Hydrodynamics of Microalgae and CO_2 flow in a Tubular Photobioreactor and consequent effects on Microalgae growth

Saumen Barua[1*] and Ujjwal Kumar Deb[2]

[1] *Department of Mathematics, Sir Ashutosh Govt. College, Chittagong, Bangladesh.*
[2] *Department of Mathematics, Chittagong University of Engineering & Technology, Chittagong, Bangladesh.*

Corresponding author: baruasaumen@yahoo.com

Abstract

In biofuel technology from microalgae, the main optimal factors for microalgae cultivations are light, CO_2 and temperature. As microalgae are photosynthetic microorganisms thus they convert sunlight, water and CO_2 to algal biomass. We consider a two phase flow for CO_2 and Microalgae suspension to understand fluid dynamics phenomena after injecting CO_2 gas inside a tubular Photobioreactor (PBR).The growth rate of the microalgae cell is taken as a function of available sun light at Chittagong University of Engineering & Technology (CUET) in our study. A 20.94m long and 0.025m tubular PBR is considered for the simulation. To observe the microalgae cell growth, we selected the 21st June for a bright sunny and the longest day of a year. From the simulation after day seven we observed a very slow growth for the microalgae culture. It is noted that the growth related to concentration of microalgae is increased by day length with respect to continuous sunlight. A small fluctuation of shear rate around U-loop area is also found in our simulation which may be caused to reduce the volumetric production due to cell fragility. From the velocity profile we found that, the velocity is generally higher in the middle of the tube gives a parabolic shape of the suspension flow.

Keywords: Microalgae, Biofuel, Tubular Reactor, CFD, Simulation.

INTRODUCTION

In the second half of the 20th century the fast economic growth took place which caused a re-orientation in the manner of utilization of energy raw materials. Again continued uses of fossil fuel as an energy source has been unsustainable because of rapid depletion of fossil fuel reserves. Their uses causes a number of unfavorable effects such as acid rain and global warming with the resultant climate change. This global climate change and environmental degradation have engaged scientists, researchers and other concerned to find alternate energy sources. Biofuel as a renewable energy is widely considered to be most sustainable alternatives to fossil fuel and a feasible means for environmental and economic sustainability [1, 2]. Biofuels are fuels obtained from biomass (organic matter such as plant and microorganisms and animal organisms). At Bangladesh where fuel such as oil, gas, and coal is too expensive day by day. To ensure a degradation free environment, alternative source of fuel (Biodiesel) is the time demanding decision. Biofuel can be classified into the 1st, 2nd and 3rd generation biofuels. Those produced from organic matter like starch, sugars, animal fats and vegetables oils are the 1st generation biofuels and they are produced using conventional methods (fermentation or esterification) that do not required high energy inputs. The 2nd generation biofuels are from cellulose products such as wood, straw, tall perennial grasses or wastes from the

wood processing industry. Using Hydrogen as the primary source of energy, the 3rd generation biofuels are microorganisms (yeast, fungi) biofuels and algae-based fuels like vegetable oils, bio-oil, jet-fuels, biohydrogen, biodiesel, renewable diesel and many others. Now Microalgae is the main raw material from which such biofuels can be produced at high efficiency levels and at low investment. The 1st and 2nd generation biofuel have several drawbacks. In 1st generation biofuel potatoes, sugar cane, soybean and rapeseed are used as raw material, shows that if too much fuel is produced from these may increase food price drastically. On the other hand 2nd generation biofuel still not popular due to the high cost of production. At present algae as a raw material 3rd generation biofuel is cost effective and provides a relatively high yield of biofuel. They are undoubtedly not a burden on the environment and that they are biodegradable [2, 3].

