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Twisted tubular photobioreactor fluid dynamics evaluation for energy consumption minimization

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ABSTRACT

This paper discusses a new tubular PhotoBioReactor (PBR) called *twisted tubular PBR*. The geometry of a twisted tubular PBR induces swirl mixing to guarantee good exposure of microalgae to Light-Dark (LD) cycles and to the nutrients and dissolved CO_2. The paper analyses the energy uptake for fluid transport through the twisted tubular PBR. The analysis is based on a comparison between the twisted tubular PBR and other tubular PBRs that have swirl mixing generation. Four types of tubular PBRs are simulated using Computational Fluid Dynamics (CFD); these results are used to evaluate energy consumption and mixing conditions. Swirl number is used to evaluate mixing conditions and swirl flow. On the other hand, microalgae particles performing undulatory motion are evaluated with Discrete Fourier Transform (DFT). Characteristics of the microalgae frequency in the swirl mixing depend on average flow velocity. Results show that the new twisted tubular PBR demands less energy for pumping than the other tubular PBRs that have swirl motion; providing an important step towards the construction of a highly efficient tubular PBR.

1. Introduction

Microalgae, as a photosynthetic microorganism, can produce valuable products using carbon dioxide and solar light. Microalgae cultivation has been studied for a long time as a way to capture atmospheric carbon responsible for the greenhouse effect, a topic that has gained more attention in recent years. In addition, the PolyUnsaturated Fatty Acids (PUFA) produced by the algae can be used for biodiesel production [4]. Microalgae can be cultivated in open tanks and ponds, which are easy to construct and to operate. Drawbacks of these systems are the risk of contamination of the culture, the inability to control operating variables and the low productivity [12,22]. Closed PhotoBioReactors (PBR) are an alternative to open ponds, since the environment and operating variables can be tightly controlled. Nevertheless, the energy needed to maintain the closed PBR operation is high, which impacts the operational costs [4]. Therefore, it is necessary to optimize PBR design and operation to reduce energy use and to improve the use of sun light energy [22].

Particularly, mixing in PBRs has been evaluated in order to trace the path of microalgae through light and dark zones. Previous research analysed PBR mixing performance to evaluate microalgae's light and dark path through the PBRs; this particular motion was referred to as Light and Dark (LD) cycles [10,11,14,15]. Moreover, other authors changed the PBRs configurations to enhance LD cycle [9,13]. For tubular PBRs the use of static mixers seemed to improve productivity of microalgae cultures (Perner-Nochta & Posten, [19]; [35]). The beneficial effects of LD cycles in enhancing microalgae culture growth has been discussed by several authors [1,20,26,27]. However, the use of mixers increased the energy use to keep the system flowing. In fact, mixing is a main contributor to the energy consumption in tubular PBRs [18]. The use of static mixers will increase the energy consumption even more.

Since mixing is an important aspect of cultivation and a major source of the energy uptake, studies concern PBR's configuration and design with special attention to culture fluid mixing [20]. Computational Fluid Dynamics (CFD) has been used to evaluate LD cycles in microalgae cultures. For instance, Soman & Shastri [24] modelled an airlift PBR using CFD and LD cycles were evaluated in order to optimize culture variables and fluid circulation. Cheng et al. [3] proposed and evaluated by CFD a novel static mixer to increase LD cycle frequency by enhancing swirl flow mixing. Yang et al. [34] studied LD cycles in a raceway PBR, in order to design a suitable mixing method to decrease the LD cycle period. Furthermore, CFD has been used to evaluate mixing energy consumption to decrease process costs. Gómez-Pérez

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et al. [7] used CFD to evaluate the effect of turbulence promoters on tubular PBR mixing conditions and showed that decreasing the average flow velocity in tubes with turbulence promoters requires less energy compared to a regular tubular PBR while keeping the same mixing conditions. Wongluang et al. [30] used CFD to study the energy consumption in tubular PBRs bends and showed that energy saving is possible if bend design uses a defined curvature. Research has proved that CFD is a versatile tool for mixing conditions evaluation in PBRs to optimize microalgae culture [20]. Also, CFD with light distribution models and mass transfer models can be integrated to improve growth rate prediction [20]. Recent work on model integration using CFD has been proposed [5,6]. The integration of different models with CFD will help to predict several variables like productivity, net energy gain and energy ratio yield.

Several authors present their research on tubular PBRs at an average flow velocity of 0.5 m/s [19,23,35]. Molina et al. [16] evaluated various flow velocities and concluded that 0.5 m/s was optimal for best productivity. This result indicates that 0.5 m/s is an average flow velocity which guarantees good mixing conditions and any flow reduction affects culture behaviour in an unpredictable way. Norsker et al. [18] found that reducing the average flow velocity from 0.5 m/s to 0.3 m/s, results in an important reduction in pumping costs. However, there was no guarantee that mixing would be sufficient when the flow velocity is reduced in tubular PBR culture [7].

Swirl mixing could be the answer to reduce flow velocity with good mixing conditions. Moreover, it is possible to obtain productivity improvement since microalgae LD cycles are enhanced [8,10]. LD cycles frequencies above 10 Hz can increase microalgae growth rate [13,29]. However, it is hard to predict its effect on growth rate as the characteristic optimal LD cycle seems to be specific for each culture [17]. Furthermore, there is not an agreement about the reasons that explain the beneficial effect of flashing light on microalgae growth [1]. Abu-Ghosh et al. [1] summarized some possible reasons for the enhancement of microalgae photosynthesis like photoinhibition prevention, slower xanthophyll cycle and less thermal dissipation.

