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The Optical Characteristics of 20 Watt Far-UVC Light and Its Application for Disinfection Chamber

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Abstract

The far-ultraviolet C (UVC) light has been used recently as an alternative disinfection system to deactivate the novel coronaviruses that cause coronavirus disease (COVID-19) without introducing any health damage to humans. We investigate that the far-UVC light from far-UVC excimer lamps (BEST 20 Watt) is a promising candidate for a far-UVC disinfection system to prevent human-to-human transmission of COVID-19. The optical characterization of far-UVC excimer lamps was examined. The maximum irradiance of the far-UVC excimer lamps is 219 nm, which is known to have antimicrobial capabilities on microorganisms, including coronaviruses. We propose a design of a disinfection chamber system based on eight 219 nm far-UVC excimer lamps which are attached vertically about 35 cm to each other, and the irradiation angle was installed at the angle of approximately 120° in order to optimize the irradiation of far-UVC light to a human body. For microorganism inactivation at a distance of around 10 cm from the human body, 219 nm far-UVC excimer lamps require less than 5 seconds of irradiation time and the required intensity of 840 $\mu W/cm^2$ at a low dose of 3000 $\mu J/cm^2$. We recommend that our proposed disinfection chamber can be used for humans and applied in public areas to decrease the spread of COVID-19 without any adverse health effect.

Keywords: COVID-19, disinfection chamber, far-UVC, optical characteristics.

I. Introduction

In late December 2019, early cases of novel coronavirus infection causing coronavirus disease (COVID-19) were detected in Wuhan City, Province of China. The novel coronaviruses have been spreading quickly not only across China but also to other countries through air travel, such as Japan [1], Thailand [2], the Republic of Korea [3], the United States [4] to Indonesia [5]. Due to its rapid spreading rate to the rest of the world, World Health Organization declared COVID-19 a global pandemic. Coronaviruses belong to a large group of enveloped viruses with single-stranded positive-sense ribonucleic acid (RNA) [6] that can infect avian species or mammals and humans through human-to-human transmission. The coronaviruses can be transmitted from infected persons from their mouth or nose in the form of droplets or aerosols when they cough, speak, sneeze or even breathe. A healthy person can also be infected by touching surfaces contaminated by coronaviruses and not washing their hands properly before touching the nose, eye, and mouth [7]. Therefore, knowing ways to lower the risk of coronavirus infection is essential.

There are several ways served as the prevention from coronaviruses: 1. keep a physical distance from other people; 2. wear a mask when interacting with others; 3. wash hands with water and soap or use hand sanitizer frequently; 4. disinfect any surfaces regularly because the coronaviruses may remain on surfaces from hours to days [8]. In addition, disinfection is a common method to inactivate coronaviruses or other hazardous microorganisms that contaminate surfaces. Disinfection

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can use chemical solutions such as chlorine [9], formaldehyde [10], or quaternary ammonium compounds [11]. Chemical disinfectant on a small surface is still acceptable but not recommended for disinfecting people or air in public areas. Spraying people with chemical disinfectants can be harmful to humans due to adverse health effects, such as skin and eye irritation [12], [13], gastrointestinal effects (causing nausea or vomiting) [14], and respiratory disorders [15]. To lower the health risk, another disinfectant system without chemical agents was developed that are more suitable for disinfecting people or air in public areas. A disinfection system using ultraviolet (UV) irradiation is an alternative method that can effectively inactivate bacteria and viruses without any chemical agents.

Ultraviolet (UV) light is electromagnetic radiation with wavelength ranges between 10 nm to 400 nm. According to its wavelength range, UV light is divided into three spectrums: UVA (from 320 nm to 400 nm), UVB (280 nm to 320 nm), and UVC (200 nm to 280 nm). UVC spectrum with a low wavelength range of 202 to 220 nm is known as far-UVC radiation. UV light has been demonstrated to be capable of inactivating fungi, bacteria, and viruses [16], [17]. Generally, conventional UV disinfection systems utilize germicidal lamps that produce UV radiation C (UVC) with peak emission around 254 nm [18]. Rubio-Romero and collaborators show that the 254 nm wavelength of UVC radiation has high efficacy in disinfecting disposable masks during the COVID-19 pandemic [19]. However, the disinfectant system of 254 nm UVC light is not recommended for direct exposure to human bodies and public area use because the radiation under 254 nm of UVC wavelength is hazardous, leading to cataracts [20] and skin cancer [21]. Shorter UVC wavelengths from 207 nm to 222 nm, namely far-UVC radiation, have antimicrobial properties as effective as 254 nm of UVC wavelength but are harmless to the eyes or skin due to their small penetration depth into the human eyes or skin [22]. Furthermore, far-UVC radiation is more suitable for disinfecting humans and safer for public area use.

