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Optimization of Radiator Position in an Internally Radiating Photobioreactor: A Model Simulation Study

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Abstract This study focused on the optimization of the illumination method for efficient use of light energies in a photobioreactor. In order to investigate the effect of radiator position, a model simulation study was carried out using *Synechococcus* sp. PCC 6301 and an internally radiating photobioreactor as a model system. The efficiency of light transfer in a photobioreactor was analyzed by estimating the average light intensity in a photobioreactor. The simulation results indicate that there exists an optimal position of internal radiators, and that the optimal position varies with radiator number and cell concentration. When light radiators are placed at the optimal position, the average light intensity is about 30% higher than that obtained by placing radiators at the circumstance or center of a photobioreactor. The method presented in this work may be useful for improving light transfer efficiency in a photobioreactor.

Key words: Photobioreactor, internal radiator, optimal position, light distribution model, light transfer, *Synechococcus*

The efficient transfer of light energy is of importance in cultivating photosynthetic microorganisms. Light energy is readily absorbed, but cannot be stored in a photobioreactor. Any light energy not absorbed will be wasted into thermal energy [24]. Moreover, the exposure of cells to excess light often leads to a decline in their growth [17]. Therefore, it is desirable to supply light energy at an appropriate level and maximize the utilization efficiency of the supplied light energy.

Most microalgal cultivation systems in use today are irradiated with natural sunlight. Thus, previous mathematical models have focused on solar irradiation in open ponds or raceways [6, 8], tubular photobioreactors [1, 22], thin panel photobioreactors [31], and flat plate photobioreactors [15, 26]. For maximal utilization of sunlight, outdoor photobioreactor systems have been improved to provide a higher surface-to-volume ratio and reduce the light path. However, it is difficult to control light intensity and penetrating direction, since the solar energy shows seasonal and diurnal variations.

To provide precise control of environmental factors, various types of indoor photobioreactor systems have recently been developed through modification of conventional bioreactors. The indoor photobioreactors are employing the artificial light sources such as fluorescent lights (light tubes) [11, 18, 19, 20, 23, 28, 30, 32], optical fibers [9, 16, 27], light emitting diodes [12, 21], and light emitting plates [5, 7]. Particularly, internal radiators are known to distribute light energy more efficiently than external radiators inside photobioreactors [16, 19, 24, 28]. However, their widespread use for microalgal mass culture has been limited by high installation cost and scale-up problem. Thus, systematic design and scale-up strategy of the photobioreactors are required for successful industrialization on a commercial scale.

To date, several light distribution models have been proposed and applied to interpret a light condition inside a photobioreactor. The mathematical model can be applied to analyze the photobioreactor efficiency, and predict the microalgal cell growth and productivity. For external irradiation, useful light distribution models have been proposed to interpret the light conditions in rectangular, cylindrical, or spherical vessels irradiated with artificial light sources [3, 4, 10, 13, 14]. A stirred draft-tube reactor was constructed for modeling purpose, and its light condition was interpreted employing a numerical analysis [5]. However, little attention has been paid to the optimization of illumination methods for efficient transfer of light energy in a photobioreactor.

Recently, we proposed a novel light distribution model for an internally radiating photobioreactor [28, 29]. In this study, the proposed model was used for systematic analysis

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of the light transfer efficiency in an internally radiating photobioreactor. The number of internal radiators affects the cost of installation, operation, and maintenance and thus the radiators should be installed at the optimal positions to supply maximal light energies to the photosynthetic cells.

Model simulation studies in this work have focused on the optimization of radiator position in a cylindrical photobioreactor equipped with internal radiators [28]. The model photobioreactor (working volume 7 l) consisted of a double-jacket cylindrical tube (7.5 cm radius, 60 cm long) and a concentric draft tube (5 cm radius, 60 cm long), both of which were made of Pyrex glass. Each radiator was shielded with a Pyrex glass tube (1 cm radius, 70 cm long), into which a fluorescent lamp (49 cm long, 1.25 cm in diameter, 18 W; DL18, BOAM USA Inc.) was inserted. The light intensity at the radiator surface (I_0) was determined by direct measurement of the photon flux density at 18 points using a quantum sensor (LI-190SA, LI-COR) connected to a Datalogger (LI-1000, LI-COR). The mean value of I_0 was 621±20 μmol/ (m^2·s).

