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Model Development and Light Effect on a Rotating Algal Biofilm

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Abstract: The idea relying on attached culture for microalgae production has attracted many interest these past years due to their energy efficiency and low water usage. Microalgae can grow and attach to the surface of an appropriate material to form a biofilm. In this paper, a rotating algal biofilm (RAB) model is introduced. It is based on the Han model. How light affects the growth and productivity of microalgae and thus the formed biofilm will be discussed through model development, more importantly, it will be seen that taking into consideration light dilution factor can increase productivity. The benefit of the system is assessed when the conveyer velocity is fast enough. Simulation show an optimal folding of the conveyer. Actual productivities for moderate velocities are assessed and compared to these extreme cases.

Keywords: microalgae, rotating algal biofilm, biomass harvest

1. INTRODUCTION

Microalgae are considered for their potential use as a feedstock, not only for biofuel production (Hu et al. (2008), Mohimani et al. (2015)) but for a multitude of industries ranging from pharmaceutics to aquaculture (Benemann (1992), Borowitzka (1995)). They can also contribute to recycle nitrogen and phosphorus within a wastewater treatment process. A keen interest in attached microalgae culture has been shown these past years. Flemming and Wingender (2010) define a biofilm as microorganisms that live in a self-produced matrix of extracellular polymeric substances (EPS). The latter are mainly polysaccharides, proteins, nucleic acids and lipids, all constitute a three dimensional polymer network that interconnects biofilm cells. The main advantage on using rotating algal biofilm (RAB) reactors is the reduced cost for harvesting, and the high productivity due to light dilution in time. Indeed, cells are never too long in sunlight, so that photo inhibition (damages due to excess of light energy), is mitigated. The time microalgae are exposed to light affect their growth, that is, after a longer exposition to high light intensity, the cells become photo-saturated and often inhibited. Photoinhibition is characterized by the denaturation of some key proteins contributing to the photosynthetic activity. RAB offer the possibility to regulate light distribution through the biofilm by varying the rotational speed and therefore changing light exposure. The rotation also, allows the biofilm to be in permanent contact with the medium for the microalgae to survive and contribute to the biofilm formation. Christenson and Sims (2012) developed a RAB reactor for maximizing algae production in waste water treatment process, while reducing nitrogen and phosphorus concentration. Gross and Wen (2014) showed that RAB can provide, on average (over a year period), 302% increase in biomass productivity when compared to a standard raceway pond. Blanken et al. (2014) introduced a bioreactor they refer to as AlgalDisk. They showed that a productivity of 20g.m⁻².d⁻¹ can be obtained with Chlorella Sorokiniana. Schnurr et al. (2014) studied the effect of light direction on algal biofilm growth rate. It was concluded that light direction had no effect on long-term algal biofilm growth as opposed to its effect on suspended algae cells present in the growth medium. Wang et al. (2017) summarize the recently developed biofilm based attached cultivation technology. All these RAB photobioreactor benefit from the simple harvesting procedure consisting in scrapping the biomass out of the formed biofilm to avoid expensive sedimentation and centrifugation operations.

Few authors tackled the challenging issue of modeling such processes. In this work, we propose a model that would account for the effect of photoinhibition and respiration. We start from a model by Han (2002), that was firstly introduced by Eilers and Peeters (1988). After some approximation we augment it with the the biofilm thickness dynamics together with considering light attenuation through the layers of the formed biofilm.

The second part of the paper focuses on light distribution of the RAB, and how it affects the productivity. It is important to know that an exposure to high light intensity renders the microalgae inhibited, affecting the growth, and inherently the biofilm. A longer exposition to darkness however, decreases the carbon content of the cells by the effect of respiration. Therefore, a good compromise
needs to be achieved for better productivity. We will show through simulation that it is possible to double the productivity. It will also be shown that an optimal value exists, it translates how light needs to be averaged for a given incident light.

The paper is organized as follows:
The different steps in the construction of our model are provided in Section 2. In section 3 the growth rate and productivity are presented to outline light distribution at steady state. Simulation results are found in Section 4. Finally Section 5 summarizes our concluding remarks.

