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The dynamics of UV light on indoor transmission: a system dynamics model of UV use in overhead ventilation

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Abstract

Empirical evidence indicates that a large fraction of the transmission of airborne pathogens occurs indoors. Despite the COVID-19 pandemic having highlighted the need to control this transmission, and extensive knowledge about the germicidal effect of UV light, the control of indoor airborne infectious pathogens has been focused mainly on ventilation that replaces a fraction of the indoor air, limiting the use of UV lights for disinfection. This paper describes the development of a system dynamics model that models the mechanics behind the germicidal effect of UV lights mounted on an overhead ventilator. This paper also compares the results of the developed model with both an empirical study and a Computer Fluid Dynamics (CFD) model of the same UV light arrangement and problem setting. Finally, the huge potential in the use of UV light-enhanced ventilators is quantified in order to complement, or even replace, other forms of ventilation.

Keywords— Airborne pathogens, Ventilation, Germicidal UV, System Dynamics

1 Introduction

There is increasing evidence to support the view that SARS-CoV-2 (or COVID-19) can be transmitted through air (Greenhalgh et al. 2021) (Morawska & Milton 2020) (Nardell 2021), with airborne droplets and aerosols accounting for more than 80% of the probability of infection (Jones 2020). However, a general consensus on the main means of transmission has been difficult to establish (Lewis 2020). Studies show presence of airborne COVID-19 particles in indoor air in hospitals (Amato-Lourenço et al. 2021), contributing to the hypothesis that airborne diseases are mostly transmitted indoors through inhalation of airborne particles (Lewis 2021*b*) instead of indirectly through contact with contaminated surfaces (Lewis 2021*a*). Documented examples of indoor transmission of COVID-19 include the Ho Chi Minh city bar infections in Vietnam (Chau et al. 2021), gym infections in Hawaii (Groves et al. 2021) and Chicago (Lendacki et al. 2021), and a choir event in the US (Miller et al. 2021).

Airborne transmission of COVID 19 has highlighted the need to eliminate pathogens from the air through mechanical ventilation, and supplementing it through portable room air cleaners and upper room Germicidal Ultra Violet (GUV) Air disinfection (Nardell 2021).

In particular upper room GUV is a technology that has existed for over 80 years (Reed 2010) and which has been shown to produce, under real life conditions, a pathogen disinfection equivalent to 20 or more air changes per hour (Mphaphlele et al. 2015). However its widespread use has been held back by insufficient awareness of the technology, misinformation about its safety and efficacy, and a shortage of expersta that can plan, install commission and maintain these systems (Nardell 2021).

UVGI Specialists have argued that the engineering specifications for the use of UVGI in specific room settings *are currently based more on common sense and on historical practice than on actual evidence*

It has been argued that *"it's unclear how much ventilation is needed to reduce infection rates to an acceptable level"* (Lewis 2021*b*), partly due to the ethical restrictions on experiments about COVID infections directly on humans.

To overcome this, indirect experiments have been carried out to estimate the levels of COVID 19 transmission in schools by measuring CO_2 concentration in classrooms under different levels of ventilation (Hou et al. 2021).

Additionally it has been documented that different measures can have qualitatively similar effects, but through very different paths, and with very different social and economic consequences.

This paper is organized as follows: Section 2 reviews extant literature in connection to the germicidal use of UV lights and the mathematical foundation for modeling ventilation in enclosed spaces. Section 3 describes the mathematical model of a UV-mounted overhead ventilator, and reviews system dynamics as the method used in this paper. Section 4 describes the SD model detailing its assumptions. Section 5 proposes a formal validation of the SD model with Subsection 5.3 detailing the comparison of the SD model with an Empirical study and and a FEM model applied to a common case setting. Section 7 describes the use of the model and finally Section 8 details conclusions and next steps for this work. The appendix includes detailed calculations and model equations for reproducibility.

