CHEMICAL ENGINEERING TRANSACTIONS
VOL. 32, 2013
A publication of AIDIC
The Italian Association of Chemical Engineering
Online at: www.aidic.it/cet
Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-23-5; **ISSN** 1974-9791
DOI: 10.3303/CET1332174

Photobioreactors for Microalgal Cultures: a Model for Photosynthesis Rate Assessment

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A model aimed at the assessment of photobioreactor performances was developed. It was focused on coupling photosynthesis kinetics and photobioreactor hydrodynamics. A lumped kinetic parameter model of photosynthetic factor was adopted to relate local irradiance and photosynthetic rate. Hydrodynamics was modelled according to a Lagrangian approach based on isotropic turbulence hypothesis. The photobioreactor performances - expressed in terms of local and global photosynthesis rate - were assessed with reference to a flat photobioreactor configuration. Irradiance level and biomass concentration were changed in the typical range of operating conditions adopted for processes reported in the literature. Results showed that set the biomass concentration, the photosynthesis rate may be optimized by tuning the level of wall irradiance.

1. Introduction

Photobioreactors are closed reactors adopted for intensive cultures of phototrophic microorganisms, e.g. cyanobacteria and microalgae. The microorganisms metabolism is based on the photosynthetic upper-pathway. Light energy and carbon dioxide are converted in chemical energy stored in organic molecules as carbohydrates. The process represents the most effective route to produce biomass - to be adopted as energy source, food, and feed - from sunlight. Microalgae can be cultivated on waste streams of gas (CO_2 polluted) and liquids (salt supplements) for producing bio-oil, biodiesel, biohydrogen, biobutanol, food additives, pigments, and cosmetics and at the same time to contribute to the CO_2 capture (Bennemann et al., 1977; Chisti, 2007; Anemaet et al., 2010; Olivieri et al., 2011; Olivieri et al., 2012; Olivieri et al., 2013; Cardon et al., 2011; Chen et al., 2011; Russo et al., 2013; Graziani et al., 2013).
The dynamic of microalgal cultures can be described by complex kinetic models including a large number of variables (Cornet et al., 1998; Kroon and Thoms, 2006; Bernard, 2011). In any case, the key variable is the intensity of the light - measured as irradiance level or photon flux density – irradiating microalgal cultures. Light is a substrate (often the key reactive), and its supply strategy strongly affects the biomass productivity.
The light affects the dynamics of the photosynthetic pathway. The metabolic network of the photosynthesis is typically described by complex kinetic models. The complexity of the models becomes higher when they describe the dynamics of the irradiance experienced by each microalgal in the suspension. Model simplifications have been proposed by lumping the biochemical network in a few steps (Eilers and Peters, 1988; Camacho-Rubio et al., 2003). Some models have introduced the concept of photosynthetic unit (PSU). They are particularly useful to describe the dynamics of the photosynthesis reactions involving the radiant energy. Models are based on the hypothesis that the PSU has a finite number of states and the transition among them depends on the photon flux. According to this hypothesis, processes as light-capture, photochemical and non-photochemical quenching, photoinhibition, and PSU repair are phenomena associated to the change of the PSU state. The characteristic time-scale of each transition spans over a wide range - from few milliseconds up to some hours - and can strongly depend on irradiance level and pigment content.

Please cite this article as: Olivieri G., Marzocchella A., Salatino P., Gargiulo L., Lettieri P., Mazzei L., 2013, Photobioreactors for microalgal cultures: a model for photosynthesis rate assessment, Chemical Engineering Transactions, 32, 1039-1044 DOI: 10.3303/CET1332174