2. MODEL OF THE ROTATING ALGAL BIOFILM

The effect of photo-inhibition is one of the main factors affecting the photosynthetic activity in microalgae, and therefore its growth. The model first introduced in Eilers and Peeters (1988), and then Han (2002) will be used in this paper. They describe the complex process of photosynthesis by two types of photosystems, PSI and PSII. The later will play a prominent role. It is described by exploiting that, assuming a slow fast dynamics using singular perturbation theory ($T > 10 \tau \approx 1 \text{min}$), $A$ reaches rapidly its pseudo steady state defined by $\dot{A} = 0$ (Hartmann et al. (2014)), therefore the Han model reduces to the following equation

$$\frac{dC}{dt} = -(k_r + k_d \sigma I)C + k_d \sigma I(1 - A)$$

(7)

The model response for low light frequencies, that is, $T > 10 \tau \approx 1 \text{min}$, the light intensity received on the surface and $b$ is given in ($n^{-1}$) and $b$ represent the extinction coefficient. From Fig. 2, it is observed that at the bottom $z = 0$, the light is the most attenuated in opposite to the light on the surface when $z = h$. The cycle $T$ correspond to the time the RAB completes one full rotation. $T^*$ is the time the biofilm is exposed to light. The light received by the biofilm is therefore expressed as follows

$$I(t, z) = \begin{cases} I(z) & \text{if } 0 \leq t \leq T^* \\ 0 & \text{if } T^* \leq t \leq T \end{cases}$$

(11)

2.2 Mean growth rate

As reported in Huisman and Weissing (1994), an accurate way of estimating the growth rate in a photobioreactor consists in taking the mean value across the depth of the photobioreactor. Here the depth average is taking across the width of the biofilm. The specific growth rate
is expressed as the balance between photosynthesis and respiration rate, i.e.,
\[ \mu = k \sigma I A - R, \]  
where \( k \) is a constant parameter. Given equation (9), equation (12) becomes
\[ \mu(I) = - \frac{k \sigma I}{1 + \tau \sigma I} C + \frac{k \sigma I}{1 + \tau \sigma I} - R, \]  
The mean growth rate across the biofilm width is expressed as follows
\[ \bar{\mu}(t) = \frac{1}{h} \int_0^h (1 - C(t, z)) \left[ \frac{k \sigma I_0 e^{-b(h-z)}}{1 + \tau \sigma I_0 e^{-b(h-z)}} \right] dz - R \]  
\[ (14) \]

2.3 Biofilm width dynamics

Given the surface biomass dynamics \( \dot{X} = \bar{\mu} X \) and knowing that \( X = \rho h \), where \( \rho [g.m^{-3}] \) is the biofilm density, it is possible to express the width dynamics according to
\[ \dot{h} = \int_0^h (1 - C) \left[ \frac{k \sigma I_0 e^{-b(h-z)}}{1 + \tau \sigma I_0 e^{-b(h-z)}} \right] dz - R h(t), \]  
The inhibition dynamics varies according to the following equation
\[ C(t, z) = -(\beta(t, z) + k_r)C + \beta(t, z) \]  
The function \( \beta(z) \) is given as
\[ \beta(t, z) = \frac{k_d \sigma^2 I(t, z)^2}{\tau \sigma I(t, z) + 1} \]  
\[ (17) \]

2.4 Structure of the RAB

In order to improve the productivity of the biofilm it is possible to consider multiple configuration of the RAB’s structure. How light is distributed across the biofilm is often measured according to the light dilution factor \( LDF \), that we also note by \( \frac{LDF}{h} = N \), where \( l_{tot} \) is the total length of the biofilm and \( l^* \) is the length of the conveyor belt (biofilm) exposed to light \( (N = 2 \text{ in Fig. 1}) \)

2.5 Productivity

In order to assess the efficiency of the process we evaluate the depth and time averaged productivity that is given in terms of \( g.m^{-2}.d^{-1} \).

Definition 1. The productivity of the RAB per illuminated area is given by
\[ P = \frac{N S}{T_f h} \int_0^{T_f} \int_0^h ((1 - C(t, z)) \phi(h, z) - R) X dz dt, \]  
\[ (18) \]

It can also be written as follows
\[ P = \frac{N S}{T_f} \left( h(T_f) - h(0) \right), \]  
\[ (19) \]

where \( \rho [g.m^{-3}] \) is the dry biomass density and \( T_f = t_h \) is the harvest time. We multiply by \( N S \) since we are interested in the productivity per unit of illuminated surface \( S \). Note that \( X = \rho h [g.m^2] \) and
\[ \dot{h} = \int_0^h ((1 - C(t, z)) \phi(h, z) - R) dz dt \]  
\[ (20) \]

The function \( \phi \) is given by
\[ \phi(h, z) = \frac{k \sigma I_0 e^{-b(h-z)}}{1 + \tau \sigma I_0 e^{-b(h-z)}} \]  
\[ (21) \]

Note that \( I_0 \) can be considered constant or varying depending on the origin of the light source (Day light or constant artificial light).

