DESIGN, MODELING AND SIMULATION OF MICROALGAE PHOTOBIOREACTORS

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Abstract. *This paper introduces a new design conception and a general computational model for compact photo-bioreactors for the cultivation of microalgae. Regarding the photo-bioreactor design, the innovation consists of the maximization of the cultivation and sun exposed area in a given volume, by utilizing circular transparent polymeric staggered tubes (crystal PVC). The geometric conception is based on the compact heat exchangers technology. As an initial modeling effort, a simplified physical model is herein introduced for one pipe photo-bioreactor operating in a closed circular mode, which combines fundamental and empirical correlations, and principles of classical thermodynamics, biochemistry, mass and heat transfer, and the resulting three-dimensional differential equations are discretized in space using a three-dimensional volume element scheme. The proposed model was utilized to simulate numerically the behavior of the photo-bioreactor operating under different operating and design conditions. Mesh refinements were conducted to ensure the convergence of the numerical results. The proposed methodology is shown to allow a coarse converged mesh for all simulations performed, therefore combining numerical accuracy with low computational time. As a result, the model is expected to be a useful tool for simulation, design, and optimization of compact photo-bioreactors.*

Keywords: *Numerical microalgae growth rate, mass fractions, dry biomass volumetric production, efficiency.*

1. INTRODUCTION

The microalgae are organisms found in aquatic atmospheres where there are the presence and the incidence of solar light, and the main characteristic of these it is the lipid structure of high density. With base in these information, researches are driven everywhere of the world to find microalgae species returned to this ideal, as well as a cultivation process that privileges the growth of these organisms in the fastest and efficient way possible, with the largest amount of lipids in her constitution.

Especially, the microalgae creation can be driven of form autotrophic, being enough them an external (solar light) source of energy and a source of inorganic carbon for they synthesize the composed ones that you/they need. The microalgae nursery, which we will call photobioreators, is developed places and thought in way to meditate and to optimize such parameters (Ugwu 2008). Like this, photobioreators are formed by tubes of PVC with high transparency index, similar of maximizing the exhibition of the microalgae the solar light and set up side by side to generate a compact (resembling each other with compact dressing room of heat) structure (Vargas 2007). The geometry, in other words, the amount of tubes, the length of these tubes and his space arrangement, turns possible to create a high degree of compacting of this structure, the one that will allow extract more biomass oil for hectare than any other culture existent, same if compared with other means of microalgae (other photobioreators models and creation ponds) creation or plantations of oleaginous (Chisti 2007).

However an efficient optimization of the system is necessary, as the system is very complex this optimization just can be made assists with it of mathematical models. (Kurano and Miyachi, 2005)

For the presented system, a mathematical model was proposed where are simulated conditions of operation of the photobioreator and generated data for his analysis. These data, through simulations, show how it is the development and the cellular multiplication of the microalgae and also give parameters for the optimization of the photobioreator and his consequent operation.

2. MATHEMATICAL MODEL

The model consists of 3 differential equations with mass swinging for the biomass, carbon gas and oxygen. The model can be represented through the following diagram in figure 1:

