SIMULATION OF LED LIGHT INTENSITY ATTENUATIONS IN THE BUBBLE CURTAIN ENCLOSURE

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Abstract− To measure the light intensity profiles of LEDs light sources in different media (air, water, and air bubble curtains) to simulate the cultivate environments of hydrogen production, three colors of LEDs lights, red (620.084nm), white (464.979nm), and blue (458.317nm), respectively, are used to simulate light intensity in the space of a rectangular glass enclosure where photosynthetic bacteria is supposed to be cultured inside. The illuminations inside the enclosure are measured by an optical fiber which is connected to the AvaSpec-2048 spectrometer. Photon fluxes are measured by LI-COR-190SA with LI-1400 data logger. From experimental measurements, the minimum illuminances in the enclosure with three different media, respectively, it is found that in the water medium case, its value is the largest and in the air medium case, its value is the lowest. Whatever volumetric air rates in air-bubbled media, the minimum illuminances are between the values in the air medium cases and in water medium cases.

Keywords: Air bubble, enclosure, illumination, LED light

1. INTRODUCTION

Biomass is one of the most promising renewable resources used to generate different types of biofuels, such as biodiesel, bioethanol, biogas and biohydrogen [1]. Hydrogen is widely recognized as clean and potential candidate as it has highest energy density among any known fuels and is the only common fuel that does not produce CO2 as a by-product when used in fuel cells for electricity generation. Biological hydrogen production from biomass is considered one of the most promising alternatives for sustainable green energy production [1]. Recently, based on the best culture conditions for photosynthetic bacteria, photo-bioreactors are designed with light-emitting diode (LED) light sources. These designs focus on lifespan, conversion efficiency, energy saving, and durability without using ultraviolet light. Using these biological characteristics and physical properties for optimizing the conditions for probiotic culture will not only protect the ecological environment but also mitigate global warming [2]. Based on shapes and design philosophy, most current algae photo-bioreactors can be classified into tubular, flat-plate, and column photobioreactors [3].

The type of light source and light intensity can all exert significant influence on the hydrogen production of photosynthetic bacteria. Current research on lighting conditions has mainly focused on the following aspects: 1) the characteristics of growth and hydrogen production of photosynthetic bacteria under different lighting intensity, 2) the characteristics of growth and hydrogen production of photosynthetic bacteria under alternating dark and light conditions, 3) the characteristics of growth and hydrogen production of photosynthetic bacteria under alternating natural lighting and artificial lighting, and 4) research on the distribution method of lighting.

Based on the structure and shape of incident energy detection meters, instruments used in the measurement of light intensity in water can be classified into three types, i.e., flat plate, hemispherical, and spherical. For the same time and location, the lighting intensity measured by the spherical receiver was the highest among the three types of receivers. Although there is no specific conversion formula for the lighting intensity measured by the three receivers, the average light attenuation coefficients obtained by three different types of receivers in the same type of liquid are similar. Usually, the attenuation of light intensity based on the depth of the water and the transmission distance follows the Beer–Lambert Law, i.e., light attenuates with an exponential decay during transmission. However, the curves obtained from practical experiments usually vary from theory. Those variations are mainly attributable to the assumptions made before the establishment of the Beer–Lambert Law. For example, the law assumes all the incident light waves are single waves and parallel to each other, that the medium is uniform and does not have light-scattering capability, etc. [4,5]. Under different depths of water, the attenuation coefficient for light transmission will also be different [6]. Equation (1) is the Beer–Lambert law for light transmission under water:

$$I_z = I_0 e^{-cz}$$
(1)

where Iz represents the intensity at transmission distance z; I_0 is the intensity of the light source, and c is the total attenuation coefficient [4]. Through the average of cosines, the relationship between the beam absorption coefficient a and downward vertical attenuation coefficient $K_E(z)$ can be constructed. According to the Gerschun equation,

$$K_E(z) = \frac{a}{\mu(z)}$$
(2)

