Development of a code for the evaluation of air sanitation efficiency of UV-C linear lamps in ventilation systems

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Highlights

- A numerical code useful for the evaluation of air sanitation efficiency of UV-C lamps in air systems is presented.
- Radiation and motion fields in an air system sanitation channel are defined and solved.
- Global UV-C dose and inactivation efficiency are calculated.
- CFD calculations are used to verify some hypotheses.
- The code is a tool to properly design the sanitation section and perform simulations of real case studies.

Keywords
HVAC and ventilation systems
Air sanitation
UV-C devices
Irradiance
UV-C dose
CFD
Simulation

Abstract
In this work, a numerical code for the evaluation of air sanitation efficiency of UV-C devices placed in air systems (HVAC and MV) is presented. The code can design the sanitation section, giving the necessary UV-C power to achieve a predefined target of sanitation for a certain airborne pathogen. The code, through a three-dimensional discretisation of the channel geometry, first evaluates the radiation field (direct and reflected irradiance) and then calculates the UV-C dose received by the pathogen. The hypothesis of rectilinear trajectories of the pathogen particles is verified through a CFD analysis. A case study is also presented to show the operating mode of the code.

Introduction

In the field of HVAC (*Heating, Ventilation and Air Conditioning*) and MV (*Mechanical Ventilation*) systems engineering, it is known that an important target is to ensure, as well as thermo-hygrometric comfort, high indoor air quality breathed by people [1]. High-quality indoor air means that people breathe air with a very low concentration of dust, micro-pollutants and (most important in this context) a minimal concentration of airborne pathogens. These pathogens, if inhaled by people, in some cases can cause serious diseases [2]. During the COVID-19 pandemic, it has been clearly understood that indoor environments could be the places where contagions among people are favoured. Indeed, if in a certain indoor environment some infected people are present, they could exhale particles of pathogens which can infect other people. The utilisation of an air system (HVAC or a simple MV) can prevent these contagions [3]: delivering fresh air from the system to the indoor environment causes a mixing with the indoor air and the consequent dilution of the pathogens particles reduces the probability of infection. In this sense, it is necessary to sanitise the air flows delivered to the building (in particular, if there is a consistent part of recirculation potentially infected). Sanitising an airflow means removing, as far as possible, a certain pathogen. Among the many options commercially available, UV-C radiation has been proven as very effective against airborne pathogens [4]. This kind of radiation, when it is put in contact with a pathogen, causes photochemical reactions that degrade DNA and RNA, resulting in the inactivation of the pathogen. One method to obtain the sanitation of airflows is to install some UV-C lamps in a section of the air system (i.e. in the *Air Handling Unit*, AHU, or in the channels). In the technical-scientific literature, many documents discuss and prove the effectiveness of UV-C radiation used to inactivate an airborne pathogen. It is possible to cite many works of Kowalski [5]–[9], some of them published also with ASHRAE and IUVA. When designing a UV-C sanitation section, three parameters must be considered: irradiance, exposure time and

dose. Irradiance is the amount of radiation received by the pathogen: it could be direct (received from the lamps) or reflected (received by the walls of the channel). The evaluation of the radiation field in the sanitation section is fundamental: the work of Yang [10] is well explanatory. Depending on the exposure time, the UV-C dose (total energy received) defines the inactivation efficiency (percentage of inactivated particles of the pathogen). The relations between dose and efficiency of inactivation for different airborne pathogens could be evaluated by the publications of IUVA [11] and the University of Milan [12].
The Authors of this paper, in cooperation with the company *Light Progress* [13], have realised a calculation code that designs the UV-C sanitation section of an air system through the consequential solving of radiation and motion fields. Given some boundary conditions, the software returns the number of a certain kind of lamp (UV-C power) necessary to obtain a pre-defined sanitation target (percentage of inactivation of a pathogen). In the following, the theory and modelling of the problem are explained, and a case study is illustrated to show the functioning of the code.

Theory and modelling of the problem

It is assumed that an air stream, entering an AHU or passing in a ventilation duct, contains some concentration of a pathogen and needs to be sanitised. The interaction between radiation and pathogen is regulated by three factors:

- Irradiance [W/m^2], the UV-C power (directly emitted by the lamps or reflected by channel walls), referred to the surface of the receptor.
- Exposure time [s], the time for which the pathogen remains in contact with the radiation.
- Dose [J/m^2], the amount of radiation received by the pathogen and calculated as the product of irradiance and exposure time.

The code, through the implementation of *Matlab* functions containing the mathematical set of equations of the problem, evaluates the radiation field and, considering a proper exposure time, calculates the dose. External *Computational Fluid Dynamics* (CFD) calculations (performed with the software *OpenFOAM*) are used to validate some hypotheses.

