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ANALYSIS OF S_f/V RATIO OF PHOTOBIOREACTORS LINKED WITH ALGAL PHYSIOLOGY

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Summary: Cleaning the waste gases from coal fired plants, burners, and anaerobic bioreactors are major concerns nowadays. CO_2 liberation in the atmosphere is a huge problem, and the only visible cost-effective alternative is sequestrating it by using high density cultures in modern closed photobioreactors (PBRs). One of the most important criteria for evaluation of PBR capacity is surface area–to-volume ratio (S_f/V). This work combined this criterion with algal physiology and predicted the biomass concentration in closed PBR as a function of light availability-S_f/V at a given algal physiological state. Several PBR designs were chosen from the literature on the basis of their S_f/V ratio. Mathematical analysis was performed in order to predict the maximum biomass concentration where specific growth rate was a function of S_f/V ratio, as well as to predict PBR's potential to support high density cultures.

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Abbreviations: PBR – photobioreactor; SGR – specific growth rate.

INTRODUCTION

Closed tubular PBRs are potentially attractive for large scale culture that is free of contaminants (Hulatt and Thomas, 2011; Ling et al., 2009; Ugwu et al., 2008; Sierra et al., 2008; Merchuk, 2007; Carvalho et al., 2006; Molina et al.,1999; Contreras et al., 1998; Chaumont, 1993; Torzillo et al., 1986). Closed devices are undoubtedly more expensive to build and maintain compared to open ponds, but they may be the only option for producing certain pharmaceuticals. On the other hand, closed PBRs make possible the efficient control of the culture variables, such as pH, temperature, concentration of CO_2 in the gas streams fed to algal suspensions, etc. (Ling et al., 2009; Behrens, 2005).

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Tubular photobioreactor (PBR), bubble columns (Sánchez et al., 2000), and flat plate PBRs are most frequently used for mass culturing of microalgae (Sánchez et al., 1999). Tubular PBRs have been successfully used for outdoor microalgae cultures (Lee and Low, 1991; Molina et al, 2001; Ugwu et al., 2002). One of the most important reasons for that is attributed to their high S_f/V ratio. A modeling approach needs to be applied to the closed PBRs in order to determine their optimal design and functioning (Luo and Al-Dahhan, 2004).

Light is the only source of energy for growth of photoautotrophic microalgae. Therefore, one of the major concerns in microalgae mass production is to achieve a sufficient supply of light in the culture. An optimal design of a PBR includes light unlimited growth kinetics, specific to each photosynthetic microorganism, which must be related to maximum possible penetration of the light into the liquid volume of the PBR (Molina et al., 1999, Rubio et al., 2003). This is possible only if the cultural medium is totally transparent to radiant energy within the wavelength range from 400 to 700 nm, useful for photosynthesis (Heldt, 2004).

Another issue under consideration is the effect of mixing on the light utilization efficiency by the photoautotrophic algae cells (Reyna-Velarde et al., 2011). Mixing ensures uniform distribution of light into the PBR, and as a result improves the light absorption by the microalgae cells. When applying high velocity to the tubes of a solar receiver, cells will move from the highly illuminated surface area to the center of the tubes where illumination decreases depending on the biomass concentration according to the Lambert's Beer law (for our mathematical analysis it is assumed that the chosen empirical formula can be used as a good approximation). Such movement can be considered as circulation from light to dark zones of the PBR, resulting in a flashing light effect. If the velocity does not support thorough mixing, cells closer to the highly illuminated surface can be photo-inhibited, whereas those at the center of the PBR tube can be light limited (Ogbonna et al., 1995). Hence, S_f/V ratio responsible as a light supply criterion is very important for the determination of maximum algal productivity (Zijffers et al., 2010, Merchuk et al., 2007).

The goal of this work was to develop a model which showed the link between given PBR geometry (S_f/V) in terms of light availability and how this influence reflected on algal physiology and more specifically on biomass maximum concentration.