The light condition inside the model photobioreactor was analyzed by calculating local light intensities and average light intensities. *Mathematica*® (version 4.0) program was used for mathematical calculation and plotting the light distribution profiles. Mathematical expressions used for estimating the local light intensity are as follows [28, 29]:

$$I_n(X, r, \theta)=\sum_{k=1}^{n}\frac{r_0 \cdot I_0}{R_{k/n}}\exp\left[\frac{-\varepsilon_m \cdot X \cdot (R_{k/n}-r_0)}{(K_X+X)(K_r+R_{k/n})}\right] \quad (1)$$

$$\text{where } R_{k/n}=\sqrt{r^2+r_T^2-2r\cdot r_T\cos[\theta-(k-1)((2\pi)/n)]}. \quad (2)$$

Equations (1) and (2) correspond to a special case, where all radiators are installed symmetrically and the symbols in these equations are explained in Nomenclature. Three model parameters of ε_m, K_X, and K_r are coefficients of maximal light absorption, light scattering by cells, and light scattering by light pathlength, respectively. In the case of *Synechococcus* sp. PCC 6301 (ATCC 27144, *Anacystis nidulans*), these parameters were experimentally determined as ε_m=50±2.6, K_X=2.7±0.11 g/l, and K_r=4.7± 0.22 cm (R^2=0.995). These model parameters were used to predict the local light intensity at arbitrary position (r, θ) and cell concentration (X).

To examine the effect of radiator position on light transfer efficiency, the light distribution profiles at different radiator configurations were obtained by using Eq. (1), and how light condition varied inside the photobioreactor region was examined. The model simulations were conducted for a case in which X, I_0, and r_T are 0.5 g/l, 621 μmol/(m^2·s), and 4 cm, respectively. Figure 1 illustrates light distribution profiles irradiated from four radiators, which are located at three different positions: (a) reactor center, $r_T=r_0/\sin(\pi/4)=\sqrt{2}\cdot r_0$, (b) the midpoint, $r_T=(R_0-r_0)/2$, and (c) the reactor inner surface, $r_T=(R_0-r_0)$. Large and small thick circles in Fig. 1 illustrate the boundaries of the reactor and the light radiators, respectively, and contour lines represent the same levels of light intensity (7, 15, 30, 75, 150, 300, and 600 μmol/(m^2·s)). The comparison of the light distribution profiles clearly indicates that the midpoint location of radiator [Fig. 1(b)] provides more efficient light transfer than the two extreme positions [Figs. 1(a) and 1(c)]. It is, therefore, expected that there is an optimal position of radiators for maximizing the light transfer efficiency inside a reactor.

To evaluate light transfer efficiencies for more general cases, the average light intensity (I_{av}) was employed as an index value. The average light intensity, which is defined as the average of the local light intensities in a photobioreactor, means the irradiance level experienced by a single cell randomly moving inside the culture [25]. The effects of the radiator number and position were investigated by comparing the values of average light intensity, when the different numbers (n=1, 2, 3, 4, 6, and 8) of internal radiators were moved along the radial direction of a photobioreactor. The average light intensity in a cylindrical

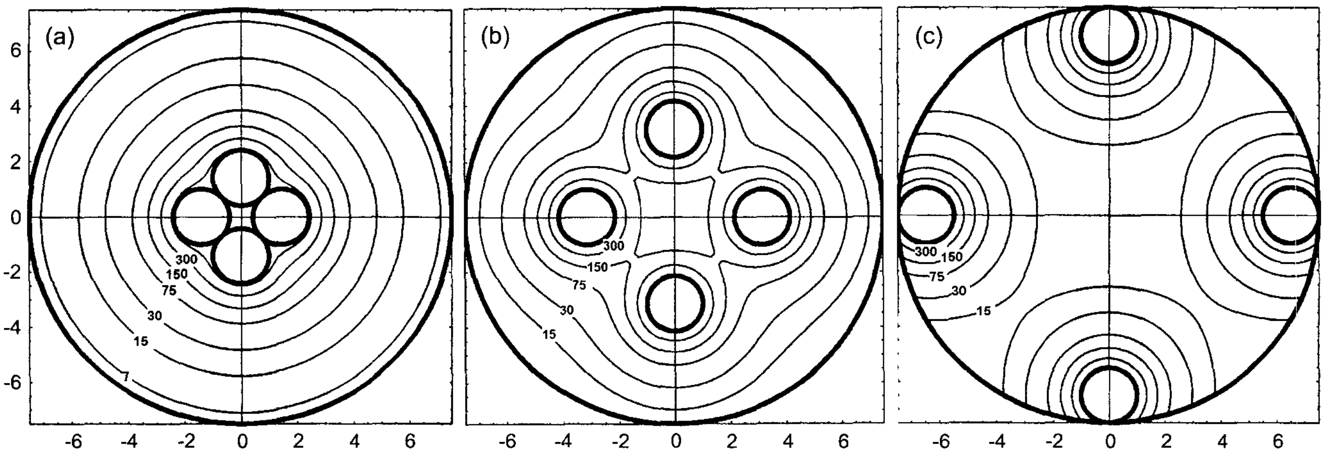

Fig. 1. Light distribution profiles inside the photobioreactor equipped with four internal radiator positions.