Geometry and three-dimensional discretisation

A rectangular duct, in which some linear lamps are placed perpendicular to the direction of the flow, is considered. The channel, or generally a part of the air system, has a length *c*, width *a* and height *b*. Width and height are referred to the transversal section of the channel, length should be considered as the available length, unobstructed and reachable by direct radiation (i.e. the space between a cooling coil and the supply fan of an AHU). The air flows along dimension *c* and the lamps are perpendicular to this direction. Each lamp is characterised by a length *L* [m], a diameter *D* [m] and a UV-C emission power *P* [W].

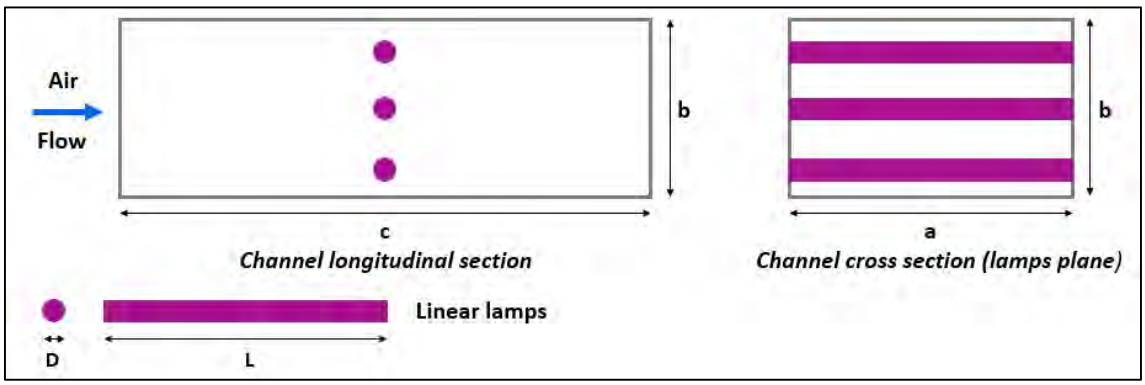

Figure 1. Schematisation of the considered geometry.

As illustrated in Figure 1, the lamps have the same length L of the channel width a. In the practice, this is not always obtainable, due to the mismatch between commercial available models of lamps and the common width of channels. In this sense, it is necessary to suppose the utilisation of *stream conveyors* (physical barriers) inside the AHU or the channels, to avoid shadow zones close to the walls and to obtain a passage width equal to the length of the lamp ($a = L$). So the width a is referred to the width of the section obtained with the utilisation of stream conveyors. In the next figure, the conveyors are shown and the width $a1$ is the total width without the conveyors.

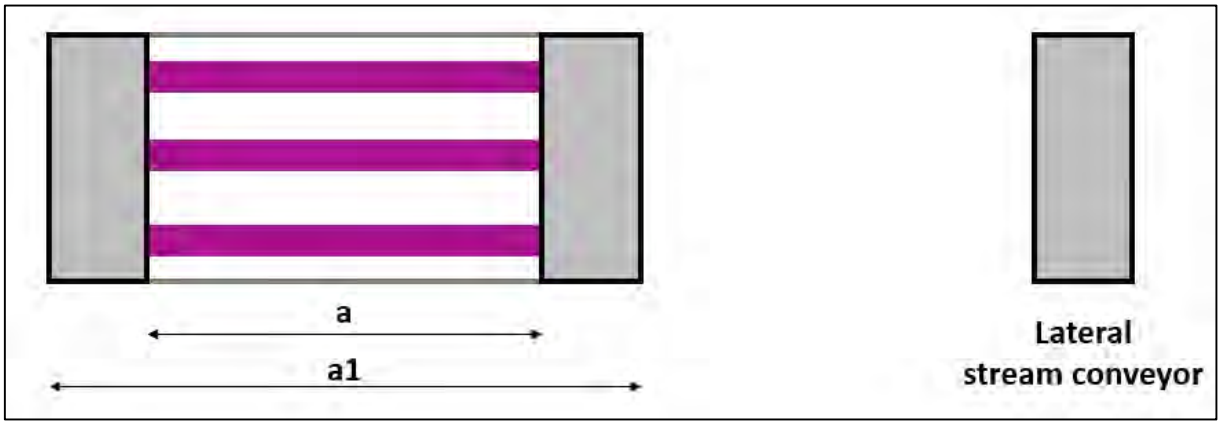

Figure 2. Utilisation of lateral stream conveyor in the sanitation section.

To calculate direct and reflected radiation over the pathogens present in the airflow, it is necessary to make a discretisation of the three-dimensional domain under analysis. This means dividing the domain into many sections and, in each of them, building a grid of many points. Each point of each transversal grid is an element of the control volume, so a pathogen particle that is present in a trajectory of the flow.