As mentioned, the PBR configuration and mixing characteristics have been considered to enhance microalgae culture performance [3,33–35]. The swirl mixing characteristics are essential to improve culture mixing conditions [13,31,32,35]. For example Zhang et al., [35] obtained an increment of 37.26% on biomass productivity when a tubular PBR was equipped with an helical mixer. Liao et al., [13] proposed a novel tubular PBR with shaded zones to simulate a LD cycle set at 100 Hz and concluded that average biomass productivity could be increased by 21.6%. Therefore, it is possible that by using tubular PBRs with swirl motion and reduced flow velocity, mixing costs reduction could be achieved while maintaining or increasing mixing conditions and productivity.

There are other means to obtain swirl flow. Wu et al. [31,32] gave a different geometry configuration for tubular PBRs. The swirl flow generated in this particular geometry was evaluated by using Computational Fluid Dynamics (CFD). The results showed that the new tubular geometry could improve mixing behaviour; however, the energy consumption was not evaluated. In general turbulence promoters will increase energy consumption, but on the other hand by applying a reduced average flow velocity, the energy consumption can be reduced. Therefore, there is a possibility to maintain good mixing conditions when applying turbulence promoters while at the same time using a low average velocity [7].

This paper makes a comparative study of mixing conditions using CFD simulations for tubular PBR types with different configurations for swirl flow generation (Fig. 1): a) tubular PBR with helical mixer [36]; b) tubular PBR with static mixer [19]; c) spiral tubular PBR [31] and a new configuration, which is proposed in this work, called d) twisted tubular PBR. The main objective is to evaluate energy consumption and look for its minimization. The study evaluates pressure drop, energy consumption, swirl number and characteristic LD cycle frequency, while the average flow velocity into the tubular PBRs is evaluated as a variable. The objective of this analysis is to seek an appropriate average flow velocity to reduce energy consumption while keeping the mixing conditions. The analysis shows that twisted tubular PBR consumes less energy than the other systems. Also, the flow velocity reduction from 0.5 m/s to 0.3 m/s reduces the energy consumption by 38% compared to a classic straight tubular reactor operation. Since the swirl number remains fairly constant for this flow velocity, it is expected that culture will have good mixing conditions.

2. Mathematical models

2.1. Fluid dynamic model

Fluid dynamics is modelled using the k-ε model [21]. This model computes average flow velocity and pressure fields by the average Navier-Stokes equations and two empirical partial differential equations, as shown below:

$$\frac{\partial \vec{U}}{\partial t} - \nabla^{*}\left[\left(\mu + \rho\frac{C_{\mu}k^{2}}{\sigma_{k}\varepsilon}\right)^{*}(\nabla\vec{U} + (\nabla\vec{U})^{T})\right] + \rho\vec{U}^{*}\nabla\vec{U} + \nabla P = 0 \quad (1)$$

$$\nabla^{*}\vec{U} = 0 \quad (2)$$

$$\rho\frac{\partial k}{\partial t} - \nabla^{*}\left[\left(\mu + \rho\frac{C_{\mu}k^{2}}{\sigma_{k}\varepsilon}\right)\nabla k\right] + \rho\vec{U}^{*}\nabla k = \frac{1}{2}\rho\frac{C_{\mu}k^{2*}}{\varepsilon}(\nabla\vec{U} + (\nabla\vec{U})^{T})^{2} - \rho\varepsilon \quad (3)$$

$$\rho\frac{\partial \varepsilon}{\partial t} - \nabla^{*}\left[\left(\mu + \rho\frac{C_{\mu}k^{2}}{\sigma_{\varepsilon}\varepsilon}\right)\nabla\varepsilon\right] + \rho\vec{U}^{*}\nabla\varepsilon = \frac{1}{2}C_{\varepsilon1}C_{\mu}k^{*}(\nabla\vec{U} + (\nabla\vec{U})^{T})^{2} - \rho C_{\varepsilon2}\frac{\varepsilon^{2}}{k} \quad (4)$$

where ρ denotes the density of the fluid (kg/m^3), $\vec{U}$ represents the average velocity (m/s), t the time (s), μ the dynamic viscosity (kg/(m·s)), P is the pressure (Pa), k the turbulence energy (m^2/s^2), ε the dissipation rate of turbulence energy (m^2/s^3), C_μ, σ_k, σ_ε, $C_{\varepsilon1}$ and $C_{\varepsilon2}$ are model parameters [21], see Table 1.

Three different boundary conditions are set for the tubular PBRs:

Wall	U = 0	
Inlet	$U = V_{avg}$	(5)
Outlet	$P = P_{atm}$	

Here, V_{avg} is a constant average flow velocity (m/s), normal to the cross sectional tube area and P_{atm} is the atmospheric pressure at the end of the tube (Pa). The last boundary condition is required to accomplish the continuity equation.

2.2. Particle tracking model

COMSOL Multiphysics can simulate particles movement using particle tracking toolbox, it uses Newton's law to evaluate the effect of gravity and drag forces acting on spherical particles motion:

$$\frac{d\vec{u_p}}{dt} = F_D(\vec{u} - \vec{u_p}) + \frac{\vec{g}(\rho_p - \rho)}{\rho_p} \quad (6)$$

where $\vec{u_p}$ is the particle velocity vector (m/s), $\vec{u}$ is the fluid velocity (m/s), ρ_p is the particle density (kg/m^3) and ρ is the fluid density (kg/m^3), $\vec{g}$ is the gravitational force (m/s^2); also F_D is the drag force coefficient (kg/s) depending on fluid and particle characteristics as predicted by the Eq. (7):