Discrete Event Based Dynamic Simulation of Algae Growth Bioreactor Considering Cyclic Light Effect

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This paper provides an integrated framework handling discrete events for the biological systems. The living organism involves various conditions including discrete phenomena. To enhance the performance and productivity of biological systems, discrete variables play a significant role in designing and operating the biological facilities such as the bioreactor. This study focuses on the algae growth bioreactor with light/dark cyclic conditions. The discrete based model describes practical behavior of algae with respect to light changes. The dynamic model includes light/dark cycle which is integrated with binary variables. The discrete event based dynamic simulation is conducted under the integrated framework. The optimal condition for algae growth in thin film bioreactor is identified. The amount of biomass production is chosen as the objective function during the optimization. Throughout the integrated work with dynamic simulation and optimization, this study suggests optimal design factors when it comes to cyclic light effect.

INTRODUCTION

The phototrophic algae produce valuable biological and pharmaceutical compounds. The design of bioreactor with a systematic approach is important to take into account the optimal design and operating condition. Little achievement, however, has been fulfilled comparing with their significance. For the efficient design of bioreactor, modeling to predict the behavior of biological systems is required. To find the practical behavior and characteristics of target objects, modeling have to handle discrete conditions such as light/dark cycle. For this reason, integrated method between discrete and continuous is applied.

This study focuses on the behavior under the cyclic light conditions. The red marine algae, *Porphyridium sp.* was used in thin film bioreactor. The continuous model with three states was developed by Eilers and Peeters (1988) to describe the photoinhibition effect as well as photosynthesis. This model shows the photoinhibition effect due to excessive light and recovery of inhibited algae (Eilers, 1993). Figure 1 demonstrates schematic representation of algae growth including photosynthesis and photoinhibition under light condition. Continuous/discrete shows biological systems of algae growth with respect to cyclic light conditions. Finally, this study suggests the optimal conditions within the integrated model.

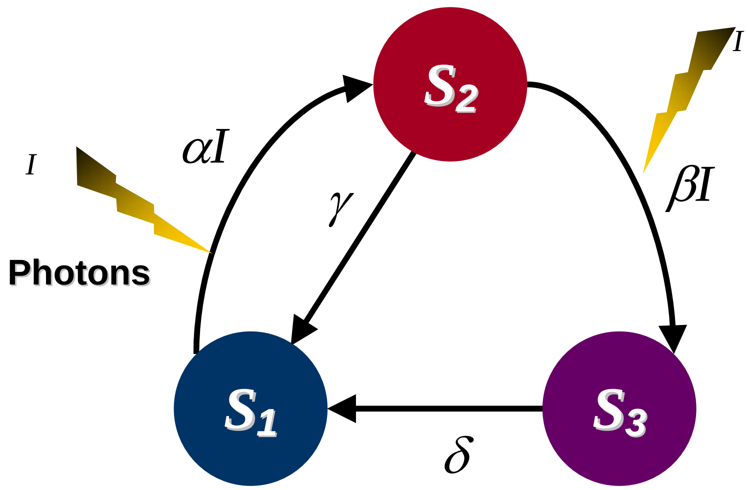

Figure 1. The structure of the three-state model: x_1, x_2, and x_3, are states and α, β, γ and δ are kinetic rate constants.

MATERIALS AND METHODS

Thins film bioreactor has several advantages in modeling the algae growth systems. Light inside the bioreactor is regarded as equal because its diameter is thin enough to ignore the shading effect due to the turbidity of algae. Algae flow throughout the tube of bioreactor, it is easy to change light/dark ratio. In this study, modeling concentrates on the cyclic light effect. Thus nutrient conditions such as concentration of carbon dioxide meet the required amount all the time. The substrate effects are not considered in this paper.

Kinetics data for simulation is based on Wu and Merchuk (2001) study. The photo flux density (PFD) is fixed during simulation. Figure 2 shows the effect of light intensity on algae growth. From the result, the specific growth rate of algae is always positive when PFD is higher than 330μEm^{-2}s^{-1}. The specific growth rate increases slowly when light intensity become stronger, which means the light efficiency is decreasing. In this study, 110μEm^{-2}s^{-1} in light intensity is used because it is supposed to be an economic light commonly.