RESIDENCE TIME AS A CRITERION FOR CO_2 UTILIZATION EFFICIENCY

Analysis of the CO_2 (from waste gases) fixation system by algae includes the detailed evaluation of the PBR light potential. One of the most important criteria, so called S_f/V ratio (surface area divided by the PBR volume; surface area-to-volume ratio), has to be linked with algal physiology for evaluation of tubular PBR performances. This is especially important when the PBR solar receiver is long tubing as shown elsewhere (Acien Fernandez et al., 2001; Ugwu and Aoyagy, 2012). Hence, one has to evaluate Sf/V, and other key PBR process parameters such as the residence time of culture in the region of light availability and as well as the influence of turbulence on algal physiology.

Let's consider the system where liquid recirculation is done by the pump. We are going to analyze the scheme Tubular PBRs and Solar receiver with maximum theoretical H_{pbr}/D_{pbr} (L_{pbr}/D_{pbr}) ratio (where H_{pbr} - stands for PBR height, D_{pbr} - stands for PBR diameter, L_{pbr} - stands for length of the solar receiver (very long transparent tubes with small diameter 0.01-0.06 m).

Maximum CO_2 bio-assimilation efficiency connects with residence time ($\tau_{residence}$,) S_f/V ratio for the given working conditions, where algal growth and average light irradiance (I_{av}) have non-limiting and non-inhibiting values.

Let's analyze the residence time in PBR ($\tau_{residence}$).

$$\tau_{residence}=H_{pbr}/v_{liquid} \text{ or } \tau_{residence}=L_{pbr}/v_{liquid},$$

where v_{liquid} is a liquid velocity m s^{-1}.

Let's assume that we need a PBR with 60 liter liquid volume and the diameter is 0.01 m.

$$L_{pbr}=0.06/(0.785.(0.01)^2)= 764 \text{ m.}$$

What liquid velocity should be considered for optimal solar receiver performance?

The authors (Acien Fernandez et al., 2001) have been studying the influence of the solar loop liquid velocity on the culture performance, at three different liquid velocities as follows: 0.50, 0.35, and 0.17 m s^{-1}, at a constant dilution rate of 0.05 h^{-1}. At the highest liquid velocity, the authors attained a maximum biomass concentration of 2.38 kg m^{-3}. A well known fact is that turbulence enhances biomass productivity. For example, Carlozzi and Torzillo (1996) noted lower biomass productivity in laminar flow relative to that in turbulent conditions for *Spirulina* cultures in tubular PBRs. A 29% increase in *Spirulina* biomass productivity was observed when the flow pattern changed from laminar to turbulent in straight tubes. However, further increase in turbulent mixing speed produced no beneficial effect; a high liquid velocity of 0.97 m s^{-1} damaged the culture and reduced the biomass productivity. The beneficial effect of limited turbulence has been observed for *Chlorella* growing in a tubular PBR. (Note: The liquid velocity can be used as a criterion for turbulence and its influence on the algal physiology when dynamic viscosity, density and diameter of the solar receiver are constant. Otherwise, Reynolds number should be more correct to be used).

Based on the theory in the field, let's assume maximum liquid velocity taken from air lift PBRs is in the range v_{liquid}=0.35-0.5 m s^{-1}. (This analysis is valid for all air lift liquid velocities).

$$\tau_{residence}=L_{PBR}/\ v_{liquid} =764/0.35= 2183\text{s}=36 \text{ min.}$$

It has to be noted, that in case of very long tube, the produced oxygen must be taken out from the liquid in order to prevent growth inhibition. This can be realized by using membrane technology. In practice, the length of the tubes is recommended to be not bigger than 80 meters (Molina-Grima et al., 1999).

