

# New analysis method for radiation modeling and sterilization effect of UVC-LED module

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**Abstract.** With the growing application of deep ultraviolet light-emitting diodes (UVC-LEDs) in water treatment, it is important to simulate the significance of modeling their output for designing UV reactors becomes crucial. In this study, we design a UVC-LED package module by 4 chips and set two different total optical powers, which are 8 mW and 12 mW respectively, and each chip wavelength is 280 nm, and the radiation distribution is simulated. Next, the irradiance uniformity under different radiation distances is discussed, and the bactericidal effect is qualitatively analyzed under different environmental mode settings. We found that as the radiation distance becomes larger, the irradiance values decrease, but evenly distributed on the petri dish. In addition, regardless of the optical power level of chips, probably in the range of the petri dish radius of 15 mm or more, the smaller the radiation distance is set, the irradiance is even smaller than those irradiance was set under bigger radiation distance; within 15 mm, the radiation distance is less, the irradiance drops sharply, which means that close-range radiation is not suitable for large-area sterilization, although the average irradiance and local irradiance are improved at this time, they are only concentrated under the light source, and there is a large blind zone in the edge region. If the pathogenic microorganisms used in water are sterilized, it is necessary to fully stir the near-aqueous microbial culture solution to achieve full sterilization. What's more, if highly resistant pathogenic microorganisms want to achieve high-efficiency bactericidal effect, only continuously to increase the total optical power of the UVC-LED chips, set a close radiation distance as possible and stir the culture solution. Through the simulation of the radiation distribution of the model and the analysis of actual situation, we can evaluate the bactericidal effect of the model in the real environment. It will be a feasible and worthy advocate method of analyzing bactericidal efficacy for the rational design of the future UVC-LED model.

## 1. Introduction

Ultraviolet (UV) disinfection is a technology that is discovered very early, it is widely used for current water treatment and food hygiene treatment. Nowadays, a new friendly method was developed to generate UV light, i.e., UV light-emitting diodes (UV-LEDs). With comparing conventional mercury lamps, UV-LEDs feature more advantages in many ways, such as adjustable wavelength from 210 nm



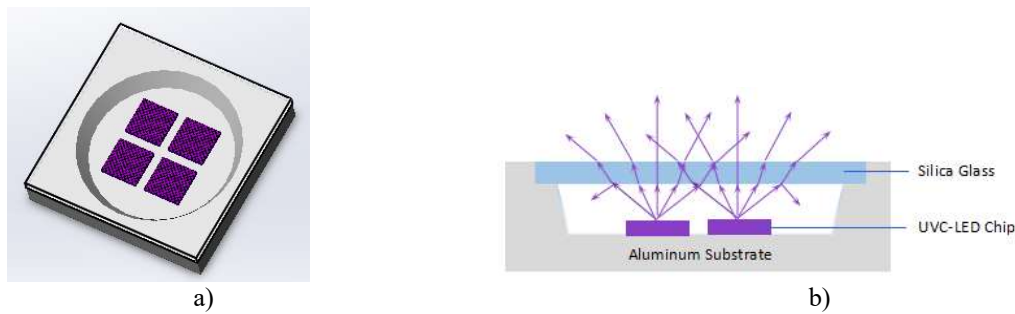
up to visible light, mercury-free, flexible architecture, mechanically robust, instant on-off functionality, low power requirements and long lifetimes [1][2].

UV-LED packaging module output efficiency is also fast improved, except single chips packaging with low efficiency, multiple chip array module which remarkably improves the total output power is include. As some people use the LED modules were equipped with 4 chips and 9 chips to sterilize and get good effect in many experiments [3-5]; but many of them just keep the radiation distance to be set 1 cm and no deep discussion on the the bactericidal effects at different distances. In fact, when designing a module package with multiple chips, the optical power is undoubtedly greatly improved, and it is necessary to explore the radiation distance, which will promote the development of late deep sterilization and large-area sterilization applications. Besides, UVC-LED chips are too expensive at current conclusion, and packaging process is also prone to exist various failures and damages. It isn't suitable for purchasing lots of chips and packaging them for related microbial inactivation experiments, the overall cost is too high. And UVC-LED module is designed to carry out experiment, the process is cumbersome and experimental results obtained are not necessarily close to the real effect. Moreover, the bactericidal effect achieved by different optical powers is basically positively related to UV dose at the same wavelength. Therefore, the application of the corresponding optical simulation software to simulate the UVC-LED model required for sterilization is very important. Virtual software can predict the efficacy of models we need. It is not necessary to conduct complex in vivo experiments to detect and determine which UVC-LED packages and environmental settings are most suitable for microbial sterilization. Although the error of the simulation software exists, it is basically negligible compared with the error that the UVC-LED model is packaged and set to perform specific living experiments.