DISCRETE EVENT BASED MODELING

In Figure 1, three states are introduced to account for the photosynthesis and photoinhibition. Algae in state 1 are called open state, which transfers into state 2 (closed state). When the algae are in state 2, they move one of two ways depending on the illuminating condition. Under excessive illuminated condition, the algae in state 2 transfer into state 3 (inhibited state). Without light, it returns to state 1. In state 3, algae return to state 1 at a recovery constant δ. Continuous mathematical modeling is developed with this concept. The mathematical relationship is shown by following formulations.

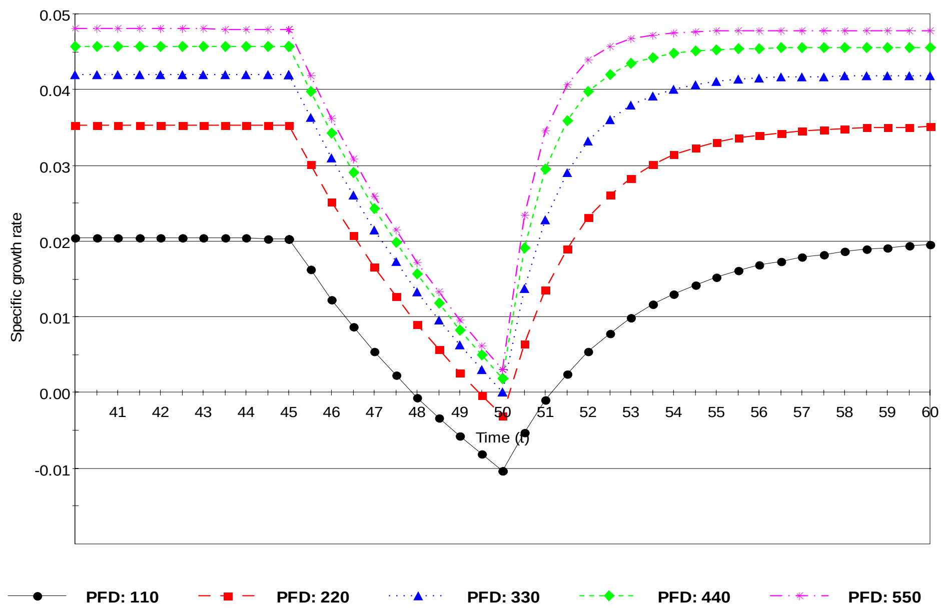

Figure 2. The specific growth rate profile: it is identified as positive when PFD is higher than 330μEm^{-2}s^{-1}.

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

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

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

$$\mu = k\gamma x_2 - Me \qquad (4)$$

where x_1, x_2 and x_3 are the amount of algae in open, closed and inhibited state, respectively. μ is the specific growth rate in algae. Because of photoinhibition effect, light/dark cycle is applying to enhance the performance of the bioreactor. To express the cyclic condition in computational model, two cyclic variables are introduced. The first one is cycle time (T_C) and the second is cycle rate (R_C). The cycle time is an adjustable variable with the flow rate in the bioreactor physically. The cycle rate is a novel concept to make the light/dark alternatives. The definition of the cycle rate is following:

darkness time in the cycle time = cycle time / cycle rate

→ cycle rate = cycle time / darkness time in the cycle time

With these two variables, the discrete event based model is formulated as followings and kinetic parameter for simulation is shown in Table 1.

$$\frac{dx_1}{dt} = -\alpha y I x_1 + \gamma x_2 + \delta x_3 \quad (5)$$

$$\frac{dx_2}{dt} = \alpha y I x_1 - \gamma x_2 - \beta y I x_2 \quad (6)$$

$$\frac{dx_3}{dt} = \beta y I x_2 - \delta x_3 \quad (7)$$

$$\mu = k \gamma x_2 - Me \quad (4)$$

$$\begin{aligned} & T_C = t_{n+1} - t_n \qquad n = 1,2,\ldots,m \\ & t_n \le t \le t_n + T_C\left(1 - \frac{1}{R_C}\right) \quad \Rightarrow y = 1 \\ & t_n + T_C\left(1 - \frac{1}{R_C}\right) \le t \le t_{n+1} \quad \Rightarrow y = 0 \\ & y \in \{0, 1\} \end{aligned} \quad (8)$$

Table 1. Kinetic parameter for the algae growth simulation

Parameter	Value	Unit	95% confidence interval
α	0.001935	$[\text{Em}^{-2}]^{-1}$	-0.00189~0.00576
β	5.7848×10^{-7}	$[\text{Em}^{-2}]^{-1}$	-0.000343~0.000344
γ	0.1460	s^{-1}	-0.133~0.425
δ	0.0004796	s^{-1}	-0.000531~0.00126
k	0.0003647	-	-0.0126~0.131
Me	0.05908	h^{-1}	0.494~0.528

RESULTS

Figure 3 shows the cycle time effect on the amount of algae in the closed state. The amount of algae in closed state is related with biomass yield directly. Thus, to verify the profile of closed state is important to know the performance of the bioreactor. The cycle time effect can be summarized as following from Figure 3.

