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ARTICLE

BIOTECHNOLOGY and BIOENGINEERING

Airlift Column Photobioreactors for *Porphyridium* sp. Culturing: Part II. Verification of Dynamic Growth Rate Model for Reactor Performance Evaluation

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ABSTRACT: Dynamic growth rate model has been developed to quantify the impact of hydrodynamics on the growth of photosynthetic microorganisms and to predict the photobioreactor performance. Rigorous verification of such reactor models, however, is rare in the literature. In this part of work, verification of a dynamic growth rate model developed in Luo and Al-Dahhan (2004) [Biotech Bioeng 85(4): 382–393.] was attempted using the experimental results reported in Part I of this work and results from literature. The irradiance distribution inside the studied reactor was also measured at different optical densities and successfully correlated by the Lambert–Beer Law. When reliable hydrodynamic data were used, the dynamic growth rate model successfully predicted the algae's growth rate obtained in the experiments in both low and high irradiance regime indicating the robustness of this model. The simulation results also indicate the hydrodynamics is significantly different between the real algae culturing system and an air-water system that signifies the importance in using reliable data input for the growth rate model.

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KEYWORDS: airlift column; photobioreactor; photosynthesis; algae; hydrodynamics; irradiance distribution

Introduction

To truly assist the design and scale up of photobioreactors, it is necessary to quantitatively describe the impacts of hydrodynamics and irradiance distribution on the growth of microorganism cells. Extensive studies exist in the literature in relating the photosynthetic rate or the cells' growth rate to the irradiance received by the cells but not to hydrodynamics. For example, many early studies use semi-empirical correlations to present the impacts of average irradiance on photosynthetic rate based on the so-called photosynthesis-irradiance (P-I) curve (Iwakuma and Yasuno, 1983; Jassby and Platt, 1976; Molina Grima et al., 1994). On the other hand, many researchers developed dynamic models stemmed from photosynthesis fundamentals to quantify the influence of each photon on the photosynthesis (Camacho Rubio et al., 2003; Eilers and Peeters, 1988; Han et al., 2000; Zonneveld, 1998). The advantages of these dynamic kinetic models include their ability to represent photoinhibition and other important photosynthesis phenomena in a transient basis.

To consider the impact of hydrodynamics on the cells' growth, a true reactor model that integrates the kinetics of photosynthesis with reactor hydrodynamics is needed. This is achievable since hydrodynamics affects cells' growth through influencing the history of irradiance delivered to the cells as mentioned in Part I of this work, which in turn affects the photosynthetic rate as described by the photosynthetic kinetic models. Because it is possible to obtain the hydrodynamic information such as the cells' trajectories by computational fluid dynamic (CFD) simulations, such a reactor model can be potentially applied to any types of photobioreactors that CFD can be reliably applied (Bitog et al., 2011). It is therefore can be a general approach with broad applications for photobioreactor design and scale-up. However, rigorous verification of such reactor models is needed before it can be used.

Luo and Al-Dahhan (2004) attempted to develop such a dynamic growth rate model. Based on a photosynthetic kinetic model called three-state growth rate model proposed

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by Eilers and Peeters (1988), Luo and Al-Dahhan's reactor model directly integrates flow dynamics, irradiance distribution, and photosynthetic kinetics to predict the performance of photobioreactors. It uses three sets of inputs, namely flow dynamics particularly the cells' trajectories inside the reactor (e.g., how the microorganism cells move in the reactor and the stress they face), irradiance distribution inside the reactor and the photosynthetic reaction kinetics.

In the first attempt to verify this model, hydrodynamic data available from a draft tube column of 20 cm diameter in an air-water system (Luo et al., 2003) was employed to predict the performance of a draft tube column photobioreactor of 13cm diameter for *Porphyridium* sp. cultures reported in Merchuk et al. (2000). Although the prediction reasonably matches the experimental data, the apparent difference between the reactor configurations and the operating conditions makes the comparison debatable.

Apparently, a more rigorous verification of the dynamic growth rate model requires more accurate inputs from all three aspects of the photobioreactor mentioned above. This requires a flow dynamic study in a real alga culturing system, a reliable irradiance distribution model and accurate photosynthetic kinetic parameters. Moreover, it is also important to test the applicability of the dynamic growth rate model at conditions of high light intensity and high biomass concentration interesting to commercial scales. These conditions, with significant flashing light and photoinhibition effects, are essential for mass production of microalgae/cyanobacteria.