In this paper, we will discuss the detailed bactericidal efficacy of UVC-LEDs package module which is equipped with 4 chips. Using the tracepro optical simulation software and the existing reliable microbial inactivation experiment data to carry out analysis. Designing the corresponding sterilization mode, focusing on uniformity of the radiation distribution under different radiation distances on the surface of the petri dish, and more qualitative analysis of the influence of radiation distance and irradiance on the sterilization effect, then to predict the appropriate UVC-LED sterilization model in reality. The development of this work will greatly reduce the workload in the actual experimental process, prevent the blind development of the experiment and save the cost of the chip, and provide a pre-effect evaluation for the rational design of the future UVC-LED model.

## 2. Model establishment

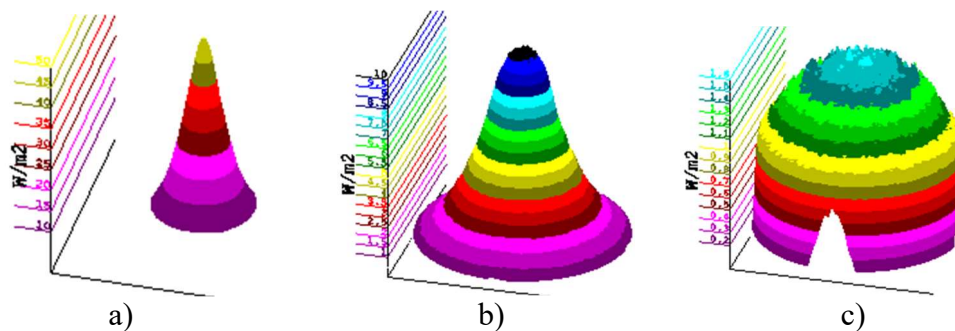
This article selects the UVC-LED package module is equipped with 4 chips as follows figure 1 a), the 4 chips is symmetrically packaged inside, and each UVC-LED chip size is set to  $1.2\text{ mm} \times 1.2\text{ mm} \times 0.15\text{ mm}$ , total UVC-LED module size is set to  $6\text{ mm} \times 6\text{ mm} \times 1.1\text{ mm}$ . Figure. 1 b) shows the light output of UVC-LED package module on the inner and outer surfaces of its quartz in optical simulation, and the wavelength of each chip is set to 280 nm. Although maximum UV light absorption from DNA is reached at a wavelength of around 260 nm [6]. But in current situation, UV-LED chips emitting at 260 nm requires a very high R&D costs, whereas the optical intensity and external quantum output is not better, but the UV-LED with 280 nm wavelength is more effective in the actual inactivation experiment, because 280 nm yields more external output and emits light with high efficiency. Besides, the optical power of single chip is set to 2 mW or 3 mW, that is, the optical power of the whole UVC-LED module is 8 mW or 12 mW, and the illumination angle is  $120^\circ$ . The chip base is packaged with an aluminum substrate, and the uppermost light-emitting surface is sealed with quartz glass. This package form is also the most common.



**Figure 1.** a) UVC-LEDs package module of 4 chips and b) light output of UVC-LEDs module in optical simulation.

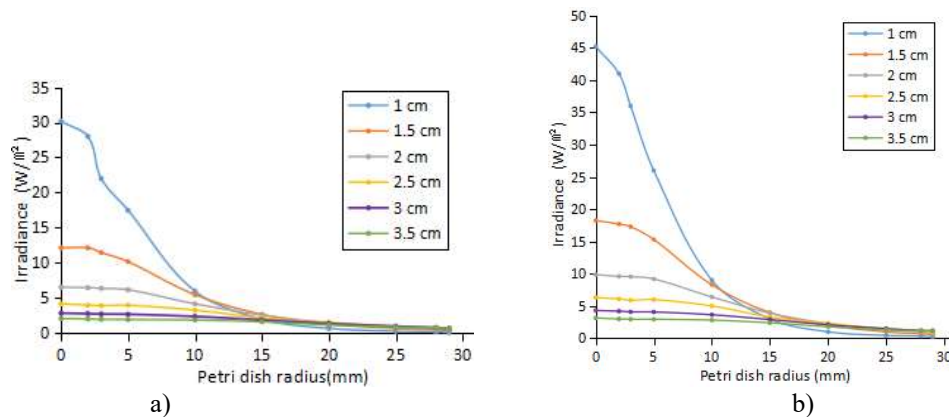
### 3. Simulation analysis and discussion

