



Effects of installation location on performance and economics of in-duct ultraviolet germicidal irradiation systems for air disinfection



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ABSTRACT

In-duct ultraviolet germicidal irradiation (UVGI) systems treat moving air streams in heating, ventilation, and air-conditioning (HVAC) systems to inactivate airborne microorganisms. UVGI system performance and costs to implement and operate the system depend greatly on the output of the UV lamps and the exposure time, which are affected by the temperature and the velocity of the air passing through the UVGI device. The type of HVAC system, the installation location of the UVGI device, and the climatic location of the building all have an impact on the air temperature and velocity the device experiences at a given time. The effects of installation location and climate were investigated using simulation of an in-duct UVGI device installed in a cooling-only VAV system operating in a hypothetical commercial building. The studied device was investigated at locations both upstream and downstream of the cooling coils of the VAV system in three climatically distinct U.S. locations. The results of the six resulting scenarios indicate that UVGI devices installed upstream of the cooling coils provide comparable if not better performance than those installed downstream. The results demonstrate the impact on performance and cost of the dynamic environment that a UVGI device could experience. It can also be observed that the generated heat of UVGI devices has a great impact on cooling and heating loads, and thus affects the overall operating cost.

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1. Introduction

Transmission of respiratory diseases by airborne pathogens is a major problem of indoor air quality (IAQ). Droplet residues generated by talking, coughing and sneezing can be suspended in the air for hours, entrained into HVAC ductwork, and distributed throughout a building [16]. In-duct UVGI systems have been demonstrated to be an effective means to combat microbial contamination in AHU [18]. In-duct UVGI systems can also be deployed to treat air streams as they pass through HVAC ductwork, and potentially reduce the respiratory diseases that are transmitted through the ductwork. Since air is being recirculated a number of times, an overall increase in removal rate is expected for in-duct air disinfection as compared to single pass system [9]. This paper will focus on the performance and economics of in-duct UVGI system in treating air streams by taking the dynamic environmental conditions as experienced in the AHU of the VAV system into consideration.

1.1. Background of UVGI systems

UVGI systems use electromagnetic energy in the UVC spectrum to damage and prevent replication of microbial DNA and RNA [14]. Microorganisms exposed to UVC irradiation, in general, follow an exponential decay in population. However, a microorganism population is not homogeneous, ranging from less to highly resistive to UVC irradiation. The decay is also often accompanied by a slight delay in response to exposure. Kowalski et al. [6] explains into details the modelling issues related to the exponential decay. Relative humidity might have an effect on UV susceptibility of microorganisms. However, some results indicate positive influence, others show negative influence [9]; effect of relative humidity is therefore not considered here. In this paper, the survival of a population of microorganisms exposed to UVC is approximated by a single stage exponential decay equation:

$$S = \frac{N_t}{N_0} = e^{-k(It)} \quad (1)$$

The surviving fraction, S , defined as the ratio of the surviving population, N_t to the initial population, N_0 , is a decreasing exponential function of the UVC irradiance, I ; the exposure time, t ; and a microorganism-specific rate constant, k . The product “ It ” is the dose

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received by the microbial population. According to Equation (1), this dose may result from any combination of irradiance and exposure time. The irradiance (as related to lamp output) and the exposure time are affected by operating environmental conditions and ageing.

1.1.1. UVC lamp characteristics

Low-pressure mercury vapour lamps are widely used in UVGI applications because most of their output is 254 nm UVC, which attains ~85% of the maximum germicidal effect produced by the optimal 265 nm wavelength [15]. The UVC output of a UV lamp is rated in still air at a temperature approximating typical room conditions after a burn-in time of 100 h [5]. However, the actual output of UVC low-pressure mercury vapour germicidal lamps is a function of the mercury vapour pressure, which varies with the temperature of the coolest location on the lamp surface. Depending upon the lamp type, maximum output occurs when cold-spot temperature is between 39 °C and 50 °C (103 °F and 122 °F) [2]. Fig. 1 shows a typical performance curve with peak UVC output at 40 °C (104 °F).

Cold spot temperature is a function of the energy balance relating input power, useful UVC emission, thermal radiation, and convection. Because the main determinants of cold spot temperature for a given lamp and orientation to air flow are the bulk air temperature and velocity of the air stream, the variation of output with these environmental conditions is commonly called “wind chill”. To combat the effect of wind chill, some manufacturers make high-output lamps. By comparing two geometrically similar lamps, a “standard-output” lamp and a “high output” lamp; the high output lamp must dissipate more energy through the same surface area, therefore, it runs hotter. Consequently, the high output lamp can maintain a higher output than the standard output lamp even at a higher velocity.

