NUMERICAL ANALYSIS OF GERMICIDAL UV-C LAMP AIR DISINFECTION SYSTEM

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Abstract. In this study, four germicidal UV-C lamps that are in a 600x600 square duct are numerically investigated. Also an UV reactor design is investigated for high resistive microorganisms. Air flow in the duct has 3000 m3/h volumetric flow rate. Simulations are conducted with commercial computational fluid dynamics solver ANSYS-FLUENT. In square duct, Lamps has 75 W UV power and their electrical efficiency depends on UV radiation generation, lamp surface temperature, contact air humidity, lamp working hours, lamp surface pollution. The radiation intensity around the lamps in the channel is evaluated by the using discrete ordinates method depending on the location. After that, the air flow on the lamps are modelled and particle motion simulation is carried out with the DPM model. The amount of UV dose received by these particles is calculated at the duct outlet, and the inactivation ratio for the general coronavirus family is examined. As a result, D90 inactivation performance is achieved in the system. The radiation distributions obtained depending on the UV power and the dose map in the duct outlet section depending on UV power are parametrically examined and presented.

Keywords. UV-C disinfection, germicidal lamp, computational fluid dynamics, indoor air quality,
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1. Introduction

The concept of indoor air quality has gained importance in recent years. The pandemic caused by the SARS-CoV-2 virus, which threatens humanity today, has once again shown the importance of focusing on this concept. The most common ways of infection of this virus, which has a great impact on the design and operating conditions of air conditioning and ventilation systems, can be summarized as follows [1].

(i) Large droplets and aerosols (when sneezing, coughing, or talking), with close contact of 1-2 m,

(ii) Airborne by aerosols (dried small droplet nuclei) that can stay in the air for hours and be carried over long distances (released when breathing, talking, sneezing, or coughing).

(iii) Through surface contact (hand-to-hand, hand-to-surface, etc.)

(iv) Fecal-respiratory.

The most effective transmission is through droplet (i) with 21%, with viruses suspended in the air (airborne) with 64%, adhered to other parks or clustered or alone (ii) and contact with (iii) 15%.

As it is known, particles suspended in the air circulation in heating, cooling, ventilation, and fresh air distribution systems. This situation brings up the fact that any microorganism or virus will be included in this flow. Therefore, considering the pandemic conditions we are in today, the design of ventilation and air conditioning systems has become more important than ever. There are three basic inactivation methods known to reduce the effectiveness of the aerosols in the airflow:

(i) Removal by mechanical ventilation

(ii) Filtration

(iii) UV-C Disinfection

It is possible to produce optimum solutions for disinfection by using these methods, which we call "Total Disinfection Management", together.