(1) To reach the saturation point (quasi steady state), illumination is required for a certain time.

(2) Once it reaches the quasi steady state, maximum value decreases due to the photoinhibition effect.

(3) Long cycle time sustains long quasi steady state but the amount of closed state drops rapidly during dark period.

(4) The Maximum value at the short cycle time is less than that at the long cycle time.

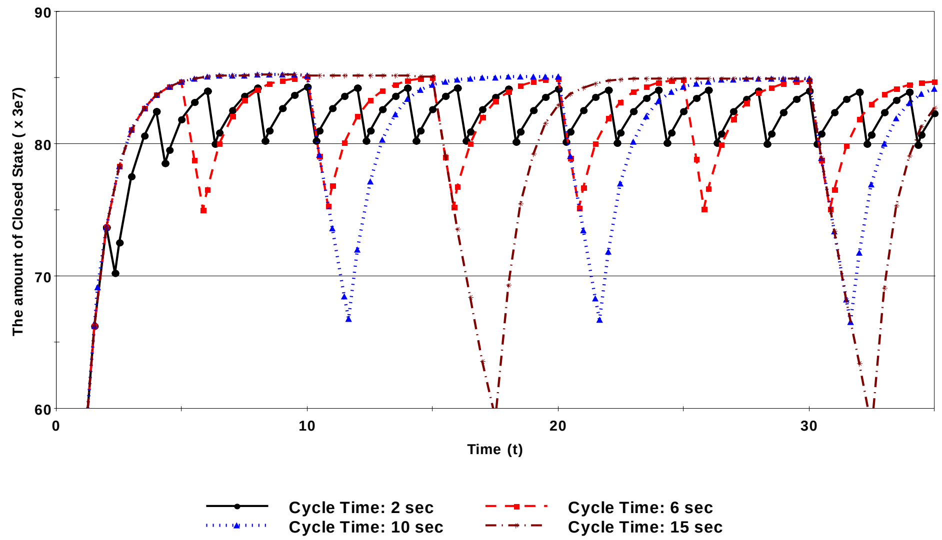

Figure 3. Cycle time effect: the profile of the amount of closed state when cycle rate is 6.

In a certain cycle rate under the same cycle time, some noticeable behavior is found in simulation. Figure 4 demonstrates the cycle rate effect and the photoinhibition effect when illumination is exceeded. Following characteristics on cycle rate effect are shown in simulation results.

(1) Over a certain cycle rate, pattern in quasi steady state is similar.

(2) Low cycle rate (longer dark time) is difficult to get the quasi steady state.

(3) For high cycle rate, it takes less time to attain the quasi steady state and the photoinhibition effect is found more clearly.

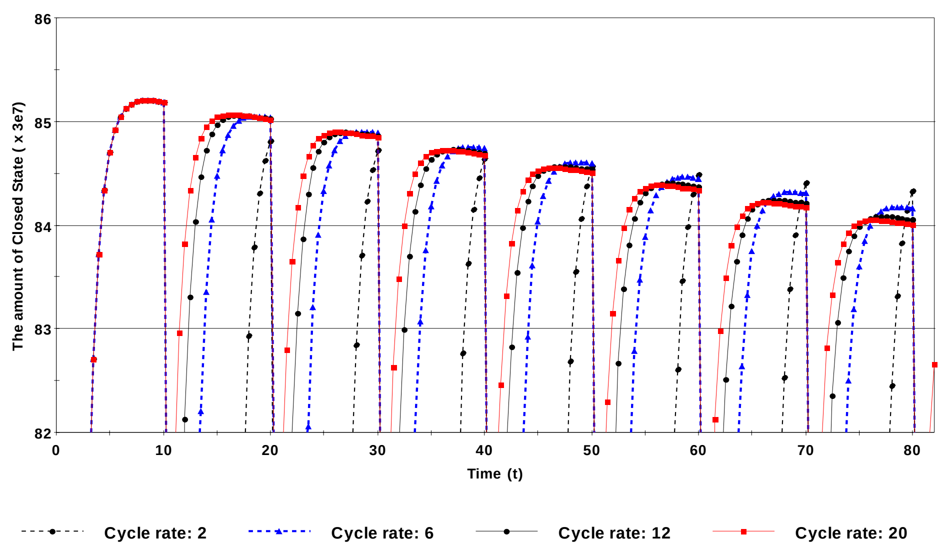

Figure 4. Cycle rate effect: the profile of the amount of closed state and photoinhibition effect is demonstrated.