2.6 Modeling dark-light cycles

Remark 1. Assuming that the length exposed to light \( l^* \) is known, that is, the \( LDF \) is known, varying the cycle time \( T \) would be equivalent to varying the RAB speed.

Note that \( T^* = \frac{T}{v} \) and \( T = \frac{T_0}{v} \), where \( v \) is the rotational speed.

The succession of light-dark cycle seen in equation (11) can be modeled according to a periodic square wave function with duty cycle given by the second argument of \( \text{square} \). The duty cycle is defined as the percent of the signal period in which the square wave is equal to one. It is also equivalent to the exposure time \( T^* \). The light received by the biofilm \( I(t) \) can be expressed as follows
\[ I(t) = I_0(t) \ast \text{square} \left( \frac{2\pi}{T_0} + t, \frac{1}{LDF} \right), \]  
\[ (22) \]

where \( I_0 \) is the light source applied from above to the process in Fig. 1. The presence of time and space variable \( t \) and \( z \), respectively, would suggest the use of partial differential equations (Lamare et al. (2017)), however to keep the modeling simple for future control and estimation purposes, we arrived at the following approximation for the dynamics of the RAB.

That the dynamics of the rotating algal biofilm in Fig. 1 can be approximated by the following ode’s
\[ \dot{h} = \sum_{i=1}^{p} (1 - C_i(t)) \left[ \frac{k \sigma I_i(t)}{1 + \tau \sigma I_i(t)} \right] - R h(t) \]  
\[ (23) \]
\[ \dot{C}_1 = -(\beta_1(I_1) + k_r)C_1(t) + \beta_1(I_1) \]  
\[ (24) \]
\[ \vdots \]
\[ \dot{C}_p = -(\beta_p(I_p) + k_r)C_p(t) + \beta_p(I_p), \]  
\[ (25) \]

where \( p \) is the number of discretization layers. It also corresponds to the number of inhibitions ode’s.

\[ \beta_i(I_i) = \frac{k_d \sigma^2 I_i^2}{\tau \sigma I_i + 1} \]  
\[ (26) \]

and
\[ I_i(t) = \frac{4}{h} \int_{z_i}^{z_{i+1}} I(t) e^{-b(h-z)} dz, \]  
\[ (27) \]

where \( z_i = \frac{h}{p} \frac{2i}{p}, \ldots, \frac{h}{p} \) for \( i = 1, 2, 3, \ldots, p - 1 \) respectively and \( z_p = h. \)

The previous approximation is justified by the biofilm being divided into \( p \) layers. Each layer is associated with its average light. By replacing \( I \) in equation (8) by \( I_1, I_2, \ldots, I_p \). The inhibition states associated with each layer follows as \( C_1, C_2, \ldots, C_p \) and hence equation (24)-(25). Note that the solution of the inhibition states is independent of the variable \( z \). The biofilm’s thickness time evolution is given
Similarly to the above discussion, we can write
\[ \dot{h} = \sum_{i=1}^{p-1} \int_{z_i}^{z_{i+1}} \left(1 - C_i(t) \right) \frac{k \sigma I(t) e^{-b(h - z)}}{1 + \tau \sigma I(t) e^{-b(h - z)}} \, dz - R h \]  
(28)

Using equation (27), the final width dynamics in equation (23) is obtained.