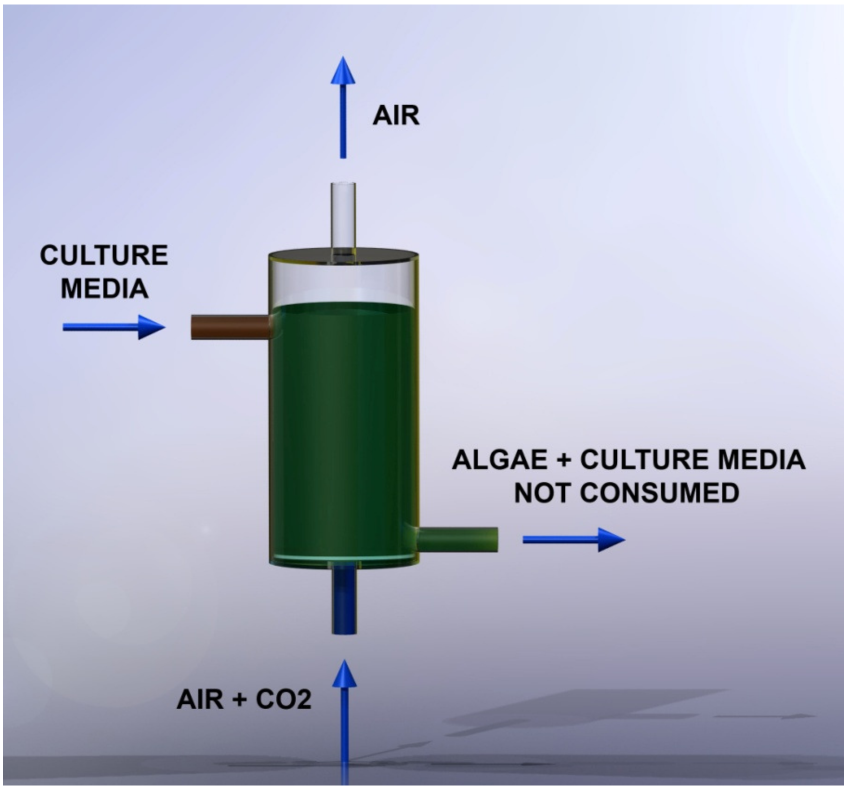

Figure 1. Diagram of the system.

Firstly we should characterize the kinetics of the system, where we will find the specific speed of growth, call of μ:

$$\mu = f(CO_2, O_2, \lambda, X) \quad (1)$$

Where CO_2 the concentration of carbon gas, O_2 is concentration of oxygen, λ it is the luminous intensity and X will be the biomass concentration. Then μ is function of those elements, in other words, the growth is dependent of those components. However, still the growth tax μ can be defined as:

$$\mu = \mu_{\max}.\mu_{CO2}.\mu_{O2}.\mu_{\lambda} \quad (2)$$

In this case, will μ max be the maximum tax of growth, μCO2 the growth tax that involves the consumed parcel of carbon gas for the microalgae will be, μO2 the growth tax that involves the portion of oxygen and μ λ will be it is tax of responsible growth for the light portion. To presented equations they act according to the following taxes presented below:

$$\mu_{CO2} = \frac{CO_2}{K_{CO2} + CO_2} \quad (3)$$

Where CO_2 is the concentration of carbon gas, KCO2 is the growth constant for CO2

$$\mu_{O2} = \frac{1}{1 + \frac{(O_2)}{Ki_{O2}}} \quad (4)$$

Where O2 is concentration of oxygen, and KiO2 is constant of inhibition for oxygen.

$$\mu_\lambda = \frac{\lambda}{K_\lambda.X + \lambda + \frac{(\lambda)^2}{Ki_\lambda.(X)}} \quad (5)$$

Where λ is the luminous intensity, Kλ is the growth constant for the light, Kiλ it is Constant of inhibition for light and X is biomass concentration.

Having calculated like this the global tax of growth μ according to equation 2 the differential equations are as:

$$\frac{dX}{dt} = D.X_{ent} - D.X + \mu.X - m.X \quad (6)$$

Where D is the dilution tax, Xent is the concentration of biomass entrance and m is the coefficient of maintenance of the biomass.

$$\frac{dCO_2}{dt} = \frac{Q_{entCO2}.\rho_{CO2}}{V_{liquido}} - Y_{CO2/X}.\mu.X - Kla_{CO2}.(CO_2 - CO_2^*) \quad (7)$$

Where QentCO2 the volumetric flow of entrance of carbon gas, ρCO2 is the density of the gaseous carbon gas before entering in the reactor, Vliquido is the volume of liquidate of the reactor, YCO2/X is the estequiometric coefficient of the consumption of CO2 for the biomass, KlaCO2 is the coefficient of mass transfer among the phase liquidates and gaseous of the reactor for CO2, CO2 * it is the concentration of CO2 that would be in the balance with the gaseous phase of the reactor, this can be defined as:

$$CO_2^* = H_{CO2}.P_{CO2} \quad (8)$$

Where HCO2 is Henry's constant for CO2, PCO2 is the partial pressure of CO2 in the gaseous phase of the reactor.