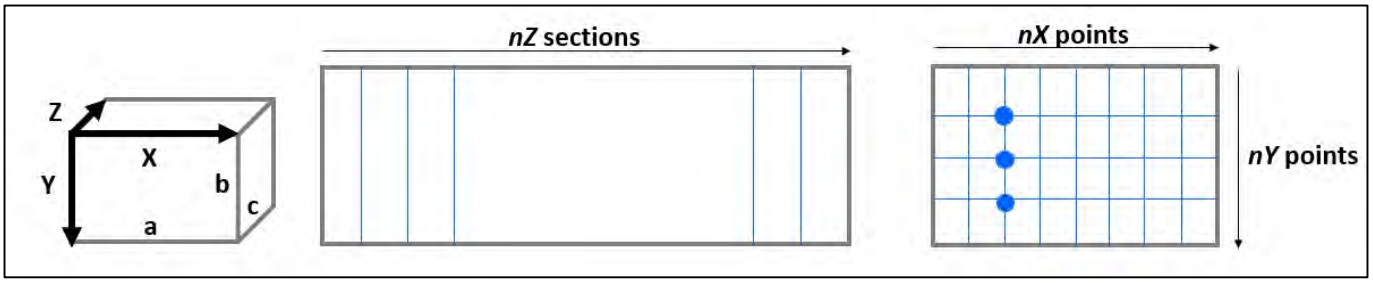

Figure 3. Three-dimensional domain discretisation.

Evaluation of irradiance

The irradiance calculation is performed by analogy with radiative heat transfer problems, in which radiative properties (view factors between irradiated and radiating elements, reflection coefficients, ...) are taken into account. For each point in the three-dimensional mesh, the contributions of direct radiation received by the lamps and reflected by the walls are calculated. Their sum will constitute, for each point, the total radiation. The direct irradiance is evaluated under the hypothesis of a cylindric field emitted by the lamps. For a given point, it is possible to calculate the view factor between point and lamp. The view factor between point and cylindric body is calculated with the indications of Yang [10], based on the publication of Modest [14]. Once this factor has been determined, using the reciprocity theorem of view factor, the radiation emitted by a lamp and received by a point is:

$$I_{l \to p} = \frac{F_{p \to l} * P}{A_l} \qquad \{1\}$$

where $I_{l\to p}$ is the irradiance generated by a lamp on a point [W/m^2], $F_{p\to l}$ is the view factor point-lamp, P is the UV-C power emitted by the lamp [W], A_l is the lateral surface of the lamp [m^2]. It is important to remark that the view factor $F_{p\to l}$ has to be adapted from the literature considering the mutual position between point and lamp. For the point under analysis, it is sufficient to repeat the calculation for each lamp and finally to sum the direct radiations.
The reflected irradiance is evaluated under the hypothesis of diffuse field emitted by the walls, which are irradiated by the lamps. The assumption of diffuse field is not properly correct for materials with high reflection indices, but it is acceptable in this context [8]. To simplify the problem and speed up the code execution time, the walls of the channel are divided into many radiant stripes. For each of them, the view factors with the points of the domain are calculated, following the general definition of view factor [14], [15]. In favour of security, the contribution of inter-reflections is neglected. The reflected radiation received by a point of the mesh is the sum of the radiations received by each radiant stripe present both on vertical and horizontal walls.

Evaluation of exposure time

The exposure time of pathogens to radiation is calculated under the assumption of rectilinear trajectory of pathogen particles contained in the air stream. Thus, for each discretization section of the sanitation tract, there is an equal exposure time, given by the simple equation of uniform rectilinear motion:

$$dt = \frac{dz}{v} \qquad \{2\}$$

where dt is the exposure time in each section [s], dz is the distance between two consecutive sections [m], v is the air velocity in the channel [m/s], depending on the airflow rate and dimensions of the channel:

$$v = \frac{\dot{V}}{a * b} \qquad \{3\}$$

with $\dot{V}$ volumetric flow rate [m^3/s].
This calculation of the exposure time, with a constant and uniform velocity of the flow, is based on the hypothesis, as well as the rectilinear trajectory, of neglecting the wall effects.
To verify these two hypotheses, a *Computational Fluid Dynamics* analysis is performed (as illustrated below). In the case studies analysed by the Authors and, generally speaking, in the practice of HVAC and MV systems, all the CFD evaluations lead to verify the adopted hypotheses. So, in this context, it is possible to consider rectilinear trajectories and constant exposure time for each section as formulated above.