Light criterion

$$S_f/V=(\pi.d.H)/(H.\pi.(D_{pbr}{}^2/4))= 4/d=4/0.01=400 \text{ m}^{-1}$$

$S_f/V=4/\ D_{pbr}$, this simple form shows that light availability depends only on tubular PBR's diameter. PBR designs resulting in a ratio value of 400 m^2/m^3

were state-of-the-art in the year 2008 (Kunjapur and Eldridge, 2010). For X-biomass concentration up to 6 kg m^{-3} during the summer at noon, light penetrates throughout the whole cross sectional area of PBR with D_{pbr}=0.01 m. It must be noted, the value S_f/V=400 m^{-1} can be considered maximum ratio for any realistic Lab (Pilot plant) PBR design. For S_f it is assumed that the light covers the whole PBR surface area.

Note – in all calculations V stands for the liquid volume in solar receiver.

S_f/V RATIO LINKED WITH ALGAL PHYSIOLOGY

It is important to have a simple relationship between SGR and S_f/V ratio in order to simulate the system behavior for the given light conditions, and to quantitatively evaluate the Tubular PBR geometry effect on algae growth. In the literature there was no such analysis published considering population level of microalgae growth. The model was developed under the following assumption:

1. The growth kinetics is not limited by the mixing and hydrodynamics which means that the analysis is made for the region of the PBR with ideal mixing.
2. There is no inhibition by O_2 concentration and there are no limitation and inhibition by CO_2.

The growth of phototrophic cultures is most often limited by light deficiency rather than by an insufficient gas supply, because the growth rates of known phototrophic microorganisms are much lower than the growth rates of chemotrophs.

Assuming Monod kinetic model,

$$\mu = \mu_{\max} \frac{S}{(K_s + S)} \tag{1}$$

$$\frac{dX(t)}{dt} = \mu * X(t) \tag{2}$$

where μ stands for specific growth rate, h^{-1}; μ_{max} stands for maximum specific growth rate, h^{-1}; S stands for substrate concentration, kg m^{-3}; X is the biomass concentration, kg m^{-3}; and K_s is the half-saturation constant, kg m^{-3}.

For cultures whose growth is limited by insufficient illumination, we may present S as a function of I_0 and S_f/V ratio as follows:

$$S = I_0 * \left(\frac{S_f}{V}\right) * \varepsilon * X \tag{3}$$

where:

S_f is the illuminated surface area of the reactor, m^2, V is liquid volume, m^3, I_0 is the intensity of the incident light on the Tubular PBR surface, μmol m^{-2} s^{-1}; and $\boldsymbol{\varepsilon}$ is the extinction coefficient of the culture.

Firstly, we included this expression into the kinetic model. Thus we obtained:

$$\mu = \mu_{\max} \frac{\left(I_0 * \left(\frac{S_f}{V}\right) * \varepsilon * X\right)}{\left(K_s + \left(I_0 * \left(\frac{S_f}{V}\right) * \varepsilon * X\right)\right)} \tag{4}$$

We know that I_{av} is a more representative parameter of light availability in Tubular PBRs than I_0, and it is a function of X concentration as follows:

$$I_{av} = \frac{I_0 * E_0}{X^n} * \left(1 - e^{-E_1 X^n}\right) \tag{5}$$

where E_0-parameter in the I_{av} (Eq5) light model [g^n/L^n]; E_1-parameter in the light model [g^n/L^n] ;n - is a constant with evaluated value [-].

Lambert-Beer's law, extensively used in photometry, is based on three assumptions: (1) the direction of the incident radiation does not change as it crosses through the culture; (2) the radiation is monochromatic; and (3) scattering effect due to solid particles is negligible compared to absorption. The Lambert-Beer's law adjustment of light attenuation is not appropriate for high biomass concentrations due to the existence of different scattering and selective absorption effects (Acien Fernández et al, 1997). Equation 5 was successfully used for on-line evaluation of algal growth dynamics (Jian Li, 2002). In this thesis, the semi-empirical approach used when derived Eq 5, as well as assumptions made and benefits when applied this model were explained in details. The E_0 and E_1 coefficients take into account the above mention effects. The simplicity of the model is very useful for PBRs design, optimization and on-line control.