$$\frac{dO_2}{dt} = \frac{Q_{entO2}.\rho_{O2}}{V_{liquido}} + Y_{O2/X}.\mu.X - Kla_{O2}.(O_2 - O_2^*) \quad (9)$$

Where QentO2 the volumetric flow of entrance of carbon gas, ρO2 is the density of the gaseous carbon gas before entering in the reactor, Vliquido is the volume of liquid of the reactor, YO2/X is the estequiometric coefficient of the generation of O2 for the biomass, KlaO2 is the coefficient of mass transfer among the liquid and gaseous phase of the reactor for the oxygen, O2 * it is the concentration of O2 that would be in balance with the gaseous phase of the reactor and it can be defined as:

$$O_2^* = H_{O2}.P_{O2} \quad (10)$$

Where HO2 is Henry's Constant for O2 and PO2 is the partial pressure of O2 in the gaseous phase of the reactor.

3. NUMERICAL SIMULATION

The values of the parameters of the proposed mathematical model are in the table 1. Those parameters were certain tends as base the parameters proposed by Molina et al 1994. The model is applicable to microalgae *Phaeodactylum Tricornutum.*

Table 1. Parameters of the mathematical model.

Variable	Symbol	Value	Unit
Tax specifies of growth maxim	μ_{max}	0,8	h^{-1}
Constant of saturation for carbon gas	K_{co2}	0,1	$g.L^{-1}$
Luminous intensity	λ	300	$w.m^{-2}$
Constant for light	K_λ	30	$w.L.m^{-2}.g^{-1}$
Constant of inhibition for light	Ki_λ	1,9	$w.L.m^{-2}.g^{-1}$
Constant of inhibition for oxygen	Ki_{o2}	2,5	$g.L^{-1}$
Dilution tax	D	-	h^{-1}
Maintenance tax	m	0,001	h^{-1}
h-1Vazão of entrance of carbon gas	Q_{entco2}	10	$L.h^{-1}$

L.h-1Densidade of the carbon gas	ρ_{co2}	1	$g.L^{-3}$
L-3Volume of I liquidate of the reactor	$V_{liquido}$	10	L
Estequiometric coefficient of income of carbon gas for biomass	$Y_{co2/x}$	1,8	$g.g^{-1}$
Coefficient of transfer of mass of the carbon gas among the phase liquidates and the gaseous phase of the reactor	kla_{co2}	3,5	h^{-1}
Constant of Henry for the carbon gas	H_{co2}	0,034	$g.L^{-1}.atm$
Partial pressure of carbon gas in the gaseous phase	P_{co2}	0	atm
Flow of entrance of oxygen	Q_{ento2}	0	$L.h^{-1}$
L.h-1Densidade of the oxygen	ρ_{o2}	1	$g.L^{-1}$
Estequiometric coefficient of income of oxygen gas for biomass	$Y_{o2/x}$	1,3	$g.g^{-1}$
Coefficient of transfer of mass of the oxygen among the phase liquidates and the gaseous phase of the reactor	kla_{o2}	3,5	h^{-1}
Constant of Henry for the oxygen	H_{o2}	0,0013	$g.L^{-1}.atm$
Partial pressure of oxygen in the gaseous phase	P_{o2}	1	atm

To solve the model the method of Runge-Kutta of 4° order it was used using the program TK Solver and the routine RK4sa.

They were made simulations looking for to optimize the cellular growth in function of the flow of carbon gas, the solar light and dilution tax, obtaining a great point of operation for the system.

4. RESULTS AND DISCUSSION

In the figure 1 we have the tax of production of algae in function of the flow of carbon gas. As the earnings can be observed in the production of algae is lineal to the point of operation of 40 liters for hour of carbon gas. Starting from that the earnings in the production passes to be very small. One of the largest operational costs of the photobioreators is the supply of carbon gas. Being like this in spite of an earnings in the production doesn't compensate of the point of the financial point of view to operate the system with flows very discharges due to the increase of the cost of the system. In fact the best operation point is to 40 liters for hour of carbon gas, a point where is possible to reconcile production with low cost. The model shows that a great point exists where that can be obtained.

