Two-phase flow model for a continuous culture of microalgae in tubular photobioreactor

*Theeradech Mookum¹⁾, Amorn Owatworakit²⁾, and Pattana Kakumyan³⁾

^{1),2),3)}School of Science, Mae Fah Luang University, Chiang Rai 57100, Thailand ¹⁾theeradech@mfu.ac.th

ABSTRACT

In the continuous culture, the culture medium is fed into the tubular photobioreactor (TPBR) continuously with a suitable flow rate until it reaches the steady state. In order to control the flow rate of the medium and microalgae suspension in the TPBR, the two-phase flow model is taking into account. The inlet flow rate is determined by the total volume of microalgae in the TPBR and the doubling time. The flow patterns were visualized in different times. The pressure and the wall shear stress were investigated. The results show that the pressure decreases along the tube length and the higher wall shear stress occurs at the U-loop.

1. INTRODUCTION

Microalgae have a great potential which can produce large amounts of biomass and biofuels (Milano 2016, Lee 2015, Chisti 2007). They can also easily grow in heterotrophic, different conditions. such as autotrophic. mixotrophic and photoheterotrophic (Brennan 2010). Particularly, photoautotrophic cultivation allows algae to accumulate much higher proportion of lipids within less time. To scale-up cultivation process can be done using batch and continuous culture. The continuous culture of microalgae is an alternative way to provide a higher degree of control than the batch culture. However, the estimation of microalgae growth may require some parameters to be optimized.

A mathematical modeling of microalgae biomass and oil production has been widely studied to design a bioreactor, to control the microbial processes and to predict the behavior of the processes more easily than laboratory experiments (Liao 2011, Sato 2010). In addition, to learn the dynamics of biomass growth and lipid production by microalgae, suitable kinetic modeling has to be developed for predicting the performance and optimization of bioreactor operating conditions (Galvao 2013). For continuous culture system, steady-state condition is necessary. Here the two-phase flow is key parameter to achieve to study behavior of media and microalgae flow.

In this study, we have to address two-phase flow model using Chlorella protothecoides UTEX 25 in continuous culture by using TPBR. This model is firstly reported about horizontal TPBR system. The model has then been applied to design in

the lab scale in order to the correlation the model parameters e.g. flow rate and to predict the performance by an actual experiment that can be achieved in term of biomass productivity.

2. MATERIALS AND METHODS

2.1 Photobioreactor

The horizontal loop TPBR shown in Fig. 1 was designed with the diameter of 0.05 m, total length of 11.41 m, and the total volume of 2.2168×10^{-2} m³. The inlet and outlet tubes have the diameter of 0.01 m. and length of 0.05 m. The microalgae suspension is first fulfilled into the TPBR and the medium is fed continuously into the TPBR controlling the flow rate by a peristaltic pump.



Fig. 1 Computational domain of the TPBR.

2.2 Mathematical Model

As the medium and microalgae suspension are two different phases, the twophase flow modeling was applied in this work. The governing equations are given by the continuity equation Eq. (1), the Navier-Stokes equations Eq. (2).

$$\nabla \cdot \boldsymbol{u} = 0 \tag{1}$$

$$\rho \frac{\partial u}{\partial t} + \rho(\boldsymbol{u} \cdot \nabla)\boldsymbol{u} = \nabla \cdot \left[-pI + \eta(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)\right] + \rho \boldsymbol{g}$$
⁽²⁾

where u denotes the velocity vector, p is the pressure, g is the acceleration vector due to gravity.

The volume of fluid method (Gopala 2008) is used to track the interface between two fluids by solving the volume fraction equation, given by

$$\frac{\partial \phi}{\partial t} + \nabla \cdot (\phi \boldsymbol{u}) = 0. \tag{3}$$

where ϕ is the volume fraction. Determining the volume fraction of the medium phase ϕ as 0, the microalgae suspension phase ϕ as 1, the interface as $0 < \phi < 1$.