Validation of the hypotheses with CFD techniques

The application of CFD techniques lets to verify the simplifying hypotheses. The solver implemented in the software *OpenFOAM* is based on a stationary and incompressible approach, due to the low velocities of these applications. The flow turbulence is analysed with a RANS (*Raynolds Averaged Navier Stokes*) study, in which two transport equations for the parameters *k* (turbulent kinetic energy) and *ε* (dissipation of kinetic energy) are defined. Some *wall functions* are added to the mathematical set of equations to model the boundary layer behaviour at the wall. The domain under analysis is two-dimensional and it is discretised with a structured mash. If the UV-C section is placed in an AHU, upstream of the lamps some devices (i.e. heat transfer coils) originating a certain level of turbulence could be present. This level of turbulence has to be evaluated according to the values of the literature. To accurately calculate the residence time (so the exposure time to the radiation), a specific transport equation has been added:

$$\nabla \cdot (\dot{V} dt) = 1 \quad \{4\}$$

Independently of the chosen level of turbulence and considering many simulations for different case studies, it is possible to state that the residence time, in the applications of interest, is approximately equal in each section of the channel.

Evaluation of UV-C dose

Each pathogen particle receives a UV-C dose equal to the product of total irradiance and exposure time:

$$d = I_{l \to p} * dt \quad \{5\}$$

where d is the UV-C dose [J/m^2].

Globally, at the exit of the UV-C treatment length, the particle receives a total dose equal to the sum of each dose in each section.

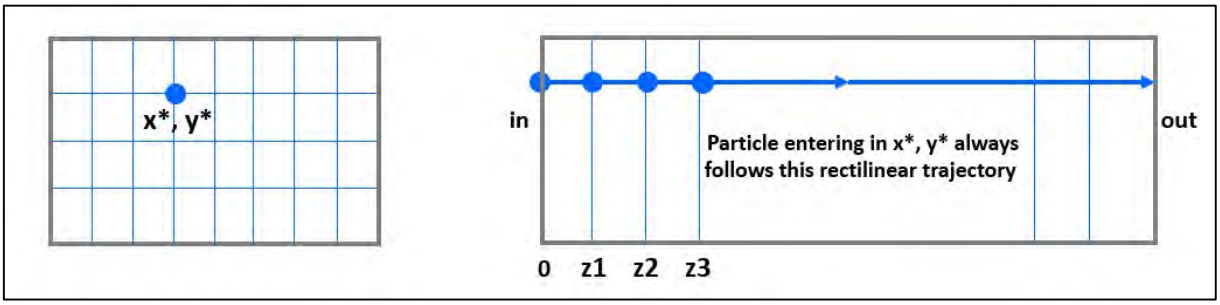

Figure 4. Schematisation of the calculation of UV-C dose.

Efficiency

At the exit of the sanitation length, it is possible to evaluate the inactivation efficiency of a pathogen through the relation dose-efficiency, associated with each trajectory. Finally, with a mass balance, the global inactivation efficiency is calculated. The dose-efficiency curves depend on the pathogen under investigation. Generally, they are well represented by a mathematical relation as follows:

$$\eta = A * e^{B*d} + C * e^{D*d} \quad \{6\}$$

where η is the inactivation efficiency, A, B, C, D, parameters of the decreasing exponential curves (obtainable from the literature). An example of a dose-efficiency curve is represented in the following figure, relating to the *SARS-COV-2* virus responsible for COVID-19 infections:

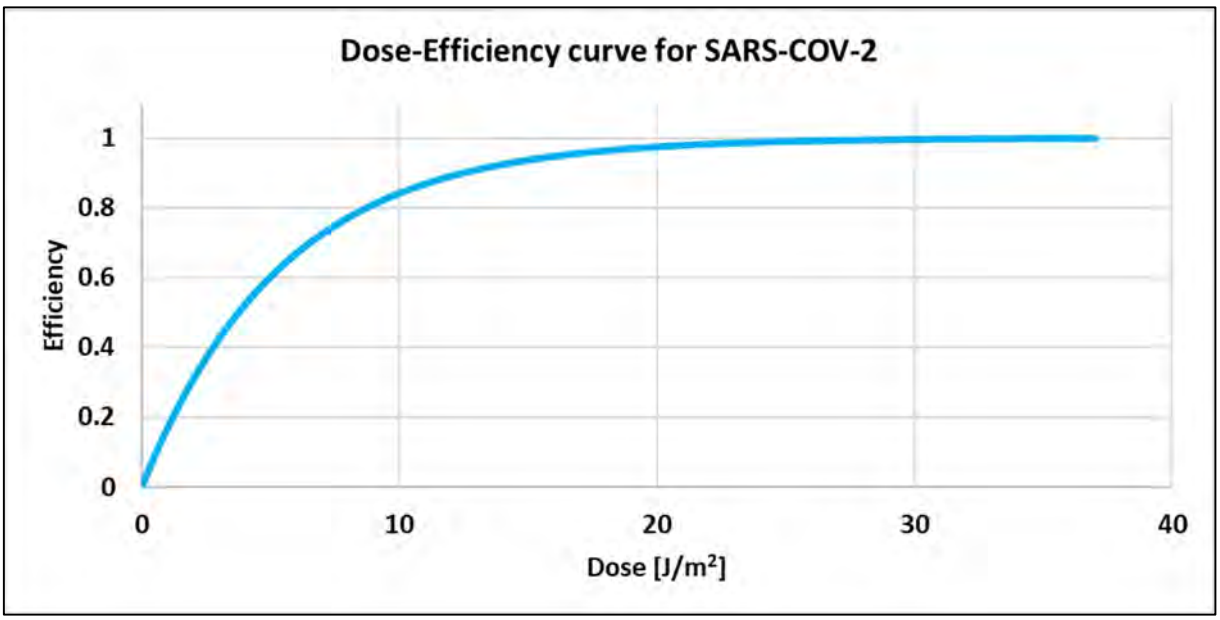

Figure 5. Curve dose-efficiency for SARS-COV-2 virus.

