

Calibration of an ultraviolet distribution model by precise measurement of underwater ultraviolet intensities

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Abstract—In Korea, disinfection of effluent from a wastewater treatment plant is now essential, and ultraviolet (UV) disinfection is known as one of the useful disinfection alternatives. The non-contact type UV disinfection method, which is distinguished by a fouling-free process, was developed, and a mathematical model for the photoreactor was developed. For the purpose of the model calibration, the study had manufactured a non-contact type UV photoreactor and measured UV intensities within the photoreactor. The two major parameters of the model were evaluated by comparing the UV intensity of the photoreactor and the model's simulation results. As the result of this study, the developed model for a non-contact type UV photoreactor could predict UV intensity within the photoreactor well. Optima parameter values came out as measuring 576 points for the calibration test and 504 points for the verification test. The coincidence index proved useful in calibrating the parameters, with the index values over 0.9 at the optimum values. This study produced optimum values for the two parameters. The UV conversion efficiency and the transmittance of UV in pure water came out to be 0.56 and 100%, respectively.

Keywords: UV Disinfection, Non-contact Type UV Photoreactor, UV Distribution Model, UV Transmittance, Calibration and Verification

INTRODUCTION

Ultraviolet light (UV) is widely used in water treatment and wastewater treatment plants to inactivate *Cryptosporidium* and other pathogenic microorganisms [1]. In Korea, over 2,030 out of 3,060 public wastewater treatment facilities have adopted UV single or UV combined system with other disinfection method [2]. In a UV disinfection system, the UV lamps are usually installed under the surface of water. Organic and inorganic materials are accumulated at quartz-water interfaces, thus reducing UV light transmittance [3,4]. A non-contact type UV disinfection system avoids this problem because there is no interface between the quartz sleeve and water [5]. The UV intensity within the photoreactor is an important design parameter because the germicidal power is proportional to the product of UV intensity and exposure time. Unlike the chemical dosage, representative intensity of a photoreactor system cannot be measured because UV light is not uniformly distributed in the photoreactor. The UV intensity is high near the lamp, and decreases as the distance grows from the lamp to the receptor.

A common method for calculating intensity in a UV photoreactor is the multiple point source summation method (MPSS). In a MPSS model, the emission of a linear lamp is approximated by assuming multiple point sources spaced evenly along with the axis of the lamp and the overall intensity at a receptor is the sum of respective intensity which originates from multiple point sources [6,7]. As the light passes through media of air, water and quartz, it is refractive and reflective

at the interface of media. The UV absorbing medium can attenuate UV transmittance. At any point of the photoreactor, UV intensity can be calculated by the UV distribution model based on the basic optics laws of refraction, reflection and absorption (or transmittance). The UV light passes through three media in the conventional submerged UV lamp system, but the light passes through the four media of air, quartz, air, and water in the non-contact type UV system. Kim et al. [5] suggested a UV distribution model for the non-contact type UV irradiation system, and based on the results of the model simulation, they predicted the non-contact type UV system requires more powerful lamps or more exposure time than a submerged system. In spite of the above demerit, a non-contact type UV system is practically useful because it is free from fouling generation problem and cleaning of the lamp sleeve. In a contact type UV disinfection system, fouling on the quartz sleeve reduces the transmittance of UV light. Depending on the water quality and UV lamp type, significant fouling may occur in a few hours or take up to several months [4]. Organics are accumulated on the quartz sleeve surface, but the inorganics of aluminum or iron complex are easier to accumulate since UV radiation is effectively absorbed by organic compounds [7].