This part of manuscript presents our further attempt to verify the dynamic growth rate model developed in Luo and Al-Dahhan (2004) to establish a quantitative tool for photobioreactor design and scale up. The following sections will first briefly describe the dynamic growth rate model, followed by measurements of the irradiance distribution inside the studied photobioreactor. The verification of the growth rate model will then be presented using not only experimental data reported in Part I of this study but also data from the literature for a more vigorous verification. These include experimentally measured and CFD generated hydrodynamic data for real culture system and air-water system, experimentally measured irradiance distribution and photobioreactor performance results reported in this study and in the literature.

Dynamic Growth Rate Model for Photobioreactor Performance

The dynamic growth rate model developed in Luo and Al-Dahhan (2004) integrates the physiology of photosynthesis and microorganism growth, the flow dynamics, and the irradiance distribution within the reactors for photobioreactor performance evaluation. This model uses the three-state photosynthesis model proposed by Eilers and Peeters (1988) to describe the photosynthetic kinetics. It assumes photosynthetic reaction center of a cell has three states: the resting state, the activated state, and the inhibited state as shown in Figure 1. The reaction center can change its state following the capture of photons, while the specific photosynthetic rate is proportional to the state transition from the activated state to the resting state during the dark reaction. The governing differential equations are:

$$\frac{dx_1}{dt} = -\alpha \cdot I(t) \cdot x_1 + \gamma \cdot x_2 + \delta \cdot x_3 \quad (1)$$

$$\frac{dx_2}{dt} = \alpha \cdot I(t) \cdot x_1 - \gamma \cdot x_2 - \beta \cdot I \cdot x_2 \quad (2)$$

$$\frac{dx_3}{dt} = \beta \cdot I(t) \cdot x_2 - \delta \cdot x_3 \quad (3)$$

$$x_1 + x_2 + x_3 = 1 \quad (4)$$

$$\frac{1}{x}\frac{dx}{dt} = \mu = k \cdot \gamma \cdot x_2 - \mathrm{Me} \quad (5)$$

where x_1, x_2, and x_3 are the fractions of the reaction centers in the resting, activated, and inhibited state, respectively; I is the instant light intensity exposed to the cells; α, β, δ, γ are the reaction constants, x is the total number of photosynthetic reaction centers or a measure of biomass concentration such as optical density, and k is the yield of the photosynthesis reaction. Me is a term to account for cellular damages due to adverse environments such as high shear stress (Wu and Merchuk, 2002):

$$\mathrm{Me} = \overline{\mathrm{Me}} \cdot e^{k_m(\tau - \tau_c)} \quad (6)$$

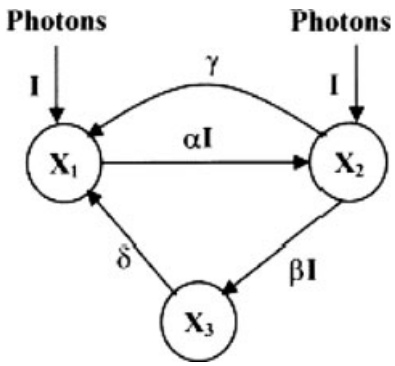

Figure 1. Structure of the three states model proposed by Eilers and Peeters (1988) (duplicated from Wu and Merchuk, 2001). A photosynthetic reaction center in state x_1 captures a photon and passes to the reactive state, x_2, at a rate proportional to the light intensity, I. The reaction center in state x_2 can either return to state x_1 at a constant rate, γ, or capture another photon and reaches the inhibited state x_3. At state x_3, the reaction center returns to state x_1 at a constant rate, δ. The chain of dark reactions is started by the direct passage of $x_2 \Rightarrow x_1$.

where $\overline{Me}$ is a maintenance coefficient, k_m is an extinction coefficient, τ is shear stress, and τ_c is the critical shear stress below which no effect on the growth is observed. Wu and Merchuk (2001, 2002) estimated the model parameters for *Porphyridium* sp. as listed in Table I through comprehensive experiments.