In this work, we used 219 nm of 20 W far-UVC excimer lamps to study the optical characteristics that can be applied as an alternative disinfection system to inactivate viruses during the COVID-19 pandemic without any chemical agents. We measured the correlation of far-UVC irradiation intensity with the distance from the light source to the target object. We analyzed the far-UVC irradiation time according to the intensity-distance measurement with the far-UVC irradiation dose of 3000 μJ/cm^2 according to the experiment performed by Kitagawa *et al*. [23]. They confirmed that the 3000 μJ/cm^2 of far-UVC irradiation dose can effectively inactivate the coronaviruses around 99.7%. We also propose the design of a disinfection chamber that is less harmful to people comprising eight 20 W far-UVC excimer lamps. We propose an effective model for the disinfection chamber by determining the eight 20 W far-UVC excimer lamps location to improve the optimization of the disinfection process. We also measured the far-UVC intensity under various distances to show the effective irradiation time for the disinfection process for humans. We found that the disinfection process for humans can be achieved in less than 5 s. with the distance to the eight far-UVC light sources about 10 cm and an intensity of 840 μW/cm^2. Accordingly, the results suggest that our disinfection system model gives uniform irradiation in the chamber; thus, excessive far-UVC irradiation in certain positions is minimal.

II. Methods

A. Far-UVC Excimer Lamps Characteristics

The detailed experimental to identify the far-UVC lamp to the application of far-UVC excimer lamp into the disinfection chamber is shown by the flow chart in Figure 1. For this experiment, we used a far-UVC excimer lamp (BEST 20 W, PT. Pulut Jaya Ersinalsal, Indonesia) based on a krypton-chlorine (Kr-Cl) gas mixture. The emission spectra of the far-UVC excimer lamp were obtained using UV-Visible spectroscopy (Maya 2000 Pro Spectrometer) sensitive to the wavelength range from 200 nm to 400 nm. The optical characteristics of far-UVC excimer lamps were measured using a Spectral Irradiance Colorimeter (HP360) under different distances from the target to far-UVC light sources, ranging from 0 to 20 cm. We estimated the irradiation time using the correlation between the irradiation dose that efficiently inactivates the coronaviruses up to 99.7% [23] and the intensity of far-UVC light as formulated by Kowalski *et al.* [17].

The required far-UVC energy to inactivate the microorganism, also known as the far-UVC dose, is a combination component between three UVC parameters, including the UVC power (in Watts unit), area of UVC irradiation (in square centimeters -cm^2- unit), and irradiation time (in seconds -s- unit). The first and second components are the far-UVC intensity (in W/cm^2 unit) that will be measured in this work. The far-UVC dose used in this work follows Kitagawa's [23] work (about 3000 μJ/cm^2).

B. Design of Far-UVC Disinfection Chamber

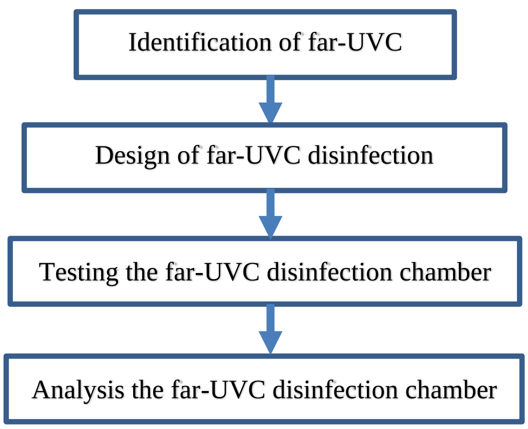

Figure 1. The flow chart of the experimental steps in this work

We designed the disinfection chamber using eight far-UVC excimer lamps with the chamber dimension of 90 cm × 100 cm × 200 cm. To reach the optimum far-UVC irradiation, the disinfection chamber wall was made from stainless sheets with reflectivity close to 99.9%. The vertical distance between each installed far-UVC excimer lamp was 35 cm with an irradiation angle of 120°.

C. Characterization of the Far-UVC Disinfection Chamber

For the far-UVC disinfection chamber model, we measured the irradiation time with various intensities and distances from a human body to the far-UVC excimer lamps. In contrast, the irradiation dose remained constant at 3000 μJ/cm^2. The intensity was varied from 4200 μW/cm^2 to 294 μW/cm^{2,} and the distance was set from 0 cm to 40 cm.