Mathematical modeling is a useful tool for designing a photoreactor or predicting the disinfection performance, but the verification of the model should come first [8,9]. The purpose of this study is to verify the model for a non-contact type UV photoreactor and present parameter values of the model. For the calibration and verification of the model, a UV photoreactor equipped with UV intensity measuring system was installed and UV intensities at hundreds of point within the photoreactor were measured. Two parameters of UV conversion efficiency (E_u) of UV lamp and transmittance of UV light of water (T_w) were selected as calibratable parameters

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METHODS

1. UV Distribution Model

In a conventional UV irradiation system, UV light emitted from a UV lamp travels through three media of air, quartz and water. On the other hand, UV light passes through the four media of air, quartz, air and water layer in a non-contact type UV photoreactor. Jacob and Dranoff [10] introduced a mathematical approach to calculate light intensity distribution within a reactor when the line source light passes through single media. Based on their concept, a multiple point source summation (MPSS) approximation was produced to calculate UV distribution in a submergible UV disinfection system where light passes through the three media of air, quartz and water [11].

MPSS approximation could be expanded to develop a UV distribution model for the non-contact type UV irradiation system where light passes through four media of air, quartz, air, and water. By assuming a linear light source to n point sources spaced equally along the lamp, Fig. 1 illustrates the light pathway from a UV lamp which hangs over the water surface to an underwater receptor point. UV light that comes from a point source i and passes through the air/quartz/air/water interfaces can be calculated by Eq. (3) [5].

$$r_1 \tan \theta_1 + r_2 \tan \theta_2 + r_1' \tan \theta_1 + r_3 \tan \theta_3 = h \quad (1)$$

$$(r_1 + r_1') \tan \theta_1 + r_2 \tan \left(\sin^{-1} \left(\sin \theta_1 \cdot \frac{n_1}{n_2} \right) \right) + r_3 \tan \left(\sin^{-1} \left(\sin \theta_1 \cdot \frac{n_1}{n_3} \right) \right) = h \quad (2)$$

$$I_i = (1 - R_{12})^2 (1 - R_{13}) \frac{P/n}{4\pi d^2} \exp(-\alpha_2 d_2) \exp(-\alpha_3 d_3) \quad (3)$$

$$I = \sum_{i=1}^n I_i \quad (4)$$

where, I =accumulated UV intensity at a receptor point; I_i =UV intensity at a receptor point originating from a UV point source, i ,

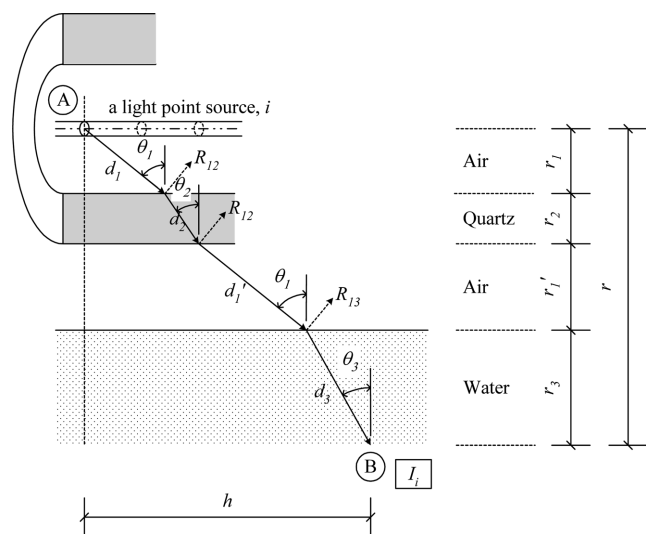


Fig. 1. Light pathway and components of refraction and reflection in a non-contact type UV photoreactor [5].

($W \text{ cm}^{-2}$); R_{12} , R_{13} =reflection rate between the interface of air/quartz, and air/water, respectively; P =nominal UV power output of the lamp being modeled (W); n =number of points being used; d =total path length of UV light and is equal to $d_1+d_2+d_1'+d_3$ (cm); h =longitudinal distance from point A to point B (cm); α_2 , α_3 =absorption coefficient of quartz and water (cm^{-1}), respectively; d_2 , d_3 =path length through quartz and water (cm), respectively.