The density ρ and η in Eq. (2) are the fraction between the medium and the microalgae represented in terms of the volume fraction as

$$\rho(\phi) = \rho_m + (\rho_a - \rho_m)\phi$$

$$\eta(\phi) = \eta_m + (\eta_a - \eta_m)\phi$$

The viscosity of the microalgae based on Krieger and Dougherty model (Krieger 1959) is given by

(4)

(9)

$$\eta_a = \eta_0 (1 + \alpha C(t))$$
(5)

where $\alpha = 2.5$ is the Einstein's intrinsic viscosity. The cell concentration C(t) is defined by (Yang 2011)

$$C(t) = \frac{C_0 C_{max} e^{\mu_{max}t}}{C_{max} - C_0 + C_0 e^{\mu_{max}t}}$$
(6)

where C_0 and C_{max} are the initial concentration and the maximum concentration of the microalgae, respectively, and μ_{max} is the maximum specific growth rate of the microalgae.

To solve the system of the Eq. (1) - (3) the boundary conditions is applied as follows:

On the inlet, the medium is fed into the PBR with constant inlet velocity

$$\boldsymbol{u}_{in} = \left(\frac{Q_{in}}{A}, 0, 0\right)^{T}$$
(7)

where Q_{in} is the inlet flow rate and A is the inlet cross section area.

The slip condition is set on the PBR wall,

$$\boldsymbol{u}\cdot\boldsymbol{n}=\boldsymbol{0} \tag{8}$$

where n is the normal vector.

On the outlet, the normal stress is set to zero, that is,

$$[-pI + \eta(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T)]\boldsymbol{n} = \boldsymbol{0}$$

The specific growth rate is determined by the Monod equation (Monod 1949)

$$\mu = \frac{\mu_{max} c_m}{\kappa_m + c} \tag{10}$$

where C_m is the medium concentration and K_m is the Monod constant. The doubling time of the cell is

 $t_d = \frac{\ln 2}{\mu}.\tag{11}$

The medium is fed continuously with the constant flow rate

$$Q_{in} = 1.111 \frac{V}{t_d}.$$
 (12)

where V is the total volume of the microalgae.

3. NUMERICAL RESULTS

The computational meshes as shown in Fig. 2 consists of 242,328 elements with 252,485 degrees of freedom. The physical parameters of the fluids used in the numerical simulation are given in Table 1.



Fig. 2 The computational meshes for the domain.

Parameter	Value
Density of microalgae, ρ_a	1020 kg/m^3
Density of medium, ρ_m	1000 kg/m^3
Viscosity of medium, η_m	$0.001 Pa \cdot s$
Viscosity of solvent, η_0	0.001 <i>Pa</i> · <i>s</i>
Initial concentration of microalgae, C_0	3.479 kg/m^3
Maximum concentration of microalgae, C_{max}	5.2 kg/m^3
Concentration of medium, C_m	0.7 kg/m^3
Monod constant, K _m	$0.05 \ kg/m^3$
Maximum specific growth rate, μ_{max}	$3.3565 \times 10^{-6} 1/s$
Volume, V	$2.2168 \times 10^{-2} m^3$
Inlet cross sectional area, A	$7.7646 \times 10^{-5} m^2$

Using the parameters in Table 1, we obtain the specific growth rate as

 $\mu = \frac{3.3565 \times 10^{-6} \times 0.7}{0.05 + 0.7} = 3.1327 \times 10^{-6} \quad 1/s,$ and the doubling time is $t_d = \frac{\ln 2}{3.1327 \times 10^{-6}} = 221262 \quad s.$ The inlet flow rate is $Q_{in} = 1.111 \times \frac{2.2168 \times 10^{-2}}{221262} = 1.1127 \times 10^{-7} \quad m^3/s,$ and the inlet velocity is $u_{in} = \frac{1.1127 \times 10^{-7}}{7.7646 \times 10^{-5}} = 1.4332 \times 10^{-3} \quad m/s.$

When the medium is fed into the TPBR with the constant rate of $1.1127 \times 10^{-7} m^3/s$, the medium flows along the tube from the inlet to the outlet by taking the doubling time of 221262 second as shown in Fig. 3.