For cells grown in a real photobioreactor, solving this set of differential equations for the cells' growth rate requires information of the instantaneous irradiance history exposed to the cells, $I(t)$, as well as the shear stress the cells experienced. The irradiance history can be calculated from the cells' trajectories and the irradiance distribution inside the reactor. The cell's trajectories and the shear stress history can be obtained from either CARPT experiments as presented in Part I or from CFD simulations. With these inputs, the governing differential equations can be solved numerically using the following initial conditions:

$$x_1 = 1, \quad x_2 = x_3 = 0, \qquad t = 0 \tag{7}$$

These conditions assume all photosynthetic reaction centers of the cells are in the resting state as if they had been kept in dark for a long time.

Irradiance Distribution Inside a Photobioreactor

Governed by the radiative transfer theory (Cassano et al., 1995; Vincenti and Kruger, 1965), the irradiance distribution inside a photobioreactor is a complex function of incident irradiance, biomass concentration and composition, flow dynamics, and reactor geometry. It should only consider the photons in the photosynthetic active range of wavelengths, or the real photon flux density (PFD) reached a cell that is the total photons come from all directions in the right range of wavelength. A rigorously derived photon transport equation was established by Cassano et al. (1995), which ended with a very complex equation.

Since solving this rigorously derived equation requires extensive computational power and determining many model parameters that are hard to obtain, it is common to simplify the photon transport equation using the famous Lambert–Beer law. Although theoretically the Lambert–Beer law is only valid for one-dimensional light propagation from a single source, some researchers found the Lambert–Beer law was sufficiently accurate to describe the irradiance distribution inside a photobioreactor (Acíen Fernández et al., 1997; Evers, 1991) in many scenarios. For example, Evers (1991) developed such a model assuming the reactor surface is homogenously illuminated and thus each point on the surface can be viewed as a light source:

$$I(d,x) = \frac{I_E}{\pi}\int_0^{\pi} \exp\{-k_x x[(r-d)\cos\theta + (r^2-(r-d)^2\sin^2\theta)^{0.5}]\}\mathrm{d}\theta \tag{8}$$

where I_E is the external incident irradiance on the homogenously illuminated reactor surface, k_x is the extinction coefficient, x is the biomass concentration, θ is the angle of incident light path, r is the cylinder radius, and d is the radial distance from the cell to the reactor surface. For a dense culture, the irradiance intensity is substantial only at the wall region where $d << r$. This model was thus further simplified by Wu and Merchuk (2001) to:

$$I = I_E \cdot \exp[-(k_x \cdot x + k_w) \cdot d] \tag{9}$$

where k_w and k_x are extinction coefficients taking into account of the reactor wall attenuation and the cellular absorptions, respectively. Apparently, this model is much easier for use due to its simplicity, if it can be experimentally verified.

Table I. Photosynthesis kinetic parameters of *Porphyridium* sp. estimated by Wu and Merchuk (2002).

Parameter	Unit	Value
K	Dimensionless	3.65×10^{-4}
k_m	Pa^{-1}	1.6×10^{-3}
k_w	m^{-1}	0.2
k_x	m^{-1}	68.9
$\overline{Me}$	s^{-1}	1.64×10^{-5}
α	$(\mu E\, m^{-2})^{-1}$	1.935×10^{-3}
β	$(\mu E\, m^{-2})^{-1}$	5.7848×10^{-7}
δ	s^{-1}	4.796×10^{-4}
γ	s^{-1}	0.1460
τ_c	Pa	2400

Experimental Results of Irradiance Distribution Measurements

In this work, to establish a reliable irradiance distribution model for the photobioreactor presented in Part I, a quantum scalar irradiance sensor (QSL-2100, Biospherical Instruments, Inc., San Diego, CA) with a spherical collector of 1.9 cm diameter was used to measure the photon flux density (PFD) in the reactor. This sensor measures photosynthetic active radiations (PAR) arriving from all directions. To continuously monitor the cells' growth, the sensor was also placed in the reactor center during the experiments. Such information can be used to estimate the extinction coefficient of irradiance due to cellular absorption.

Figure 2 shows the irradiance measured immediately after the inoculation (optical density is 0.006) at different locations on the same axial level (around 10 cm below the free liquid surface) in the draft tube airlift column. Similar results were obtained for the bubble column and the split column.