As shown in Eq. (5), E_u is electrical to UV conversion efficiency, and its value varies by manufacturer or aging of a UV lamp. This efficiency ranges as 35-38% for a commercial low-pressure mercury vapor lamp [4]. In practice, the transmittance is often measured using a 1 cm path length, and the relationship between the UV transmittance of water (T_w , %) and the absorption coefficient is computed as Eq. (6).

$$P = E_u \cdot P_E \quad (5)$$

$$\alpha_3 = \ln(100/T_w) \quad (6)$$

where, P_E is the electric power of lamp (W) and T_w is UV transmittance of water (%).

By Snell's law in Eq. (7), refractive angles of θ_1 , θ_2 , θ_3 are related to the refractive index; n_1 , n_2 , n_3 . At the adjacent interface of i and j , reflection rate is determined by Fresnel's law in Eq. (8).

$$n_1 \sin \theta_1 = n_2 \sin \theta_2 = n_3 \sin \theta_3 \quad (7)$$

$$R_{ij} = \frac{1}{2} \left[\left(\frac{n_j \cos \theta_i - n_i \cos \theta_j}{n_i \cos \theta_j + n_j \cos \theta_i} \right)^2 + \left(\frac{n_j \cos \theta_i - n_i \cos \theta_j}{n_i \cos \theta_i + n_j \cos \theta_j} \right)^2 \right] \quad (8)$$

The other paper described the equations and solutions in great detail [5]. Based on the approaches mentioned above, a computational model which can simulate 3-dimensional distribution of UV intensity within the non-contact type UV photoreactor was developed and coded using the Microsoft Excel Visual Basic Application.

2. UV Measuring and Calibration/Verification Test

A non-contact type UV photoreactor and a series of UV measuring devices were installed to measure UV intensity at any specific position within the photoreactor. The photoreactor had the following dimensions: 16 cm width \times 35 cm height \times 75 cm length, and was made with 1 cm thick acrylic board. Deionized water was filled to a specific depth.

One commercial low pressure UV lamp (Philips Co.) was positioned at the center of a quartz tube and set on top of the photoreactor. The UV lamp was 85 cm long and 40 Watt electric power. An underwater UV measuring device was made and installed on the photoreactor. The UV measuring device consisted of UV sensor (Solar Light Co., PW254-420-BSW, waterproof), a moving sensor holder, a vertical rod that connected the sensor with sensor holder, a geared rail and a DC motor. The DC motor was controlled by a handmade I/O controller connected to a computer. By the programmed signal, the DC motor works with a fixed speed and direction or stops. As the DC motor works, both the sensor holder and UV sensor simultaneously move forward or backward.

The UV sensor measures monochromatic wavelength of 254 nm and it is connected to the UV photometer (Solar Light Co., LM100) that is connected to the I/O controller. The I/O controller transforms the detected analog signal (UV intensity) into a digital signal and transfers it to the computer. Therefore, real time UV intensity can be stored on the data-logging computer.

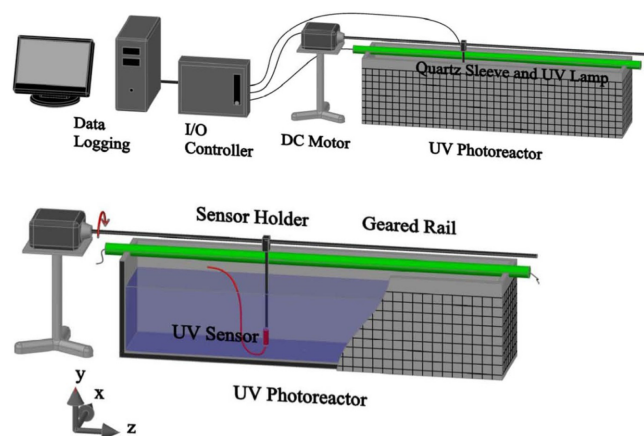


Fig. 2. UV measuring system for a non-contact type UV photoreactor.

Along the programmed sequence, the UV sensor moves exactly 2 cm forward and then waits for 5 seconds until the water surface is calm. The UV intensity is measured 10 times for 10 seconds, storing the average value (at that point). This sequence is repeated until the sensor arrives at the center of photoreactor in z direction. The measuring devices are then moved along the x or y axis for 2 cm and the sequence starts again.

