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Modelling and Simulation of a Bubble Column Photobioreactor for the Cultivation of Microalgae Nannochloropsis Salina

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The objective of the research is to obtain the valid model of a photobioreactor for the cultivation of microalgae Nannochloropsis salina. An axisymmetric two-dimensional model of internal-illuminated bubble column photobioreactors was developed by considering the gas and liquid mass balances and the light intensity. The validation of the model against experimental data with the inlet gas flow rate of 800 mL/min and enriched with 0.5 % and 2 % CO_2 gives average errors of 5 % and 4 %. The simulation results show that the microalgae growth is marked by the increase in its concentration from 0.08 g/L on the first day to 0.51 g/L on the sixteenth day for CO_2 concentration of 2 %. The inlet CO_2 concentrations of 0.5 %, 1 %, 2 %, and 4 % give the maximum concentrations of microalgae of 0.421 g/L, 0.472 g L, 0.502 g/L, and 0.514 g/L. However, the effect is not significant when the CO_2 concentration is above 4 %. Change in the gas flow rate does not give significant influence on the microalgae growth.

1. Introduction

One of the ways to streamline the production of commercial microalgae is the examination of mixing phenomena in photobioreactors in which microalgae receive optimal light intensity, carbon dioxide and nutrients. Good mixing in photobioreactors also needs to minimise the dead zone that may lower the microalgae productivity. The development of computational fluid dynamic (CFD) allows for further study regarding the mixing phenomena in photobioreactors. Seo et al. (2012) proposed a model for a two-dimensional bubble column photobioreactor with multiphase system and the mixing process was modelled in three dimensions. Pegallapati and Nirmalakhandan (2012) developed a macroscopic model for microalgae growth in a bubble column photobioreactor with CO_2-transport between phases.

Modelling of a flat plate photobioreactor has been carried out (Sforza et al., 2014). In the study, the researchers considered mass balance related to the biomass growth in a continuous stirred-tank reactor without recycle, while assuming that there is no mixing in the axial direction as in plug flow reactors. The simulation results were validated with experimental data, and then the simulation for industrial scale photobioreactors was performed. However, the simulation results for industrial scale reactors have not been validated and required optimisation on the operating conditions.

Muharam (2013) also presented the model for a bubble column photobioreactor. However, the model has not been validated with experimental data. Nauha and Alopaeus (2013) reported the growth model using compartment method to facilitate modelling. The recent study by Zhang et al. (2015) in a flat plate photobioreactor was carried out by considering the differences of the initial CO_2 concentration, the phosphate concentration and the light intensity. The model describes the algae growth, the CO_2 concentration, and the uptake rates of phosphate, nitrate, and ammonium absorbed by microalgae Chlorella kessleri for 21 d. The model has been validated using experimental data.

In this study, a three-dimensional model of the microalgae growth inside an internally-illuminated bubble column photobioreactor was simplified into a two-dimensional axisymmetry. The model is approached microscopically and considers the hydrodynamics in the gas and liquid phases, the CO_2 mass transfer from the gas phase to the liquid phase, the light intensity distribution in the photobioreactor to grow microalgae Nannocloropsis salina,

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the uptake of nutrients (phosphate, ammonium, and nitrate) by microalgae and the temperature effect. The model was validated with experimental data obtained by Pegallapati and Nirmalakhandan (2012). The model was simulated to determine the effects of the inlet CO_2 concentration and the inlet gas flow rate on the microalgae growth.

2. Method

2.1 Modelling of microalgae growth

The effects of the inlet CO_2 concentration and the inlet gas flow rate on the growth of microalgae Nannocloropsis salina in an internally-illuminated bubble column photobioreactor was investigated using mathematical models of the photobioreactor. An axisymmetric two-dimensional model was developed by considering the gas and liquid mass balances and the light intensity. The microalgae culture is placed in the space between the inner cylinder and the outer cylinder as seen in Figure 1. Dispersion models of gas and liquid phases were used to describe the flow patterns in the photobioreactor. Unlike diffusion, dispersion emerges from the movement of the convective fluid caused by the main factors like the relative movement of the gas and liquid phases, smelting bubbles, carry-forward of the fluid which pushed the mass behind the gas bubbles rise, and the movement of backflow due to the mass balance, as well as the events of turbulence generated by the flow of gas (Rubio et al., 2004).

