameters on the inactivation efficacy, 42 experimental conditions were conducted with the variation of input voltage, capacitance capacity, flash frequency and airstream velocity. The results indicate that the one-pass inactivation efficiency ranges from 63.12% to 88.87%. Inactivation efficiency has positive correlation with input voltage, capacitor capacity and flash frequency of the device, and negative correlation with airstream velocity. The factors affecting the inactivation efficiency in descending order are input voltage, capacitor capacity, flash frequency and airstream velocity. As the power consumption indicator P/G (input power per airflow volume) increases, the inactivation efficiency shows a near linear increase. This study developed a comprehensive evaluation method on the inactivation efficacy by selecting higher ratio of efficiency to input power under the premise of ensuring inactivation efficiency. Optimal combinations of parameters could be obtained with the method in the applications.

1. Introduction

In recent years, there has been some large-scale outbreaks of respiratory diseases like bird flu, which seriously affected human life safety, and caused the attention of indoor airborne microorganisms inactivation significant [1]. Indoor micro-organisms pollution has three mainly sources: indoor people and equipment [2], outdoor micro-organisms and air conditioning systems [3]. With the air conditioning system operating, microorganisms will breed and spread to the indoor air [4]. Therefore, the inactivation of airborne bacteria in air duct flow has been well-researched for decades.

Filtration and UV (ultraviolet) lamps [5] are the most commonly methods to inactivate airborne microorganisms in the flowing air stream for the HVAC systems. Air filter has high efficiency for the microorganisms, however, with microorganisms accumulating on the air filter continuously, air filters will become potential sites for microbial growth once the conditions are suitable, which will cause secondary pollution to the indoor environment [6]. UV lamps have been demonstrated to be an effective mean to reduce the airborne bacteria concentration in buildings, but single-pass inactivation efficiency is relatively low for in-duct application. Moreover, UV lamp needs to be preheated and generates heat during operation, and it will produce ozone when the wavelength of UV light is below 200 nm. These problems have limited the applications of UV disinfection in many places.

To remove the airborne bacteria more efficiently, safely and energy-savingly, efforts are made to improve the traditional methods and develop new technologies. Electrostatic technology [7], bipolar air ionization technology [8], cold plasma technology [9] and pulsed xenon lamp technology are several representative types.

The pulse xenon lamp setup is composed of a pulse xenon light, a boost module, a trigger module and a storage capacitor. It converts the electric energy into radiant energy and emits pulsed light covering a wide range of wavelength from 200 nm to 1100 nm. In addition to the same sterilization mechanism as the UV light (200–390 nm wavelength), pulsed xenon lamp also works by the photothermal effect and the continuous pulse effect [10]. The three effects can superpose on each other to destroy the cell wall and the nucleic acid structure of the microorganism completely [11]. Based on its sterilization mechanisms, the high penetration, high energy conversion efficiency, without preheating, start quickly, no ozone generation, etc., the pulse xenon lamp is considered as high research value in the field of air sterilization.

Numerous studies of pulsed xenon lamp to inactivate

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Nomenclature

W	energy released from storage capacitor during pulsed xenon lamp illumination (J/times)
C	power storage capacitor capacity of pulsed xenon lamp (μF)
U	input voltage of pulsed xenon lamp (kV)
c	staphylococcus aureus concentration in sampled air (cfu/m^3)
n	total number of colonies on culture plates of six-stage sampler (cfu)
t	sampling time (min)
η	one-pass inactivation efficiency of pulse xenon lamp device (%)
Φ	the ratio of efficiency to input power (%/W)
P	measured value of input power (W)
f	flash frequency of pulsed xenon lamp (Hz)
R	resistance of pulsed xenon lamp (Ω)
G	air volume (m^3/s)
R	range of each factor
x, y	parameters
u	uncertainty
S	standard deviation
Subscripts	
up	upstream
down	downstream
i	instrument

microorganisms have been conducted for a variety of purposes, in particular, for food sterilization and surface sterilization.

The significant inactivation effect of pulsed lamp on various microorganisms has been well-documented [12–14]. Anderson [15] studied the sensitivity of different microorganisms to the pulsed light, and arranged their sensitivity as following: Gram-negative bacteria > Gram-positive bacteria > fungal spores. Gram-negative bacteria only had a poly Sugar film of 1–2 nm thick, while Gram-positive bacteria cell wall would play a protective role. Arroyo et al. [16] and Cheigh et al. [17] compared the inactivation effect of pulsed light and UV-C light on the vegetative cell populations of powdered infant formula, the results indicated that the pulsed light was more time-saving and energy-saving to achieve the same inactivation level.

