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ESTIMATE OF PRODUCTION OF BIODIESEL FROM MICROALGAE IN COMPACT TUBULAR PHOTOBIOREACTOR

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Abstract. *Microalgae are presented as an alternative energy source to oil capable of producing energy through form of biofuel. With this, the Center for Research and Development in Self-Sustainable (NPDEAS/UFPR) is developing and constructing tubular photobioreactors for cultivation of microorganisms compact. Along with the construction, maintenance and experiments, a mathematical and computational model is being developed to estimate the amount of biodiesel that are photobioreactors NPDEAS able to obtain, and thus compare the computational data with literature data. The model combines theoretical concepts of thermodynamics with classical theoretical and empirical correlations of Fluid Mechanics and Heat Transfer. The physical domain is discretized with the Volume Element Model (VEM) through which the physical system (reactor pipes) is divided in lumped volumes, such that only one time dependent ordinary differential equation, ODE, results for temperature, based on the first law of thermodynamics. The energetic interactions between the volumes are established through heat transfer empirical correlations for convection, conduction and radiation. The computer simulation showed that the compact tubular photobioreactors is a great alternative for biodiesel production because productivity can reach approximately twice the productivity of literature.*

Keywords: *Computational Mesh, microalgae, biodiesel, photobioreactor, numerical simulation*

1. INTRODUCTION

Microalgae are presented as an alternative energy source to oil, capable of producing energy through form biofuel. Thereby industries are increasingly investing resources so that researchers could produce a maximum of biofuels from microalgae. In comparison with the production of oilseeds with respect to biodiesel production, the cultures of microalgae have a number of advantages such as, for example, doubling the biomass in a short time due to large biodiversity and also having high density lipid in structure (Xu, Miao and Wu, 2006) provides a productivity (liters of oil produced per acre per year) ten times higher than oilseed plant can have a good productivity and ability to be grown in areas not suitable for agriculture and less generation of waste (Chisti, 2007; Lawrence, 2006).

The algal biomass production in open ponds has lower energy costs and cash but in turn has less yield volumetric productivities than in the closed photobioreactors such as piping systems, which may have volumetric productivities about 30 times higher than in open lagoons (Chisti, 2007). The advantage of cultivating microalgae in closed photobioreactors is that they provide an excellent framework for measuring crop production in a controlled environment (Ugwu, Aoyagi, and Uchiyama, 2008). This avoids problems with contamination, and allows maintenance of a stable physical and chemical environment, for example, evaporation, pH, nutrients (Wood, Caetano and Martins, 2010; Kunjapur and Eldridge, 2010; Morweiser, Kruse and Posten, 2010.).

Microalgae are strongly affected by factors such as temperature, light intensity, pH and the nutrient composition of the medium. All direct influence on their cellular composition (Kitaya, Azuma and Kiyota, 2005). When you can control these conditions through the photobioreactor engineering and architecture, it is possible to obtain higher yields of microalgal biomass. The pH and composition of nutrients in the culture medium can be controlled by devices installed in the photobioreactor. The light intensity and temperature are more difficult to control in photobioreactors outdoors, because they depend on the sun and the wind speed and temperature on site (Bereguel, Rodriguez and Garcia, 2012).

This paper seeks through experiments in photobioreactor and numerical simulation estimate the production of biodiesel from microalgae in photobioreactors compact tube (FTC) built at the Center for Research and Development in Self-Sustainable Energy - NPDEAS (See Figure 1).

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Figure 1. Compact tubular photobioreactor (CTP) NPDEAS.

2. MATERIALS AND METHODS

2.1 Compact Tubular Photobioreactorforcultivate microalgae

Various geometries for closed photobioreactors using transparent tubes can be found in the literature. In NPDEAS at the Federal University of Paraná are being built some FTC for growing microalgae (Satyanarayana1, and Mariano Vargas, 2011). Its structure consists of 3710 m of transparent PVC tubes Crystal distributed in a compact geometry with 14 columns and 53 rows of tubes (total of 742 tubes) where each tube has 5 m long with a radius of 0.03 m. This compact photobioreactor is considered to have a capacity of approximately 12600 L of microalgal biomass using only 10 m2 of built area. Another key point of this photobioreactor is that he has the lateral area of 122 m2 which is exposed to sunlight, this parameter of paramount importance for crop growth.