The UV profiles are symmetric in x or z direction because the photoreactor is a rectangle. So, measurements were carried out in 1/4th of the photoreactor space. The exact grid points consisted of 1-7 cm (4 points) in x direction, 15-29 cm (8 points), and 1-35 cm (18 points) from the edge corner of the photoreactor. Therefore, all the measuring points were 576, or the product of $4 \times 8 \times 18$.

$Z_m(i, j, k)$ indicates the measured intensity in three-dimensional coordinates, and i, j, k stand for i, j, k -th grid in x, y, z direction from the edge corner of the photoreactor.

The measuring experiments were conducted twice: The first for calibration and the second for verification. The first occurred while the photoreactor was filled to a 30 cm depth with deionized water, with a total 576 grid points. The second was conducted with a water depth of 28 cm, 2 cm lower than that of the calibration experiment. The measuring points in the verification experiment were 504, or the product of $4 \times 7 \times 18$. Experiments were carried out at room temperature (about 20 °C) and it was not significantly increased by UV irradiation heat.

RESULTS AND DISCUSSION

The UV light is refractive, reflective, and absorbed while passing through multiple media. Among the parameters related to light irradiation, the refractive indexes of light vary slightly in a normal condition, and the index is 1.38 for water and 1.52 for quartz material [10]. Reflection is a physical property that is calculated by Fresnel's law, which is defined by refractive angles and refractive indexes of the adjacent materials. Quartz sleeve absorbs UV and the transmittance of UV in 1mm thick quartz is known to be about 90% [6]. The UV transmittance of water depends on water quality and environment such as temperature, pH, turbidity, and inorganic materials. Based on practical operation data, UV transmittance of water was

used to suggest as 90% for the preliminary design of water disinfection process [6]. Electrical to germicidal UV conversion efficiency can also be a calibration parameter. In this study, UV transmittance of water (T_w) and UV conversion efficiency (E_u) were chosen as calibration parameters.

The modeling is regarded as ideal when the simulation results match up exactly with the measuring data. But ideal modeling is difficult to achieve because a mathematical model cannot include all of the environmental variables. Besides, measuring error also occurs. To find the optimal parameter's value, the UV intensity at each grid point $Z_c(i, j, k)$ was calculated by the model simulation using a specified T_w and E_u . Then, the relative errors between the measured value, $Z_m(i, j, k)$, and calculated value, $Z_c(i, j, k)$, at the same grid point were computed by Eq. (4). Individual coincidence index, $CI(i, j, k)$, at each grid point was calculated by Eq. (10). Then, the coincidence index (CI), which is the arithmetic average of $CI(i, j, k)$ for the whole points, was obtained by Eq. (11) at a specified T_w and E_u . CI is a similar concept to the 'Nash-Sutcliffe efficiency coefficient' which is commonly used to assess the predictive power of hydrological discharge models [12]. CI can range from $-\infty$ to 1. A CI of 1 corresponds to a perfect match between model and observations. Essentially, the closer CI value to 1, the more accurate the calculation is.

$$RE(i, j, k) = \sqrt{\left(\frac{Z_m(i, j, k) - Z_c(i, j, k)}{Z_m(i, j, k)}\right)^2} \quad (9)$$

$$CI(i, j, k) = 1 - RE(i, j, k) \quad (10)$$

$$CI = \frac{1}{N} \sum_{i=1}^8 \sum_{j=1}^4 \sum_{k=1}^{18} CI(i, j, k) \quad (11)$$

$RE(i, j, k)$ is the relative error between $Z_m(i, j, k)$ and $Z_c(i, j, k)$; $Z_m(i, j, k)$ and $Z_c(i, j, k)$ is measured and calculated intensity at i, j, k -th grid point, respectively; $CI(i, j, k)$ is individual coincidence index at a point, i, j, k ; CI is coincidence index; and N is the total number of grid points. In this calibration experiment, N was 576 ($4 \times 8 \times 18$).