2 Literature Review

Review publications about the use of UV lights as germicide. (Nardell 2021) (Mphaphlele et al. 2015)

2.1 The germicidal use of UV light

GUV was first explored in the 1930's, when the deactivation of infectious particles was achieved through the use of direct UV light exposure, UV light "curtains", resulting in the implementation the first Ultraviolet Germicidal Irradiation (UVGI) systems. Studies documented a reduction in the incidence of measles and chickenpox in schools (Wells et al. 1942) with most of the clinical benefits of using UVGI systems to reduce pathogen incidence largely anecdotal (Stead et al. 1996).

In the 1970's, UVGI systems were used to test the relative susceptibility of different bacteria to UV light, and Riley et al. researched the relative efficiency of UVGI systems, documenting how a 17 W lamp achieved equivalent results to a rate of ventilation of 10 air changes per hour (Riley et al. 1976).

Despite these promising results, little research into the use of UVGI was carried out until the early 1990's (Beggs & Sleigh 2002).

Upper level UVGI systems were proposed to disinfect air in closed spaces as early as 2002 (Beggs & Sleigh 2002), considering an upper level of UV irradiation

The 200 to 280 nm electromagnetic wavelength (UVC spectrum) has been used extensively for its germicidal properties, as the RNA and DNA in the micro-organisms are damaged through the absorption of UVC photons, preventing their replication and survival (Raeiszadeh & Adeli 2020).

Review publications about the use of UV lights in overhead ventilators. Recommendations about the use of UVGI in public health settings have been proposed by the Center for Disease Control CDC in 2009 (Whalen 2009).

3 Methodology

3.1 The mathematical modeling of UV Disinfection

The mathematical modeling of the UV light disinfection process is well documented and has been identified invariably as a logarithmic process involving exponential decay, multiple decay, shoulder decay or photo-reactivation, of which single decay is the one most widely used approach (Kowalski 2009).

Micro-organisms exposed to UV radiation receive a dose of energy D_{UV} per unit area dependent upon the irradiance I to which it is exposed and time of exposure t_E. The dose received causes a single stage decay where the survival fraction of pathogens S decreases exponentially with the time of exposure, as expressed in Equation (1).

$$S = e^{-k \cdot D_{UV}} \tag{1}$$

with k being the UV deactivation rate constant, also known as the kinetic rate constant, which is the energy required by a specific pathogen species to be deactivated by UV light radiation, and D_{UV} the dose dependent on the Irradiance I and the exposure time t_E according to Equation (2),

$$D_{UV} = I \cdot t_E \tag{2}$$

This principle is applied to the case of UV lights mounted on a overhead ventilator. The mathematical derivation of the model and then system dynamics model are presented next.

3.2 The dynamic modelling of indoor UV disinfection

System Dynamics (SD) is a modeling technique based on control theory's state space representation of a complex systems, used to understand and influence the behaviour of a system representing a specific problem, and assuming that "behaviour arises out of system structure" (Oliva 2004). Two identifying features of SD are its state representation, and its modelling domain.

System states are represented by stocks, also called levels, that accumulate through flows into (or out of) these stocks, and may be causally linked with other auxiliary variables. The SD method considers that all variables are either a stock or a flow but sometimes it is just convenient to represent stocks or flows as auxiliary variables as a result of the timescale of the problem being represented by the model.

The SD state-space representation is simulated in the time domain, and the model is tracked through time by progressively time-stepping the variables by recalculating relationships and accumulations.

Would a skecth be beneficial to show how the light is mounted on the fan?

4 Model description

4.1 General model

Our model considers a room installed with an overhead ventilator, where UV lights have been fitted to the top of the fan blades with radius r. These UV lights neutralize airborne pathogens in the air passing through the fan. If we consider a fan that is at distance H from the ceiling (ventilator head), then a first approximation of the model is that the airborne particles exposed to the UV lights will be contained in the cylindrical space from the ceiling to the fan blades, with height H and diameter $2r$.