For a number of layer equal to \( p = 4 \), the biofilm is divided as in Fig. 3

![Biofilm divided into 4 layers](image)

Fig. 3. Biofilm divided into 4 layers. For each separate layer corresponds an average light intensity

3. LIGHT DILUTION AND PRODUCTIVITY

We are interested in this section to see how the distribution of light affects the productivity of the RAB for the case where the conveyor belt of our process is in standstill position, i.e., \( N = 1 \) or when it is moving very fast. Let us consider eq. (16) and (17). For the scenario where the RAB moves fast, we assume that the variation rate of light is much faster than the dynamics of \( C \) (typically minutes) so that averaging can be applied (Verhulst (2006)). Note that we still consider that the dynamics of \( A \) (with typical time constants in the range of ms), still more rapidly reaches its steady state.

\[
\dot{C} = - (\beta(z) + k_r)C + \beta(z) \quad \text{(29)}
\]

\[
\beta(z) = \frac{1}{T} \int_0^T \beta(t, z) \, dt \quad \text{(30)}
\]

Using equation (11) and knowing that \( T = NT^* \), we can show

\[
\beta(z) = \frac{1}{N} \beta(z) \quad \text{(31)}
\]

3.1 Growth rate

At steady state the growth rate is expressed as follows

\[
\mu_{ss}(z) = (1 - C_{ss}(z)) \frac{k \sigma I(t, z)}{1 + \tau \sigma I(t, z)} - R \quad \text{(32)}
\]

Similarly to the above discussion, we can write

\[
\mu_{ss}(z) = (1 - C_{ss}(z)) \frac{k \sigma I(t, z)}{N(1 + \tau \sigma I(t, z))} - R \quad \text{(33)}
\]

The photo-inhibition at steady state is given according to

\[
C_{ss}(z) = \frac{\beta(z)}{\beta(z) + Nk_r} \quad \text{(34)}
\]

One can verify that

\[
1 - C_{ss}(z) = \frac{Nk_r}{Nk_r + \frac{k \sigma I(t, z)}{1 + \tau \sigma I(t, z)}} \quad \text{(35)}
\]

Finally after some algebraic simplification the growth rate simplifies to

\[
\mu_{ss}(z) = \frac{kk_r \sigma I(t, z)}{k \sigma I(t, z)^2 + N \sigma I(t, z)} - R \quad \text{(36)}
\]

Integrate through the width of the biofilm to have the following mean growth rate

\[
\bar{\mu}_{ss} = \frac{1}{h} \int_0^h \frac{kk_r \sigma I(t, z)}{k \sigma I(t, z)^2 + N \sigma I(t, z)} - R \, dz \quad \text{(37)}
\]

Dividing by \( kk_r \sigma \) to have

\[
\bar{\mu}_{ss}(h) = \frac{1}{h} \int_0^h \frac{k \sigma I(t, z)}{k \sigma I(t, z)^2 + N \sigma I(t, z)} - R \, dz \quad \text{(38)}
\]

where we have used the following change of variable

\[
J(z) = I_0 e^{-b(h - z)} \quad a_1 = \frac{k \sigma}{kk_r} \\
dJ = b J \, dz \quad a_2 = \frac{N \tau}{k} \\
J(0) = I_0 e^{-b(h - 0)} \quad a_3 = \frac{N}{k \sigma} \\
J(h) = I_0 \\
\int_{J(0)}^{J(h)} \frac{dz}{a_1 J(z)^2 + a_2 J(z) + a_3} - R \quad \text{(39)}
\]

so basically the resulting integral is a function of \( J(h) = I_0 \) and \( J(0) = I_0 e^{-b(h - 0)} \). Let \( A_1 = 2a_1 J(0) + a_2 \), \( A_2 = 2a_1 J(h) + a_2 \), and \( \Delta = 4a_1 a_3 - a_2^2 \) then

\[
\bar{\mu}_{ss}(h) = \frac{2}{\Delta} \arctan \frac{A_2}{2 \Delta} - \frac{2}{\Delta} \arctan \frac{A_1}{\sqrt{\Delta}} \quad \text{if} \quad \Delta > 0
\]

\[
= \frac{2}{A_1} - \frac{2}{A_2} \quad \text{if} \quad \Delta = 0
\]

\[
= \frac{1}{\sqrt{\Delta}} \ln \left| \frac{A_2 - \sqrt{\Delta} A_1}{A_2 + \sqrt{\Delta} A_1} \right| \quad \text{if} \quad \Delta < 0
\]

3.2 Productivity at steady state

Now that we have an expression of the steady state mean growth rate, the productivity per unit of enlightened
The Han parameters used in the simulation are summarized in Table 1. The incident light intensity close to $I = 288 \mu\text{mol.m}^{-2}\text{s}^{-1}$. Note that this value correspond to approximately the same value as the one for the averaged light. We conclude by saying that in order to increase the productivity the RAB needs to receive in average a light intensity close to $I = 288 \mu\text{mol.m}^{-1}\text{s}^{-1}$.