The irradiance in either the riser or the downcomer of the draft tube column were quite uniform, with averages of 324 and 267 $\mu E/m^2 s$, respectively, except one point. The uniformity of the measured irradiance implies that the lamp

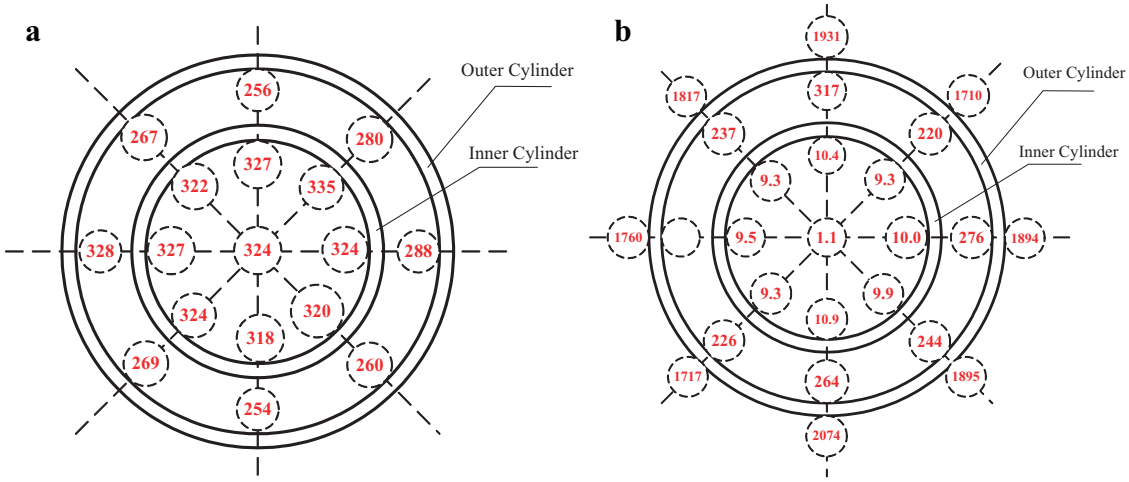

Figure 2. Irradiance distribution measured in the draft tube column reactor described in Part I of this work (unit: $\mu E/m^2 s$). a: Under low PFD and biomass concentration (optical density of 0.006 with four lamps on). **b:** Under high PFD and biomass concentration (optical density of 0.99 with all lamps on). [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

bank provided a rather uniform illumination on the reactor surface. It is noteworthy here that the irradiance inside the draft tube were interestingly larger than the irradiance in the downcomer. This is due to the focusing effects of the curved surface of the liquid filled column and the low biomass concentration presented in the reactor. Since the light attenuation at low biomass concentration is not prominent, the incident photons can penetrate deeply into the reactor center. Moreover, due to the curved reactor surface, more photons travel through the reactor center. As the irradiance sensor can detect photons from all directions, the measured irradiance is higher in the reactor center.

Such an effect is not significant when the medium's optical density is high. Under such condition, the photon transportation is dominated by cellular absorption. Figure 2b shows the irradiance measurements repeated at the same locations as shown in Figure 2a but under higher biomass concentration (optical density of 0.990) and higher external irradiance (all lights were switched on).

It is obvious that the irradiance intensity decreases sharply when moving away from the wall at high biomass concentration. Plotting the measured irradiance (after azimuthally averaged) versus the distance between the sensor and the wall on a logarithm coordinate gives a straight line, as shown in Figure 3. This experimental result supports that the irradiance distribution inside an airlift column reactor at high biomass concentration can be adequately represented by Equation (9).

To estimate the extinction coefficient due to cellular absorption, the irradiance intensity in the center of the bubble column photobioreactor was monitored. The results for the bubble column reactor were used since it does not have any internals. Following the method proposed by Acíen Fernández et al. (1997) and Rebolloso Fuentes et al. (1999), the measured irradiance in the center of the bubble column reactor were normalized by the initial irradiance and plotted versus the medium's optical density, which is shown in Figure 4. The slope of the obtained straight line thus is the product of the extinction coefficient and the distance between the irradiance sensor and the illuminated wall. In a bubble column reactor, this distance should be the averaged distance of any points on the spherical sensor to the wall, which was calculated to be 0.0575 m.