Model using the I_{av} parameter:

$$\mu = \mu_{\max} \frac{\left(I_{av} * \left(\frac{S_f}{V}\right) * \varepsilon * X\right)}{\left(K_s + \left(I_{av} * \left(\frac{S_f}{V}\right) * \varepsilon * X\right)\right)} \qquad (6)$$

This specific growth rate model can be used for quantitative evaluation of SGR vs. S_f/V relationship when I_{av} does not exceed $I_{av(critical)}$ where the inhibition by light takes place.

Response surface analysis of this model was performed (where I_{av} and D_{pbr} ($S_f/V=4/D_{pbr}$) are independent variables and SGR is a function of them) for the following ranges of parameters: I_{av}=0-270 µmol m^{-2} s^{-1} and D_{pbr}=0.01-0.15 [m], (SGR_{max}=0.11 1/h; X=1.3 [kg m^{-3}], E_0=.026 [g^n/L^n]; E_1=10.1 [g^n /L^n]; n=0.87 [-];ε =10; Ks(S_f/V)=850.0. At a very low X biomass concentration, we have I_{av}*(S_f/V)*ε*X>>Ks(S_f/V) and the algae SGR is close to $SGR_{max.}$ If I_{av}*(S_f/V)*ε*X<<Ks(S_f/V) it means high X concentration and low I_{av}; therefore, the culture has a linear growth (Fig. 1).

In conclusion, for the given conditions (D_{pbr}=0.14 m, I_{av} =270 µmol m^{-2} s^{-1}) SGR had a value much lower than SGR_{max} and was about 0.0264.

The task of modeling (Joshi, 2001) solar light attenuation by the biomass at high concentrations in microalgal cultures is crucial (Luo and Al-Dahhan, 2004). The

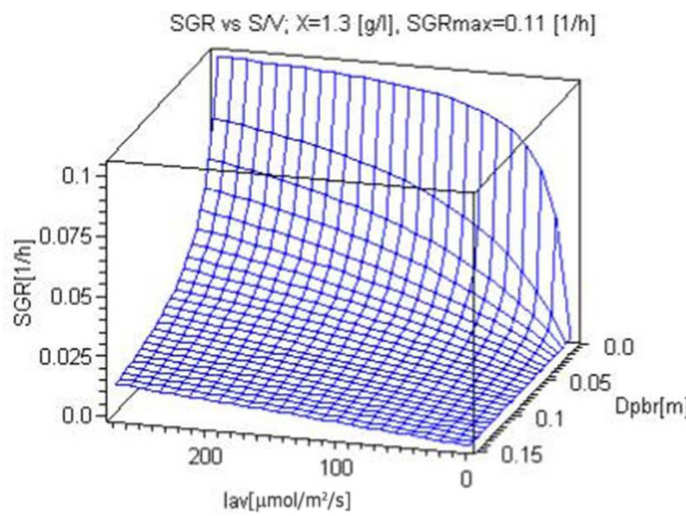

Figure 1. Response surface analysis – SGR vs I_{av} and D_{pbr} ($S_f/V=4/D_{pbr}$).

equation which determined average light path as a function of biomass concentration and initial irradiance on the PBR surface can be presented in the following form:

$$I_{av} = \frac{I_0 * E_0 * (1 - e^{-E_1 X\ (t)^{n_1}})}{X(t)^{n_1}} \quad (7)$$

where X -is the biomass concentration [kg/m^3]; n_{1-} is a constant [-].