In the literature, there are recent studies dealing with the use of UV-C lamps in the air flow. F. Atci et al. [2] examined the in-duct disinfection with numerical methods in their study. They considered four different lamp arrays in 61x61x183 cm channel dimensions and modelled the particles in the air flow with the DPM algorithm and analysed the air flow with the SIMPLE and PRESTO! algorithm. The UV radiation distribution in the channel is analysed using the discrete ordinates method. For the lamp arrays they examined, they observed that the particles in the air are exposed to a UV dose of 19.12 J/m^2 in the best scenario. They stated that this dose value inactivated the MS2 Bacteriophage virus at the rate of 56.05% at the duct outlet. A. Capetillo et al. [3] compared EPA tests with CFD simulations and interpreted that the results are in good agreement with experimental results for different microorganisms and viruses. In their analysis for a single lamp, they stated that only 6.2% of the particles in the channel are exposed to double the average dose, while the remaining particles could only receive half the average dose. They stated that this situation had significant effects on the total efficiency of the UV disinfection system. W.J. Kowalski et al. [4] proposed a solution method for modelling UVGI systems. They are confirmed their findings with experimental studies with a margin of error of ±%15. On the other hand, they stated that the effects of air relative humidity in UV-C disinfection are not yet understood. On the other hand, the rate constants of pathogens to UV radiation are an issue that needs to be investigated to determine the inactivation performance. Capetillo et al. [5] discussed the use of UVC lamps for in-duct air disinfection in their study. The amount of UV dose to which the particles suspended in the air flow are exposed is calculated using computational fluid dynamics simulations. They created their numerical models with the inputs of the UV disinfection tests performed by the EPA (Environmental Protection Agency) agency. They compared their findings with EPA agency test results, which revealed test results with different UV lamp numbers and configurations. As a result of the comparison, they observed that the UV radiation distribution findings are in good agreement with the experimental data. The study reveals that the UV resistance coefficient unique to each microorganism, which reveals the resistance of different microorganisms to UV radiation, should be investigated in more detailly. For some microorganisms, it is suggested that although the accuracy that can be a reference in the verification of the numerical model results has been determined, this coefficient has not been determined with sufficient accuracy for other microorganisms. This situation shows that there can be misconceptions when questioning the adequacy of the UV disinfection system. Yi Yang et al. [6] developed a new model to determine the UV radiation field based on the view factor model in their study. The model results are well agreed with the experimental data. In the computational fluid dynamics simulations, they carried out investigations on the inactivation efficiency of the model for E. coli bacteria. They observed that the amount of inactivation decreased for increasing air flow rate and increased for increasing lamp size. On the other hand, the local dynamic loss coefficient of the UV lamp for the air flow is calculated as 0.085 by them. Yi Yang et al. [7], in their study, a numerical model that includes multiple physics by determining the trajectories of particles in the air using the Langrangian method is proposed. Their model based on the view factor model developed with their previous studies. In their findings, they calculated the inactivation amount of S. Marcencens bacteria as 100%, the inactivation amount of MS2 bacteriophage as 54.43%, and the inactivation amount of B. atrophaeus bacteria as 0%. When they compared their findings with the EPA test reports, they reported that they calculated 100% accuracy for S. marcescens bacteria, 15% deviation for MS2 bacteriophage, and 100% accuracy for B. atrophaeus bacteria.

In this study, the design steps of UV disinfection systems are explained. Calculation of the average dose amount does not provide clear evidence for the adequacy of the system design. For this reason, the dose distribution at the duct outlet is also presented in this study. In addition, when the dose distributions are examined, it reveals the necessity of examining numerical methods in system design with UV disinfection. Inactivation performance also depends on the type of microorganism examined. A reactor design for fungal spores, which are the most difficult to inactivate, is also considered within the scope of the study, and the dose distribution and inactivation performance in the outlet channel section are presented. In addition, the effects of these systems on power consumption are discussed.

2. Material and Method

In this section, the system design stages, and the content of these steps are detailed. Also, sample designs are shown. As can be seen in Fig. 1, the mathematical model of the system is created in the first step. The model structure is divided into finite volumes (meshing) and turned into a numerical model. The numerical model uses three different equations, (i) discrete ordinates method, (ii) continuity, momentum and k-ε turbulence model (iii) discrete phase model (DPM). SIMPLE algorithm is implemented as iterative solver. Boundary conditions and governing equations is explained under cont'd subsections.

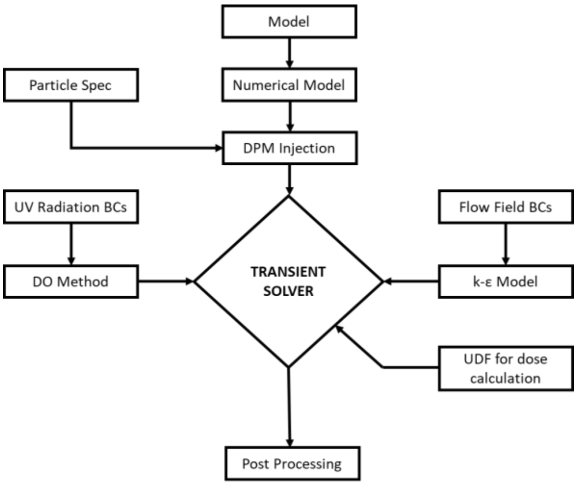

Fig. 1 – Numerical System Design Algorithm

2.1 Discreate Ordinates Method

Discrete Ordinates (DO) method is used for solving radiation distribution emitted from UV-C lamps. Governing equation for DO is represented with Equation-1 [8].