Therefore, since optical density is dimensionless, the extinction coefficient due to the cellular absorption is:

$$k_x = 7.6257/0.0575 = 132.5\,\mathrm{m}^{-1} \qquad (10)$$

This value is higher than the value reported by Rebolloso Fuentes et al. (1999) ($82\,\mathrm{m}^{-1}$), who used a similar approach to evaluate this parameter. It is also slightly above the range of k_x ($68.7–126\,\mathrm{m}^{-1}$) reported by Oswald (1977). Wu and

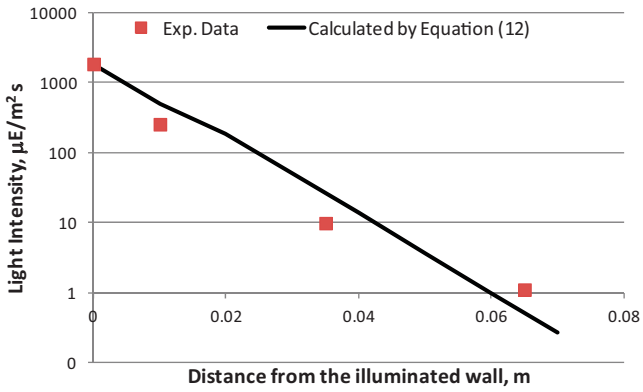

Figure 3. Azimuthally averaged irradiance versus distance between the sensor and the outer illuminated wall. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

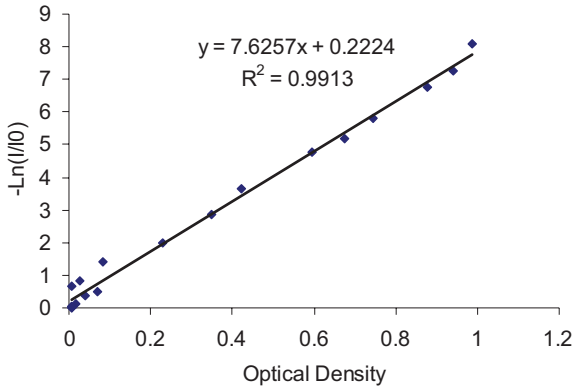

Figure 4. Relationship between the optical density and the irradiance intensity at the center of bubble column photobioreactor. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

Merchuk (2001) arbitrary selected the lowest value (i.e., $k_x = 68.7\,\mathrm{m}^{-1}$) from this range.

On the other hand, the light transmittance of acrylic is reported to be 82% over 3 mm thickness (http://www.sdplastics.com/ac350.html). This transmittance corresponds to an attenuation coefficient of $-\ln(0.82)$. For a 5 mm thick wall, the extinction coefficient of the wall can be calculated as:

$$k_w = -\ln(0.82)/3 \times 5 = 0.33 \qquad (11)$$

The light intensity inside the reactor thus can be expressed as:

$$\frac{I}{I_w} = \begin{cases} \exp[-k_x \cdot x \cdot d] & \text{(Outside or without the draft tube)} \\ \exp[-(k_x \cdot x \cdot (d - 0.005) + k_w)] & \text{(within the draft tube)} \end{cases} \qquad (12)$$

where k_x and k_w are $132.5\,\mathrm{m}^{-1}$ and 0.33, respectively.

To verify Equation (12), it has been used to estimate the irradiance intensity inside the draft tube column. As shown in Figure 3, the experimental results and the model estimation match reasonably well.

Verification of the Dynamic Growth Rate Model

To verify the dynamic model developed in Luo and Al-Dahhan (2004), four cases using different data sets were considered. Three sets of hydrodynamic data obtained from the draft tube column reactor described in Part I of this work will be used: one from experimental results for an air-water system reported in Luo and Al-Dahhan (2008), one from CFD simulation results for an air-water system reported in Luo and Al-Dahhan (2011), and one from the experimental results for the *Porphyridium* sp. system reported in Part I of this work. Two sets of photobioreactor performance data will also be used to compare against: one from the results reported in Part I of this work, and the other one from the experimental results reported in Merchuk et al. (2000). In Merchuk et al. (2000), *Porphyridium* sp. was grown in a draft tube column photobioreactor same as described in this study.

Case 1

In the first attempt, the hydrodynamic results measured from an air-water system by CARPT and CT (Luo and Al-Dahhan, 2008, 2010) were used to simulate the photobioreactor performance results reported in Merchuk et al. (2000). Figure 5 shows the simulation results comparing with the experimental results of Merchuk et al. (2000). Photosynthesis kinetic parameters reported in Wu and Merchuk (2001) as listed in Table I were used as is. As can be seen, the model predictions captured the right trend of the biomass concentration evolution and the impact of superficial gas velocities on the reactor performance. However, it appreciably over-estimated the reactor performances.