Microalgae are photosynthetic microorganisms that convert sunlight, water and carbon dioxide to algal biomass [4]. It is estimated that there are around 50,000 species of algae in the world and out of this only 30,000 algal species have been identified and examined so far. They live in all geographic zones in the world, but are the most populous in the northern hemisphere. Here their annual production amounts to about 1.5 million tons. The Green algae, containing green chlorophyll, yellow xanthophyll and orange carotene; red seaweeds, with red brown algae, whose pigment corpuscles are filled with brown fucoxanthin, next to chlorophyll and xanthophyll are the most frequently gathered and used algae. Microalgae occur in all ecosystem not only aquatic but also in soil ecosystems and are characterized by being adapted to living in a highly broad spectrum of environmental conditions [2]. Other benefits from microalgae include they can be used as a healthy food, as producers of useful compounds, biofilters to remove nutrients and other pollutants from wastewaters and as indicators for environmental changes [5]. Microalgae can be grown with minimal inputs including the land, sunlight, water, some macro- and micro-nutrients and carbon dioxide (CO_2). The land need not be fertile, productive land; the ability to grow algae in wasteland regions means that the technology does not compete directly with food cropping. Similarly, low quality water is also applicable. The commercial-scale production of algal biofuels is a major challenge. Most of the currently used harvesting techniques have several drawbacks, such as high cost, non-feasibility of scale-up or flocculants toxicity, which impact the cost and quality of products. Substantial amounts of research and development initiatives are needed to develop a cost and energy-effective process for the dewatering of algae since harvesting cost may itself contribute up to one-third of the biomass production cost [6].

Microalgae can be grown in suspension or attached on solid surface. Each system has its own advantages and disadvantages. Currently, suspend-based open ponds and enclosed photobioreactors are commonly used for algal-biofuel production. In general, an open pond is simply a series of outdoor "raceways," while a photobioreactor is sophisticated reactor design that can be placed indoors (greenhouse) or outdoors. The success of mass production of microalgae for biodiesel depends on the design and performance of the PBRs. If we consider economic factors, only PBR systems are now widely recognized for mass production aside from raceway ponds. Tubular Photo-bioreactors (PBR) are widely known as the most efficient choice compared with other closed methods including annular, flat plate, spiral, helical, torus, stirred tank, vertical column, plastic bags etc. of outdoor microalgae cultivation because of its wide illumination area for light penetration inside the culture, fairly good biomass productivity and relatively cheaper maintenance cost [7].

The main optimal factors for microalgae cultivations are light, CO_2, temperature and pH. The algal culture system can be illuminated by the solar light, artificial light or both. In outdoor cultivation since the ultimate source of light is the sun, which cannot be controlled; so studies on the optimization of light for PBRs are usually done indoors with artificial illumination. Using artificial light successfully for photosynthesis, photons with wavelengths between 600nm and 700nm must be generated. Temperature also plays a vital role in microalgae cultivation. The optimal temperature for microalgae cultures is generally between 20°C and 24°C, although this may vary with the species and composition of the culture medium. Microalgae have different growth pH requirements too and the pH range for most cultured algal species is between 7 and 9, with an optimum range of 8.2–8.7. Among the four prime factors, CO_2 is the main factors for microalgae production because CO_2 is the main carbon source for photosynthetic culture of microalgae. Since algae live on a high concentration of carbon dioxide, nitrogen dioxide (NO_2), greenhouse gases (GHG) and pollutants in the atmosphere from different sources will be the algal nutrients [5, 8]. During the cultivation time CO_2 is injected in the tubular PBR. But CO_2 creates bubbles inside the PBR which impacts flow patterns and ultimately microalgae production is affected, which is not negligible in the case of production processes. In this study, a two phase flow, which means to understand fluid dynamics phenomena after injecting the CO_2 gas in the tubular PBR together with microalgae suspension, is investigated. The consequent effects on the cell concentration due to the sunlight at CUET and some fluid dynamics phenomena including Share rate, Pressure and velocity profile are also investigated.

MATHEMATICAL MODEL
In this study, an airlift driven horizontal loop tubular photobioreactor is considered. A uniform mixture of microalgae suspension and CO_2 were injected inside the tubular photobioreactor. This mixture is considered as an incompressible two phase Newtonian fluid and the flow problem is assumed to be laminar in our simulation.