For a given room of size V with an overhead ventilator with a nominal flow of M, the air will be recirculated through the ventilator on average in the cycle time t_c, as per Equation (3). The air that is flowing through overhead ventilator will be exposed to the UV lights fitted to its blades during an exposure time t_E which is dependent on the diameter of the ventilator D, the distance of the ventilator blades from the ceiling H, and M nominal flow, as reflected in Equation (4). A detailed derivation of Equation (4) can be found the Appendix.

$$t_c = \frac{V}{M} \tag{3}$$

$$t_E = \frac{\pi H D^2}{4M} \tag{4}$$

The number of quanta present in the air in the room Q will decrease with their exposure to the UV light at a rate that is dependent on the efficiency of the germicidal process η_{ger} and the cycle time t_c in the room, as per Equation (5).

$$\frac{dQ}{dt} = -\eta_{ger}\frac{Q}{t_c} \tag{5}$$

4.2 UV germicidal process

The efficiency of the UV light germicidal process η_{ger} is the fraction of the quanta left N_q after these have been exposed (t_E) to a source of UV radiation, as seen in Equation (6). Quanta will be removed from the population at a rate dN_q/dt dependent on the adjustment time for this process AT, as per Equation (8).

$$\eta_{ger} = \frac{N_q(t_E)}{N_q(t=0)} \tag{6}$$

$$\eta_{ger} = 1 - e^{-kIt} \qquad \forall t \in [0..t_E] \tag{7}$$

The exponential function in Equation (7) has a differential equivalent as per Equation (8) with an adjustment time AT,

$$\frac{dN_q}{dt} = -\frac{N_q(t)}{AT} \tag{8}$$

This adjustment time depends on the quantity of radiation needed by particles to be deactivated, the species-dependent inactivation rate constant k, and the amount of radiation energy (dose) that is received by the particle D_{UV} by being exposed to UV light.

$$AT = \frac{1}{k \cdot D_{UV}} \tag{9}$$

The dose that is received by the particles depends on the irradiation I over time that reaches the particles, and this irradiation depends on the distance $d(t)$ that the particle has to the UV

lights as source of radiation. The dose D received by the particles during the exposure time t_E as per Equation (10).

$$D_{UV} = \int_0^{t_E} I(t)\, dt \tag{10}$$

The irradiation $I(t)$ received by particles depends on their distance from the UV light source, and this distance $d(t)$ will change over time as the particle moves from the ceiling to the ventilator blades, with $d(t = 0) = H$ and $d(t = t_E) = 0$ as per Equation (11),

$$d(t) = H(1 - \frac{t}{t_E}) \tag{11}$$

As a result, the irradiation that reaches the particle will vary over time according to Equation (12), derived from the inverse square law Voudoukis & Oikonomidis (2017).

$$I(t) = \frac{H^2}{d(t)^2} I_0 \tag{12}$$

4.3 System Dynamics representation of the model

An SD model integrates the equations shown in the previous sections to calculate the decrease in quanta in a room through the use of an overhead ventilator fitted with UV lights.

Equations (3) and (5) are represented through a first degree balancing feedback loop diagram, where the endogenous variables, exogenous variables, and the causal links and their polarities are represented. Figure 1, shows the Balancing loop B1, and the polarities, positive or negative, are indicated in the causal link arrows. The stock is the quanta in the room and a single balancing loop R1 represents an exponential decrease to zero of this quanta stock Q.

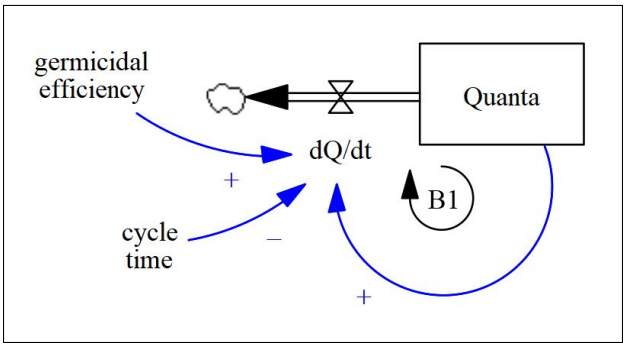


Figure 1: SD representation of Quanta variation

The change in quanta dQ/dt is mediated by the germicidal efficiency of the UV lights and the cycle time representing the problem setting. The germicidal efficiency corresponds to the fraction of infective quanta inactivated after they have been exposed to the UV lights, as per Equation (8), and corresponds to a first degree exponential adjustment to zero, mediated by a the fraction adjustment time, the time when there is an actual decrease in quanta , which is only during the exposure time t_E, when particles move from the ceiling to the ventilator blades, as shown in Figure 2.