Case 2

In this attempt, the CFD generated hydrodynamic data for an air-water system (Luo and Al-Dahhan, 2011) were used to simulate the photobioreactor performance reported in Merchuk et al. (2000). The predicted photobioreactor performance is shown in Figure 6. As can be seen, the prediction based on CFD simulated particle trajectories

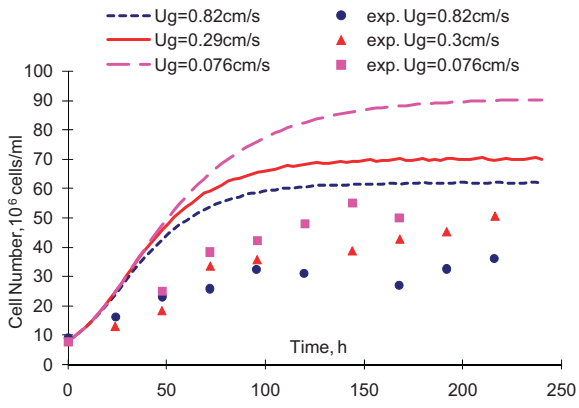

Figure 5. Comparisons of photobioreactor performances measured by Merchuk et al. (2000) with the predicted results using hydrodynamic data obtained from an air-water system (Luo and Al-Dahhan, 2004) at different superficial gas velocities. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

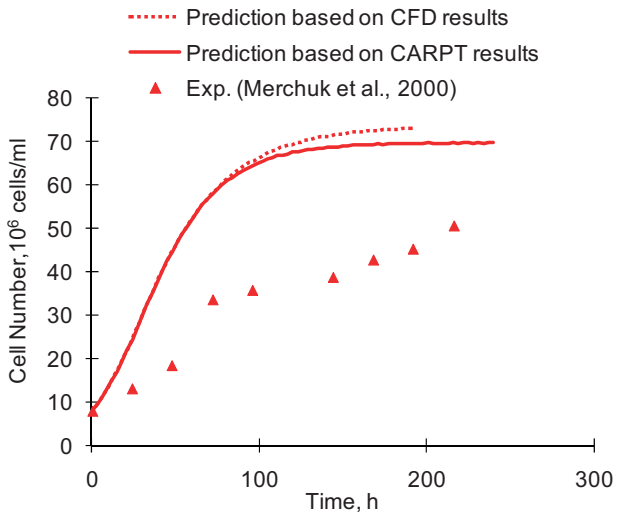

Figure 6. Comparisons of photobioreactor performance measured by Merchuk et al. (2000) versus the predictions using hydrodynamic data obtained either from CFD simulation (Luo and Al-Dahhan, 2011) or from experimental measurement (Luo and Al-Dahhan, 2008). In both predictions, hydrodynamic data of an air-water system under superficial gas velocity of 0.3 cm/s were used. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

considerably over-estimated the experimental reactor performance, but close to the prediction based on the CARPT data. This result indicates that CFD simulation is comparable to experimental techniques in getting the hydrodynamic data needed for photobioreactor analysis. However, such CFD simulations should be conducted for a true algae culturing system with realistic physical properties to allow reliable predictions of the photobioreactor performance.

Case 3

In this attempt, the hydrodynamic data reported in Part I of this work for the *Porphyridium* sp. culturing system were used. Figure 7 shows the comparison between the simulation results and the experimental results of Merchuk et al. (2000) under different superficial gas velocities. As can be seen, the simulation results match the experimental results reasonably well. The impacts of the superficial gas velocity on the reactor performance were also predicted correctly. These predictions clearly excel the predictions made in Case 1 and 2 when hydrodynamic data from an air-water system were used. Apparently, the change in physical properties plays a significant role in this situation. As discussed in Part I of this work, the increase of viscosity of the algae culture medium enlarged the turbulent sub-layer in the vicinity of the illuminated wall, causing algae cells less likely to reach the wall region. This phenomenon in turn reduced the availability of light energy delivered to the cells, resulting in lower growth rate.