$$\nabla(I(\vec{r},\vec{s})\vec{s}) + (a+\sigma_s)I(\vec{r},\vec{s}) = \frac{an^2(\sigma T^4)}{\pi} + \frac{\sigma_s}{4\pi}\int_0^{4\pi} I(\vec{r},\vec{s'})\phi(\vec{s}\,\vec{s}')d\Omega' \quad (1)$$

In Equation-1, the first term on the left is the emission term, and the term on the right is the scattering term. Here **r** is the position vector and **s** is the direction vector. **s'** is the scattering vector and s is the distance. I is defined as the radiation intensity. Angular scattering and pixelization are important here. For this analysis, angular scattering and pixelization values are used as 5x5 and 3x3, respectively.

2.2 k-ε Turbulence Model

Solving the airflow in duct, the standard k-ε turbulence model is implemented to Navier Stokes equation. For solving governing equations with turbulence dissipation ANSYS – FLUENT solver is used. Second order upwind scheme is selected as discretization scheme and SIMPLE algorithm is implemented as solver. Three dimensional continuity and Navier-Stokes equations are discretised and governing equations are [8]:

$$\frac{\partial\rho}{\partial t} + \nabla(\rho\vec{v}) = 0 \quad (2)$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla(\rho\vec{v}\vec{v}) = -\nabla p \quad (3)$$

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k - \rho\epsilon \quad (4)$$

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + \frac{C_{1\epsilon}\epsilon G_k}{k} - \frac{C_{2\epsilon}\rho\epsilon^2}{k} \quad (5)$$

$$\mu_t = \frac{\rho C_\mu k^2}{\epsilon} \quad (6)$$

Here, k is turbulence kinetic energy, and ε is energy dissipation. G_k represents generation of turbulence kinetic energy by mean velocity gradient. $C_{1\epsilon}$, $C_{2\epsilon}$ are constants, σ_k and σ_ϵ are the turbulent Prandtl numbers for k and ε respectively.

2.3 DPM Model

DPM (Discreate Phase Model) can predict trajectory of a discreate phase particle by integrating force balance on the particle [4]. For z direction of model used in this study, force balance can be written as,

$$\frac{du_p}{dt} = F_D(u-u_p) + \frac{g_z(\rho_p-\rho)}{\rho_p} \quad (7)$$

where $F_D(u-u_p)$ is drag force per unit particle mass can be written as,

$$F_D = \frac{18\mu}{\rho_p d_p^2}\frac{C_D Re}{24} \quad (8)$$

Here u is fluid velocity, u_p is particle velocity, μ is viscosity of fluid, ρ is fluid density, ρ_p particle density, d_p particle diameter. Re is relative Reynolds number, calculated as,

$$Re = \frac{\rho d_p|u_p-u|}{\mu} \quad (9)$$

2.4 Dose and Inactivation

It should be ensured that the particles injected into the air flow receive a sufficient dose. For this, the amount of dose taken by a particle during its movement in the air flow must be determined. The dose amount can be determined by Equation – 10 [1].

$$D = \int_{t_0}^{t} I(x, y.z)dt \qquad (10)$$

Here t_0 is the starting time and t is the time until the particle leaves the channel. I is local radiation density [W/m^2] that depends on particle's location. After calculating the UV radiation dose received by each particle during the channel movement, the total dose received by the particles can be calculated and the average dose amount of the disinfection system can be calculated as,

$$\overline{D} = \sum_{i=1}^{n} \frac{D(n)}{\Delta T} \qquad (11)$$

Where $\overline{D}$ is the average dose and ΔT is the mean duration of motion, n is the number of particles injected into the channel. By determining the average dose amount, the inactivation performance (removal rate) of the disinfection system can be calculated with Equation - 12.

$$RR = 1 - S \qquad (12)$$

Here S is removal rate which can be evaluated as,

$$S = \exp(-k\overline{D}) \qquad (13)$$

Here k is inactivation constant that is specific for injected microorganism type to ventilation duct. In this study, a user defined function (UDF) is used that records the local radiation distribution at each time step to determine the dose.

2.5 Sample Designs

There are four UV-C lamps in a ventilation duct which can be seen in Fig. 2a and Fig. 2b at two different models. Also, a reactor design which can achieve D90 in activation for high-resistant to UV-C radiation (fungal spores) is shown in Fig. 2c.