Currently, pulsed xenon lamp technology has drawn attention in the field of surface sterilization, especially in the medical field. It has been evaluated that the surface disinfection efficiency of pulsed xenon UV system was about 70%–80% [18,19].

In this present study, the pulsed xenon lamp is mounted in the HVAC ducting (in-duct device). It is not designed to treat specific surfaces within the HVAC system, but to destroy the bioaerosols in the flowing air stream as it passes through the device. Few researches have been made on this field. Maclean [20] found that airborne bacterial contamination levels were reduced by the pulsed UV-rich lamp of HVAC systems from more than 540 cfu/1000 L to less than 405 cfu/1000 L during a 1-h period.

Based on the pulsed xenon lamp sterilization technology, most of the current researches focused on the influence of microbial species and external environmental parameters on the inactivation efficiency [21]. From the previous studies, it can be seen that the radiation energy of the pulsed xenon light has certain influence on the bactericidal effect. The energy input by single flash of pulsed xenon lamp is related to the input voltage of the boost module, as well as the capacity of the storage capacitor. Besides, by changing the flash frequency, the trigger module controls the cumulative output energy in a unit time. The output energy of xenon lamp is affected under the synergies, followed by the sterilization effect.

In the previous researches, the effect of photoelectric characteristic parameters, such as input voltage, capacitance and flash frequency, on dynamic air sterilization efficiency has been relatively few studied. Thus this paper studied the impact of the power characteristics of pulsed xenon lamp (input voltage, capacitance capacity and flash frequency) and an external environmental parameter (airstream velocity) on one-pass inactivation effect. Experiments were conducted to study the advantages and development prospects of pulsed lamp sterilization technology in the sense of the inactivation efficiency and energy efficiency. A comprehensive evaluation method was presented for pulsed xenon lamp inactivation devices, which will be instructive for the designing and application of the in-duct pulsed xenon lamp inactivation technology.

2. Materials and methods

2.1. Selection and preparation of microorganisms

Referenced to "Antibacterial and cleaning function for household and similar electrical appliances-Particular requirements of air cleaner" [22], experimental bacteria should be *Staphylococcus aureus* or other non-pathogenic microorganisms. This study selected *Staphylococcus aureus*, a type of non-pathogenic Gram-positive bacteria, as the experimental bacteria. The *Staphylococcus aureus* used in this experiment was provided by China Center of Industrial Culture Collection (CICC), No. 10897.

The culture medium was prepared as follows: (1) Weighed 33 g nutrient agar with an electronic balance and put it into a beaker of

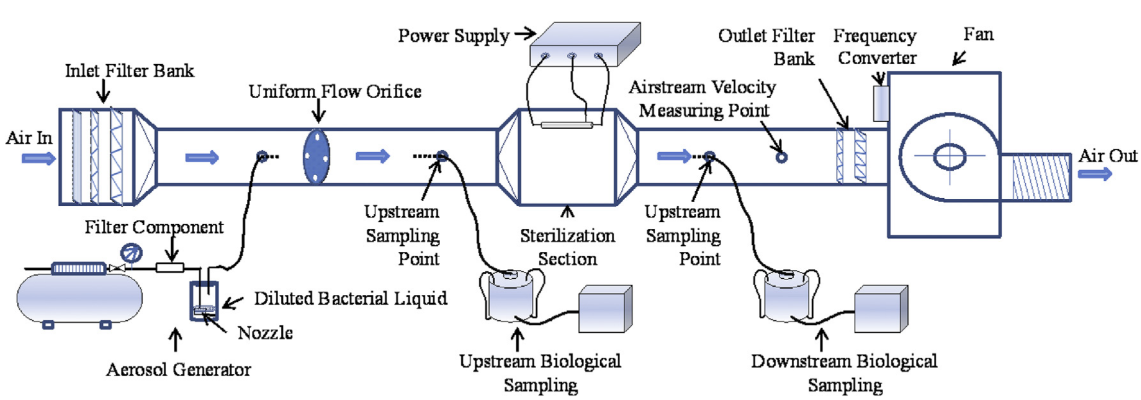

Fig. 1. Schematic of the experimental set-up.