Figure 2 shows the irradiance distribution on a petri dish with 30 mm radius of the irradiance of the UVC-LED module in the radiation distance of 1 cm, 2 cm and 5 cm, and the optical power is 2 mW. we can be clearly found that when the radiation distance is bigger, the irradiance distribution is expanding, and it can be obtaining a uniform distribution from the center to the edge, The specific changes will be expanded in depth below.



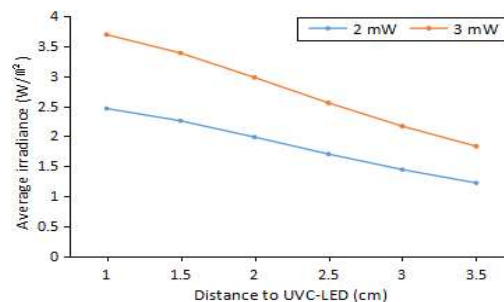
**Figure 2.** Irradiance distribution on a petri dish at different distances: a)  $d=1$  cm b)  $d=2$  cm c)  $d=5$  cm.

In the figure 3, we set the receiving surface radius of the petri dish to 30 mm, which is used as a model for the culture dish in the experiment, focusing on the diffusion of the irradiance value from the center of the culture dish to the edge at different radiation distances from the ultraviolet light source to the receiving surface, and the latter step will delve into the bactericidal effect. The observed radiation distances were 1 cm, 1.5 cm, 2 cm, 2.5 cm, 3 cm and 3.5 cm, respectively, and the total optical power of UVC-LED modules used in figure 3 a) and figure 3 b) were 8 mw and 12 mw, respectively. Besides, we can see that regardless of the optical power level of the chip, probably in the range of the petri dish radius of 15mm or more, the smaller the radiation distance is set, the irradiance is even smaller than those irradiances was set under bigger radiation distance; within 15mm, the radiation distance is less, the irradiance drops sharply. This shows that close-range illumination is not suitable for large-area sterilization. But with the bigger and bigger radiation distance, the irradiance distribution is also more and more well-proportioned on petri dish. Thereby, as the total optical power of the package module continues to increase, it is expected to break through the environmental sterilization of only 1 cm radiation distance in long-term experiments, so as to select a more distant or deep-water layer sterilization method, and is efficiently sterilized by a uniform radiation distribution pattern.



**Figure 3.** irradiance delivered to the surface of the petri dishes in different distances from radiation source, using different model which the total optical power of LED is a) 8 mW and b) 12 mW.

The above discussion is about the specific irradiance distribution on petri dish. Next in figure 4, the average irradiance of UVC-LED modules of the two optical powers at different radiation distances is discussed, long ago we known as the radiation distance increases, the irradiance decreases, but through simulation analysis, we found when the optical power of the chip is larger, the irradiance decreases with the radiation distance, and its decline is even larger, indicating that the irradiance attenuation is more serious. Therefore, it would be an important issue to figure out some ways to reduce the irradiance attenuation when the radiation distance increases while the total power is increased.