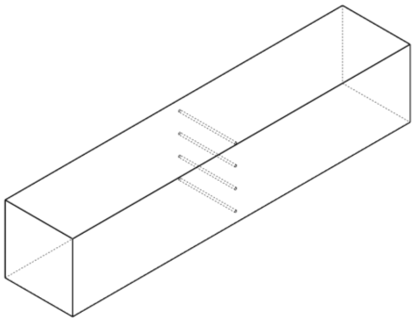

Fig. 2a – Sample Design-1 (Far Arrangement)

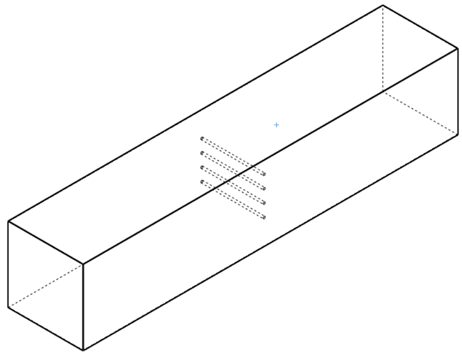

Fig. 2b – Sample Design-2 (Close Arrangement)

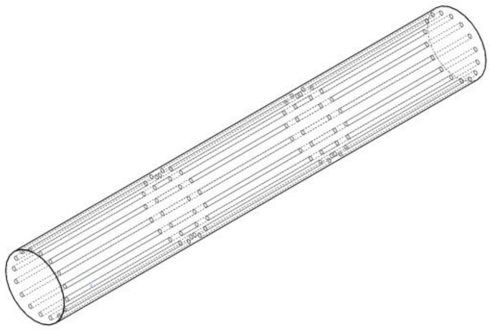

Fig. 2c – Sample Design-3 (Reactor Design)

Sample designs which are given in Fig-2a and Fig-2b contain the same number of lamps. The diameters of the lamp are 16mm. and arc length is 500 mm. Channel dimensions are 600x600x5000. these square channel sample designs are taken from the ISO 15714-2019 [9] standard, a standard for the test procedure of UV-C disinfection systems. The difference between them is the central distance between the lamps in the middle plane where the lamps are located. The central distance between the lamps is 125 mm in the design with far arrangement given in Fig - 2a, the central distance between the lamps is 100 mm in the design with close arrangement given in Fig-2b. In Fig-3c, the sample design geometry for the disinfection of microorganisms which resistive to UV radiation is given. There are 48 lamps with 38 mm diameter and 1.5 m arc length in the relevant geometry. The duct cross-sectional area is taken at the same ratio as the square duct cross-sectional area to make a well comparison. Channel length is 5000 mm

2.6 Validation

The validation of the numerical model is carried out by validating the irradiation field created by the UV lamp with radiation distribution experimental data. A drawing of the validation model is given with Fig - 3. Validation model Kowalski et al. [5] taken from his 2001 study. In Fig G25T8 Philips UVC lamp located in the air volume.

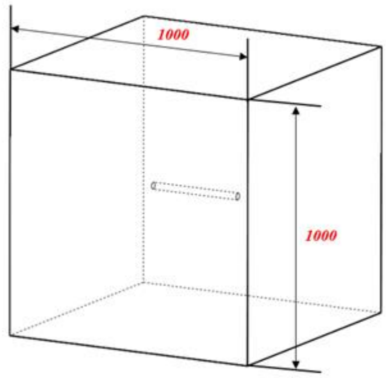

Fig. 3– Validation Model

The G25T8 Philips UVC lamp used has a power of 6.6 W. The arc length of the lamp is 35.56 mm and its radius is 1.27 mm.