The dynamics of microalagal exposition to the light source depends on both photobioreactor design and operating conditions. Indeed, the radiation history of the PSU depends on the light field in the suspension, and the cell trajectory within the photobioreactor. As regards the first issue, the light decay inside the photobioreactor depends on several phenomena: I) external phenomena, including light reflection and refraction at the photobioreactor wall and the daytime spectrum of both irradiance angle and light intensity (when sunlight source is adopted); II) internal phenomena, including absorption, scattering, and reflection associated to the microalgae and the photobioreactor design (Acién-Fernández et al., 1997). Effects of internal phenomena are described by means of the coefficient K of light exponential decay across microalgal suspensions. K depends on the light-path (LP), the dry weight specific absorption coefficient (a^*_{DW}), and biomass concentration (X) and it is defined according to Eq(1):

$$K = \mathbf{ln}\frac{I^0}{I_{LP}} = a^*_{DW} \cdot X \cdot LP \tag{1}$$

where I^0 and I_{LP} are the irradiance levels at the inner side of the wall and at a LP distance from the wall.
As regards the second issue, the photobioreactor hydrodynamics affects the microalgae flow in the liquid phase and in particular the cyclic alternation between light and dark regions. It should be highlighted that the photobioreactor hydrodynamics depends on the design (flat, tubular, annular, cylindrical) and on operating conditions (single-phase/two-phase, laminar/turbulent, gas and liquid flow rate, etc) (Chisti, 2006; Jansenn et al. 2003).
Sheth et al. (1977) proposed a model to couple the photosynthesis kinetics, the light intensity field, and the photobioreactor hydrodynamics. Since the pioneering work of Sheth et al. (1977), several models have been proposed (Wu and Merchuk, 2001; Marshall et al., 2010; Papáček et al., 2011). However, these models are penalized by criticisms due to the different time-scales of the kinetics and of the hydrodynamic phenomena: i) the light-capture and photochemical quenching of the PSU are characterized by time-scale of millisecond; ii) photoinhibition and repair processes of the PSU are characterized by time-scale of hundreds of seconds; iii) for high-concentrated culture the light decays in few millimetres. As a consequence, a very fine spatial- and time-discretization of the photobioreactor integrated over a representative time interval requires an accurate modelling strategy.
This contribution reports a model aiming at evaluating performances – estimated as photosynthesis rate - of a photobioreactor (flat bubble column. A Lagrangian stochastic model was adopted to describe the microalgal dynamics based on well-consolidated turbulence models. A three state configuration was adopted for the PSU-light interaction. The light-path, irradiance level, turbulence level, and biomass concentration ranged over the typical range reported in the literature.

2. Photobioreactor model

The lumped kinetic model of photosynthesis by Eilers and Peeters (1988) and Camacho-Rubio et al. (2003) was adopted in the present simulation. The PSU is characterized by thee states: open or resting (x_1), activated or closed (x_2), and damaged or non-functional (x_3). x_1, x_2 and x_3 are the fraction of PSU in each state (Figure 1). The PSUs in open state is activated by the photons capture (PC) process. The fate of activated PSUs depends on the probability to be further irradiated. The natural fate is to transfer the fixed energy to the successive photosynthetic pathway, a step identified by Camacho-Rubio et al. (2003) and known as the well-known photochemical quenching (PQ) process. The second fate of the activated PSU is the non-photochemical quenching (NPQ): the extra photons may be discharged by means of the dissipative processes without state change. If the NPQ processes is not sufficient to dissipate the exceeding irradiance, photoinhibition (PI) process occurs: a x_2-PSU irradiated by an extra photon is inhibited, it assumes the damaged state x_3. The x_3–PSU does not participate to the photosynthesis process and may recover the open state according to a repair (REP) mechanism. Figure 1 reports a sketch of the state flow and kinetics. According to Eilers and Peeters (1988), the photosynthetic model is:

$$\begin{aligned}
\frac{dx_1}{dt} &= -\alpha I x_1 + \gamma x_2 + \delta x_3 \\
\frac{dx_2}{dt} &= \alpha I x_1 - \gamma x_2 - \beta I x_2 \\
\frac{dx_3}{dt} &= \beta I x_2 - \delta x_3
\end{aligned} \tag{2}$$