To find the optimal condition with respect to two cyclic variables, the optimization is performed. As two cyclic variables are changes, the optimal condition found at desired moment. The light condition is 110μEm^{-2}s^{-1}. The objective function is set to maximize the biomass yield and its formulation is equation (9), (10) and (11). These formulations are subject to the equation (5), (6), (7) and (8).

$$\max_{y\in\{0,1\}}(Y) = f(T_C, R_C, y) \quad (9)$$

$$s.t. \quad \frac{dY}{dt} = (k\gamma x_2 - Me - \beta I)x_2 \quad (10)$$

$$\begin{aligned} &T_C{}^L \le T_C \le T_C{}^U \\ &R_C{}^L \le R_C \le R_C{}^U \end{aligned} \quad (11)$$

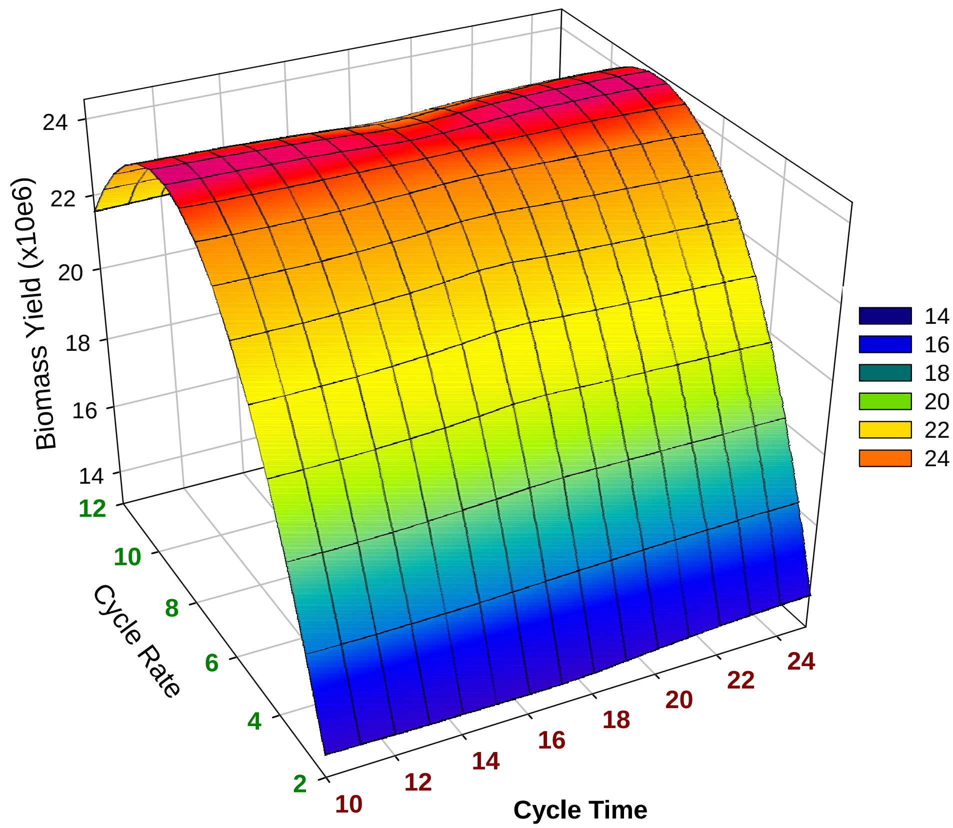

Figure 5. Biomass yield change when PFD is 110 μEm^{-2}s^{-1}

The optimization result is given in Figure 5 and the optimal cycle time and rate are 23.2 s and 8.33 respectively.

CONCLUSION

This study suggests the integrated method to explain the algae growth. Discrete event based dynamic simulation and optimization shows the biological behaviors with systems engineering approach. This framework integrating discrete variables enhances the practical solution of biological systems to find out the optimal conditions.

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