III. Result and Discussion

A. Optical Characteristics of Far-UVC Excimer Lamps

Figure 2 shows the measured emission spectra from a far-UVC excimer lamp used in this experiment. The emission spectra have the maximum emission at 219 nm and also show lower fluences at the higher wavelength from 237 nm to 260 nm. The wavelength of maximum emission is in the far-UVC spectra range (from 207 nm to 222 nm), which has an effective antimicrobial property without causing skin or eye damage as compared to the 254 nm UVC light [22], [24].

To optimize the inactivation of coronaviruses, we estimated the irradiation time by measuring the intensity versus distance of the far-UVC excimer lamp to the target object. Figure 3 illustrates the radiation intensity by distance from the 219 nm far-UVC excimer lamp. Starting with 100% intensity value at 0 cm distance, the intensity at 10 cm distance is incredibly decreased to 19% from the initial intensity. Then, the measured intensity is only 9% of the initial intensity at a distance of 30 cm.

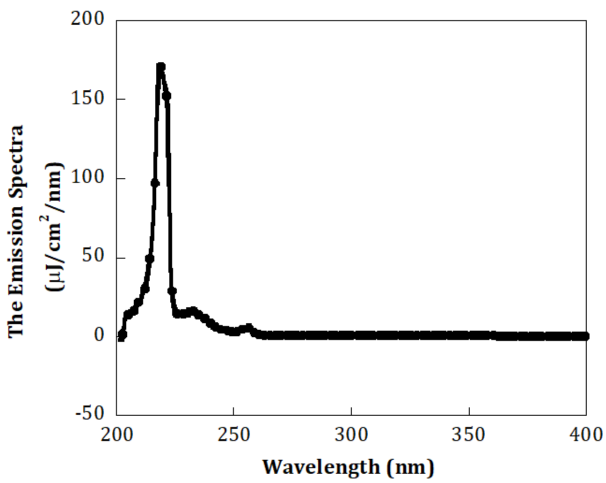

Figure 2. The measured emission spectra of far-UVC excimer lamps (BEST 20 W, the main peak of 219 nm)

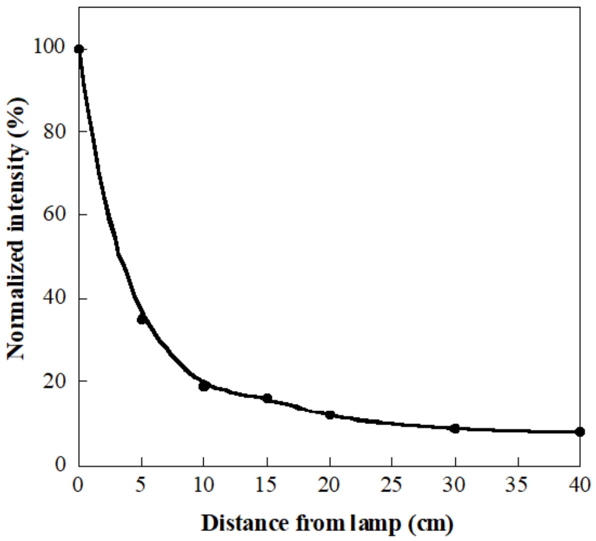

Figure 3. Normalized irradiation intensity by distance from the 219 nm far-UVC excimer lamp

These results indicate an inverse relationship between the far-UVC excimer lamp to target object distance and the far-UVC intensity. The intensity rapidly decreases with increasing distance. From these results, we can calculate the irradiation time using. This formula was proposed by Kowalski *et al.* [25] by determining the measured intensity value at a certain distance with a certain far-UVC irradiation dose.

Table 1 presents the calculated far-UVC irradiation time for several intensity values and distance to the target object for a far-UVC irradiation dose of 3000 μJ/cm^2. From Table 1, the far-UVC intensity of 4200 (J/cm^2 at 0 cm) requires an irradiation time of 0.71 s. The required irradiation time is increased to 7.94 s at a 30 cm of distance with an intensity of 378 μJ/cm^2. A previous report demonstrated that a 222 nm far-UVC irradiation time of 30 s with the far-UVC irradiation dose of 3000 μJ/cm^2 and intensity of 100 μW/cm^2 can effectively reduce around 99.7% of viable coronaviruses [23]. We found that the far-UVC irradiation time required to inactivate viruses (with the far-UVC irradiation dose of

Table 1
The Calculated Far-UVC Irradiation Time for Several Intensity Values and Distance to the Target Object for Far-UVC Irradiation Dose of About 3000 μJ/cm^2

Distance* (cm)	Normalized intensity (%)	Intensity (μW/cm^2)	Irradiation time (s)
0	100	4200	0.71
10	19	789	3.76
20	12	504	5.95
30	9	378	7.94
40	8	334	8.92

*Distance: the distance between the far-UVC excimer lamp to the target object

3000 μJ/cm^2) is increased with the decrease of far-UVC intensity and the increase of far-UVC to target object distance. From our result, we recommend using a 219 nm far-UVC excimer lamp for the disinfection chamber application to find the optimal far-UVC irradiation time used for humans.