Thus, the downward vertical attenuation coefficient $K_E(z)$ at any depth z in the sea, can be obtained by the average cosine

of this location and the absorption coefficient of seawater. Using this attenuation coefficient, the changes in the intensity of underwater light transmission can be written as [4]:

$$I_z = I_0 e^{-K_E(z)\cdot z}$$ (3)

Under certain conditions, the relationship between the attenuation of an LED light source, the density of microalgae cells, and the distance of light transmission can be illustrated with the Beer–Lambert law. The effects on the efficiency of light absorption as a result of changes in light attenuation due to changes in the density of microalgae cells and the distance of light transmission is one of the critical issues in the engineering of efficient reactors, in particular the culturing process of high-density microalgae. As the manufacturing process of LED determines its small light scattering angle, its optical radiation transmission direction is vertical, resulting in the high concentration and penetration of light. Thus, by controlling the concentration of algal cells within a certain range, the mutual shading effects and scattering phenomenon among algae can be reduced, thereby effectively controlling the influence of light attenuation on the culturing of high-density cells [7]. Greenwald et al. [8] show that a diffusion model for cell motion (1) accounts for high bioproductivity at irradiance values previously deemed restricted by photoinhibition, (2) predicts the existence of optimal culture densities and their dependence on irradiance, consistent with available data, (3) accounts for the observed degree to which mixing improves bioproductivity, and (4) provides an estimate of effective cell diffusion coefficients, in accord with independent hydrodynamic estimates.

This study uses light as the photon stream and employs the Beer–Lambert law and experimental measurements for simulating the mathematical model of light intensity distribution in a rectangular enclosure. In addition, different flow rates of air are injected into the tank to investigate the influences of bubbles upon distributions of LEDs light intensity determined through experiments in the enclosure.

2. EXPERIMENTS

This study mainly focuses on two different types of experiments: 1. Using LI-COR-190SA sensors for measuring the photosynthetic photo flux density (PPFD) at the exterior of the rectangular enclosure and 2. Using an AvaSpec-2048 model spectrometer and an L-shaped fiber where the average cosine corrector is installed on the fiber head for measuring the illuminance in the interior of the rectangular enclosure. The experimental schematic and measurement locations are shown in Fig. 1. By changing experimental parameters, including different media such as air, water, gas–liquid mixture (water with bubbles) and LEDs of various power, different experimental data, such as the LED PPFD and illuminance, are recorded.

2.1. Setup

The length of the LED arrays used in this experiment was 60 cm, categorized into red, white, and blue wavelengths, and each light tube contained 36 LEDs (source: Da Zhen International Co., Ltd.). The wavelengths of the LEDs were as follows: 458.317 mm (blue), 620.084 mm (red) and 464.979 mm peak (white). This experiment used an Agilent direct-current power supply (U8002A) to power the three

LED light sources, and the experimental measurements were conducted under input power settings of 15, 25, and 35 W.

The experimental equipment used in this study consists of rectangular glass containers, a setting and positioning base, LED light stands (5 sets), a sensor stand, and positioning sliders for adjusting the distances of fiber in rectangular enclosure. Precise fixtures are designed and mounted on the optical table for sensor location adjustments. Verifications whether the light intensity distribution satisfied the Lambert-Beer law or not are conducted. The positioned heights of the L-shaped fiber and the two LI-190SA sensors were 17, 32 and 47 cm, respectively. These three heights were chosen so as to mitigate the influence of unstable conditions at the surface and bottom of the unstable liquid where bubbles form. The glass tank contains water with a liquid level of 55 cm. This experiment used the AALBORG PFA rotameter, whose basic specifications are as follows: the airflow range is 0–6 cc/min, accuracy is ±2% F.S. 11, and maximum pressure range is 200 psi. High-pressure air from the compressor is injected into the water in the rectangular enclosure via a small hole in the hose, to produce uniform and stable bubble volume flow rates of at 5.2, 13.1, 21.6 ml/min, respectively.