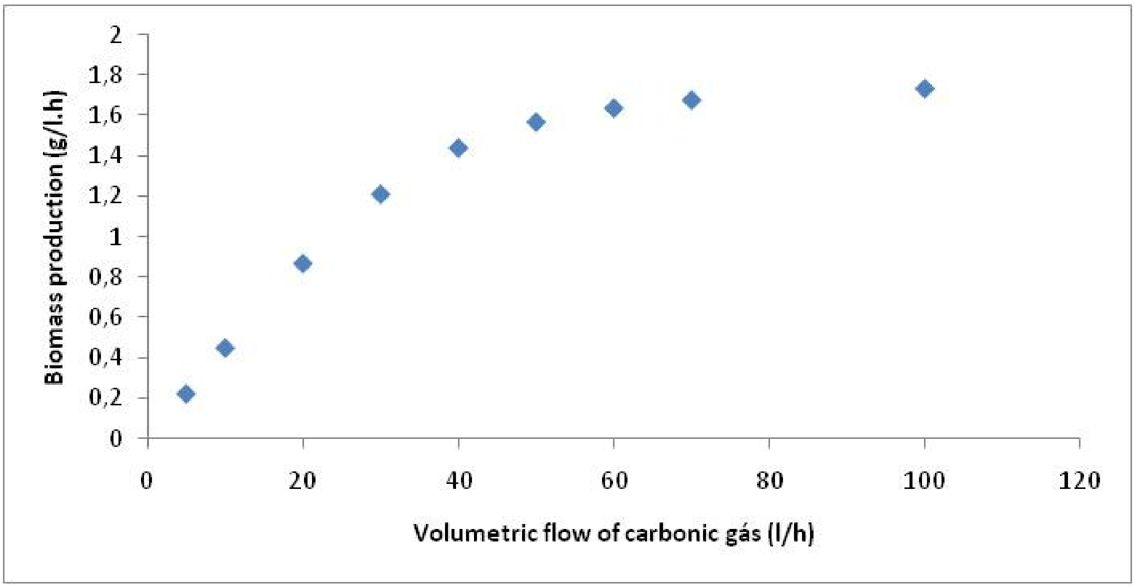

Figure 2. Biomass production in relation to volumetric flow of carbonic gas.

With the relationship to the biomass production for the intensity of the light, we can see the behavior of the system in the figure 2. The great point of the system is around 600 watts for square meter. We see that an increment in the radiation to leave of that point maintains the constant production and in the point of 1500 watts for square meter there is no growth. That can be explained by the known phenomenon as picture inhibition where the light in excess inactive photosynthesis of the cell due to a very big amount of photons that they damage the responsible proteins for the photosynthesis. It can also be observed that the growth of the biomass production in relation to light is lineal until the point of 300 watts for square meter. Starting from that the earnings in biomass production is small arriving to interrupt the growth in the point of 1500 watts for square meter. That shows that in cultivations where artificial light a tax of radiation of 300 watts is used by square meter is enough for a great biomass production, without an additional cost of electric light to generate more radiation. Being like this seeking as much production as economy the great point for the intensity of the light is of 300 watts for square meter.