Description of the calculation code and analysis of a case study

The calculation code solves design problems (calculating the UV-C power necessary for a certain dose) or verifies a configuration (considering a UV-C power previously known).

Boundary conditions

The necessary input data are:

- The three dimensions of the channels.
- The material, that affects the reflection properties. The investigated materials are galvanised steel, stainless steel, aluminium (traditional one and a special type named *Vega* [16]) and a particular polymer (*ePTFE*) used as coating of the channel walls.
- The eventual protection of the lamps. Lamps can be placed naked in the channel or can be shielded with specific protection (quartz or *uvlon*).
- The volumetric airflow.
- Temperature, that affects the emission power of the lamps.

If a design problem needs to be solved, another condition is the resistance of the airborne pathogen against UV-C radiation. There are three levels of resistance, corresponding to the doses for SARS-COV-2 inactivation efficiencies of 90.0 %, 99.0 % and 99.9 %. Otherwise, it is possible to insert a certain number of lamps to verify a configuration.

When the calculation is finished, the software shows us:

- The necessary UV-C power.
- The configuration of the lamps.
- The total irradiance on the centre-line of the channel.
- The distribution of the dose received at the exit of the UV-C section.
- The overall efficiency for different pathogens.

Case study

The following table assigns the input conditions of the case study.

Table 1. Input parameters for the case study.

Channel geometry and material			
Width (total)	a1	1.8	m
Width (between the conveyors)	a	1.5	m
Hight	b	1.2	m
Length	c	0.5	m
Material	Aluminium		
Airflow			
Volumetric flow rate	$\dot{V}$	12 600.0	m^3/h
Temperature	T	18.0	°C
Lamps characteristics			
Diameter	D	20.0	mm
Length	L	1.5	m
Total power	P_{tot}	155.0	W
UV-C power	P	55.0	W

In the following, two configurations are compared: the first one (4 lamps) is the result of a design calculation to obtain a 90.0 % inactivation of SARS-COV-2 and the second one is the result of a verification calculation obtained with 6 lamps.

Table 2. Lamps and UV-C power necessary in the case study.

	Configuration 1	Configuration 2	
Number of lamps	4	6	
Total power installed	620.0	930.0	W
Total UV-C power	220.0	330.0	W

The following figures are referred to the configuration of the lamps, distribution of the total irradiance on the centre-line of the channel and the distribution of inactivation dose, for the two configurations.