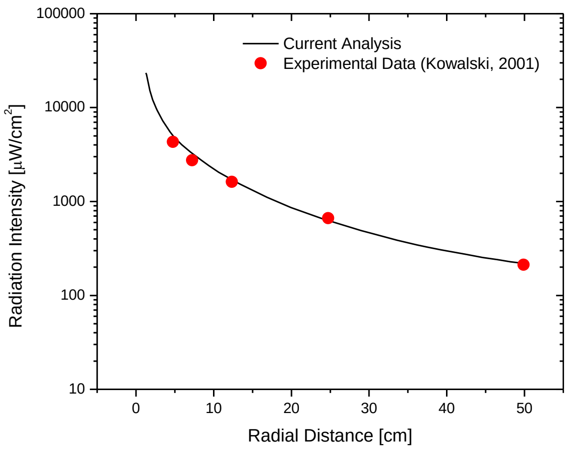

Fig. 4– Comparison with Experimental Data

As can be seen with Fig-4, the results obtained with the present analysis well agreed with the experimental data. For the analysis, 1399143 mesh numbers were used. Convergence criteria are given in Tab-1. Each analysis for the square channel took an average of 187 minutes. For the reactor, it took 76 hours and 37 minutes.

Tab. 1 – Convergence Criteria

Model	Value
DO Discretization	$1x10^{-12}$
Continuity	$1x10^{-6}$
k- ε Standard Equation	$1x10^{-6}$
Momentum	$1x10^{-6}$

2.7 Boundary Conditions

A total of 7 analyses are carried out at different lamp UV powers within the scope of the study. The air flow rate is considered as a constant 3000 m^3/h for each analysis. UV power of 75W is determined for the lamps (for reactor lamps has 135 W UV power). The channel outlet is at an absolute pressure of 0 Pa. Inactivation is examined for the general coronavirus family, and the inactivation coefficient is 0.009716 [m^2/J] [1]. However, the inactivation coefficient of fungal spores, which has a very high resistance to UV radiation, is considered in the reactor design (k=0.0009 m^2/J). In each analysis, 400 particles were injected into the channel in a homogeneous distribution from the channel inlet section. The duct inner surface reflectivity is considered as 50% as recommended in the ISO 15714-2019 standard.

The energy efficiency of UV lamps can be calculated by Equation - 14.

$$\eta_{tot} = \eta_{UVC}\eta_T\eta_\phi\eta_a\eta_f \quad (14)$$

Here, η_{UVC} is the efficiency of the lamp to produce ultraviolet radiation at a wavelength of 253.7 nm, η_T is efficiency depending on lamp surface temperature, η_ϕ efficiency depending on the humidity of the air carrying the virus, η_a is depending on lamp operating hours (ηa), and η_f is efficiency due to surface contamination. Considering the applications, the average UVC radiation efficiency of the lamps is around 35%. Also the temperature efficiency can be between 40%-90% depending on the location of the UVC system in a practical sense. No information is found in the literature on cleaning efficiency. However, for a safe design, it is considered appropriate to take an average of 99%, provided that the lamp is cleaned frequently. Although there are some experimental studies on moisture efficiency, these studies are for a certain microorganism and special radiation distributions. It is an area that needs to be studied for any microorganism. For operating hours efficiency, using the performance of the lamp at the end of the renewal life given by the lamp manufacturer will be appropriate in terms of safe design (this value is around 60%). When all these efficiency parameters are considered, it is seen that the total efficiency is around 15-20%. the best efficiency at 25°C temperature, 40-50% relative humidity and 2.5 m/s air velocity. Efficiency analyzes is carried out under these assumptions by reverse engineering. More detailed studies should be done in the future.

3. Results

3.1 Far Arrangement Sample Design

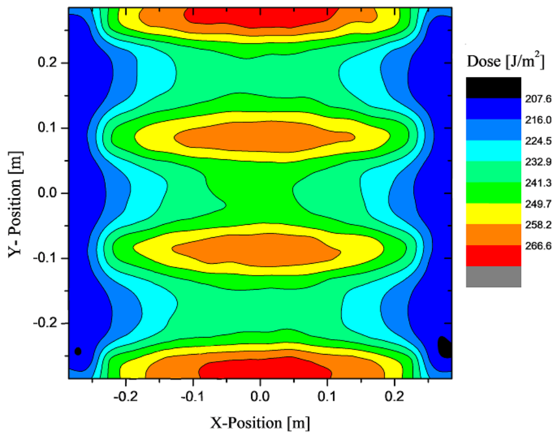

Fig. 5– Far arrangement sample design duct outlet dose map

In Fig-5 duct outlet dose map is given for close arrangement sample design. It can be said that the amount of dose received by the particles are more regularly distributed compared to the closely spaced design. In addition, as expected, the particles in the flow around the lamp receive a higher dose than the particles in other parts of the flow.