Fig. 3 The evolution of the medium flow in different times.





Fig. 4 The magnitude of the velocity on the cross-sections x = 0.5 m, x = 1 m, and y = 0.05 m.

Fig. 4 shows the magnitude of the velocity on the cross-sections x = 0.5 m, x = 1 m, and y = 0.05 m. The numerical results show that on the inner core the velocity is higher than on the wall tube, whereas on U-loop the velocity is highest. Fig. 5-6 show the wall shear stress, it is noted that higher velocity gives higher wall shear stress, especially at the inner U-loop (B and H).

The 2016 World Congress on **Advances in Civil, Environmental, and Materials Research (ACEM16)** Jeju Island, Korea, August 28-September 1, 2016



Fig. 5 (a) Wall shear stress along (b) the type I curve.

The 2016 World Congress on **Advances in Civil, Environmental, and Materials Research (ACEM16)** Jeju Island, Korea, August 28-September 1, 2016







Fig. 6 (a) Wall shear stress along (b) the type II curve.



Fig. 7 The pressure along the tube.

Fig. 7 presents the pressure distribution along the tube. The result shows that the pressure decreases from the inlet to the outlet.

4. CONCLUSION

The two-phase flow model is used in this work to study the behavior of the medium and the microalgae flow in the TPBR. The inlet flow rate is determined by the total volume of the microalgae and the doubling time. The time taken of the medium flow from the inlet to the outlet is nearly the same. The higher velocity occurs at the U-loop, this leads to the higher wall shear stress. The pressure along the tube decreases from the inlet to the outlet.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the financial support of the National Research Council of Thailand. We also thank to Mae Fah Luang University for providing the laboratory.

REFERENCES

- Brennan L., and Owende P., (2010), "Biofuels from microalgae a review of technologies for production, processing, and extractions of biofuels and coproducts", *Renewable and Sustainable Energy Reviews*, **14**, 557-577.
- Chisti Y., (2007), "Biodiesel from microalgae", *Biotechnology Advances*, **25**(3), 294–306.

Galvao R.M., Santana T.S., Fontes C.H.O., and Sales E.A. (2013), "Modeling of Biomass Production of Haematococcus pluvialis", *Applied Mathematics*, **4**, 50–56.

- Gopala V. R., and Wachem B. G. M. Van., (2008), "Volume of fluid methods for immiscible-fluid and free-surface flows", *Chemical Engineering Journal*, **141**, 204–221.
- Krieger I.M. and Dougherty T.J., (1959), "A mechanism for non-Newtonian flow in suspensions of rigid spheres", *Transactions of The Society of Rheology*, **3**, 137–152.
- Lee O.K., Seong D.H., Lee C.G., and Lee E.Y. (2015), "Sustainable production of liquid biofuels from renewable microalgae biomass", *Journal of Industrial and Engineering Chemistry*, **29**, 24–31.
- Liao Q., Liu D.M., Ye D.D., Zhu X. and Lee D.J. (2011), "Mathematical modeling of twophase flow and transport in an immobilized-cell photobioreactor", *International Journal of Hydrogen Energy*, **36**(21), 13939–48.
- Milano J., Chyuan H., Masjuki H.H., Chong W.T., and Kee M. (2016), "Microalgae biofuels as an alternative to fossil fuel for power generation", *Renewable and Sustainable Energy Reviews*, **58**, 180–197.
- Monod J., (1949), "The growth of bacterial cultures", *Annual Review of Microbiology*, **3**, 371-394.
- Sato T., Yamada D., and Hirabayashi S. (2010), "Development of virtual photobioreactor for microalgae culture considering turbulent flow and flashing light effect", *Energy Conversion and Management*, **51**(6), 1196–1201.
- Yang J., Rasa E., Tantayotai P., Scow K.M., Yuan H., Hristova K.R. (2011), "Mathematical model of *chlorella minutissima* UTEX2341 growth and lipid production under photoheterotrophic fermentation conditions", *Bioresource technology*. **102**(3), 3077-82.