2.2. Measurements and Calibrations

Following the calibration of the light sources, the illuminance of the red, white, and blue LED light sources when light was injected into the rectangular enclosure, and the PPFD of the same LED light sources after the light passed through the rectangular enclosure were measured. Meanwhile, the liquid medium inside the rectangular enclosure was also changed to determine the influence of the medium on illuminance and PPFD. The main media used in this experiment were air, water, and a gas–liquid mixture (liquid with bubbles). The experiment used the AvaSpec-2048 model spectrometer and LI-COR-190SA sensors for measuring the illuminance and PPFD of light that passed through the rectangular glass enclosure after attenuation by the tank and the medium. The measurement data from the LI-COR-190SA sensor was received and stored by the LI-1400 data logger. The location of fiber receiver was changed by adjusting the positioning mechanism so as to study the partial changes in the illuminance of incident lights in the glass rectangular enclosure and to measure the trends in the changes.

The procedure for the calibration of the spectrometer and the L-shaped fiber is as follows. 1) Switch on the standard light source, stabilize the distance, and ensure the containers are empty. 2) Ensure the L-shaped fiber at the receiving end is well positioned and fix the distance. 3) Cover the receiving point and press the dark current calibration button. 4) Release the cover, and press the reference button for calibration of the light source. 5) Position the LEDs at the exact same location as the standard lights and switch on the LEDs. 6) Switch off the standard lights and fill the container with liquid. The measurement process is now ready to begin. The calibration procedure for LI-COR-190SA is as follows. The LI-190 sensor is connected to the LI1400 data logger prior to the start of the experiment. The individual calibration values listed on the LI-190 sensor are entered into the LI-1400 data logger, and the calibration is completed. In addition, the symmetry of the light intensity of the five rows of LEDs needs to be calibrated to ensure that the position and alignment of the light sources are symmetrical. The experimental process involves comparing the illuminance of the symmetrical LED

light tubes on the left and the right sides to ensure they are within the error range of the calibration value, i.e., ±20 Lux.
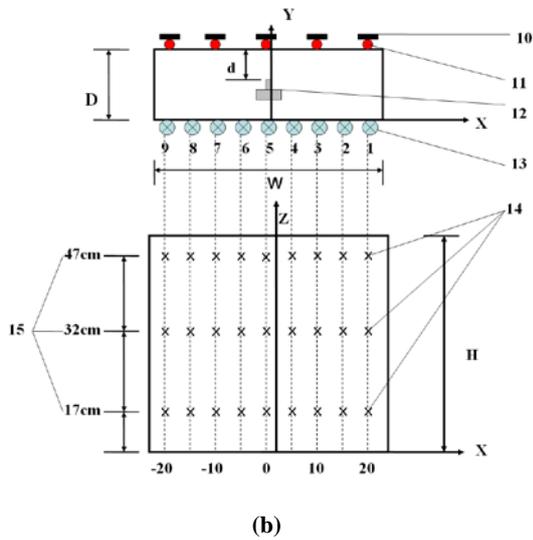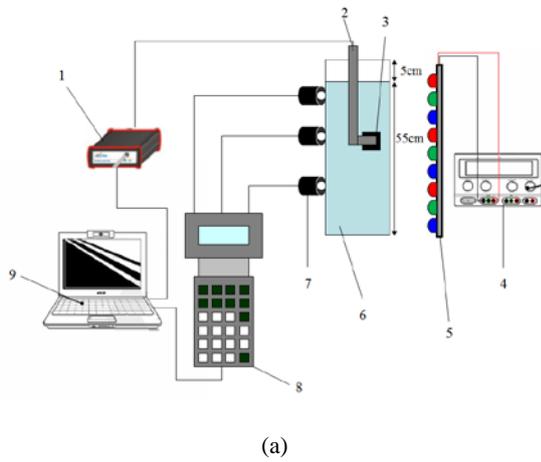

(a)

(b)

Fig. 1. (a) Experimental setup: 1. AvaSpec-2048 spectrometer, 2. L-shaped fiber, 3. corrector, 4. direct-current power supply, 5. long bar LED light source, 6. rectangular glass enclosure, 7. LI-190 sensors, 8. LI-1400 data receiver, 9. notebook computer; (b) experimental measurement locations.