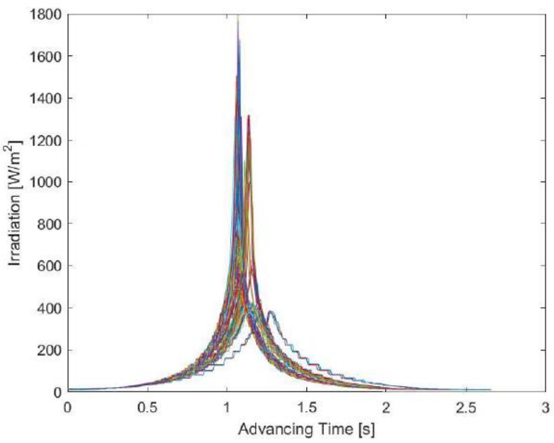

Fig. 6– Far arrangement sample design the intensity of radiation to which particles are exposed during their movement.

In Fig. 6, the radiation intensity that each particle is exposed to during its movement is given depending on time. For this design, it is observed that a particle moving near the lamps in the middle section of the duct is exposed to a maximum radiation intensity of 1800 W/m^2. For the general coronavirus family, the average dose value obtained in this design is 237.51 J/m^2. When the inactivation amount of this design is calculated with Equation-13, it can be said that the inactivation amount is 90.05%. However, when Fig. 7 is examined, there are particles that have not received sufficient dose in the outlet section. Fig. 7 shows that particles that have received enough dose in the outlet section with the green area (%36.75), and the particles that have not received the enough dose with the red area (%63.25). For this reason, it is incomplete to question the adequacy of a UV system design with only the average dose amount.

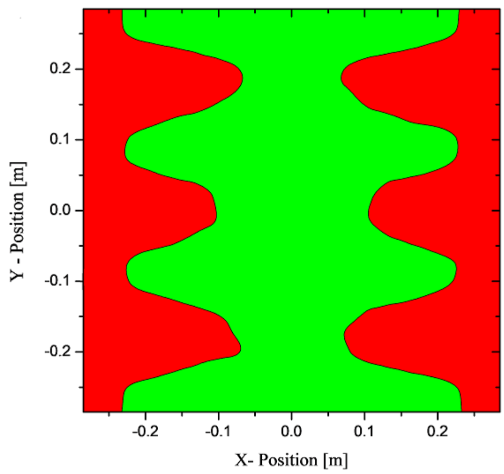

Fig. 7– Far arrangement sample design duct outlet safe zone investigation

3.2 Close Arrangement Sample Design

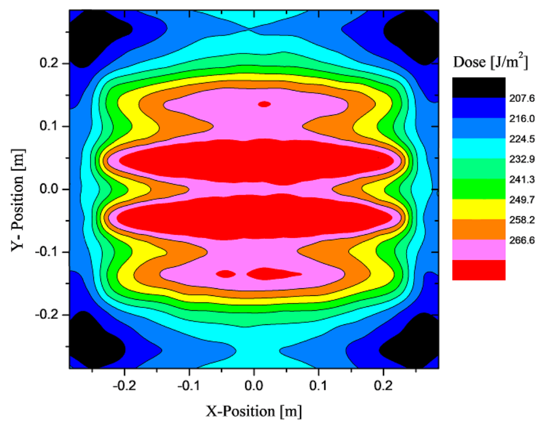

Fig. 8– Close arrangement sample design duct outlet dose map

Fig. 8 shows the dose distribution of the particles in the outlet section of the close arrangement sample design. Particles exposed to intense radiation is concentrated at the midpoint of the cross-section, in contrast to the far arrangement sample design. In Fig. 9, the radiation intensity that each particle is exposed to during its movement is given depending on time. For this design, it is observed that a particle moving near the lamps in the middle section of the duct is exposed to a maximum radiation intensity of 2500 W/m^2 as expected.