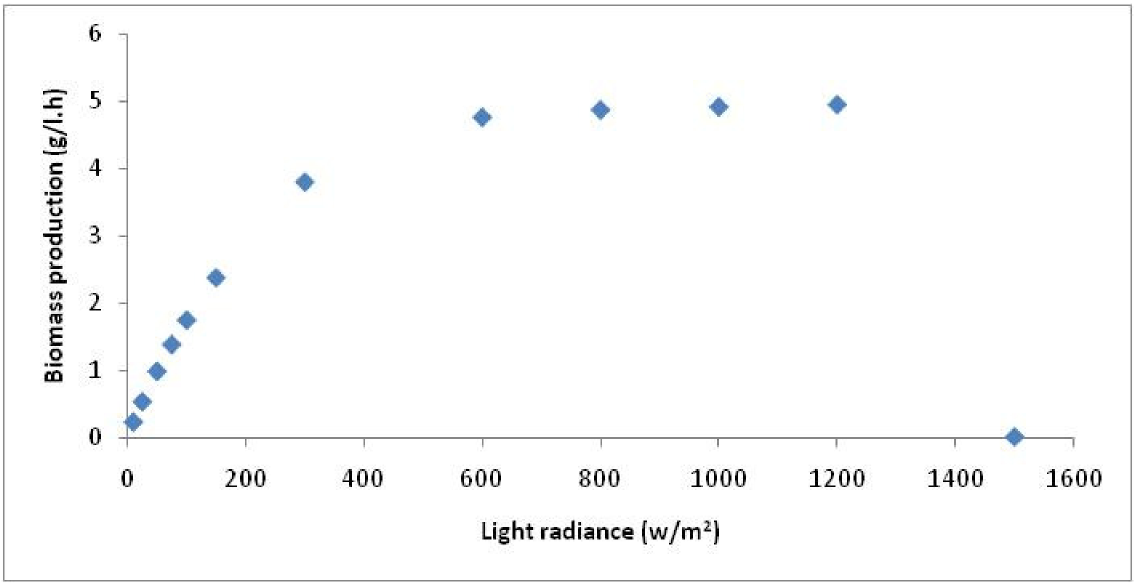

Figure 3. Biomass production in relation to light radiance.

The third analyzed parameter was the behavior of the system in relation to dilution tax as it can be observed in the figure 3. As it can be observed, taxes of very high dilution reduce the production, getting to interrupt the growth of the system as it can be observed in the point where the dilution tax is of 0,075 $^{h-1}$. That demonstrates the need to optimize that parameter. As the best operation point can be observed with the largest production is with the tax of dilution of 0,02 $^{h-1}$. However with a the tax of dilution of 0,01 $^{h-1}$ is obtained the same result practically. That reduces in half the consumption of energy for the pumping of the fluid of the system. Being like this the tax of great dilution that he/she reconciles productivity with a lower cost of operation is the point of 0,01 $^{h-1}$.

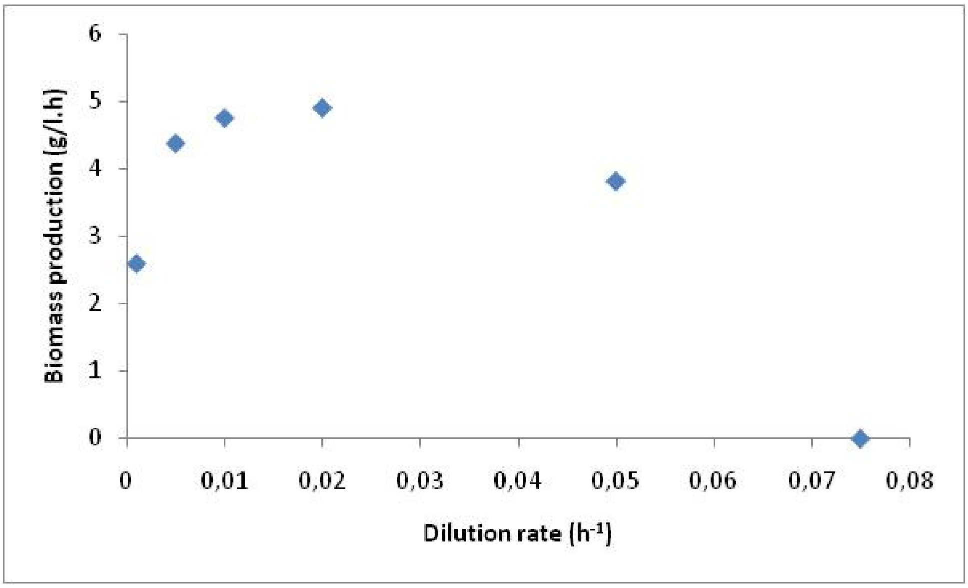

Figure 4. Biomass production in relation to dilution rate.

Being like this, the great point of operation of the system given by the model is of 300 watts for square meter of light intensity, 40 liters for hour of carbon gas and a tax of dilution of 0,01 $^{h-1}$.

5. CONCLUSION

The developed model was capable to optimize the system of production of algae. It was possible to find a great operation point, where the biomass production is of 4,75 g/l.h.

However the model still was not validated experimentally. The cultivation conditions optimized cannot be quantitatively correct. In spite of that the model gave conditions of evaluating the key effect of parameters for the optimization of the system.

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