B. Design and Characterization of the Far-UVC Disinfection Chamber

Figure 4 illustrates the proposed design of the disinfection chamber using 219 nm far-UVC excimer lamps with the dimension of 90 cm × 100 cm × 200 cm. The configuration of far-UVC excimer lamps was explained in the materials and methods section. Figure 5 represents the constructed far-UVC disinfection chamber utilizing eight far-UVC excimer lamps from (a) the front side and (b) the left side.

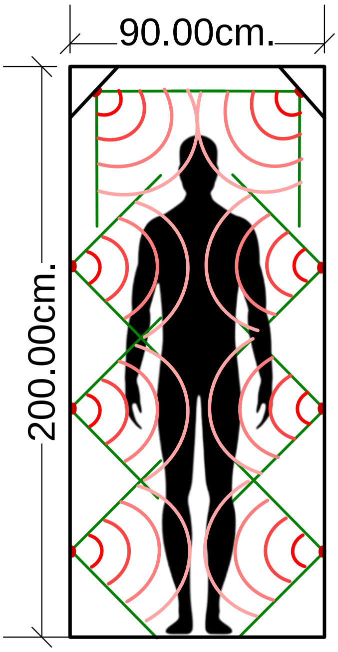

Figure 4. The proposed design of the disinfection chamber using eight of 219 nm Far-UVC excimer lamps. (Red dots indicate the placement of the lamps, and radial lines show the distance of 10 cm, 20 cm, 30 cm, and 40 cm, from the center of lamp correspond with the minimum radiation time of 0.7 s, 3.5 s, 7.1 s, 8.9 s, and 10.2 s respectively. Green lines are vertical and horizontal (not shown) radiation of the lamp for 90 degrees)

(a) (b)

Figure 5. The constructed far-UVC disinfection chamber utilized eight far-UVC excimer lamps from (a) Front side, and (b) Left Side

To investigate the correlation between far-UVC intensity and the irradiation time for the characterization of our 219 nm far-UVC disinfection chamber, we measured the far-UVC irradiation time under various intensities and various distances to the human body from 0 cm to 40 cm. The measured far-UVC irradiation time with various intensities and distances from far-UVC excimer lamps to the human body is described in Table 2. We found that the far-UVC irradiation time requires less than 9 s at a 30 cm distance. Therefore, the minimum far-UVC irradiation time required to inactivate 99.7% of viruses is about 9 s. To shorten the far-UVC irradiation time, it is required to increase the intensity twice or thrice the initial value. For example, if we increase the intensity to 8000 μW/cm^2, the required far-UVC irradiation time becomes less than 5 s at a 30 cm distance. From (1), the larger intensity gives the less far-UVC irradiation time required to inactivate the viruses.

From Table 2, the far-UVC excimer lamp has an average intensity of 840 μW/cm^2 at a distance of 10 cm and requires less than 5 s to inhibit the microorganism and virus's growth (with the irradiation of 3000 μJ/cm^2). Further, as the distance increase to 40 cm, the intensity decreases to 294 μW/cm^2 and the irradiation time increases to 10.2 s. Using eight far-UVC excimer lamps for our disinfection chamber, as described in Figure 3, uniform irradiation exposure to a human body is achievable. Therefore, the far-UVC excimer lamp position (in Figure 3) can minimize the excessive irradiation of any human body parts. To optimize the far-UVC disinfection chamber performance, it is recommended that users rotate their bodies at least once inside the chamber. Our previous experiment used one far-UVC lamp with 150 W and a wavelength of 222 nm as a sterilization lamp used in a closed room or a building [26]. We found that our 222 nm far-UVC sterilization lamp is safe for human skin and eyes compared to UVC light with a wavelength of 254 nm [26]. A previous study by Bulchan *et al.* [27] reported the correlation of the far UVC intensity with the distance from the far UVC light source. They simulated the irradiation from a single far UVC lamp of 12 W in the air-filled box and measured the far UVC intensity with different light source positions. The results agree with our results that the far UVC

TABLE 2
THE MEASURED FAR-UVC INTENSITY FOR VARIOUS DISTANCES AND ITS CORRELATION IRRADIATION DOSE TO INHIBIT THE MICROORGANISM AND VIRUS'S GROWTH RATE OF ABOUT 3000 μJ/CM^2. THE DISTANCE IS DEFINED AS THE DISTANCE BETWEEN EACH FAR-UVC EXCIMER LAMP AND TO THE HUMAN BODY