The fraction adjustment time is representative of the speed a which this fraction of infective quanta exposed to UV light increases in time. The fraction accumulation speed depends on the energy required to inactivate the infective quanta, represented by the Species Inactivation constant k, and the actual energy delivered by the UV lights, represented by the Radiation Dose $D_U V$, which in the SD model is represented by an accumulation of the irradiation received by

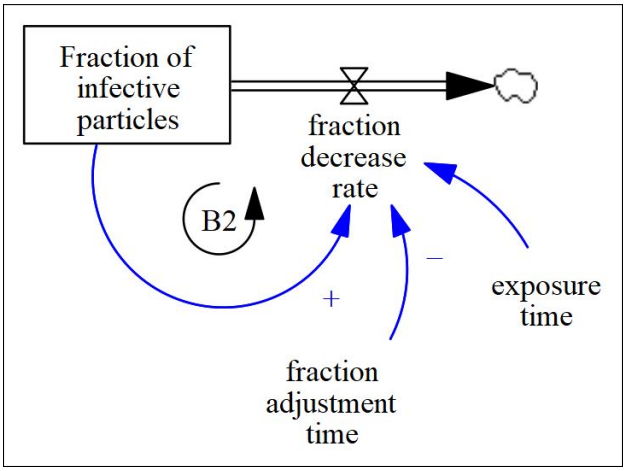


Figure 2: SD representation of infective fraction variation

the particles as these move from the ceiling to the blades, as per Equation (10). This Dose accumulation happens only for a time t_E for each particle.

Figure 3 shows the SD model representation of all of these elements and their relationships, and how the room and the ventilator modules in the model interact. Additionally, exogenous variables are indicated in green, and listed EXO variable types in Table 1.

Additionally, Table 1 lists all other variables considered in the model indicating their *Class*, either Stock, Flow or Auxiliary.

Table 1: Model variables (ordered alphabetically)

Variable Name	**Type**	**Symbol**	**Unit**	**Class**
Cycle time	Endo	t_c	$[s]$	Aux
Distance from ceiling	Endo	d	$[m]$	Aux
Dose increase rate	Endo	DIR	$[J/m^2]$	Flow
Exposure time	Endo	t_E	$[s]$	Aux
Fraction adjustment time	Endo	FAT	$[s]$	Aux
Fraction decrease rate	Endo	FDR	$[\%/s]$	Flow
Fraction of Infective	Endo	Q	$[\%]$	Stock
Irradiation	Endo	I	$[W/m^2]$	Aux
Quanta	Endo	Q	$[quanta]$	Stock
Quanta decrease Rate	Endo	QDR	$[quanta/s]$	Flow
Radiation dose	Endo	D_{UV}	$[W/m^2]$	Stock
Room volume	Exo	V	$[m^3]$	Param
Species inactivation	Exo	k	$[m^2/J]$	Param
Ventilator diameter	Exo	D	$[m]$	Param
Ventilator flow	Exo	M	$[m^3/s]$	Param
Ventilator head	Exo	H	$[m]$	Param

4.4 Model assumptions

The most important model assumptions are:

- *A1 - Perfectly mixed model*: An even distribution of particles across the room volume is assumed, also denoted as a perfectly mixed reaction tank model.