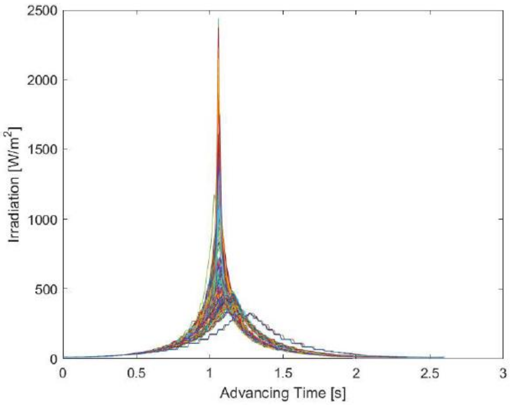

Fig. 9– Close arrangement sample design the intensity of radiation to which particles are exposed during their movement.

The distribution of the safe zone in the outlet section of the arrangement sample design is given in Figure 10. While the safe zone area indicated in green on the exit section is 46%, the risk zone area is 54%.

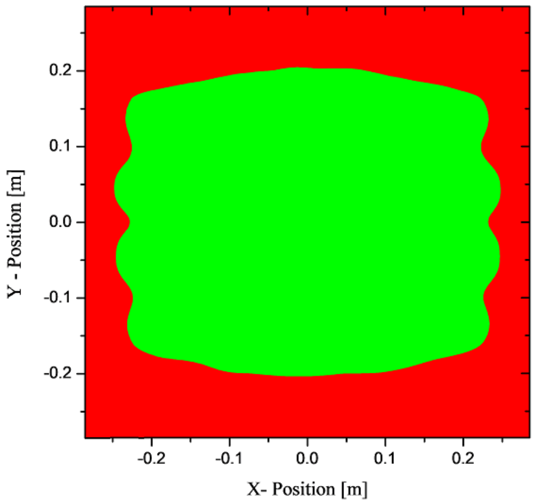

Fig. 10– Close arrangement sample design duct outlet safe zone investigation

3.3 Reactor Design

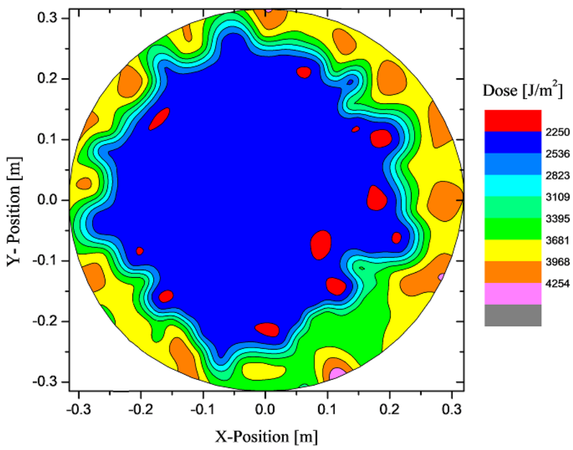

Fig. 11– Reactor design duct outlet dose map

In the reactor design for UV-resistant microorganisms, the dose distribution at the outlet is observed as in Fig. 11. The findings show that the dose amount of the particles increases around the radially arranged lamps and decreases along the channel center axis. Main reason of this, it can be said that the particles close to the center move approximately 1.5 times faster than the other particles, considering the fully developed velocity profile.

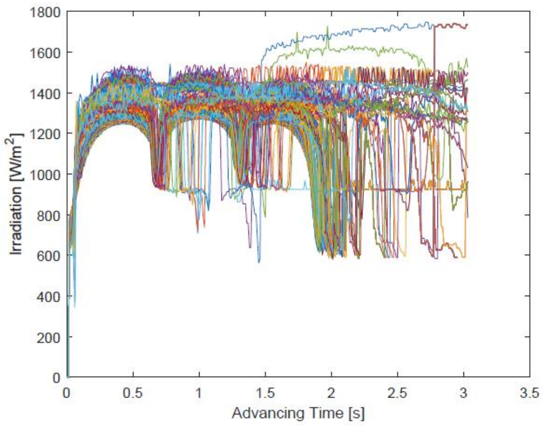

Fig. 12– Reactor design the intensity of radiation to which particles are exposed during their movement.