To simplify computation, in this work we used a prototype of the FTC to cultivate microalgae *Scenedesmus sp* (see Figure 2). With only 30 tubes 1 m long, being distributed in 5 columns and 6 rows. Its capacity is 105 L of cultivation only 1.5 m2 of floor space. Cultivation began at 8 hours on 01/02/2013 and was up to 22 hours on 07/02/2013. During the 7 days of culture was used as nutrient CO2 only by inserting air.

Figure 2. Prototype of CTP NPDEAS.

2.2 Mathematical equations

In this work we used the Volumes Element Method (VEM) which subdivided into several volume elements (VE) or cell volume centered for simplify the partial differential equations into ordinary differential equations, thus providing a mathematical model of low computational effort. The system of differential equations depends on the air temperature, flow velocity of the fluid, direct sunlight, diffused radiation, air velocity and geometry of the photobioreactor.

In the present formulation, it is assumed that the growth of algae occur only in transparent tubes. The mathematical domain to the transparent tubes is divided into two kinds of volume elements: a) EV_w the walls of the transparent pipes, e b) EV_f for the fluid flowing inside the transparent pipes.

This method produces unique differential equations for each cell by applying the principles of energy and conservation of species. The energetic interactions between cells are established through empirical correlations heat transfer by convection, radiation and conduction.

To this initial interpretation of the problem was used for each VE one pipe of the photobioreactor, ie, has 1484 volume elements to be calculated temperature profiles.

The mathematical model describes the energy balance in EV_w and EV_f as shown below:

a) EV for the transparent walls of the pipes (EV_w):

The mathematical model for the temperature variation between the EV_w, due to fluid flow, solar radiation and interactions with the environment is given by Equation (1).

$$\dot{Q}_{rad}^{(j)} - \dot{Q}^{(j)} - \dot{Q}_{air}^{(j)} = m_w^{(j)} C_w \frac{dT_w^{(j)}}{dt} \tag{1}$$

where C_w is the specific heat of the wall (J /kg.K), m_W is the mass of the wall (kg), $\dot{Q}_{rad}$ is the solar radiation that strikes the walls of the pipes in the tubular photobioreactor (W/m^2), T_w is the wall temperature of the pipes and t is time (s)

The heat transfer between the wall and the air ($\dot{Q}_{air}$) is calculated by Equation (2).

$$\dot{Q}_{air}^{(j)} = h_e A_e \left(T_w^{(j)} - T_\infty \right) \tag{2}$$

where h_e is the coefficient of convective heat transfer between the pipe wall and the air (W/m^{2}K), A_e is the area outside the pipe wall (m^2) and T_∞ is the ambient temperature (K).

The convective heat transfer between the fluid and the pipe wall ($\dot{Q}$) is calculated by Equation (3).

$$\dot{Q}^{(j)} = h_i A_i \left(T_f^{(j)} - T_w^{(j)} \right) \tag{3}$$

where A_i is the internal area of the pipe wall (m^2), T_f the fluid temperature (K) and h_i is the coefficient of convective heat transfer between the pipe wall and the fluid (W/m^{2}K)

The solar radiation falling on the tubes is given by the sum of the direct radiation to diffuse radiation according to Equation (4).

$$\dot{Q}_{rad} = Rad_{dir} + Rad_{dif} \tag{4}$$

b) EV for the fluid flowing within the tubes (EV_f):

According with Figure 5 uses the Thermodynamics First Law for calculating the temperature variation between the EV_f (microalgae + nutrients + H_2O + O_2), the mathematical model is given by Equation (5).

$$\dot{Q}^{(j)} + \dot{m} C_f T_f^{(j-1)} = m_f^{(j)} C_f \frac{dT_f^{(j)}}{dt} + \dot{m} C_f T_f^{(j)} \tag{5}$$

where is the mass flow (kg/s), m_f is the mass fluid (kg) and C_f is the specific heat of the fluid (J /kgK),

To estimate the biomass concentration was used the principle of conservation of species that calculates the amount of biomass entering ($\frac{\dot{m}}{\rho V} C^{(j-1)}$) and out ($-\frac{\dot{m}}{\rho V} C^{(j)}$) a respective EV, is calculated along the quantity of biomass which is generated ($\mu C^{(j)}$) and consumed ($-m C^{(j)}$) according to Equation (6).

$$\frac{dC^{(j)}}{dt} = \frac{\dot{m}}{\rho V} \left(C^{(j-1)} - C^{(j)} \right) + C^{(j)} \left(\mu - m \right) \tag{6}$$

where C is the biomass concentration (g/m^3), μ is the specific growth rate (s^{-1}), m is maintenance rate (s^{-1}), ρ is the specific mass (kg/m^3) and V volume of EV (m^3).