The photosynthesis rate Φ was assumed proportional to the PQ rate. Accordingly, the value of x_2 was the ratio between Φ and the maximum photosynthesis rate Φ^{MAX}, associated to all the PSUs constantly activated. The kinetic parameters were (Wu and Merchuk, 2001): α=1.935·10^{-3} μE/(s m^2), β=5.7848·10^{-7} μE/(s m^2), γ=0.146 s^{-1}, δ=4.796·10^{-4} s^{-1}.
The photosynthesis rate may be enhanced by the so called flashing-light effect: the fast turnover between dark and light zones of the photobioreactor. Of course, the turbulence of the suspension in the photobioreactor is the main engine of the turnover. The turbulence level for gas sparged systems - flat photobioreactor and bubble column - is mainly controlled by bubbles (Sato and Sekoguchi, 1975).
The microalgal flow may be described according to the turbulence field described by the turbulent diffusivity (D_T). The main hypothesis were: i) isotropic turbulence field; ii) negligible inertia of microalgal cells (no-slip velocity). According to Visser (1997), the Lagrangian tracking of a microalgal was:

$$P(t+dt) = P(t) + \overset{(A)}{\sqrt{2D_T dt}} \cdot \xi + \overset{(B)}{\nabla D_T} \cdot dt + \overset{(C)}{u_L} \cdot dt \qquad (3)$$

where P(t) is the coordinates of the microalgal position at time t, ξ a vector (components are non correlated Gaussian random numbers and characterized by zero mean and unit variance), and u_L the liquid velocity. The term (A) in Eq(3) is the pure random diffusive component of the motion P(t+dt)-P(t), the term (B) is a non-random advective or deterministic component, and the term (C) is related to the liquid flow field.
The simulation regarded flat photobioreactors: rectangular bubble column characterized by a thin light path. Mixing was provided by uniform gas-sparging at the bottom. Sato and Sekoguchi (1975) stated that the turbulent diffusivity of the liquid phase in gas-liquid flow was mainly due to bubble flow according to:

$$D_T = 1.2\, \varepsilon_G \frac{d_B}{2} U_B \qquad (4)$$

where ε_G is the gas-holdup, d_B the Sauter mean bubble diameter, and U_B the mean bubble slip velocity. Operating conditions investigated were: ε_G =2 - 10%, d_B = 2 - 10 mm, and U_B = 10 - 30 cm/s. The D_T resulted in the range 5 - 200 mm^2/s.
Boundary conditions are reflecting conditions at the photobioreactor walls.
The simulation procedure included: i) particle tracking estimation by means of Eq(3); ii) estimation of the irradiance history I(t) for each PSU by mean of Eq(1); iii) dynamic estimation of the three PSU state (x_1(t), x_2(t) and x_3(t)) by means of Eq(2).
The time-averaged mean of I(t), x_1(t), x_2(t), and x_3(t) was calculated between 0 and t. The statistic soundness of the assessed dynamics was checked by verify that the mean of I(t), x_1(t), x_2(t), and x_3(t) approached a steady state value.
Provided that simulations were carried out for a representative statistically integration time, the spatial profile of the time-averaged value of the PSU states x_1, x_2 and x_3 were assessed. The overall performance of the photobioreactor was assessed in terms of $x_2=\Phi/\Phi^{MAX}$.

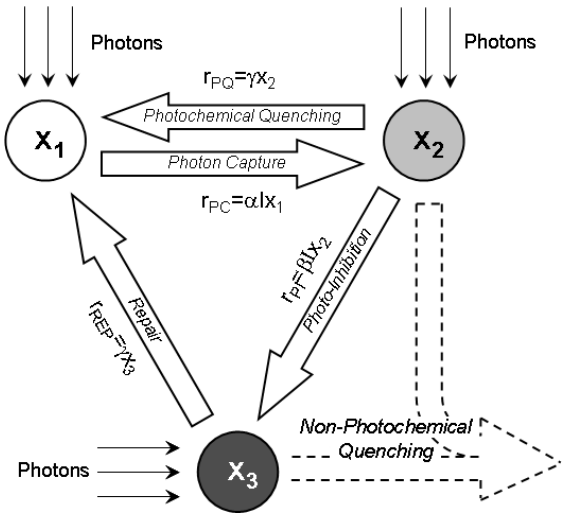

Figure 1: The lumped kinetic model of photosynthesis after Eilers and Peeters (1988)

a^*_{DW} was assumed always equal to 0.25 m^2/g.