photobioreactor can be calculated by integrating Eq. (1) over the region of $0 \le r \le R_0$ and $0 \le \theta \le 2\pi$:

$$I_{n,av}(X)=\frac{n}{A_n}\left[\int_{\delta}^{\frac{2\pi}{n}-\delta}\int_0^{R_0} r\cdot I_n(X,r,\theta)\,drd\theta \right. \\ +2\int_0^{\delta}\int_0^{\alpha} r\cdot I_n(X,r,\theta)\,drd\theta \\ \left. +2\int_0^{\delta}\int_{\beta}^{R_0} r\cdot I_n(X,r,\theta)\,drd\theta \right] \tag{3}$$

where $A_n=\pi(R_0^2-n\cdot r_0^2)$ (4)

$$\alpha=r_T\cos\theta-\sqrt{r_0^2-r_T^2\sin^2\theta} \tag{5}$$

$$\beta=r_T\cos\theta+\sqrt{r_0^2-r_T^2\sin^2\theta} \tag{6}$$

$$\delta=(\pi/2)-\cos^{-1}(r_0/r_T) \tag{7}$$

Details on the mathematical derivation are described elsewhere [28, 29].

Figure 2 shows the variation of average light intensity (at 0.5 g/l cell concentration) with changing the location of radiators from the inner surface of a reactor to the reactor center. For convenience, the model simulation results are presented in terms of dimensionless radial distance ($\rho=r_T/(R_0-r_0)$) and dimensionless average light intensity ($I_{av}/I_{av,max}$). The arrow indicates the optimal position at which the average light intensity is maximized for each curve. The bell-shaped patterns of average light intensity can be seen from Fig. 2, and one can find that the optimal position of the radiators varies with the number of internal radiators. The simulation results also indicate that locating the four radiators at the optimal position results in 21.3% and 30.3% increase of light energy transfer, as compared to that at the circumscribed position and the reactor center, respectively.

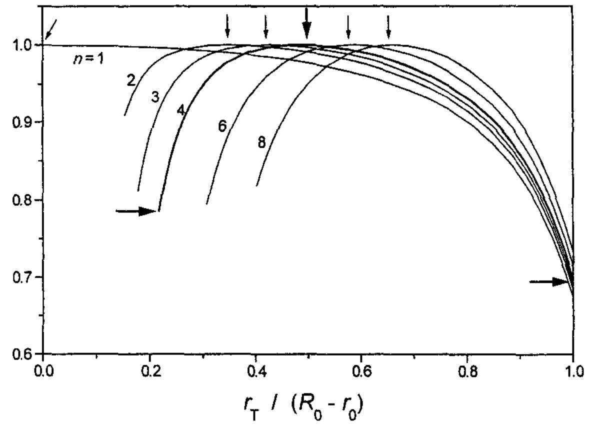

Fig. 2. Variations in the average light intensity with the position of internal radiators.

Small arrows indicate the position where the average light intensity is maximal. Large arrows indicate, from the left, the position of radiators when the radiators are located at the reactor center, optimal position, and circumscribed position in a photobioreactor equipped with four internal radiators.

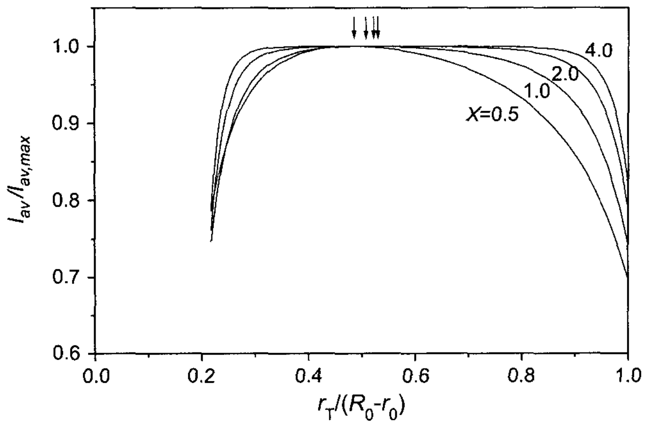

Fig. 3. Variations in the average light intensity with cell concentration in a photobioreactor equipped with four internal radiators.