3. RESULTS AND DISCUSSION

Figure 2 shows the measured illuminance distributions along the thickness direction (distance d) and at three vertical positions, z=17 cm, 32 cm, and 47 cm, respectively, of white light LEDs in the enclosure filled with air. Seven measurements, starting from y=5 cm to y=17 cm for every step of 2 cm, are conducted to demonstrate the decaying rate changing with y coordinates, i.e. the thickness direction of rectangular glass enclosure. It is found that near the light source plane (y=0 cm), illuminances do not change for these three vertical locations; but when it is approaching the middle of thickness (actually, y=9 cm), the illuminance values at the middle location z=32 cm will be larger than other two locations. This result may attribute to the illuminances from all light sources are additive. Furthermore, illuminance distributions along the thickness direction are not linear; the decaying function can be fitted into a higher order polynomial which is different to the relation in equation (1). And

comparing to the incident illuminance on y=0 cm, the maximum decaying rate of illuminance is 52%.
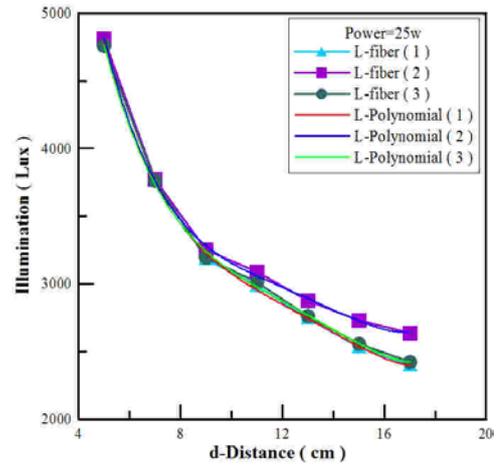

Fig. 2. Illuminance distributions in rectangular glass enclosure fill by air and subjected to white LEDs lights in 25W of power.

In similar, figure 3 shows the illuminance distributions along the thickness direction (distance d) and at three vertical positions, z=17 cm, 32 cm, and 47 cm, respectively, of white light LEDs in the enclosure filled with water. The decaying rate is greater than the air-filled case. Also, illuminance distributions along the thickness direction are not linear; the decaying function can be fitted into a higher order polynomial which is different to the relation in equation (1). And comparing to the incident illuminance on y=0 cm, the maximum decaying rate of illuminance is 63.6%.
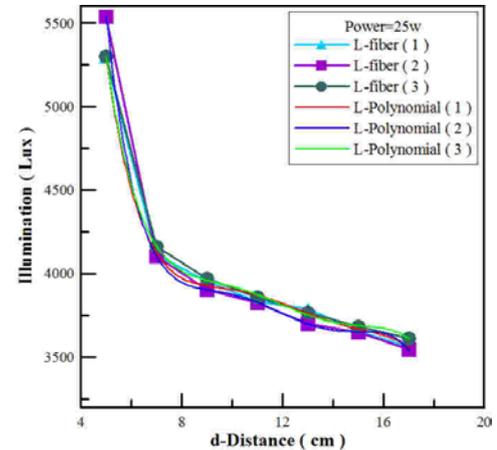

Fig. 3. Illuminance distributions in rectangular glass enclosure fill by water and subjected to white LEDs lights in 25W of power.