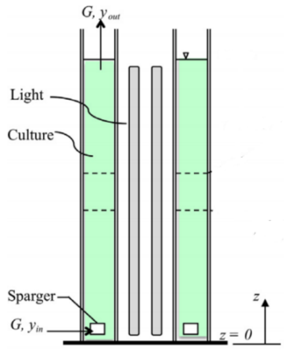

Figure 1: Internally-illuminated photobioreactor

2.2 Gas and liquid-phase mass balances

In the gas phase, CO_2 transport is described by Eq(1):

$$\frac{\partial C_{CO_2,G}}{\partial t} - \left(\frac{1}{r}\frac{\partial}{\partial r}\left(rD_{rad,G}\frac{\partial C_{CO_2,G}}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_{ax,G}\frac{\partial C_{CO_2,G}}{\partial z}\right)\right) + \left(u_{rad,G}\frac{\partial C_{CO_2,G}}{\partial r} + u_{ax,G}\frac{\partial C_{CO_2,G}}{\partial z}\right) = -R_{CO_2} \tag{1}$$

where the axial and radial dispersion coefficients according to Joshi (1980) are as Eqs(2) and (3):

$$D_{ax,G} = 50D_R^{\frac{3}{2}}\left(\frac{U_G}{\varepsilon_G}\right)^3 \tag{2}$$

$$D_{rad,G} = D_{ax,G} \tag{3}$$

Mass transport of *j* components i.e. CO_2, microalgae and nutrients in the liquid phase is shown by Eq(4):

$$\frac{\partial C_j}{\partial t} - \left(\frac{1}{r}\frac{\partial}{\partial r}\left(rD_{rad,L}\frac{\partial C_j}{\partial r}\right) + \frac{\partial}{\partial z}\left(D_{ax,L}\frac{\partial C_j}{\partial z}\right)\right) = R_{j,L} \tag{4}$$

The axial and radial dispersion coefficients are as Eqs(5) and (6) (Krishna et al., 1999):

$$D_{ax,L} = 0.06321(gD_R)^{0.5}\left(\frac{U_G{}^3}{gu_{water}}d_R\right)^{0.125} \tag{5}$$

$$D_{rad,L} = 0.01D_{ax,L} \tag{6}$$

To determine the flux between the two phases, the correlation of k_L is introduced as Eq(7):

$$J = k_L(C^*_{CO_2} - C_{CO_2,L}) \tag{7}$$

The CO_2 concentration in the liquid phase, $C_{CO_2,L}$, is in equilibrium with the one in the gas phase, $C^*_{CO_2}$, and related to the CO_2 mole fraction, y_{CO_2} in the gas phase as in Eq(8):

$$C^*_{CO_2} = \frac{p y_{CO_2}}{RTH_{CO_2}} \tag{8}$$

Henry's dimensionless constant, H_{CO_2} is estimated using Eq(9):

$$H_{CO_2} = \kappa H'_{CO_2} \exp\left[K_3\left(\frac{1}{T} - \frac{1}{T_o}\right)\right] \tag{9}$$

where κ is 2478.96 m^3.Pa/mol and K_3 for CO_2 is 2,400. In the experiments reported by Molina Grima et al. (1994), the global CO_2 mass transfer rate is described by Eq(10):

$$R_{CO_2,L} = k_L a_{CO_2}(C^*_{CO_2} - C_{CO_2,L}) \tag{10}$$

where $k_L a_{CO_2}$ is estimated from the correlation available for oxygen (Eq(11)):

$$k_L a_{CO_2} = k_L a_{O_2}\sqrt{\frac{d_{CO_2}}{d_{O_2}}} \tag{11}$$

In this study, the value of $k_L a_{O_2}$ is calculated using the correlation reported by Akita and Yoshida (1973) (Eq(12)):

$$k_L a_{O_2} = K_2 d^{0.5}_{CO_2} u_{water}{}^{-0.12}\left(\frac{\tau_{water}}{\rho_{water}}\right)^{-0.62} D_R^{0.17} g^{0.93} \varepsilon_G{}^{1.1} \tag{12}$$

The reaction rate of the dissolved CO_2 is expressed as Eq(13):

$$R_{CO_2,L} = R_{CO_2,int} - \frac{1}{Y} R_{algae} \tag{13}$$

where Y is a constant stating the amount of CO_2 consumed per 1 g of microalgae. Based on several studies, an average Y of 1.83 g CO_2 is consumed by microalgae to produce 1 g biomass (Wang et al., 2011).