There are interesting examples in which the same number of internal radiators was equipped at different positions inside cylindrical photobioreactors. Ogbonna *et al.* [19] located four internal radiators symmetrically at the midpoint from the reactor center to jacket, while Wohlgeschaffen *et al.* [32] located all four radiators at the reactor center. Based on the simulation results, it can be concluded that the configuration employed by Ogbonna *et al.* [19] is more desirable than that used by Wohlgeschaffen *et al.* [32] from the viewpoint of light transfer efficiency. While a single-radiator system gives the maximal average light intensity at the reactor center (ρ=0), the optimal position for a four-radiator system is located near the midway between the reactor center and the reactor inner surface (ρ=0.48).

In order to further investigate the optimal position of internal radiators, the effects of cell concentration on light transfer efficiency were examined. Figure 3 shows the variation of average light intensities with cell concentrations (0.5, 1.0, 2.0, and 4.0 g/l). Model simulations were conducted for the model photobioreactor equipped with four internal radiators. As the cell concentration was increased, the shape of the curves became flattened and the position of arrows moved slightly towards the reactor center. Thus, in the case of dense cultivations with limited light supply, the position of internal radiators becomes less important, since most light energy emitted from the radiators cannot penetrate into the culture broth. The dependence of optimal position of radiators on radiator number and cell concentration is summarized in Fig. 4. The results shown in Fig. 4 imply that the optimal position of radiators is largely determined by the number of radiators. On the other hand, the variation of optimal radiator position is relatively small with the changes in cell concentration. In view of this result, it appears that the method presented in this work can be applied to a batch

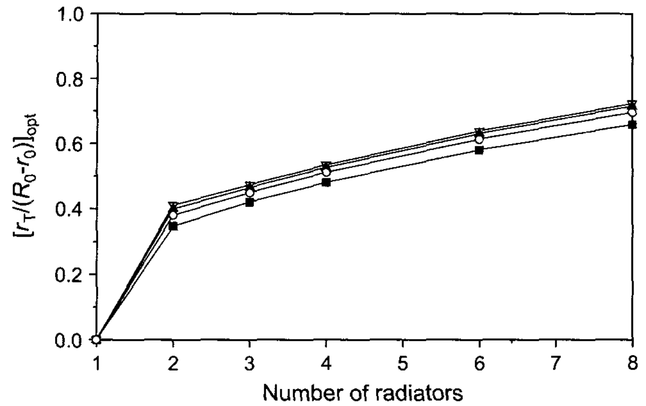

Fig. 4. Dependence of optimal radiator position on the radiator number when cell concentrations are 0.5 (■), 1.0 (○), 2.0 (▲), and 4.0 (▽) g/l.

culture system where the cell concentration varies during cultivation.

In conclusion, our simulation study indicates that there exists an optimal position of internal radiators and that the optimal position varies markedly with the number of radiators in a photobioreactor. The radiators can be installed at desirable positions once the optimal position of radiators is determined following the procedures presented in this work. It is expected that the model-based approach is useful for the design of an energy-efficient photobioreactor and plays an important role in optimizing the light transfer efficiency in a photobioreactor.

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NOMENCLATURE

A_n : cross-sectional area of reactor with n internal radiators, cm^2
I_0 : light intensity on radiator surface, mmol/ (m^2·s)
I_n : light intensity with n light radiators, mmol/ (m^2·s)
$I_{n,av}$: average light intensity with n radiators, mmol/ (m^2·s)
k : index number for radiators
K_X : light scattering constant by cell concentration, g/l
K_r : light scattering constant by light pathlength, cm
n : number of radiators
r : distance from reactor center, cm
r_0 : radius of insulating glass tube, cm
r_T : distance between reactor center and translated position of radiator, cm
R_0 : radius of reactor, cm
$R_{k/n}$: distance from the *k*th radiator center after translation, cm
X : cell concentration, g/l
α : short distance between reactor center and radiator surface, cm
β : long distance between reactor center and radiator surface, cm
δ : angle of tangent line from reactor center to radiator surface, radian
ε_m : maximal specific absorption coefficient
θ : angle in cylindrical coordinate, radian
θ_T : angle after translation, radian
ρ : dimensionless radial distance defined as $r_T/(R_0-r_0)$

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