Considering the light intensity distributions with bubble curtains with three volumetric air rates of 5.2 ml/min, 13.1 ml/min, and 21.6 ml/min, respectively, in the enclosure, the measured results are shown in figure 4. In these results, the power of light sources is set to 25 W. In figure 4(a), since the volumetric air rate is low, measured illuminance distributions are similar to the result in figure 3. But, if increasing the volumetric air rates, the transition zone of distribution profiles are smoothed and the minimum illuminance is decreased. Comparing to the case of volumetric air rates of 5.2 ml/min to rates of 13.1 ml/min and 21.6 ml/min,

respectively, the minimum illuminance is decreased by 8.6% and 14.3%, respectively. Comparing figure 2, 3, and 4 together, it can be found that the minimum illuminance in figure 3 (the water medium case) is the largest and figure 2 (the air medium case) is lowest. Whatever volumetric air rates, the minimum illuminance in figure 4 is between the results in figure 2 and figure 3.
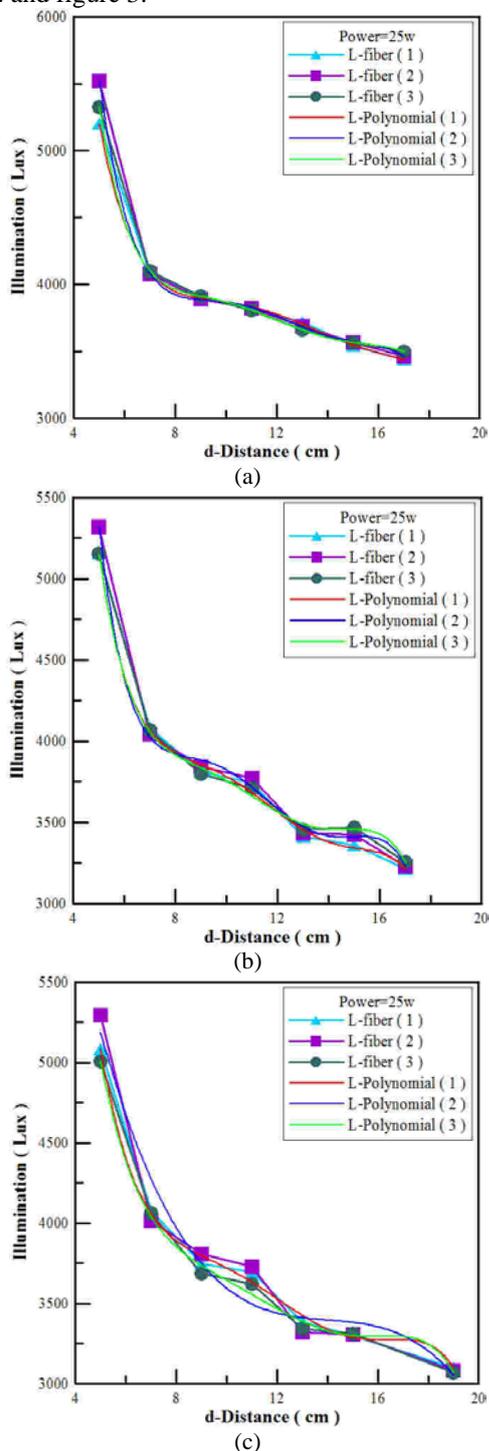

(a)

(b)

(c)

Fig. 4. Illuminance distributions in rectangular glass enclosure fill by air curtains with three volumetric air rates of (a) 5.2 ml/min, (b) 13.1 ml/min, (c) 21.6 ml/min, and subjected to white LEDs lights in 25W of power.

4. CONCLUSIONS

In this study, effects that influenced changes in the illuminances of the white LED light source in a rectangular glass enclosure were measured. Light intensity experiments were conducted in three kinds of media—air, water, and water mixing air bubbles—using fiber sensors and PPFD sensors. The input power of white LEDs lights is set to 25W. From experimental measurements, this study discovered that the largest illuminance of the white LED light source is in water, followed in descending order, in medium of air bubble curtains, then in air. Comparing to the case of volumetric air rates of 5.2 ml/min to rates of 13.1 ml/min and 21.6 ml/min, respectively, the minimum illuminance is decreased by 8.6% and 14.3%, respectively. Therefore, for hydrogen production application, using the design of gas bubble curtains is proper because the bubble will not cause great light fades to light and will increase the mixing effects in the cultivation enclosure, hence, it will be beneficial for the growth of algae and to improve the efficiency of hydrogen production purposes.

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