D = 0 cm		**D = 10 cm**		**D = 20 cm**		**D = 30 cm**		**D = 40 cm**	
I (μW/cm^2)	T (s)	I (μW/cm^2)	T (s)	I (μW/cm^2)	t (s)	I (μW/cm^2)	t (s)	I (μW/cm^2)	t (s)
4200	0.71	840	3.57	420	7.14	336	8.93	294	10.20
6000	0.50	1200	2.50	600	5.00	480	6.25	420	7.14
8000	0.18	1600	1.88	800	3.75	640	4.69	560	5.36

intensity is exponentially decreasing with the increase of the light source distance, as shown in Figure 2.

Sun *et al.* proposed a disinfection system utilizing a UVC light source [28]. They reported that a system of high-intensity-short UVC irradiation time has the same disinfection effect as the low-intensity-longer irradiation time. The optimum UVC irradiation was achieved at a distance from 1.25 cm to 1.5 cm and irradiation time from 10 s to 18 s. Therefore, the longer irradiation time or the higher UVC intensity would result in a better disinfection effect. Recently, Eadie *et al.* [29] demonstrated that the KrCl excimer (far UVC lamp with a wavelength of 222 nm) significantly decreased the transmission of airborne viruses, including severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2). The 222 nm far-UVC lamp irradiated a room-size chamber filled with aerosolized *Staphylococcis aereus*. Their design shows that the far-UVC excimer lamp can inactivate the aerosolized *Staphylococcus aereus* effectively with a 98% reduction in less than 5 min in a room-size chamber. In addition, the simulation study by Welch *et al.* [30] shows that the human coronavirus can be inactivated by a low dose of far UVC irradiation with a wavelength of 222 nm. They can estimate the susceptibility constant of airborne human coronavirus, which is close to 99.7% at a low dose far UVC irradiation of 12.4 cm^2/mJ. These results are in good accordance with our result that the far UVC in the wavelength range of 200–235 nm can highly decrease the airborne pathogens, including coronavirus. Thus, the far UVC is suitable for the disinfection system for public areas.

In addition, the disinfection chamber has been successfully demonstrated by the faculty of engineering, university of Indonesia (FTUI) working with the FTUI Alumni Association in an attempt to decrease the rapid transmission of COVID-19 in Indonesia [31]. They reported that the required irradiation time of 5 *s* to 10 *s* can inactivate about 88–99% of microorganisms and coronaviruses attached to human attires. However, the intensity of the disinfection chamber that FTUI developed is not documented. Moreover, the addition of far-UVC excimer lamps may result in increased intensity. However, to prevent the human skin and eyes damage caused by far-UVC radiation, the American conference of governmental industrial hygienists (ACGIH) recommends the maximum irradiation dose of 3000 $\mu J/cm^2$ of UVC radiation with a wavelength from 200 nm to 305 nm is limited to 8 hours a day [32]. In our proposed model, we use the optimum far-UVC excimer lamps (eight lamps) with the proportional position and angle in the disinfection chamber combined with the optimum irradiation time, therefore, the excessive far-UVC exposure may be avoided for human bodies.

IV. Conclusion

To summarize, we have investigated the optical characterization from 219 nm far-UVC excimer lamps (BEST, power 20 W) with a maximum intensity of 4200 $\mu W/cm^2$. Thus, we propose the design of a disinfection chamber utilizing the 219 nm far-UVC excimer lamps to optimize the ability of microorganisms and virus inactivation with the irradiation dose of 3000 $\mu J/cm^2$. As our result for the investigation of the far-UVC disinfection chamber, it requires an irradiation time less than 5 s with an intensity of 840 $\mu W/cm^2$ at a 10 cm distance to the human body. As the distance increases, the intensity decreases, and the required irradiation time increases. Our experimental results suggest that our 219 nm far-UVC disinfection chamber can be used as a promising alternative to prevent COVID-19 human-to-human transmission without involving any chemical agents.

Declarations

Conflict of Interest

The authors have declared that there is no conflict of interest.

CRediT Authorship Contribution

Nidya Chitraningrum: Methodology, Writing - Original Draft, Writing - Review & Editing; Yusuf Nur Wjiyanto: Conceptualization; Indra Sakti: Investigation; Hana Arisesa: Investigation; Dadin Mahmudin: Investigation; Deni P. K.: Investigation; Pamungkas Daud: Investigation; Budi Prawara: Resources.

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