**Figure 4.** The average irradiance on petri dish which optical power of each chip is 2 mW and 3 mW.

For the discussion of irradiance, we will eventually implement the analysis of specific bactericidal effects. In table 1, we surveyed several recent representative documents and obtained some reliable data. From table 1, we can first reflect the UV dose of different microorganisms are different, then, we can compare the sensitivity of these microorganism to UV or the inactivated ability of several pathogens as follows:  $\Phi$  X174 < Escherichia coli < Bacillus subtilis < MS2 or Q  $\beta$  < adenovirus [7-11]. In addition, through a large number of previous simulation analysis and the specific microbial experimental inactivation data from the table, we can conduct deep sterilization analysis for specific microorganisms. Taking microbes inactivated to achieve 4 log inactivation, it can be considered as safe sterilization [12]. And we know the logarithm of inactivation is directly proportional to the UV dose, as the formula of the first-order model of Chick-Watson is described as follows [13]:

$$\text{Log}(N_0/N) = K \cdot \text{UV dose}$$

The formula can be seen the UV dose is directly related to the inactivation logarithm under different environmental settings, so UV dose can be used as an indirect criterion for bactericidal effect, which is similar to the number of inactivation inactivation as a standard for safe sterilization. UV dose is calculated by the formula of the product of the irradiance and the exposure time. Then, we can analyze the bactericidal efficacy of the model based on UV dose of the existing reliable experiments.

From table 1, it can be seen that *Escherichia coli* is the most easily inactivated microorganism, reaching 4 log inactivation and nearly requiring UV dose of 14 mJ/cm<sup>2</sup>[8][9]. From figure 4, it can be seen that the optical power of single chip is 3 mW, the UVC-LED package module has about an average irradiance of 3 W/m<sup>2</sup> when the radiation distance is 2 cm. It can be analyzed and exposed for about 60 seconds, under this environment setting, the UV dose of 18 mJ/cm<sup>2</sup> can be achieved 4 log inactivation of *Escherichia coli*. If the radiation distance is set to 1cm, although the average irradiance is improved, it can be analyzed from figure 3 that the environmental setting at this time is not suitable for large-area sterilization of close-range air surface microorganisms, the irradiance is concentrated only directly under the light source, and there is a large blind zone in the edge area. If pathogenic microorganisms from water are used for sterilization, it may be feasible to achieve more comprehensive sterilization of microorganisms on the surface of the near water layer by adding a magnetic stirrer tool. As in the experimental method they used in table 1, many of them set a radiation distance of 1 cm, and a magnetic stirrer was added to the bottom of the culture dish containing the bacterial liquid to fully agitate to achieve full sterilization. If you want to achieve relatively large area of air sterilization, you can increase the radiation distance, or achieve large-area sterilization by frequent moving light source equipment under close-range illumination, but exposure time can be considered. It also be seen from the table that adenovirus is a relatively strong UV-resistant microorganism, achieving 4 log inactivation and need UV dose of nearly 90 mJ/cm<sup>2</sup>[9]. For such highly resistant microorganisms, for achieving an efficient sterilization, only continuously increasing the total optical power of light source, being set the radiation distance as relatively close as possible, and stirring is required to achieve an effective sterilization from previous irradiance distribution.

**Table 1.** The inactivation effect in different microorganism by 280nm wavelength UVC-LEDs.

Microorganism	Log inactivation	UV (dose mJ/cm <sup>2</sup> )	Dose response per log inactivation (mJ/cm <sup>2</sup> )	Reference
<i>Bacillus subtilis</i>	4	48	12.00	Oguma Kumiko, 2018
<i>Escherichia coli</i>	4	13.8	3.45	Oguma Kumiko et al.,2013
<i>Escherichia coli</i> K12	3	9	3.00	Beck et al.2017
adenovirus	4	89	22.25	Beck et al.2017
MS2	2	38.5	19.25	Beck et al.2017
Q $\beta$	1	13.3	13.30	Oguma Kumiko et al.2015
Q $\beta$	4	75	18.75	Oguma Kumiko, 2018
$\Phi$ X174	3.2	8.9	2.78	Aoyagi et al., 2011

#### 4. Conclusion

With the design and analysis of the corresponding sterilization mode of UVC-LEDs module, we get much useful view and more qualitative analysis about the uniformity of the radiation distribution under different radiation distances and the influence of UV dose on the sterilization effect. We found the overall irradiance value decreases as the radiation distance becomes larger, but the irradiance attenuation trend on the culture dish is more uniform, resulting in a more uniform radiation distribution. Regardless of the optical power level of UVC-LED modules, when the radiation distance is set smaller and smaller, the irradiance will decrease sharply within a certain range of the radius of the petri dish surface. When the radius is larger than this radius, the irradiation is irradiated that the degree will be reduced to a smaller irradiance than the setting of its radiation distance, which means close-range illumination is not suitable for large-area sterilization, although average irradiance and local irradiance under close-range radiation are improved, but the irradiance at this time is only concentrated directly under the light source, and a large blind zone exists in the edge region. So this environment setting isn't suitable for large-area sterilization of close-range air surface microorganisms; sterilization of waterborne pathogenic microorganisms also requires thorough agitation of near-aqueous microbial culture solution to achieve