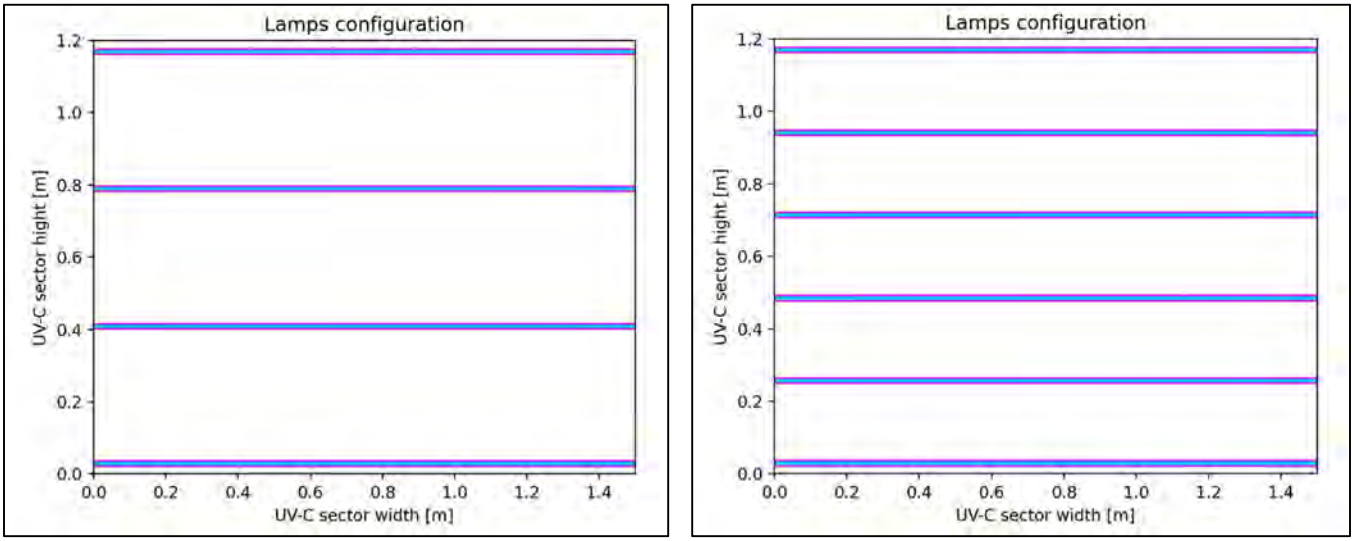

Figure 6. Disposition of lamps (lamps plane, left conf.1, right conf.2).

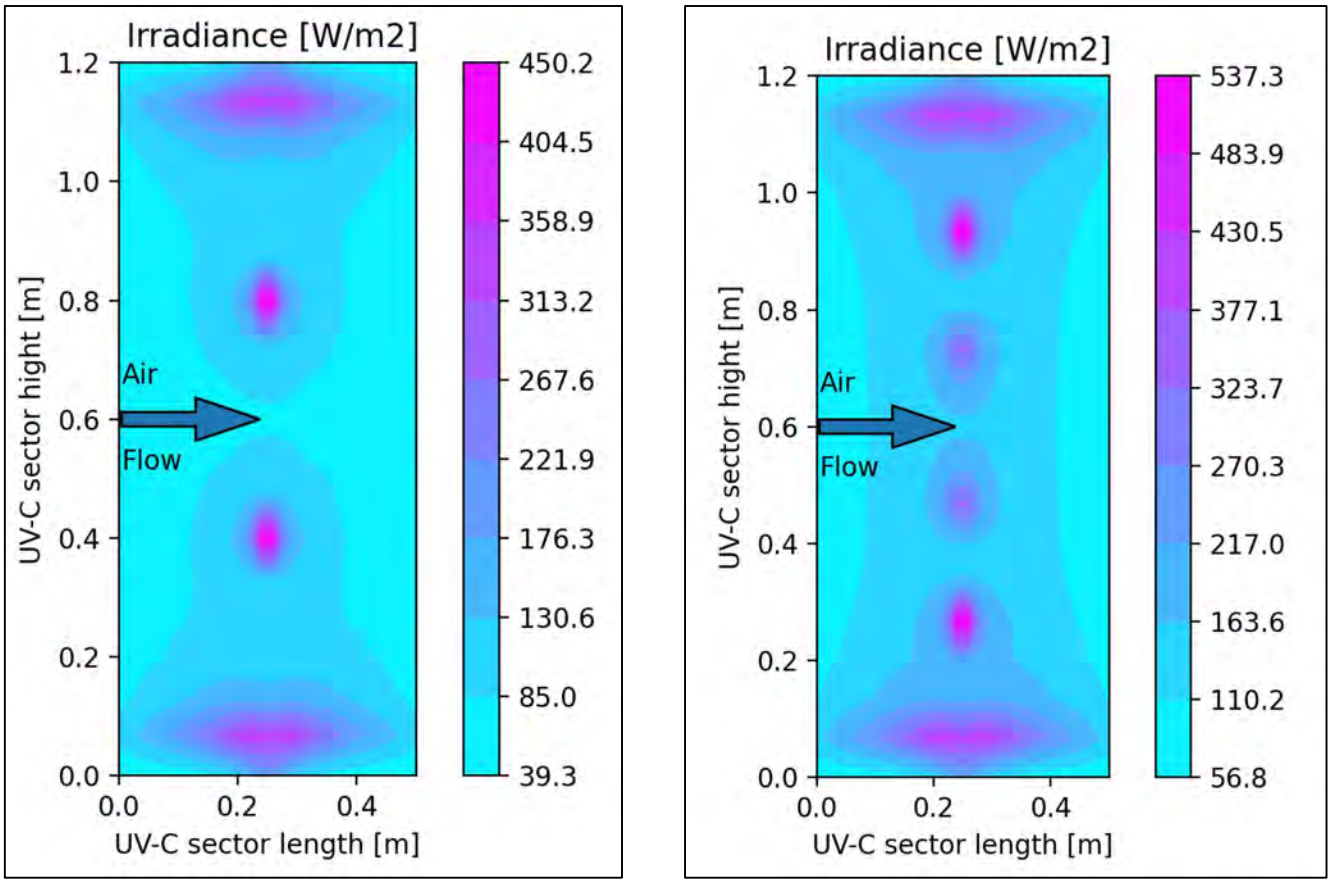

Figure 7. Irradiance on the centre-line (left config.1, right config.2).