2.3 Microalgae growth

In general, the microalgae growth rate is expressed by the following Eq(14):

$$R_{algae} = \mu C_{algae} - k_d C_{algae} \tag{14}$$

where μ is a specific growth rate constant of microalgae and k_d is a death rate constant of microalgae. The μ constant is adapted from the modified Monod equation. Eq(15) for μ is based on the incorporation of the merged information stating specifically the microalgae growth,

$$\mu = \mu_{max}(\phi_{CO_2})(\phi_I)(\phi_T)(\phi_{NH_4^+})(\phi_{NO_3^-})(\phi_{PO_4^{3-}}) \tag{15}$$

Eq(15) includes the effects of the concentrations of dissolved CO_2 (ϕ_{CO_2}), ammonium ($\phi_{NH_4^+}$), phosphate ($\phi_{PO_4^{3-}}$) and nitrate ($\phi_{NO_3^-}$) nutrients, as well as the light intensity (ϕ_I) and the ambient temperature (ϕ_T) on the microalgae growth rate. The effect of the dissolved CO_2 substrate applied in this study is based on the type of expression in accordance with the non-monotonous Haldane model explaining the inhibition effect at high CO_2 levels (Pico-Marco et al., 2006) as seen in Eq(16). The effect of the light intensity as well as the ambient temperature is described in Eq(17) and Eq(18) (Pegallapati and Nirmalakhandan, 2012). The effects of phosphate, nitrate, and ammonium nutrients are taken from Kasiri et al. (2015).

$$\phi_{CO_2} = \frac{C_{CO_2,L}}{K_{S_{CO_2}} + C_{CO_2,L} + \frac{C_{CO_2,L}}{K_{I_{CO_2}}}} \tag{16}$$

$$\phi_I = \frac{I}{K_e + I + \frac{I}{K_I}} \tag{17}$$

$$\phi_T = 1{,}066^{(T-293)} \tag{18}$$

2.4 Nutrient and light intensity

The absorption rates of nutrients by microalgae were modelled by applying the Droop equation (for ammonium) and Caperon-Meyer equation (for phosphate and nitrate) (Kasiri et al., 2015) (Eqs(19) – (21)):

$$R_{PO_4^{3-}} = -\varphi_{PO_4^{3-}} \frac{C_{PO_4^{3-}} - C_{PO_4^{3-},0}}{K_{\varphi_{PO_4^{3-}}} + C_{PO_4^{3-}} - C_{PO_4^{3-},0}} C_{algae} \tag{19}$$

$$R_{NO_3^-} = -\varphi_{NO_3^-} \frac{C_{NO_3^-} - C_{NO_3^-,0}}{K_{\varphi_{NO_3^-}} + C_{NO_3^-} - C_{NO_3^-,0}} C_{algae} \tag{20}$$

$$R_{NH_4^+} = -\varphi_{NH_4^+} \frac{C_{NH_4^+}}{K_{\varphi_{NH_4^+}} + C_{NH_4^+}} C_{algae} \tag{21}$$

The phenomenon of the light penetration inside the photobioreactors is described by the Lambert-Beer law (Molina Grima et al., 1994), which is expressed by Eq(22):

$$I = I_o e^{-RC_{algae}K_a} \tag{22}$$

The light extinction coefficient, K_a, is estimated using an empirical equation as described in Eq(23) (Molina Grima et al., 1994):

$$K_a = 1.7356X + 0.0199 \tag{23}$$

Where X is the mass fraction of the total pigment absorbing light and its value ranges between 2 – 3 % of the total mass of microalgae (Molina Grima et al., 1994).

3. Result and discussion

3.1 Model validation

The model was validated by comparing the calculated results of the model with the experimental data obtained from Pegallapati and Nirmalakhandan (2012). The process parameters used are shown in Table 1.

Table 1: Process parameters

Parameter	Value
Gas flowrate	800 mL/min
Initial microalgae concentration	0.08 g/L
CO_2 concentration in the inlet gas	0.5 % and 2 %
Microalgae	Nannochloropsis salina
Incident light intensity	101 μEinstein/m^2.s

Figure 2 shows the profiles of the microalgae concentration for two different CO_2 concentrations in the inlet gas for 16 d. The figure depicts the harvesting carried out every day starting from the fourth day to the sixteenth day with the withdrawn volume being 10 % of the total volume for each harvesting. The model calculation results indicate good agreement with the experimental ones with the average errors for the CO_2 concentrations of 0.5 % and 2 % of 5 % and 4 %. Both the calculated and simulation results show that the microalgae growth is marked by the increase in its concentration from 0.08 g/L on the first day to 0.40 g/L on the sixteenth day for the CO_2 concentration of 0.5 % and to 0.51 g/L for the CO_2 concentration of 2 %.