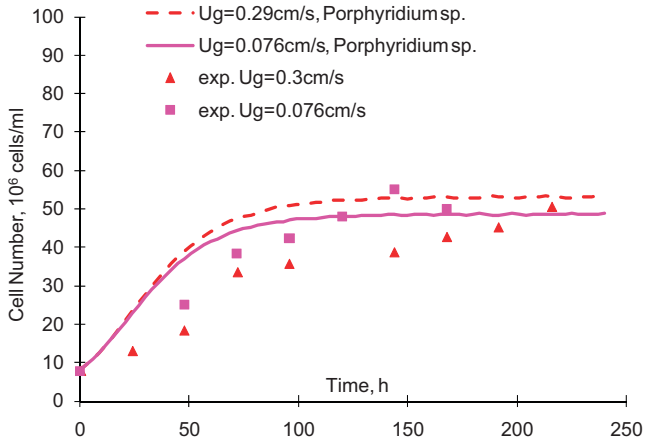

Figure 7. Comparison of the photobioreactor performance measured by Merchuk et al. (2000) against the predictions using hydrodynamic data obtained from a *Porphyridium* sp. culturing system reported in Part I of this work. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

Case 4

In the last attempt of verifying the dynamic growth rate model, the hydrodynamic data reported in Part I of this work is used to simulate the reactor performance reported in Part I. To do that, the parameters of the photosynthetic kinetic model need to be re-established.

Figure 8 compares the growth rate of *Porphyridium* sp. measured in this work with the experimental data reported in Merchuk et al. (2000). Both experiments were carried out in a draft tube column with similar configurations and superficial gas velocities (U_g of 0.3 cm/s). Please note that

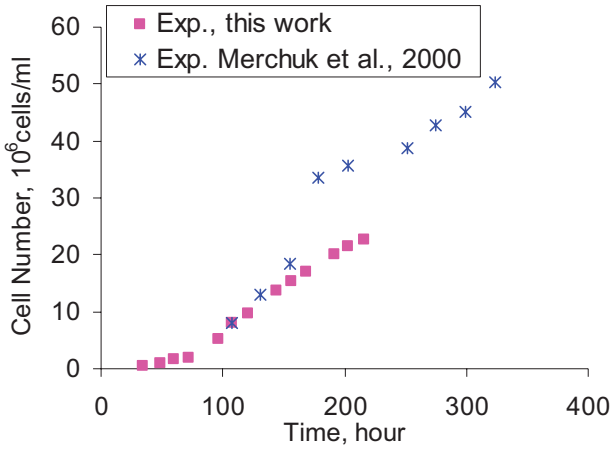

Figure 8. Comparison of the photobioreactor performance measured in this study and the ones measured by Merchuk et al. (2000) at a superficial gas velocity of 0.3 cm/s. Only data obtained at the low PFD stage in this work are shown for better comparison. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

data of Merchuk et al. (2000) were shifted rightwards for better comparison due to the differences in the lag times. Moreover, since the experimental results of Merchuk et al. (2000) were originally presented by cell number concentration, the optical density data measured in this study were converted into cell number concentration.

Figure 8 clearly shows the difference between the experimental results. Without a discernible lag period, the biomass concentration profile measured by Merchuk et al. (2000) initially has a slope close to the profiles obtained in this study, but shows a jump at time around 170th hour, and eventually reaches a biomass concentration about twice of what obtained in this work. This suggests a different photosynthetic efficiency and thus the kinetic parameters of *Porphyridium* sp. for these two experiments. This is reasonable considering the fact that the species used in both experiments might have different origin and the complexity in handling the *Porphyridium* sp. culturing system. Many factors could affect the experimental results that might not be controlled to the same level, such as nutrient composition, trace chemicals, media, and temperature.

Considering the fact that the growth rate obtained in this study is about half of the rates measured by Merchuk et al. (2000), two parameters in the photosynthetic kinetic model listed in Table I were reduced by a half: the yield of the photosynthesis reaction (k) and the maintenance parameter (Me). This is equivalent to assume the efficiency of the dark reactor is reduced by half. The other photosynthetic parameters listed in Table I were used as is.