If we describe algae growth inhibition by light in the Aiba's form:

$$SGR_{Iav} = \frac{I_{av}}{Ks_{Iav} + I_{av} + \frac{I_{av}^2}{K_{I\,av\max}}} \quad (8)$$

$$SGR_{Iav} = \frac{\left(I_0 * E_0(1 - e^{-E_1 X(t)^{n_1}})\right)}{\left(X\ (t)^{n_1}\left(Ks_{Iav} + \frac{I_0 E_0 (1 - e^{-E_1 X(t)^{n_1}})}{X\ (t)^{n_1}} + \frac{I_0^2 E_0^2 (1 - e^{-E_1 X\ (t)^{n_1}})^2}{(X(t)^{n_1})^2 K_{Iav\max}}\right)\right)} \quad (9)$$

Then, SGR as a function of S_f/V and I_{av} is written as follows:

$$SGR_{total} = \mu_{max}.SGR_{(Sf/V)} * SGR(_{Iav}) \quad (10)$$

where $SGR_{(Sf/V)}$-is specific growth rate as a function of S_f/V ratio, h^{-1}; $SGR(_{Iav})$-is specific growth rate as a function of average light intensity where inhibition by light takes place, h^{-1}; SGR_{total}-is overall specific growth rate, h^{-1}.

After substitution we obtain:

$$Substrate = \frac{I_{av} * S_f}{V \quad * \varepsilon * \quad X(t)} \quad (11)$$

$$SGR_{(Sf/V)} = \frac{I_{av} * S_f}{V * \varepsilon * X(t) * \left(Ks_{S_f V} + \frac{I_{av} * \quad S_f}{V * \quad \varepsilon * \quad X\ (t)}\right)} \quad (12)$$

Hence, the SGR_{total} can be written as follows:

$$SGR_{total} = \frac{A_{SGR_{total}}}{X\ (t) * B_{SGR_{total}} \quad * C_{SGR_{total}} \quad * D_{SGR_{total}}} \quad (13)$$

Where

$$A_{SGR_{total}} = \mu_{\max} * I_0^2 * E_0^2 * S_f * (1 - e^{-E_1 * X(t)^{n_1}})^2$$

$$B_{SGR_{total}} = (X(t)^{n_1})^2 V * \varepsilon$$

$$C_{SGR_{total}} = K_{s_{S_f V}} + \frac{I_0 * E_0 * (1 - e^{-E_1 * X\ (t)^{n_1}}) S_f}{X\ (t)^{n_1} * V * \varepsilon * X\ (t)}$$

$$D_{SGR_{total}} = K_{s_{Iav}} + \frac{I_0 * E_0 * (1 - e^{-E_1 * X\ (t)^{n_1}})}{X\ (t)^{n_1}} + \frac{I_0^2 * E_0^2 * (1 - e^{-E_1 * X(t)^{n_1}})^2}{(X(t)^{n_1})^2 * K_{Iav\max}}$$

Furthermore, the biomass balance is written as follows:

$$\frac{dX(t)}{dt} = SGR_{total} * X(t) \quad (14)$$

Hence:

$$\frac{dX(t)}{dt} = \frac{A_{SGR_{total}}}{B_{SGR_{total}} \quad * C_{SGR_{total}} \quad * D_{SGR_{total}}} \quad (15)$$

Having the biomass balance and model for SGR as a function of S_f/V and I_{av}, where light limitation and inhibition are taken into account. Solving the equation 15 for different initial conditions (X_0-inoculum) and given process time (t=14 days), we may evaluate different industrial tubular PBRs' performances by substituting their real PBR diameters (S_f/V ratios, respectively). We evaluate the industrial PBRs from the mini review of (Pulz, 2001), the S_f/V ratios of industrial PBRs are in the range S_f/V=6.7 m^{-1} raceway ponds to S_f/V=86.7 m^{-1} and D_{pbr}=0.046 m for Tubular PBRs. Maximum D_{pbr} reported in the literature is about D_{pbr}=0.40 m, but achieved biomass concentration is very low and cannot be increased by any manipulations of the regime parameters (conditions assume only natural source of light!).

Hence, the analysis will be made for S_f/V =10-87 m^{-1} considering only S_f and V, where V is the liquid in the solar receiver. Maximum ratio equals S_f/V=400 m^{-1}, D_{pbr}=0.01 m will be a reference point in this analysis, and upper limit of S_f/V (lowest D_{pbr} diameter). For the lower limit

S_f/V->min, we are choosing D_{pbr}=0.4 m (S_f/V=10 m^{-1}).