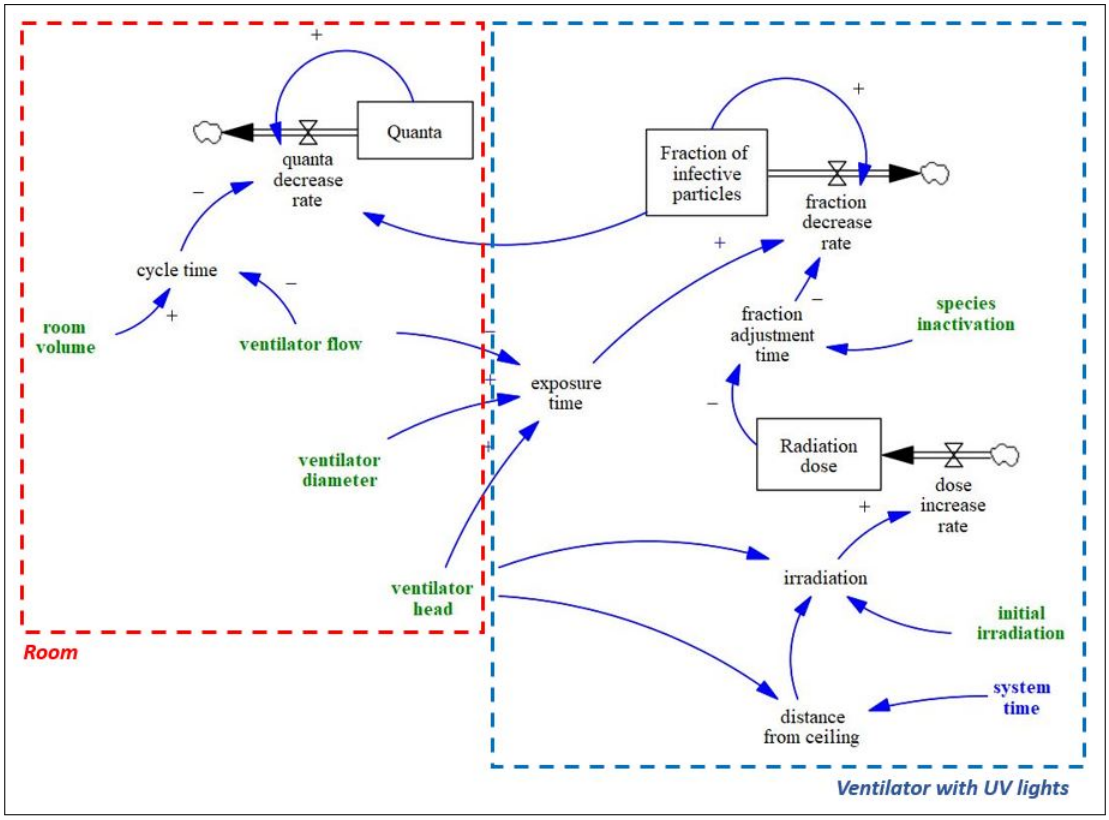


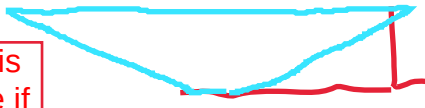
Figure 3: Model showing room and ventilation sections

- *A2 - Laminar particle movement*: The model considers the movement of the particles from the ceiling to the ventilator blades as perpendicular to the blades.
- *A3 - UV light position*: The model considers that particles moving from the ceiling to the ventilator blades have the same exposure to UV light only dependent on their distance from the ceiling. In other words, the UV lights are assumed to be present in the whole ventilator surface, as represented by equation (13).
- *A4 - Reach of UV lights on airborne particles*: Another assumption is that the particles subject to ventilator blades' UV lights corresponds only to the cylindrical space of height H from the ceiling to the ventilator blades with diameter $2r$.
- *A5 - No effect of repeated exposure to UV lights*: The dose, as represented by equation (10), only considers the effect of passing through the ventilator one time. With turbulent airflows, particles may travel past the ventilator blades multiple times adding to the amount of UV light exposure.
- *A6 - Homogeneous pathogen particles*: The model considers all particles to have the same UV deactivation rate constant k. In reality, there will be variation in the UV resistance within sub-populations of the particles. This assumption results in the model considering a single exponential decay as the mechanics behind the disinfection process.