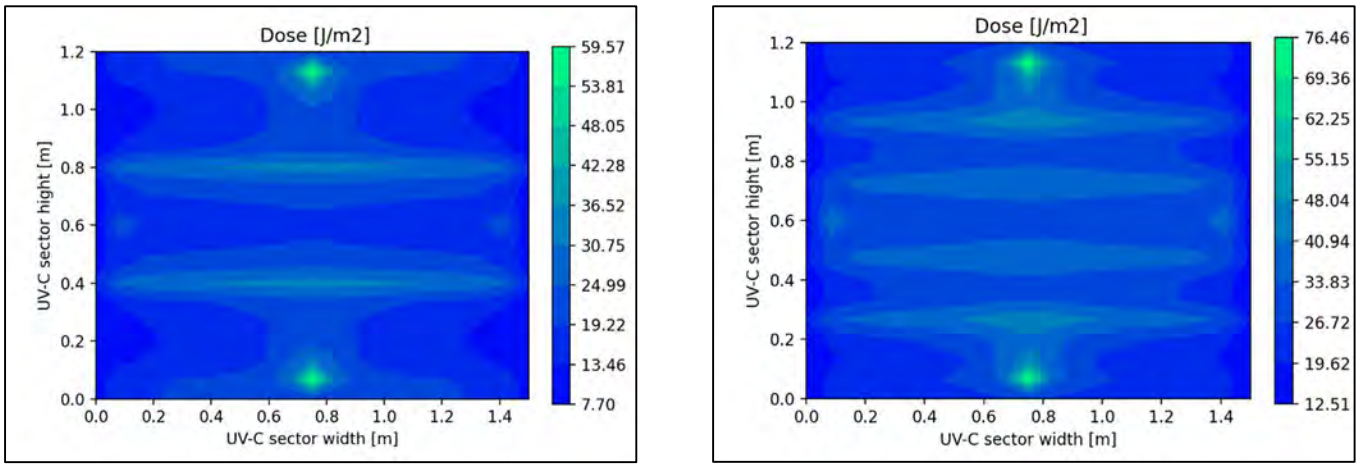

Figure 8. Dose at the exit of the sanitation length (left config.1, right config.2).

The following table reports the inactivation efficiency for different airborne pathogens. This is a very important fact: with the same sanitation technology (UV-C lamps), it is possible to reduce the concentration of different pathogens potentially present in the airflow.

Table 3. Inactivation efficiency for different pathogens.

Airborne pathogen	Configuration 1	Configuration 2
Sars-Cov-2	93.18	98.70
Legionella pneumophila	88.21	96.47
Mycobacterium tubercolosis	74.99	91.63
Pseudomonas aeruginosa	46.09	69.97

Except for pseudomonas aeruginosa, a Gram-negative bacterium very resistant to UV-C treatment, the concentration of the other pathogens (in particular with the second configuration) is greatly reduced: for SARS-COV-2, it is possible to obtain a reduction close to the target of *2-log* (99.0 %).

The case study with 6 lamps has been validated with a CFD analysis. The structured mesh is composed of 70 000 elements, the tested levels of turbulence are 3.0 %, 12.0 % and 22.0 % at the inlet. At the exit of the channel, the static pressure is equal to the ambient pressure. The considered velocity is 1.94 m/s (according to equation {3}), imposed at the inlet.