In Fig. 12, the radiation distribution of the particles in the reactor during their movement is given. As can be seen in the findings, the amount of radiation exposed between the lamp sets placed at 3 levels reached the maximum level. In addition, some particles were attached to the lamp side surfaces and could not exit through the flow channel.

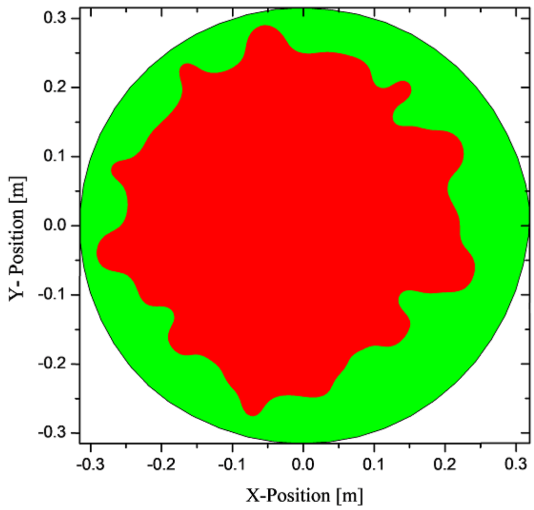

Fig. 13– Reactor design duct outlet safe zone investigation

In Figure-13, the safe zone distribution of the outlet section in the reactor design is given. Here, while the safe zone area, which is determined by the green color and concentrated around the lamps, is 41.91%, the risk zone area is 58.09%. On the other hand, a total power consumption of 37.2 kW is required for the operation of this system. The average dose value calculated for this power consumption is 2930.4 J/m^2. Again, when Equation -13 is applied, D90 inactivation can be achieved.

4. Conclusions

Within the scope of this study, the inactivation performance of four UV lamps with 75 W UV power, positioned perpendicular to the air flow in two different layouts (far and close arrangement), are investigated in the air duct. In addition, a reactor design for inactivation of microorganisms with high resistance to UV radiation is investigated. The important results can be summarized as follows;

- The average dose obtained with four lamps with 75 W UV radiation is 237.51 J/m^2. D90 inactivation performance is achieved. However, when the dose distribution at the duct outlet and the safe zone are examined, it can be say that there are particles that leave the channel without receiving sufficient dose.
- In the proposed designs, moving the lamps away from each other allows a more regular dose distribution in the output section. However, the safe zone area decreases from 46% to 36.75%.
- A more detailed design should be considered for microorganisms resistant to UV radiation. Although an average of 2930.4 J/m^2 UV dose is obtained in the examined design and D90 performance is achieved, when the outlet section is examined, it is observed that a risky zone area is formed around the axis of the air duct.
- For the reactor design, the system power consumption is calculated as 37.2 kW. (Total UV efficiency is %20)
- In the reactor design made by the authors [1], the examination in previous studies differs in the outlet section dose and safe zone area found by this study. The main reason for this is the assumption that the UV dose distribution and the safe zone area calculated in the duct outlet within the scope of the previous study are assumed to move along a straight line with a constant and the same with inlet velocity. Within the scope of this study, particle analyzes are carried out with the DPM model and the particles carried out their movements in accordance with the velocity profile formed in the in-channel flow. The uniform distribution of the lamps around a radial path, limits the channel cross-sectional area through which the particles will move. This caused an increase in the velocity of the air flow along the channel axis and shortened the exposure time of the particles to UV radiation. On the other hand, the problem being solved is a Hagen - Poiseuille flow and when the air flow velocity profile is examined, it can be observed that the maximum velocity is along the duct axis. This explains the difference with the authors' previous work. For this reason, particle analyzes should be done in modeling the UV-Disinfection system and more realistic results / predictions should be obtained with these analyzes.

In addition to all these, another aim of the study is to present how UV systems should be analyzed with numerical methods, with a scientific methodology. Inspections in which different disinfection systems such as climatic data of the air and filtering and UV systems are used together should also be carried out in the duct. The most important parameter among the specified climatic data is the relative humidity of the air. The detailed effects of relative humidity on both system inactivation efficiency and power consumption can be discussed in future studies.

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