5. CONCLUSION

Processes based on biofilms solve the drawbacks that suspended microalgae culture experience in terms of energy and time. A mathematical model for a rotating algal biofilm process is presented. It outlines the positive effect that light can have on maintaining a positive biofilm growth thanks to photosynthesis. In contrast, photoinhibition acts in the opposite direction. Light attenuation through the biofilm layers is modeled by the Beer-Lambert effect. Dividing the biofilm in multiple layers and taking the average light intensity for each part, allows to have a relatively good approximation. We have shown that for high light intensity, it is possible to counteract the effect of inhibition by averaging light. In fact, it has been possible to double the productivity by choosing the optimal $LDF$. It turns out that maximum productivity occurs when the averaged incident light is close to the optimal value that maximizes the mean growth rate when the RAB is fully exposed to light.

REFERENCES

Benemann, J.R. (1992). Microalgae aquaculture feeds. *Journal of Applied Phycology*, 4(3), 233–245.
Blanken, W., Janssen, M., Cuaresma, M., Libor, Z., Bhaiji, T., and Wijffels, R. (2014). Biofilm growth of chlorella sorokiniana in a rotating biological contactor based photobioreactor. *Biotechnology and bioengineering*, 111(12), 2436–2445.

Borowitzka, M.A. (1995). Microalgae as sources of pharmaceuticals and other biologically active compounds. *Journal of Applied Phycology*, 7(1), 3–15.

Christenson, L.B. and Sims, R.C. (2012). Rotating algal biofilm reactor and spool harvester for wastewater treatment with biofuels by-products. *Biotechnology and bioengineering*, 109(7), 1674–1684.

Eilers, P. and Peeters, J. (1988). A model for the relationship between light intensity and the rate of photosynthesis in phytoplankton. *Ecological modelling*, 42(3-4), 199–215.

Flemming, H.C. and Wingender, J. (2010). The biofilm matrix. *Nature Reviews Microbiology*, 8(9), 623.

Gross, M. and Wen, Z. (2014). Yearlong evaluation of performance and durability of a pilot-scale revolving algal biofilm (rab) cultivation system. *Bioresource technology*, 171, 50–58.

Han, B.P. (2002). A mechanistic model of algal photoinhibition induced by photodamage to photosystem-ii. *Journal of theoretical biology*, 214(4), 519–527.

Hartmann, P., Béchet, Q., and Bernard, O. (2014). The effect of photosynthesis time scales on microalgae productivity. *Bioprocess and biosystems engineering*, 37(1), 17–25.

Hu, Q., Sommerfeld, M., Jarvis, E., Ghirardi, M., Posewitz, M., Seibert, M., and Darzins, A. (2008). Microalgal triacylglycerols as feedstocks for biofuel production: perspectives and advances. *The plant journal*, 54(4), 621–639.

Huisman, J. and Weissing, F.J. (1994). Light-limited growth and competition for light in well-mixed aquatic environments: an elementary model. *Ecology*, 75(2), 507–520.

Lamare, P.O., Aguillon, N., Sainte-Marie, J., Grenier, J., Bonnefond, H., and Bernard, O. (2017). Gradient-based optimization of a rotating algal biofilm process. *Submitted to Automatica*.

Moheimani, N.R., McHenry, M.P., De Boer, K., and Bahri, P.A. (2015). Biomass and biofuels from microalgae. *Biofuel and biorefinery technologies. Springer-Verlag GmbH*.

Schnurr, P.J., Espie, G.S., and Allen, D.G. (2014). The effect of light direction and suspended cell concentrations on algal biofilm growth rates. *Applied microbiology and biotechnology*, 98(20), 8553–8562.

Verhulst, F. (2006). *Nonlinear differential equations and dynamical systems*. Springer Science & Business Media.

Wang, J., Liu, W., and Liu, T. (2017). Biofilm based attached cultivation technology for microagal biorefineriesa review. *Bioresource technology*, 244, 1245–1253.

Wu, X. and Merchuk, J.C. (2001). A model integrating fluid dynamics in photosynthesis and photoinhibition processes. *Chemical Engineering Science*, 56(11), 3527–3538.