I COMPUTATIONAL DOMAIN AND MESH DESIGN
The photobioreactor considered in our study is showed in the Figure 1 with radius of 0.025 m and length of 20.94m. The surface area and volume of the photobioreactor are $3.279m^2$ and $0.04043m^3$ respectively. A coarse mesh design is considered for our simulation with 1, 25,691 elements and 10, 55,747 degrees of freedom.
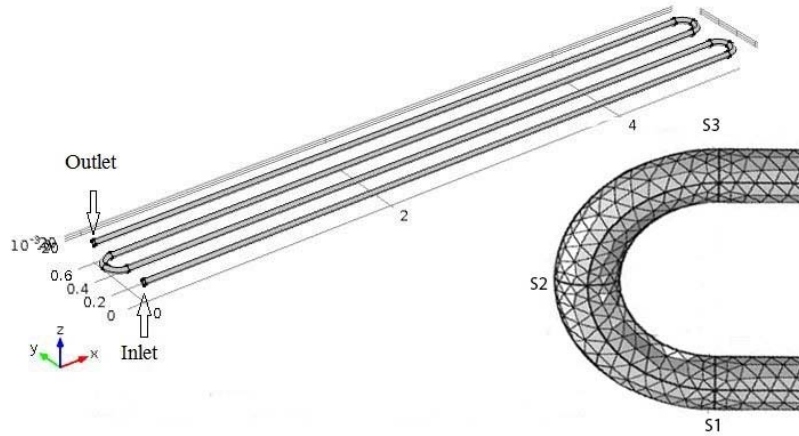
Figure 1: Computational domain and mesh design for horizontal loop tubular photobioreactor.

II GOVERNING EQUATIONS

We consider the mixture between the microalgae suspension and CO_2 is uniform thus a two phase flow model for the mixture is reckoned which is incompressible Newtonian fluid. We also consider the flow problem is laminar. The governing equations for the flow are the continuity equation and the Navier-Stokes equations as follows:

$$\nabla \cdot \vec{u} = 0 \qquad (1)$$

$$\rho \frac{\partial \vec{u}}{\partial t} + \rho (\vec{u} \cdot \nabla) \vec{u} = \nabla \cdot [-pI + \eta(t)(\nabla \vec{u} + (\nabla \vec{u})^T)] + \rho \vec{g} + \vec{F}_{st} \qquad (2)$$

where $\vec{u}$ denotes the velocity of the mixture, ρ and η are its density and viscosity respectively, p is the pressure, $\vec{g}$ is the gravity, I is the identity matrix and $\vec{F}_{st}$ is the surface tension force. The separation of the two-phase flow is described by the Cahn-Hilliard advection-diffusion equation [10]:

$$\frac{\partial \phi}{\partial t} + u . \nabla \phi = \nabla . \frac{\gamma \lambda}{e_p^2} \nabla f \qquad (3)$$

where φ is the dimensionless phase field variable, e_p is a parameter controlling interface thickness, γ is the mobility, λ he mixing energy density. The function f is given by following equations:

$$f = -\nabla \cdot e_p^2 \nabla \varphi + (\varphi^2 - 1)\varphi + \frac{e_p^2}{\lambda} \frac{\partial \psi}{\partial \varphi} \qquad (4)$$

$$\lambda = \frac{3e_p \sigma}{\sqrt{8}} \qquad (5)$$

$$\gamma = \chi e_p^2 \qquad (6)$$

where the term $\frac{\partial \psi}{\partial \varphi}$ denotes the phi-derivative of external free energy, σ is the surface tension coefficient and χ is the mobility tuning parameter. The density and viscosity of the mixture are functions of volume fraction of microalgae suspension V_l. The volume fraction of microalgae suspension is $V_l = (1 + \varphi)/2$ and the volume fraction of CO$_2$ gas is $V_g = (1 - \varphi)/2$. For the two phase flow model, the density and viscosity are defined to vary smoothly over the interface according to

$$\rho = \rho_g + (\rho_l - \rho_g)V_l \qquad (7)$$

$$\eta = \eta_g + (\eta_l - \eta_g)V_l \qquad (8)$$

In the equations above subscripts l and g are used for the algae suspension and CO$_2$ gas, respectively. The surface tension force in (2) is defined as

$$\vec{F}_{st} = G\nabla\phi \qquad (9)$$

where G is the chemical potential (Jm^{-3}) given by

$$G = \frac{\lambda f}{e_p^2} \qquad (10)$$

The viscosity η_l in (8) is given by $\eta_l = \eta_o \eta_r(t)$, where the relative viscosity (η_r) to be a ratio between microalgae suspension viscosity(η_l) and water viscosity(η_o). Occurrence of microalgae cell proliferation changes the concentration and subsequently the viscosity of the algal suspension. A microalgae cell is assumed to be a small sphere in our study [10]. Then relative viscosity relating to concentration is determined by Einstein's relative viscosity equation as follows:

$$\eta_r(t) = 1 + \varepsilon C(t) \qquad (11)$$

where ε is the Einstein's coefficient [11]. Based on the experimental data obtained by Hon-nami and Kunito [12], the cell concentration $C(t)$ in (11) depending on the growth rate μ can be expressed by the following logistic function

$$C(t) = C_0 + \frac{a}{1 + be^{-\mu t}} \qquad (12)$$

where C_0 is the initial concentration of the suspension and a and b are constant. As availability of light is an important limiting factor for biofuel production so we consider

the specific growth rate of microalgae depends on average light irradiance according to E. Molina's study [8] which is given by the following equation:

$$\mu = \frac{\mu_{max} I_{av}}{I_k + I_{av}} \tag{13}$$

where I_k is a constant depending upon microalgae culture condition and μ_{max} is the maximum growth rate of microalgae. If we ignore the dynamical and physiological properties of algae cell, the average irradiance (I_{av}) depends mainly on incident irradiance (I_0) available on the surface of the photobioreactor and is given by

$$I_{av} = \frac{I_0}{DK_a C_0}[1 - e^{(-DK_a C_0)}] \tag{14}$$

where K_a is the extinction coefficient of the biomass, $D = \frac{d}{\cos\theta}$, d is the diameter of the photobioreactor tube and θ is the angle of incidence of direct radiation depending on a function of five parameters including the declination(δ), solar hour (sh), geographic latitude (ψ), surface slope (β), and surface azimuth angle (τ), and the hour angle (ω) [13]

$$\cos\theta = \sin\delta\sin\psi\cos\beta - \sin\delta\cos\psi\sin\beta\cos\tau + \cos\delta\cos\psi\cos\beta\cos\omega +$$
$$\cos\delta\cos\psi\sin\beta\cos\tau\cos\omega + \cos\delta\sin\beta\sin\tau\sin\omega \tag{15}$$

According to Grima et. al.'s study [8], we found that the horizontally placed tube absorbs higher irradiance with respect to change in solar hour. Thus, the surface slope β is set to zero degree, which provides the following simplest form of (15), i.e,

$$\cos\theta = \sin\delta\sin\phi + \cos\delta\cos\psi\cos\omega \tag{16}$$

where the declination δ is defined by

$$\delta = 23.45\sin[\frac{360}{365}(284 + N)] \tag{17}$$

where N is the day of the year [13]. To calculate an hour angle ω, we follow the concept of Duffie and Beckman [13]. They considered that the angular displacement is 15 degree per hour for earth rotation from east to west, and the value is negative for morning hours and positive for afternoon hours. Thus an hour angle ω can be determined by

$$\omega = 15(sh - 12) \tag{18}$$

In our simulation the geographical location for the Tubular photobioreactor is Chittagong University of Engineering and Technology, Chittagong, Bangladesh where the value for the geographical latitude ψ is $22°27'50''$

III BOUNDARY AND INITIAL CONDITIONS

In this simulation the inlet initial velocity for CO_2 is $0.5 ms^{-1}$ and the fluid flow is uniform. The volume frictions of CO_2 and microalgae suspension are 0.05 and 0.95. Also we considered no-slip boundary condition on the wall i.e. $\vec{u} = 0$ and zero normal stress at the outlet of the domain which are given by

$$[-pI + \eta(t)(\nabla\vec{u} + (\nabla\vec{u})^{T})]n = o$$

NUMERICAL RESULTS

In our study, COMSOL Multiphysics has been used to run simulation. The simulation is carried out on the seventh day of culture. The model parameter Maximum growth rate (μ_{max})=$0.0000175 s^{-1}$, Constant(I_k)=$114.67 \mu mol m^{-2} s^{-1}$, Incident Irradiance(I_0)= 1630 $\mu mol m^{-2} s^{-1}$, Einstein co-efficient(ε) = $2500 m^3 kg^{-1}$, Initial concentration(C_o)=$0.55 kg m^{-3}$,Constant(a)=1 Constant(b)=200, Extinction coefficient(K_a)= 36.9 $m^2 kg^{-1}$, CO_2 viscosity($\eta_{g)=}$ 0.000625 Pa·s, Water viscosity($\eta_{0)=}$, 0.001 Pa·s, CO_2 density(ρ_c)= $0.001799 kg m^{-3}$,Microalgae density(ρ_m)= 1020 $kg m^{-3}$, Day of the year(N)=172,Phiderivative of external free energy($\frac{\partial f}{\partial \phi}$)=0.01