3. Results

Figure 2 shows simulation results for a test carried out setting: light path at 10 mm, biomass concentration at 1 g/L, wall-irradiance I^0=2,000 μE/(m^2 s), turbulent diffusivity at 20 mm^2/s. a^*_{DW} was assumed equal to 0.25 m^2/g and the light exponential decay coefficient K was 2.5. The Figure 2A is the irradiance I(t) experienced by a microalgal in the flat photobioreactor for 30 s. Figures 2B, 2C, and 2D report, respectively, $x_1(t)$, $x_2(t)$ and $x_3(t)$ assessed by setting the I(t) reported in Figure 2A. The dynamics of x_1 and x_2 are characterized by oscillations characterized by few second periods, reflecting the microalgal meandering flow between light and dark zones. The change of the x_3 state is just lightly detectable over the integration time reported.

The time-averaged mean of I approached a constant value - 65 μE/(m^2 s) – after about 1,000 s. This constant value was equal to the spatial-averaged mean of I calculated according to the relationship:

$$\langle I \rangle = I^0 e^{-K}/K \tag{5}$$

The harmony between the time-averaged mean and the spatial-averaged mean of I was a further confirmation of the statistical soundness of the random walk model.

The simulation time required to approach a steady state value for the time-averaged mean of x_1, x_2, and x_3 was of about 20,000 s. The result is a consequence of the large spectrum of characteristic times of kinetic steps: t_{PC} (= 1/αI = 0.26 s) < t_{DT} (= LP^2/D_T = 5 s) ≈ t_{PQ}(= 1/γ = 6.8 s) < t_{PI} (= 1/βI = 870 s) < t_{REP} (= 1/δ = 2,085 s).

Figure 3 reports the profile of the time-averaged value of I and x_2 (z=0 at the irradiated wall) assessed for simulations reported in Figure 2. The analysis of the figure highlights that more than 60% of the photobioreactor is under dark conditions because the sharp gradient of the light intensity. Nevertheless the region of the photobioreactor far from the irradiated wall is under dark conditions, the x_2 mean value profile is quite constant. This apparent discrepancy is due to the beneficial effects of the turbulent mixing that supply sufficient turnover between ligh/dark zones. As a consequence, the photosynthesis rate (e.g. x_2) is not negligible even in the dark zone.

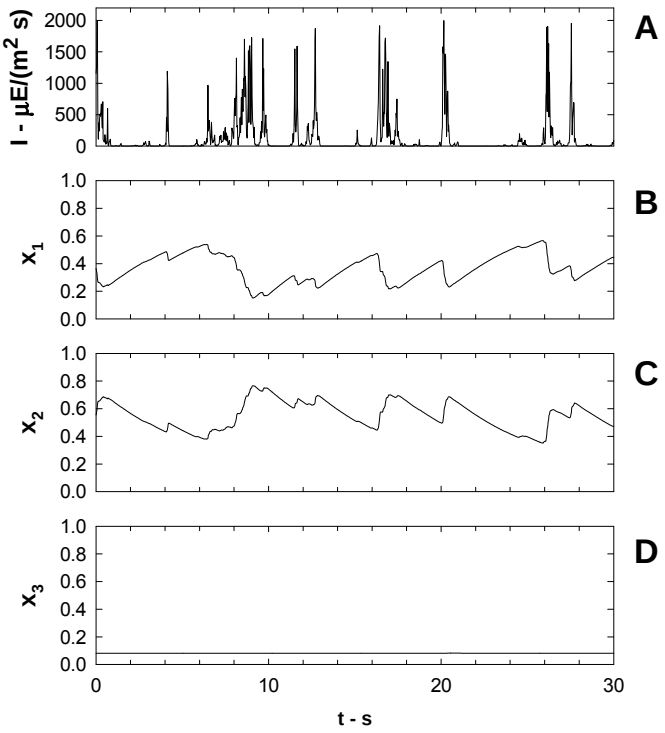

Figure 2: Time series of I(t), $x_1(t)$, $x_2(t)$, and $x_3(t)$ for a PSU subject to random walk in a flat photobioreactor. I^0=2,000 μE/(m^2 s), LP=10 mm, X=10 g/L and D_T=20 mm^2/s

Φ/Φ^{MAX} is mainly affected by the light path, the wall irradiance, the biomass concentration, the specific dry-weight absorption coefficient and the turbulent diffusivity.
Figure 4 reports the value of Φ averaged over the LP and assessed for different wall irradiance. Simulation referred to a flat photobioreactor characterized by light path of 10 mm and turbulent diffusivity of 20 mm^2/s. Three values of biomass concentration were investigated: 0.1, 1 and 10 g/L.