This study used the equation for the specific growth rate given by Sánchez et al (2008), equation (Eq.(7)) that this depends on the temperature, light and medium intensity also shows effects of photoinhibition.

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$$\mu = \frac{\left(A_1 e^{\left(\frac{E_a}{RT_f}\frac{T_f - T_0}{T_0}\right)} - A_2 e^{\left(\frac{E_b}{RT_f}\frac{T_f - T_0}{T_0}\right)} \right) I_{AV}^{\,b+\frac{c}{I_0}}}{I_{AV}^{\,b+\frac{c}{I_0}} + \left(I_K \left(1 + \left(\frac{I_0}{K_i} \right)^a \right) \right)^{b+\frac{c}{I_0}}} \qquad (7)$$

where I_k represents a constant of affinity of the algae with light ($\mu Em^{-2}s^{-1}$), I means the average light intensity within the tubes of the tubular photobioreactor ($\mu Em^{-2}s^{-1}$), I_0 representing the light intensity on the surface of the tube photobioreactor ($\mu Em^{-2}s^{-1}$), K_i is a parameter photoinhibition ($\mu Em^{-2}s^{-1}$), *a, b, c and n* are empirical parameters (Grima, 1999), A_1 and A_2 are factors frequency (h^{-1}), E_a and E_b are activation energy (*Kcal/mol*), R is the general gas constant (*Kcal/mol*), T_f is the fluid temperature (K) and T_0 is the initial temperature (K). The average light intensity in the tubes of the tubular photobioreactor (I_{AV}) is given by Equation (17).

$$I_{AV} = \frac{I_0}{\pi R} \int_0^R \int_0^\pi e^{-CK_a\left((R-S)\cos\phi + \sqrt{R^2 - (R-S)^2 \sin^2\phi} \right)} d\phi dS \qquad (17)$$

where K_a absorption coefficient of the biomass (m^2g^{-1}biomass), R is the radius of the tube (m), S is the distance from the tube surface to an inner point (m) and φ is the angle of incidence of the light path.

2.3 Mesh Fotobiorreatore 3D Visualization

The code to generate the mesh of the photobioreactor is being programmed in FORTRAN. This code generates a file extension VTK (Visualization Toolkit) which will be read by a visualization program. VTK extension files are widely used to generate meshes for its structural part simplified. For 3D visualization software Visit will be used, because it is free software, and also for having high performance graph (VISIT, 2008).

The code is still under construction, currently only generates the meshes of the photobioreactor tubes in a generic way, so that the user has the power to choose what is the fabric configuration that you want to simulate. In Figure 3 is shown as an example of the mesh four tubes distributed in a 2x2 matrix. In this mesh tube was divided into eight sections which correspond to the elements of volumes.

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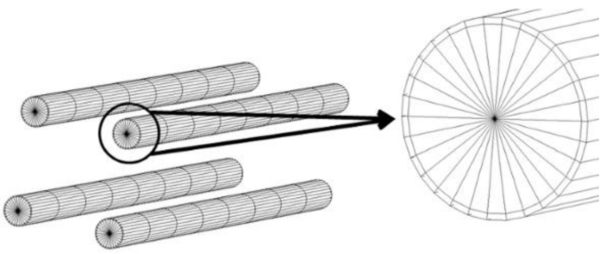

Figure 3. Mesh Tubes photobioreactor.

3. RESULTS AND DISCUSSION

The experimental and numerical data can be viewed in Figure 4. Note that the results obtained by numerical simulation are close to the experimental data, it shows that the mathematical and computational modeling is efficient and can estimate the amount of biomass concentration.

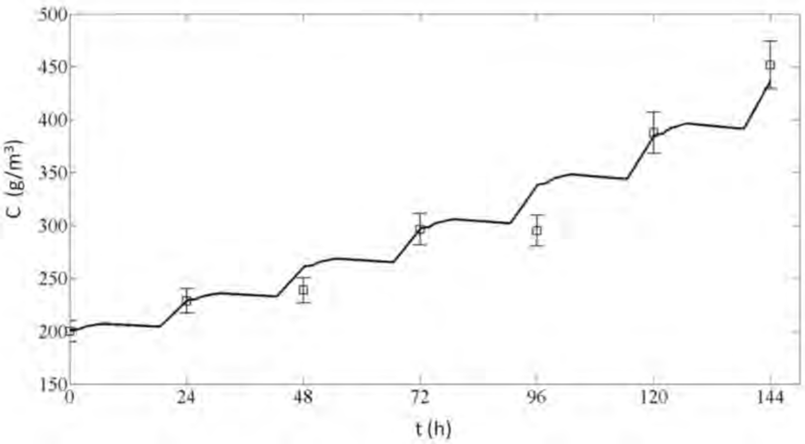

Figure 4. Numerical results and experimental prototype FTC.