S1   S2   S3
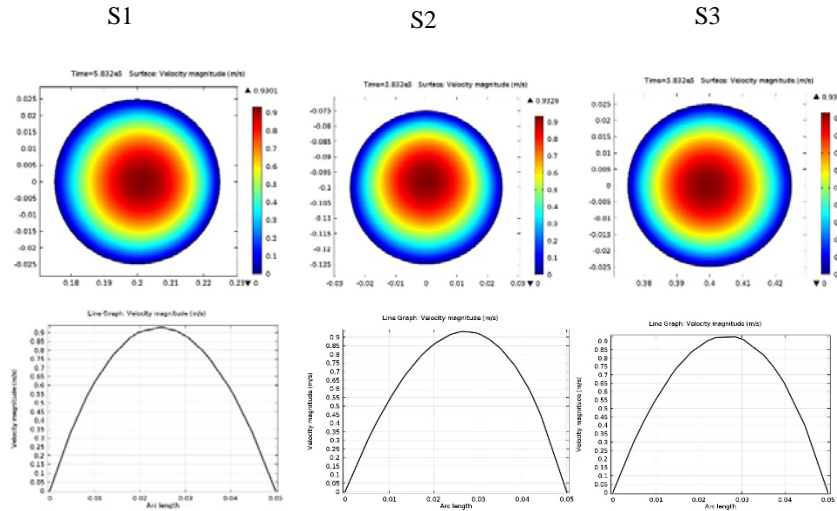

Figure-2: Velocity magnitude of the three cross section of the second U-loop area

Figure-2 represent the velocity magnitude of the two-phase flow along three cross-sections the second U-loop of the tubular photobioreactor and at which are the beginning (S1), the middle (S2) and the end (S3) respectively. The results show that the velocity magnitude is generally high at the middle of the tube. Comparing the magnitude of the velocity on the three planes, it is found that there is no significant different in the velocity magnitude. The highest flow speed at the middle plane (S2) of the second U-loop is higher. It is $0.9326 \, ms^{-1}$ whereas $0.9301 \, ms^{-1}$ in the beginning (S1) and end (S3) of the U loop.
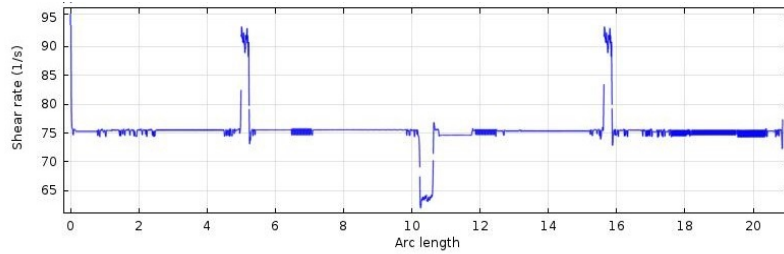
Figure-3: Shear rate distribution along the entire computational domain.

We know that while fluid moves inside the tube, the movement of fluid receives the shear stress in the wall of the domain. In order to understand the movement of fluid inside the tube, we study the shear rate distribution for the straight and the U-loop portion of the computational domain. Figure-3 demonstrate the shear rate distribution for the entire domain. We observed that the shear rate is uniform in the straight portion and it fluctuates positively in the curved (U- loop) area. In figure-4 we observed a uniform pressure drop from the inlet to the outlet in the entire computational domain.
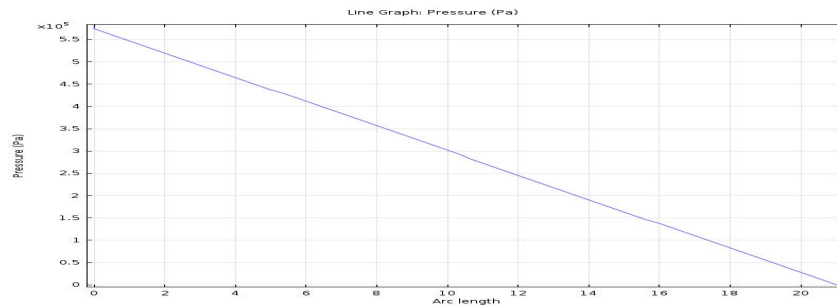