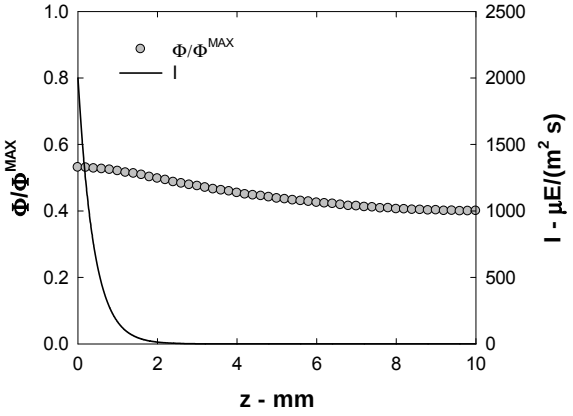

Figure 3: Time-averaged value of I(t) and $x_2(t)$ vs. the distance from the irradiated wall of the photobioreactor. I^0=2000 $\mu E/(m^2\ s)$, LP=10 mm, X=10 g/L and D_T=20 mm^2/s

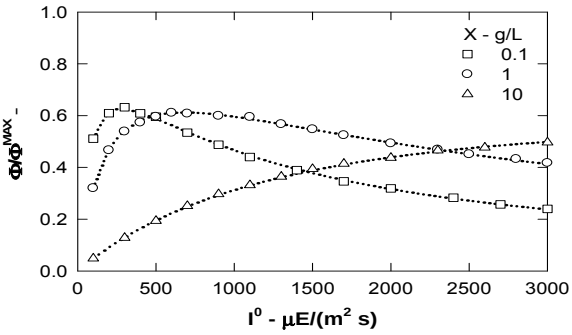

Figure 4: Mean photosynthesis rate in flat photobioreactor as a function of wall irradiance (D_T=20 mm^2/s, LP=10 mm) for three different levels of microalgal concentration

X=0.1 g/L. The photosynthesis rate has a maximum at I^0 ~ 300 $\mu E/(m^2\ s)$. For I^0 >300 $\mu E/(m^2\ s)$, the photoinhibition phenomena is evident and the photosynthesis rate decreases with I^0. The microalgae are not steadily exposed at I^0 because the turbulen turnover is always active. However, K is just 0.25 because X is low and the inner part of the photobioreactor are still too much irradiated.

X=1 g/L. Φ still exhibits a maximum but at I ~700 $\mu E/(m^2\ s)$. The photoinhibition phenomena are less marked than that observed setting X=0.1 g/L.

X=10 g/L. The photoinhibition phenomena are practically negligible. The increase of I^0 has always a beneficial effect of the photosynthesis rate. This behaviour was experimentally observed by Richmond et al. (2003) and Richmond et al. (2004). They carried out ultra-high density cultures (X>10 g/L) in thin flat photobioreactor and pointed out: i) the biomass productivity increased with the wall irradiance; ii) photoinhibition phenomena were not observed. Richmond et al. (2003), Richmond et al. (2004) and Jansenn et al. (2003) related this result to the favourable light-dark turnover induced by both high density cultures and turbulent mixing in short light-path photobioreactors.

4. Main remarks

A model of photobiorecator was developed. It was based on: Langrangian random walk - bubble induced turbulence – of microalgae coupled with the Eilers and Peeters (1988) photosynthetic model. The simulation was implemented for a flat photobioreactor.
Results showed that set the biomass concentration, the photosynthesis rate may be optimized by tuning the level of wall irradiance.

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