An example of the measured and calculated intensities at the same plane is shown in Fig. 3. The UV intensity decreases as the distance from water surface increases. As suggested by other researchers [3,6], 'decreasing at the end of a lamp' pattern is observed and shown in Fig. 3(a). When E_u was set at 0.45 and T_w at 95%, most of the calculated UV intensities (Fig. 3(b)) appeared to be lower than the observed intensities. The calculated intensities (before calibration) along the y axis (Fig. 3(d)) ranged from 0.4 to 2.5 mW cm^{-2} which were 0.9-1.8 mW cm^{-2} lower than the observed intensities. This implies that E_u and/or T_w should be higher than the assumed value. The calculated intensities while E_u set 0.45 and T_w were set at 95% and the observed intensities for the whole 576 points are plotted in Fig. 4. If all the measured and calculated values are exactly identical, then the marks will be positioned on the diagonal line and CI will be 1. But in this case, almost all of the marks are plotted lower than the diagonal line thus CI is as low as 0.47.

The CI variations are shown in Fig. 5 when T_w varies from 94 to 100% and E_u varies from 0.4 to 1. The optimum condition that maximized CI appeared when E_u was 0.56 and T_w was 100%. Therefore, the calibrated parameter can be seen as having a value of 0.56 for E_u and 100% for T_w . As shown in Fig. 4(b), CI increased as

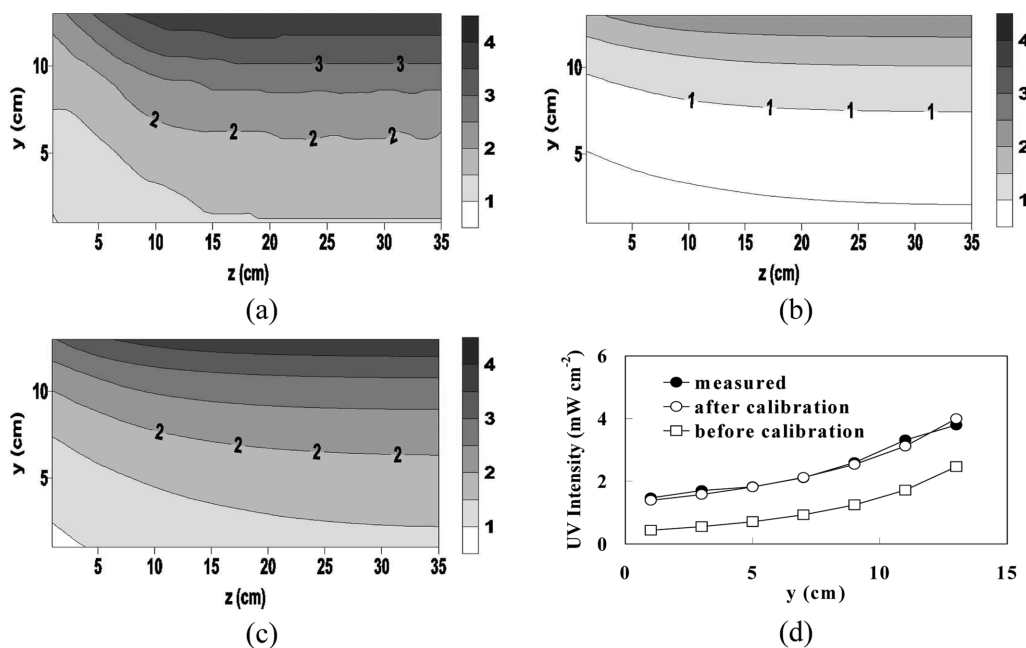


Fig. 3. UV intensity profile. (a) Measured UV intensity (Z_m) in a y - z plane ($x=7$ cm) (b) Calculated UV intensity (Z_c) in a y - z plane ($x=7$ cm) before calibration and (c) Calculated UV intensity in a y - z plane ($x=7$ cm) after calibration (d) Longitudinal distribution of UV intensity before and after calibration ($x=7$ cm, $z=35$ cm).