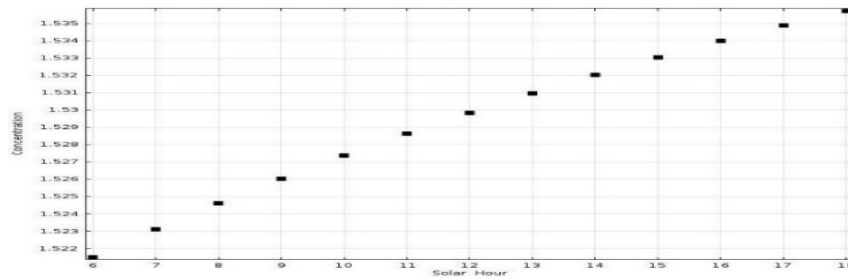Figure-4: The Pressure profile for the computational domain from inlet to outlet.

Figure-5: The cell concentration of microalgae culture with time

A graph of cell concentration against time is represented in Figure-5. The cell concentration of microalgae culture on the seventh day from morning (06:00) to the evening (18:00) increases about 0.013 kg/m^3 which is very slow. We can interpret from this result that the growth related to concentration of microalgae is not fixed but increased with day length with respect to continuous light.

CONCLUSION

In our study, a two phase flow model for microalgae suspension and CO$_2$ is considered to understand the flow dynamics inside a photobioreactor and the concomitant essence on microalgae cell growth. The growth rate of the microalgae cell is taken as a function of solar irradiance at CUET in our study. From our study we observe that, a general parabolic shape of velocity profile is found at different cross-sections inside the tubular photobioreactor. A very slow growth of microalgae is found due to light irradiance after the day seven for the microalgae culture in our simulation. In case of shear rate distributions we found irregular shape around U-loop area while it is regular for straight part of the computational domain.

Acknowledgment

References

[1]   Alam F, Mobin S, Chowdhury H, "Third generation biofuel from Algae" 6th BSME International Conference on Thermal Engineering (ICTE 2014)

[2]   Frac M, Jezierska S-Tys2 and Jerzy Tys,"Microalgae for biofuels production and environmental applications : A review" African Journal of Biotechnology Vol. 9 (54), pp. 9227-9236, 27december, 2010

[3]   Veillette M, Chamoumi M, Nikiema J, Faucheux N and Heitz M, "Production of Biodiesel from Microalgae" Chemical Engineering and Biotechnological Engineering Department, Université de Sherbrooke ,Canada

[4]   Chisti Y, "Biodiesel from microalgae beats bioethanol"

[5] Bitog JP, Lee IB, Lee CG, Kim KS, Hwang HS, Hong SW, Seo IH, Kwon KS, Mostafa E,   Application of computational fluid dynamics for modeling and designing   Photobioreactors for microalgae production: A review, Computers and Electronics in Agriculture, 76 (2011), pp. 131-147.

[6]   Singh M, Shukla R, and Das K "Harvesting of Microalgal Biomass" Biorefining and Carbon Cycling Program, College of Engineering ,The University of Georgia Athens, Georgia

[7]   Deb UK, Chayantrakom K, Lenbury Y, "Comparison of Single-phase and Two-phase Flow Dynamics in the HLTP for Microalgae Culture", International Journal of   Mathematics and Computers in Simulation. Issue 5, Vol 6, 2012, pp. 496-503.

[8]   Grima EM, Fernandez FGA, Camacho FG, ans Christ Y,"photo-bioreactors: light   regime, mass transfer and scaleup," Journal of biotechnology; vol. 70, pp. 231-247, Nov 1998.

[9]   Cahn JW, Hilliard JE, Free energy of a non-uniform system. I. Interfacial energy, Journal of Chemical Physics 28(2) (1958), pp. 258-267.

[10] Wu X, Merchuk J C, Simulation of algae growth in a   Bench scale internal loop airlift Reactor Chemical Engineering Science,59 (2004), pp. 2899-2912.M. Young,The Technical Writer's Handbook.Mill Valley,   University Science, 1989

[11] Einstein A, Ann. de. phys., 19, (1906), pp. 289-306.

[12] Hon-nami K, Kunito S, Microalgae cultivation in a tubular bioreactor and utilization of their cells, China Journal of Oceanology and Limnology, 16 (1998), pp. 75-83

[13] Duffie JA, Beckman WA, Solar Engineering of Thermal Process, John Wiley and Sons, Newyork, (1980).