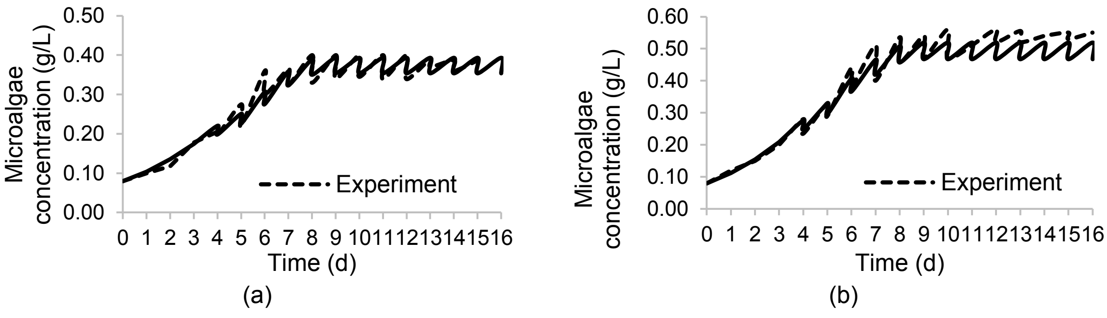

Figure 2: The microalgae concentration for the CO_2 concentration of (a) 0.5 % and (b) 2 %

3.2 Microalgae distribution

The microalgae distribution in the photobioreactor can be seen in Figure 3. Due to the axisymmetric model, the change in the microalgae concentration occurs only in the axial and radial directions. The concentration gradient in the axial direction is greater than the radial direction. The significant change in the microalgae concentration at the same spatial position happens from the first day to the third day. The change is not significant from the third day to the sixth day.

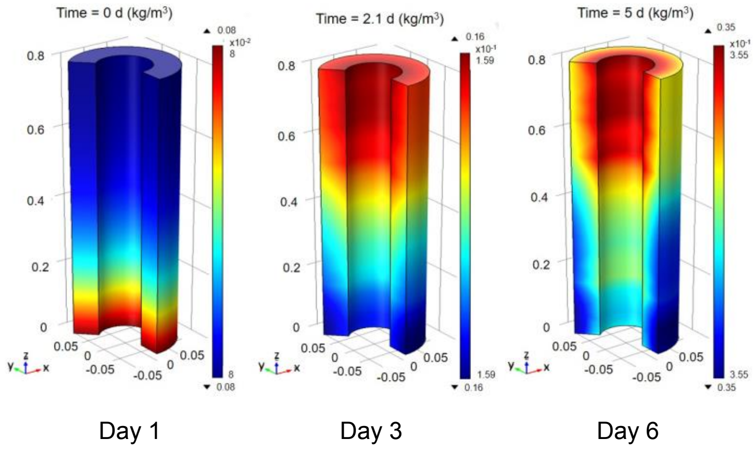

Figure 3: The microalgae concentration (in g/L) with respect to time

4. Sensitivity analysis

The sensitivity analysis was conducted to understand the effects of process variables on the microalgae growth. Two process variables examined in this research are the CO_2 concentrations in the inlet gas and the inlet gas flow rate.

4.1 CO_2 concentration

Figure 4 displays the effect of the CO_2 concentration on the microalgae concentration. It appears that the higher CO_2 concentration gives higher microalgae concentration. The CO_2 concentrations of 0.5 %, 1 %, 2 % and 4 % are able to grow microalgae with maximum concentrations of 0.421 g/L, 0.472 g/L, 0.502 g/L, and 0.514 g/L. The increase in the CO_2 concentration is considered the same as the increase in reactant concentration in a chemical reaction because CO_2 is a substrate for the microalgae growth in the liquid phase. However, the increase in the CO_2 concentration above 4 % does not give a significant impact on the microalgae growth.

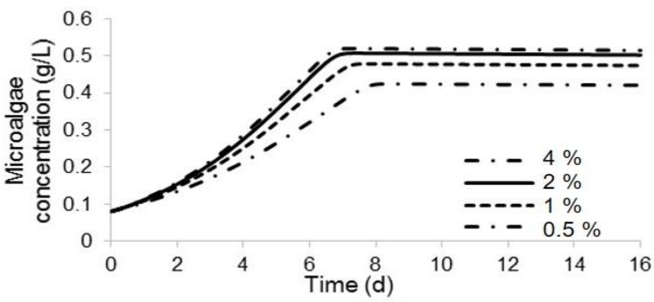

Figure 4: The effect of the CO_2 concentration on the microalgae concentration

4.2 Inlet gas flow rate

The effect of the inlet gas flow rate on the microalgae growth is presented in Figure 5. It can be seen that the change in gas flow rate does not give a significant impact on the microalgae growth. This happens because the axial dispersions in the gas and liquid phases provide good mixing such that the distribution of dissolved CO_2 concentration throughout the reactor is also good. However, the increase in the gas flow rate may cause growth reduction since it increases the shear stress on microalgae.