A1 results in a greater diffusion of infectious particles in the room, and as a result the concentration gradients within the room are ignored. As a result A1 at some points will underestimate the actual germicidal effect of the UV lights if the concentration of airborne particles is higher, and will over estimate the germicidal effect in the opposite case. A2 considers a laminar flow towards the blades, maximizing the flow towards the blades, minimizing the exposure

You will also have groups with less resistance to UVC. Hence the average probably gives the average resistance and the most realistic effect.

time of the airborne particles to the UV lights, and underestimating the germicidal effect of the UV lights as a result. Assumption A6 considers all quanta needing the same UV energy to be deactivated, ignoring subgroups with higher UV resistance. This results in an overoptimistic expectation of the disinfection effect of UV lights in the room. Some of these assumptions could have cancelling effects. A3 assumes a higher UV intensity airborne particles by assuming that the light source is located in the whole area corresponding to the ventilator blades of diameter $2r$ overestimating the UV light germicidal effect.



As the cone shape (outside the Diameter is not taken into account either i am not sure if this is actually overestimating it.

5 Model Validation

Notwithstanding the philosophical understanding that a model cannot be validated in a completely objective way (we refer you to Sterman (2000) pp.845-850, for a discussion of this philosophical stance), a formal validation of the model is presented in this paper, applied to a case study described in Section 5.2. By following the guidelines of Barlas (1996), a validation is presented both regarding model structure and behaviour, presented in Section 5.1, and through the comparison of the model's results with two other studies: an empirical study (Nielsen et al. 2021), and a finite element model (FEM), both with the same case setting. These results are shown in Section 5.3.

5.1 Formal model validation

As per Barlas (1996) the model describe in this paper, is a casually-descriptive (white-box) model which requires both an assessment of the aggregate behaviour of the model, and a justification of the claim to the structure of the model that is presented, with particular focus to Boundary Adequacy, Structure Assessment, Dimensional Consistency, Parameter Assessment, Integration Error.

For a complete discussion of assessment tests for dynamic models, we refer you to Senge & Forrester (1980), Barlas (1996) and Sterman (2000, p. 858-861). In this paper we will briefly describe only the assessments performed on this model.

5.2 Case description

The case corresponds to a closed room with an initial concentration of airborne pathogens. The room has an overhead ventilator fitted with UV lights. The case parameters are laid out in Table 2.

The models (SD and CFD) and empirical test reflect the decrease in active airborne pathogens over time with the same setting.

Table 2: Case parameters

Parameter	**Symbol**	**Value**	**Unit**
Initial irradiation	I_0		$[W/m^2]$
Room volume	V	665	$[m^3]$
Species inactivation[1]	k	0.0054 - 0.0126 (Jolis 2002)	$[cm^2/J]$
Ventilator diameter	D	3	$[m]$
Ventilator flow	M	350	$[m^3/min]$
Ventilator head	H	2,41	$[m]$

[1]The pathogen used is the MS2 virus

Table 3: Under and overestimation of germicidal effects of UV light by model assumption

Underestimation	**Overestimation**
* Perfectly Mixed Model (A1), * Laminar particle movement (A2), * Reach of UV light intensity (A4), * No repeated exposure (A5)	* Perfectly Mixed Model (A1), * UV Light Position (A3) * Homogenous particles (A6)

5.3 Model Analysis and comparison

6 Model application

7 Discussion

Some of the aspects to include in the discussion include

1. Use of Modeling Model and method limitations
2. Computing power versus usability in simulations

7.1 Use of SD modelling

The use of SD modelling for the representation of Physical Models is a form of State representation of complex control systems, which is suitable for the representation of complex systems.

8 Conclusions and next steps

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Appendix

Calculation of Exposure time t_E

Consider an overhead ventilator of diameter D, hanging at a distance H from the ceiling, and with a nominal flow capacity of M. The exposure time is the time a particle will take to travel from the level of the ceiling to the level of the ventilator blades. This time can be represented in equation (13).

$$t_E = \frac{H}{v} \tag{13}$$

where v is the velocity of the particle. This velocity is dependent on the area of the ventilator A and the ventilators nominal flow M, as shown in equation (14).

$$v = \frac{M}{A} \tag{14}$$

with a ventilator area A

$$A = \frac{\pi D^2}{2} \tag{15}$$

finally, the exposure time t_E is represented next, and reflected in equation (4)

$$t_E = \frac{\pi H D^2}{4M} \tag{16}$$

System Dynamics model Equations

The equations of the system dynamics model are presented next.