Figure 9 compares the experimental results obtained in this work and the simulation results using the hydrodynamic data obtained from this study and Equation (12) for the light intensity distribution inside the reactor. As can be seen, the dynamic model predicted the reactor performance measured in this work remarkably well in both low and high PFD regions. These results strongly suggest that the dynamic growth rate model can be used to predict the performance of photobioreactors under conditions of high biomass concentration and high PFD. However, recalling the unsuccessful predictions made by using results from an air-water system, it has to be pointed out that reliable information about flow dynamics, light intensity distributions, and photosynthesis are essential for the prediction capability of the dynamic model. Therefore, in-depth knowledge of the flow dynamics, the irradiance distribution, and the kinetics for the photosynthesis are critical for photobioreactor design, scale-up, operation, and process intensification.

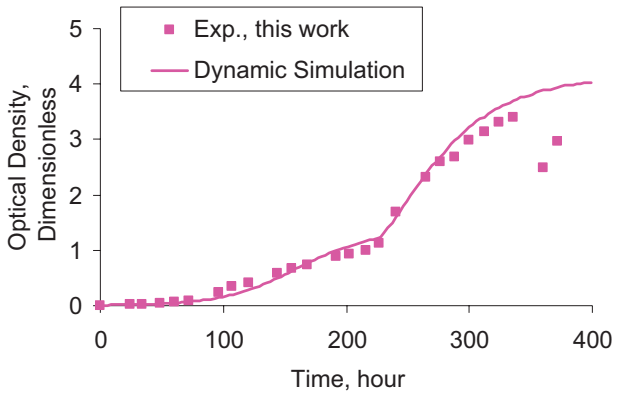

Figure 9. Comparison of the photobioreactor performance measured in this work and the predicted results using the hydrodynamic data obtained in this work for the *Porphyridium* sp. system. Model parameters: Equation (13) was used for the light intensity distribution and parameters listed in Table I were used for photosynthetic growth rates with adjusted k and Me. [Color figure can be seen in the online version of this article, available at http://wileyonlinelibrary.com/bit]

Remarks

In this work, verification of the dynamic growth rate model developed in Luo and Al-Dahhan (2004) was attempted using different sets of data reported in Part I of this work and from the literature. Irradiance distribution inside the studied reactor was also measured and correlated by the Lambert–Beer law. The dynamic growth rate model developed in Luo and Al-Dahhan (2004) successfully predicted the algae's growth rate in this study and also in the study of Merchuk et al. (2000) when reliable hydrodynamic data were used. On one hand, these results demonstrated the robustness of the developed dynamic growth rate model and indicated its potential application in conditions of industrial interests under high PFD and biomass concentration. On the other hand, the results signify the importance of using hydrodynamic data obtained from real culturing system to get reliable simulation results. This is also true when computation fluid dynamics (CFD) is used to obtain the needed hydrodynamic information. It should also noteworthy that the reliability of this model relies on the accuracy of the inputs from flow dynamics, irradiance distribution, and the photosynthetic kinetics. Better understanding of these fundamentals thus is crucial to photobioreactor design, scale-up, and operation.

Nomenclature

$\overline{d}$	average distance of any points on the spherical irradiance sensor to the illuminated wall in Equation (10), m
d	radial distance to the column wall, m
I	instantaneous incident light intensity on the cells, $\mu E/m^2 s$
I_E	external incident irradiance on the homogenously illuminated reactor surface
I_w	light intensity on the illuminated wall, $\mu E/m^2 s^1$
k	yield of the photosynthesis reaction
k_m	an extinction coefficient for shear stress effects in Equation (6)
k_w	extinction coefficient of irradiance intensity due to reactor wall, m^{-1}
k_x	extinction coefficient of irradiance intensity due to cellular absorption, m^{-1}
$\overline{Me}$	a maintenance coefficient in Equation (6)
Me	maintenance constant to account for cellular damages due to adverse environments such as high shear stress

r radial position of a interested point within the column in Equation (8), m

R radius of the airlift column, m

t time, s

U_g superficial gas velocity, cm/s

x the total number of photosynthetic reaction centers or a measure of biomass concentration. In this work, it is the optical density of the culture. dimensionless

x_1 the resting state of the photosynthetic reaction center

x_2 the activated state of the photosynthetic reaction center

x_3 the inhibited state of the photosynthetic reaction center

Greek Symbols

$\alpha, \beta, \delta, \gamma$ reaction constants in Equations (1)–(6) of the three state photosynthetic model

θ angle of incident light path in Equation (8)

τ_c critical shear stress below which no effect on the growth is observed

τ shear stress

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