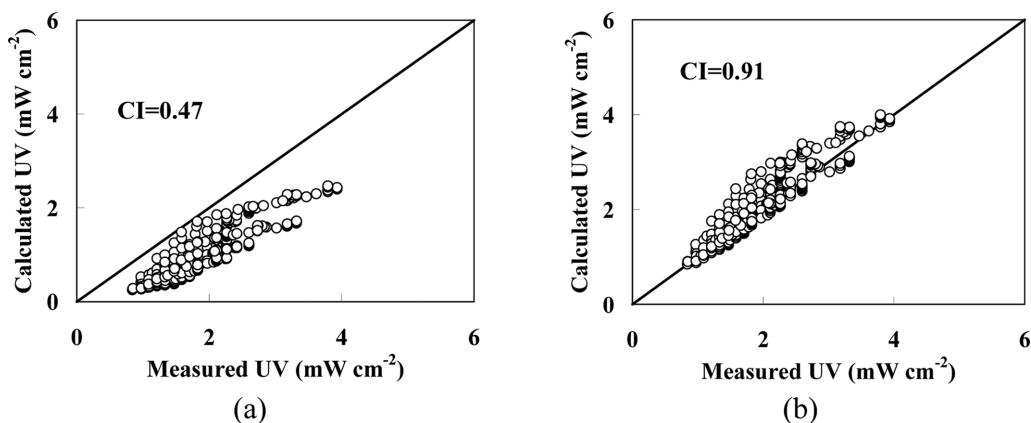


Fig. 4. Coincidence of measured value (Z_m) and calculated value (Z_c) in case of (a) $E_u=0.45$ and $T_w=95\%$ and (b) $E_u=0.56$ and $T_w=100\%$.

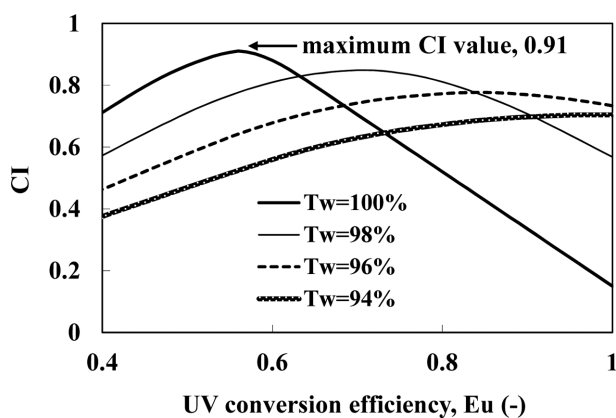


Fig. 5. CI values for the various UV conversion efficiency (E_u) and UV transmittance of water (T_w).

high as 0.91 in this calibration experiment. Thus, the UV emission power of the lamp is 56% of the electric power. In addition, UV transmittance of pure water is 100%, meaning that it is not absorbed or diminished while passing through the pure water layer. UV transmittance is dependent on the water constituents. T_w value range of source water or treated water is over 97% [13-15], while raw wastewater is 30-50% and the effluent of the wastewater treatment plant is about 90% [16-18].

The cross-sectional distribution of the calculated UV intensity in the y - z plane gets very close to the measured intensity if comparing Fig. 3(a) and 3(c). After the calibration, the longitudinal profile is also very close to the measured intensities as seen in Fig. 3(d).

Verification was performed in a different geometric condition from the calibration test. Water level was 2 cm lower than that of calibration test and it resulted in lesser number of measurement points