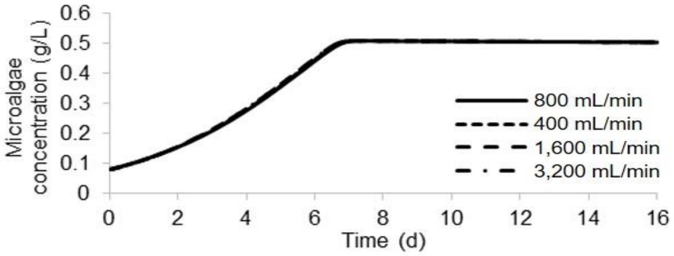

Figure 5: The effect of the inlet gas flow rate on the microalgae growth

5. Conclusions

The model validation against experimental data with the inlet gas flow rate of 800 mL/min and enriched with 0.5 % and 2 % CO_2 gives the average errors of 5 % and 4 %. The microalgae growth is marked by the increase in its concentration from 0.08 g/L on the first day to 0.51 g/L on the sixteenth day for the CO_2 concentration of 2 %. Increasing gas flowrate has no significant effect on the microalgae growth.

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Reference

Akita K., Yoshida F., 1973, Gas Holdup and Volumetric Mass Transfer Coefficient in Bubble Columns, Industrial & Engineering Chemistry Process Design and Development 12 (1), 76–80.

Joshi J.B., 1980, Axial Mixing in Multiphase Contactors — A Unified Correlation, Transactions of the Institution of Chemical Engineers 58, 228–236.

Kasiri S., Abdulsalam S., Ulrich A., Prasad V., 2015, Optimization of CO_2 Fixation by Chlorella Kessleri Using Response Surface Methodology, Chemical Engineering Science 127, 31–39.

Krishna R., Urseanu R., van Baten J.M., Ellenberger J., 1999, Influence of Scale on the Hydrodynamics of Bubble Columns Operating in the Churn-Turbulent Regime: Experiments versus Eulerian Simulations, Chemical Engineering Science 54, 4903–4911.

Molina Grima E., Garcia Camacho F., Sanchez Perez J.A., Fernandez Sevilla J.M., Acien Fernandez F.G., Contreras Gomez A., 1994, A Mathematical Model of Microalgal Growth in Light-limited Chemostat Culture, Journal of Chemical Technology and Biotechnology 61, 167–173.

Muharam Y., Dianursanti, Zada, M.I., 2013, Bubble column photobioreactor simulation for chlorella algae cultivation, Prosiding Seminar Nasional Teknik Kimia Teknologi Oleo dan Petrokimia Indonesia 2013, 27 November 2013, Universitas Riau-Riau, Indonesia.

Nauha E.K., Alopaeus V., 2013, Modelling Method for Combining Fluid Dynamics and Algal Growth in a Bubble Column Photobioreactor, Chemical Engineering Journal 229, 550–568.

Pegallapati A.K., Nirmalakhandan N., 2012, Modeling Algal Growth in Bubble Columns under Sparging with CO_2-Enriched Air, Bioresource Technology 124, 137–145.

Pico-Marco E., Navarro J.L., Bruno-Barcena J.M., 2006, A Closed Loop Exponential Feeding Law: Invariance and Global Stability Analysis, Journal of Process Control 16 (4), 395–402.

Rubio F.C., Camacho F.G., Sevilla J.M., Chisti Y., 2004, A Mechanistic Model of Photosynthesis in Microalgae, Biotechnology and Bioengineering 81 (4), 459–473.

Seo I., Lee I., Huang H., Hong S., Bitog J., Kwon K., Lee C., Kim Z. Cuello J., 2012, Numerical Investigation of a Bubble-Column Photo-Bioreactor Design for Microalgae Cultivation, Biosystems Engineering 113 (13), 229–241.

Sforza E., Enzo M., Bertucco A., 2014, Design of Microalgae Biomass Production in a Continuous Photobioreactor: An Integrated Experimental and Modelling Approach, Chemical Engineering Research and Design 92 (6), 1153–1162.

Wang M., Lawal A., Stephenson P., Sidders J., Ramshaw C., 2011, Post Combustion CO_2 Capture with Chemical Absorption: A State-of-the-Art Review, Chemical Engineering Research and Design 89 (9), 1609–1624.

Zhang, X., Gong, X., Chen, Y., 2015, Kinetic models for astaxanthin production by high cell density mixotrophic culture of the microalga Haematococcus pluvialis, Journal of Industrial Microbiology and Biotechnology 23 (1), 691–696.