With the results of Figure 3 can analyze the annual productivity of the prototype photobioreactor can develop into a year of cultivation. Maximum productivity in only one week cultivation was 2,299.5 L/(ha.year). This data shows a value lower than the values found in the literature for Chist (2007) who obtained 50,000 L/(ha.year) to 135,000 L/(ha.year) oil microalgae. This low yield may have occurred for several reasons: The cultivation was stopped before reaching its maximum cell growth, temperature and luminosity too high, the prototype of the FTC has little shading on inner tubes to twitch the FTC has approximately 60% of their pipes about the shadow of the external pipes. The fluid temperatures reached 36 °C and 1500 W/m2 radiation, these values are out of range for optimal growth of the microalgae *Scenedesmus sp*. whose optimum temperature 25 ^{o}C.

Using the mesh FBR generated by computer code shown in section 2.3, can further analyze the behavior of temperature in the fluid and the wall of the tubes. This analysis is performed on the first day simulation, the following hours: 06h15min, 10 hours, 12 hours, 14h30min, 19 hours and 21 hours, and can be seen in Figure 5.

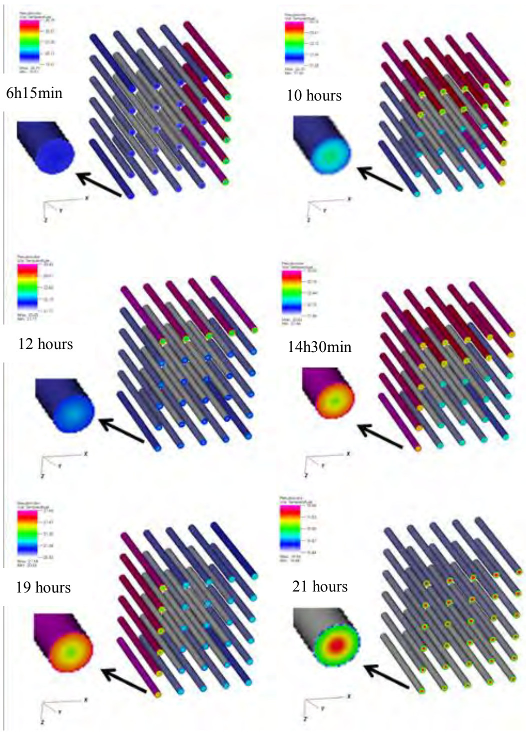

Figure 5. Results for 3D application Visit (2008), the tube wall temperature and fluid (inside tubes) to 6h15min, 10 hours, 12 hours, 14h30min, 19 hours and 21 hours on the first day of computer simulation.

Since the data obtained in the numerical simulation of reality are within the experimental data was then simulated a crop of 14 days for a FTC NPDEAS seen in Figure 1, in order to calculate their annual productivity. Upon completion of the simulation computer model found as maximum productivity 213,760 L/(ha.year), about a hundred times more than the prototype of the FTC. This effect is characteristic of a good temperature control and light efficiency.

In Table 1 we can observe the productivity related to the FTC NPDEAS (prototype and FTC FTC) and the data found in the literature[2]. Note that the microalgae[b] 70% oil in the biomass yield is lower than found with the FTC contained only 11.25% oil in the biomass. This is because the FTC was designed for maximum efficiency in getting the sunlight without overheating the entire system, keeping the microalgae in their optimal temperature range.

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Tabela 1. Yield data from oil.

Cultivation	Oil [L/(ha.year)]
Soja[(1)]	446
Palm[(1)]	5.950
Microalgae[(2)]	136.900
Microalgae[(3)]	58.700
Microalgae – Photobioreactor Prototype[(4)]	**2.299,5**
Microalga - Photobioreactor[(4)]	**213.760**

[(1)] Date from literature [2].
[(2)] Date from literature [2], 70% of oil in the biomass.
[(3)] Date from literature [2], 30% of oil in the biomass.
[(4)] Date from NPDEAS, 11,25% of oil in the biomass.

It was concluded that the FTC built in NPDEAS are a great alternative for the production of biodiesel, because their productivity reaches approximately to double the yields found in the literature.

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4. ACKNOWLEDGEMENTS

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6. RESPONSIBILITY NOTICE

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