full sterilization. When highly resistant pathogenic microorganisms are sterilized, from analysis of the irradiance distribution, for achieving high-efficiency bactericidal effect, only the total optical power of chips is continuously increased and the radiation distance is set as relatively close as possible, and possibly achieve an effective sterilization by stirring the culture solution. The analysis of bactericidal effect also shows the close-range high-flux is suitable for sterilization to small-area point light sources. When applications are sterilized on air surface, UV source devices should be frequently moved to avoid the unsterilized edge portion. It is similar to add a stirrer when sterilizing waterborne pathogenic bacteria.

Through the simulation of the radiation distribution of the model and the analysis of the actual situation, the evaluation of the bactericidal effect of the model in the real environment can be achieved and a appropriate UVC-LED sterilization model can be predict. it can be regarded as a feasible and worthy advocate method of analyzing bactericidal efficacy and and provide a pre-effect evaluation for the rational design of the future UVC-LED model. It also will greatly reduce the workload in the actual experimental process, prevent the blind development of the experiment and save much cost.

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### References

- [1] Shur, M.S., Gaska, R., 2010. Deep-ultraviolet light-emitting diodes. *IEEE Trans. Electron Dev.* 57, 12-25.
- [2] Würtele M.A., T. Kolbe, M. Lipsz. et al., 2011. Application of GaN-based ultraviolet-C light emitting diodes e UV LEDs e for water disinfection. *Water Res.* 45, 1481-1489.
- [3] Guo-Qiang Li, Wen-Long Wang, Zheng-Yang Huo. et al., 2017. Comparison of UV-LED and low pressure UV for water disinfection: Photoreactivation and dark repair of *Escherichia coli*. *Water Res.* 126, 134-143.
- [4] Merve Pelvan Akgün, Sevcin Ünlütürk, 2017. Effects of ultraviolet light emitting diodes (LEDs) on microbial and enzyme inactivation of apple juice. *International Journal of Food Microbiology.* 260, 65-74.
- [5] Chevrement A.-C., Farnet A.-M., Sergent M. et al., 2012. Multivariate optimization of fecal bioindicator inactivation by coupling UV-A and UV-C LEDs. *Desalination.* 285, 219-225
- [6] Bolton, J.R., Cotton, C.A., 2008. *The Ultraviolet Disinfection Handbook*. American Water Works Association, Denver.
- [7] Oguma Kumiko, Surapong Rattanakul, 2018. Inactivation kinetics and efficiencies of UV-LEDs against *Pseudomonas aeruginosa*, *Legionella pneumophila*, and surrogate microorganisms. *Water Res.* 130, 31-37.
- [8] Oguma Kumiko, Ryo Kita , Hiroshi Sakai. et al., 2013. Application of UV light emitting diodes to batch and flow-through water disinfection systems. *Desalination* 328, 24-30.
- [9] Beck Sara E., Ryu Hodon, Boczek Laura A. et al., 2017. Evaluating UV-C LED disinfection performance and investigating potential dual-wavelength synergy. *Water Res.* 109, 207-216
- [10] Oguma Kumiko, Surapong Rattanakul, James R. Bolton, 2015. Application of UV Light-Emitting Diodes to Adenovirus in Water. *J. Environ. Eng.* 142(3), 04015082
- [11] Aoyagi, Y., Takeuchi, M., Yoshida, K. et al., 2011. Inactivation of bacterial viruses in water using deep ultraviolet semiconductor light-emitting diode. *ASCE.* 137 (12), 1215-1218.
- [12] US Environmental Protection Agency, 2006. National Primary Drinking Water Regulation: Long-Term 2 Enhanced Surface Water Treatment Rule; Final Rule. *Federal Register*.
- [13] Hijnen, W.A., Beerendonk, E.F., Medema, G.J., 2006. Inactivation credit of UV radiation for viruses, bacteria and protozoan (oo)cysts in water: a review. *Water Res.* 40 (1), 3-22.