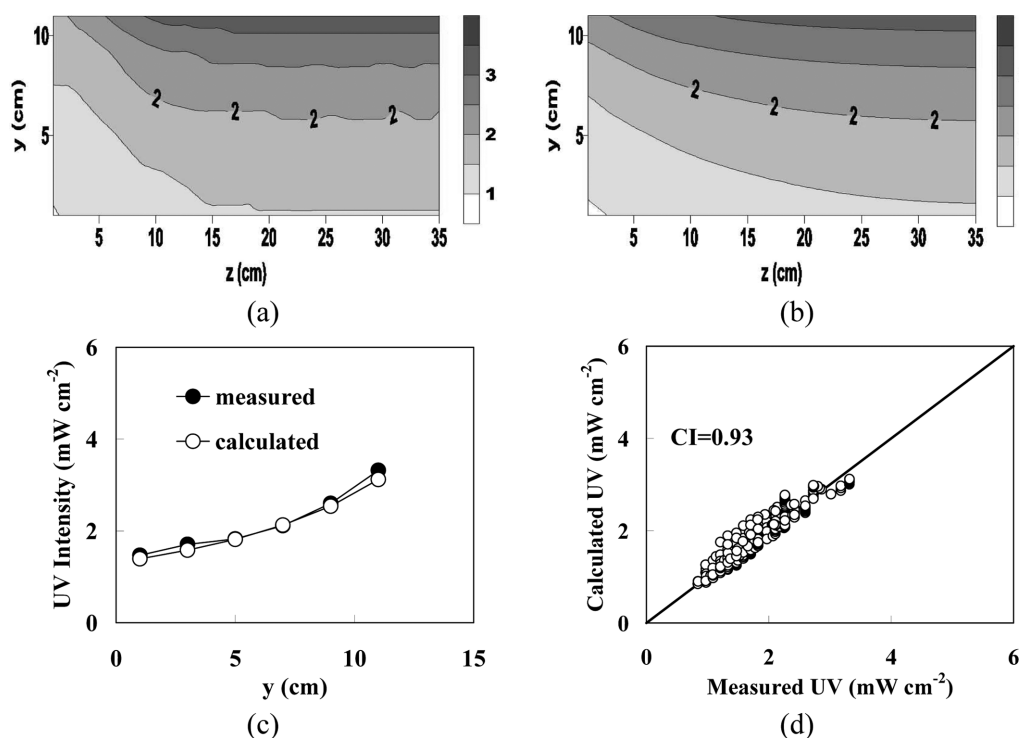


Fig. 6. Results of verification experiment. (a) Measured UV intensity in a y-z plane ($x=7$ cm) (b) Calculated UV intensity in a same y-z plane ($x=7$ cm) (c) Longitudinal distribution of UV intensity ($x=7$ cm, $z=35$ cm) and (d) Coincidence and coincidence index.

(504). Model simulation was also carried out by using the same geometric input data and the obtained calibration parameter values. The UV intensity distribution obtained from the verification test in a certain y-z plane is shown in Fig. 6(a). The modeling result at the same y-z plane is also shown in Fig. 6(b). In this case, input parameter values were the same as obtained optimum values from the calibration test (0.56 for Eu and 100% for Tw). The two figures are similar to each other, and the CI is calculated as 0.93, which is higher than that of calibration test. The longitudinal distribution of calculated intensities is also very close to the measured intensities with the experiment, thereby verifying the obtained parameter values. Therefore, it can be concluded that the developed mathematical model is suitable to describe the non-contact type of UV photoreactor. Besides, the obtained UV transmittance of pure water is 100% and UV conversion efficiency of this lamp is 0.56. While fouling is one of the major parameters in contact type of photoreactor, fouling cannot be a parameter in non-contact type of UV system because there is no contact between water and quartz sleeve. In this case, UV conversion efficiency of UV lamps becomes one of the significant design parameters.

CONCLUSIONS

A mathematical model which can predict the UV intensity within a non-contact type UV photoreactor WAS calibrated by measuring three-dimensional UV intensity distributions in this study. Two parameters of UV conversion efficiency of UV lamp and UV transmittance of water were selected as calibratable parameters. Coincidence index between the measured and calculated intensity was introduced to calibrate optimal parameter values. By comparing the measured

value and the calculated value for the entire grid points of the photoreactor, the optimal UV conversion efficiency was found to be 0.56 and the transmittance of pure water was 100%. The average coincidence index for the entire 576 points was as high as 0.91 in the calibration test. The parameter values obtained in this study were successfully verified by the other set of measurement and CI was a proper index for the calibration.

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