A simulation with the above-described model developed for Tubular PBRs was performed assuming that only a solar receiver is considered, and that the light is supplied continuously 24 hours a day. Note: Dark liquid volume was not considered. (As mentioned previously, we recognized 3 different Light/Dark cycles: 1. L/D cycle in Tubular PBR; 2. L/D cycle -Dark tank<->solar receiver; 3. Natural Sunlight cycle-12/12h.)

The trends shown by the simulation results presented in Table 1 are in agreement with real experimental data obtained from algae plants (Pulz, 2001, Molina-Grima EG, 2000). The simulation results can be more precise if SGR is taken for the particular strain culturing in each plant. The results from the above analysis can be interpreted as follows:

– For low light intensities tubular PBRs with D_{pbr}> 0.40 m are not effective;
– For high light intensities I_0=3270.0 [μmol m^{-2} s^{-1}] (hot summers; tropical regions, deserts). Tubular PBRs with diameters up to D_{pbr}=0.20 m can be successfully used;
– Tubular PBRs with diameters 0.05 m to 0.15 m have great theoretical potential in tropical regions (USA deserts, North Africa, etc);
– Algae strains resistant to shear stress and having high SGR may successfully be used in tubular PBRs where biomass concentration up to 6 kg m^{-3} can be achieved.

It must be noted that 20 kg m^{-3} biomass concentration during photoautotrophic growth reported in the literature is possible to be achieved ONLY in very thin 0.01 m (or less) tubular PBRs which is unrealistic for industrial applications (simulation not shown).

Table 1. Simulation results with the kinetic model where SGR is a function of S_f/V ratio (D_{pbr}) and light illumination (light limitation and inhibition) is considered. Assumptions: No mixing and no mass transfer limitations; no limitation by nutrients; no inhibition by O_2 concentration; no limitation and inhibition by CO_2 concentration.

Conditions-X_0=0.1 [κg m^{-3}], SGR_{max}=0.11 [h^{-1}], I_0=3270.0[μmol m^{-2} s^{-1}], time=14 [day]		
Tubular PBR diameter [m]	Biomass concentration [kg m^{-3}]	S_f/V ratio [m^{-1}]
d=0.40	X=2.48	S_f/V=10
d=0.20	X=3.50	S_f/V=20
d=0.14	X=4.15	S_f/V=28.6
d=0.08	X=5.38	S_f/V=50
d=0.0467	X=6.85	S_f/V=85.7
d=0.03	X=8.30	S_f/V=133
d=0.01	X=13.12	S_f/V=400

Note: The kinetics constants in calculations are taken from experiments performed with *Chlorella vulgaris* species (unpublished results). The process time duration responded to the stationary phase of growth curve. The simulation results from the table are in agreement with results published elsewhere (Pulz, 2001, Molina-Grima EG, 2000).

Additionally, this analysis shows that PBRs with diameters up to 0.20 m have great potential in terms of light availability in very hot tropical regions and for fast growing shear stress resistant *Chlorella* species. With tubular PBRs, we may safely expect to achieve a biomass concentration in the range 2-4 kg m^{-3} for liquid velocities up to 0.8 m s^{-1}. This is in agreement with reported optimal liquid velocities 0.20 m s^{-1} - 0.50 m s^{-1} and biomass concentrations published elsewhere (Molina-Grima EG, 2000).

This requires the following measures to be undertaken:

– Any engineering solution which is going to minimize the dark liquid volume in the scheme must be utilized.
– Increasing the radial mixing in the tubular PBR may be very beneficial for Light/Dark cycles' improvement "flash light effects" (where liquid velocities are in the range between 0.20-0.50 m s^{-1} or above depending on PBR design).

CONCLUSIONS

The novel model will be extremely useful in obtaining appropriate growth kinetics in a tubular PBR or solar receiver tube, which in turn will enable simulations predicting biomass productivity, optimization and scale up of the PBR depending on the selected species and their light-dependent behavior.

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