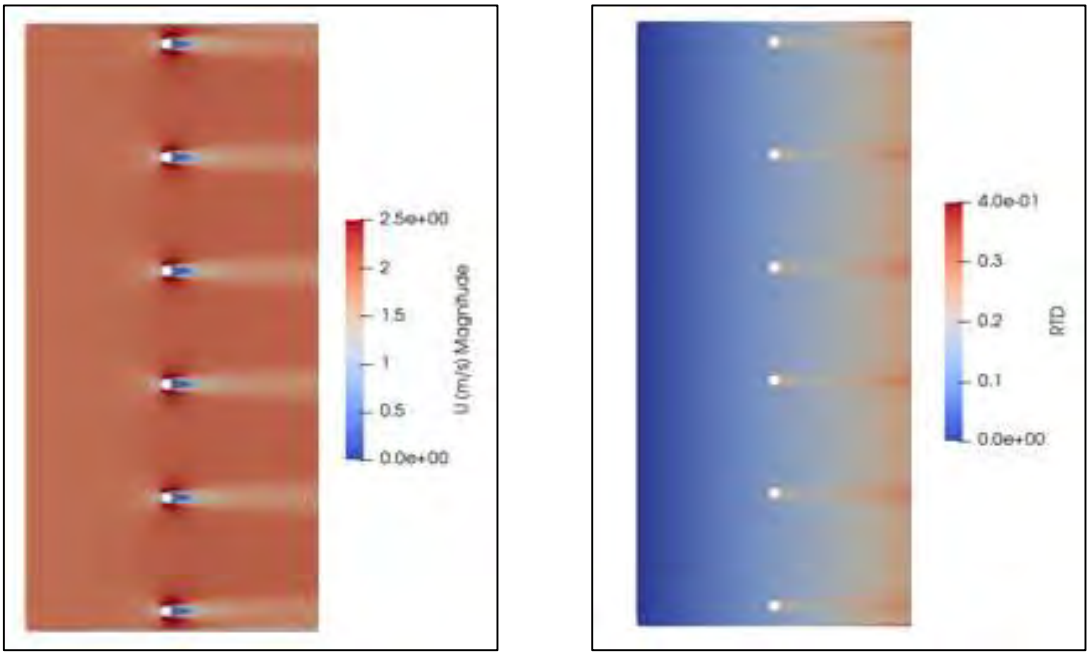

Figure 9. Velocity field (left) and residence time distribution (right) for configuration 2.

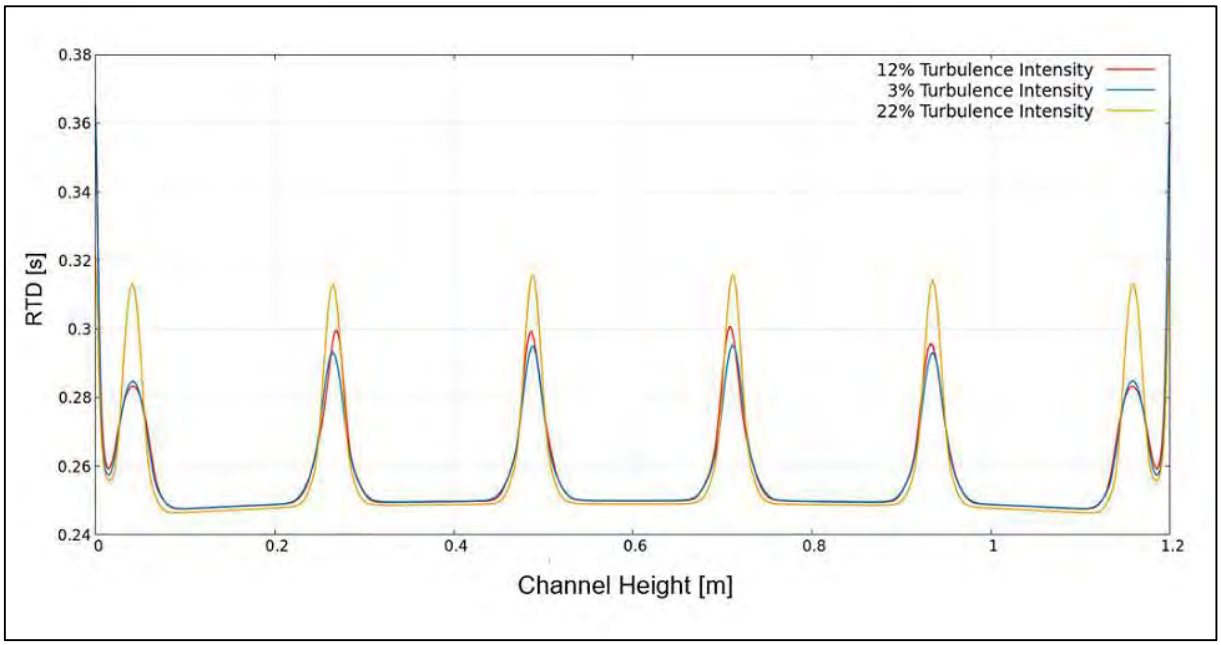

Figure 10. Analysis of the residence time for different levels of turbulence for configuration 2.

Figure 9 shows the velocity field (left) and residence time distribution (right) in the channel: downstream of the lamps it is possible to observe the presence of a vortex effect, while between the lamps the flow remains undisturbed. Figure 10 represents the residence time of the trajectories at the exit of the sanitation section. The hypothesis of uniform rectilinear motion is confirmed by the CFD analysis, with a mean velocity and a mean residence time in accordance with the above formulation. The following table highlights this fact, reporting the results for the three different levels of turbulence:

Table 4. Mean velocity and mean residence time for different levels of turbulence for configuration 2.

Level of turbulence [%]	Mean velocity [m/s]	Mean residence time [s]
3.0	1.89091	0.26148
12.0	1.88654	0.26197
22.0	1.88612	0.26236

Conclusions

In the paper, a simulation code able to design a UV-C sanitation section of an air system has been presented. The code solves the radiation and motion fields to calculate the local dose received by the pathogen particle and the global inactivation efficiency. Some simplification hypotheses have been verified with Computational Fluid Dynamics calculations. A case study has been analysed, to show the potential of the code. The code represents a useful tool to design or verify sanitation sections and can be used to simulate real conditions. In the future, the code could be modified if other kinds of configuration have to be simulated, i.e. with the lamps disposed on more than one row or parallel to the flow.

Acknowledgement

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