The lamp considered in this study is a widely used single-ended twin-tube high-output hot cathode lamp (Philips TUV PL-L 60W HO) for which a validated polynomial cross-flow performance model was developed by Lau et al. [11]. Fig. 2 shows contours of predicted relative output (actual lamp output as a fraction of the maximum output) as a function of air temperature and velocity.

1.1.2. UVGI device characteristics

For in-duct application, one or more lamps are installed in an air distribution duct, in an air-handling unit, or in a factory-fabricated assembly. Several properties of these assemblies have a strong effect on the dose delivered, including lamp configuration, enclosure geometry, and enclosure reflectivity. Design airflow rates may vary from 5 m/s (1000 fpm) or more in air-distribution ducts to less than 2 m/s (400 fpm) in air-handling units (AHU). Much lower velocities may occur during part-load operation of variable air volume (VAV) systems.

The combined effects of lamp output, device geometry and surface reflectivity determine the irradiance distribution while the combined effects of geometry and airflow determine the single-pass exposure time for air passing through a device. On average,

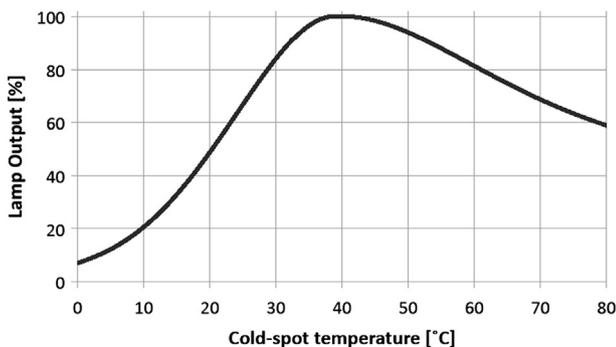


Fig. 1. Lamp UVC output as a function of cold-spot temperature [15].

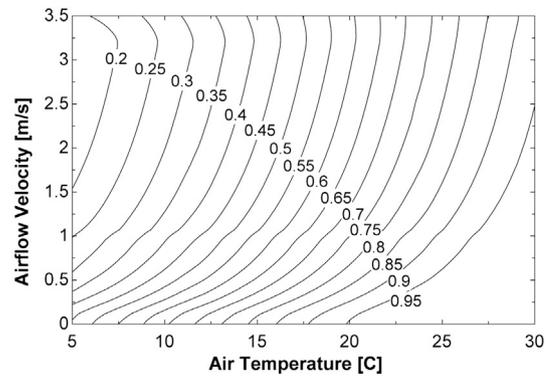


Fig. 2. Study lamp ambient condition response characteristics, in which contours are relative to maximum lamp output [11].

exposure time is the air change rate of the device, i.e., the irradiated volume divided by the volume flow rate. Single-pass inactivation efficiency is the complement of survival and can be derived from Equation (1):

$$\eta_{UVGI} = 1 - S = 1 - e^{-k(It)} \quad (2)$$

The design UV dose for particular values of S and k can be obtained by rearranging Equation (1):

$$(It)_{design} = \frac{\ln(S_{design})}{-k} \quad (3)$$

By combining Equations (2) and (3), the expression for device efficiency at off-design condition becomes:

$$\eta_{UVGI} = 1 - e^{\ln(S_{design}) \frac{It}{(It)_{design}}} \quad (4)$$

For a lamp assembly of given enclosure geometry, lamp configuration, and reflectivity, the dose for an off-design environmental condition in Equation (4) can be expressed as a fraction of design dose by taking into account both the effects of temperature and velocity on lamp output and of flow rate on residence time (Equation (5)).

$$\frac{It}{(It)_{design}} = \left(\frac{\text{LampOutput}}{\text{LampOutput}_{design}} \right) \left(\frac{V_{design}}{V} \right) \quad (5)$$

2. Methodology

The investigation involved a hypothetical case study building and UVGI system. The methodology consisted of four steps: 1) whole building energy simulation to determine air flow rates and air temperatures at the AHU where UVGI device is installed, 2) UVGI device sizing based on worst-case design strategy, and modelling to determine annual distribution of single pass inactivation efficiency using air flows and temperatures passed from the whole building simulation, 3) modelling of airborne contaminant concentration using a well-mixed space model incorporating UVGI device efficiency results, and 4) life-cycle cost analysis to investigate the total cost involved in the deployment of UVGI system.

2.1. Whole building energy simulation

The environmental conditions, which the UVGI device is exposed to, depend very much on the installation location of the

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