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Dynamic model of an industrial raceway reactor for microalgae production

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ABSTRACT

A dynamic model for microalgae production in raceway reactors is developed in this work. The model takes into account fluid-dynamic, mass transfer, and biological phenomena taking place in microalgae bioreactors. The model has been calibrated and validated using real data from a 100 m^2 pilot-scale raceway reactor. Results demonstrate that in raceway reactors large accumulation of oxygen takes place into the channel whereas carbon losses into this section are scarce, these phenomena influencing the overall productivity of the reactor. The model can be used to determine characteristic parameters (biological and engineering ones) of existing reactors. Moreover, it can be used to simulate the effect of different designs and/or operation conditions into the performance of the system. Simulations allow us demonstrating that to increase the productivity of raceway reactors it is recommendable to reduce the water depth into the cultures and to increase the mass transfer capacity of the entire reactor.

1. Introduction

Microalgae have a large biotechnological potential for producing valuable substances for feed, food, nutraceutical, and pharmaceutical industries [1,2]. Furthermore, other applications can be attributed to the photosynthetic process performed by these microorganisms such as CO_2 mitigation, wastewater treatment and biofuels production, thus allowing researchers to develop new biotechnological processes [3–6]. By these reasons, the use of microalgae is receiving a lot of interest recently. Independently of the final application, two types of photobioreactors are mainly used to produce microalgae: (i) closed photobioreactors as tubular or flat panels reactors, in which high-value products are produced by strains highly sensitive to contamination; and (ii) open reactors as open ponds and raceway reactors, simpler and less expensive ones where contamination-proof strains can be produced [7,8]. In addition to contamination risk, raceway reactors have additional drawbacks such as low biomass concentrations, poor gas-liquid mass transfer, and lack of temperature control. In general, raceways have a scarce control of operating conditions that diminishes the final productivity achieved; however at commercial scale >95% of algae production worldwide is performed in raceway reactors due to their low constructions cost, easy scale-up, and low energy requirement [9].

Engineering aspects of raceway reactors were previously studied [10], but now they are being characterized to improve the efficiency of this technology [11–15]. In this sense, the fluid-dynamic and mass transfer capacity of raceway reactors as a function of design and operational conditions is being optimized. It is important to note that the fluid-dynamic and mass transfer capacity determine the evolution of culture parameters as dissolved oxygen, pH and CO_2 availability, all of them influencing the performance of the cells, and thus the final productivity achievable.

Models combining the fluid-dynamic and mass transfer capacity of raceway reactors with the biological performance of the cells under different conditions are very scarce. Till now, few steady-state models has been reported considering the entire reactor as a stirred tank reactor, thus evaluating the performance of the cultures as a function of average value of culture parameters as light availability, pH, and nutrients concentration [16–19]. However, raceway reactors are plug-flow reactors exposed to changing solar light, thus culture conditions change on time and space inside the reactor. Due to this reason, dynamic models that take into account the temporal-spatial distribution of culture parameters are necessary to adequately simulate this type of reactors. Moreover, these dynamic models are necessary to optimize the design and operation of the systems, helping to understand the different dynamics and phenomena taking place. Furthermore, these models can be used as predictive and simulation tools in order to properly design and operate these systems, as well as to design control strategies for optimal biomass production [20,21].

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In summary, in the present work, a dynamic model of microalgae production in raceway reactors is developed. The model is based on a previously reported model for tubular reactors [22]. The model is based on mass balances, transport phenomena, thermodynamic relationships, and biological phenomena taking place into the reactor, thus being based on fundamentals principles instead of empirical equations. It takes into account the kinetic of different phenomena inside the reactor, thus a complete dynamic simulation model can be obtained. The model allows predicting the evolution of the main variables of the system such as biomass concentration, pH, dissolved oxygen, and total inorganic carbon in the liquid phase, in addition to oxygen and carbon dioxide exchange for the gas phase. The model has been calibrated and validated using experimental data from a 100 m^2 pilot-scale raceway reactor, and it was used to determine the influence of design parameters in the performance of the system. This model is presented as a powerful tool for the optimization of design and operation of this type of photobioreactors.

2. Materials and methods

2.1. Microorganism and culture medium

The microalga strain used was *Scenedesmus almeriensis* (CCAP 276/24). This microalgae is characterized by a high growth rate, withstanding temperature up to 45 °C and pH values up to 10, although its optimum conditions are 35 °C and pH 8 [23]. Experiments were performed using Arnon medium prepared using fertilizers instead of pure chemicals.

2.2. Raceway reactor and operation conditions

The raceway reactor used is located at 36° 48′N–2° 43′W in Research Center “Las Palmerillas”, property of Cajamar Foundation (Almería, Spain). The reactor consisted of two 50 m length channels (0.46 m high × 1 m wide), both of them connected by 180° bends at each end, with a 0.59 m^3 sump (0.65 m long × 0.90 m wide × 1 m deep) located 1 m part of the way down one channel (Fig. 1). The entire reactor, including the sump, was made of white 3 mm thick fiber glass. The liquid was circulated by a marine plywood paddle-wheel with 8 paddle, with a 1.2 m diameter, which is driven by an electric motor (Ebarba, Barcelona, Spain) with gear reduction and speed control using a frequency inverter (Ibérica, S.A. Barcelona, Spain). The reactor can be divided in three main parts depending on its fluid-dynamic characteristics (channels, paddle-wheel and sump), such as was observed in Fig. 1. For this reason, three pH-T and dissolved oxygen probes were situated at the end of each of these parts, (5083 T and 5120, Crison, Barcelona, Spain) connected to transmitters (MM44, Crison, Barcelona, Spain) and data acquisition software (Labview, National Instruments, USA). Air or CO_2 gas was automatically injected at the bottom of the sump through a diffuser to control the dissolved oxygen and pH of the culture. The gas flow rate entering to the reactor was measured by a mass flow meter (PFM 725S-F01-F, SMC, Tokyo, Japan).

Experiments were performed in semicontinuous mode. For this purpose, the reactor was filled with Arnon medium up to 15 cm water depth (15 m^3 volume), prepared from fertilizers instead of pure chemicals, and it was inoculated with a 10% total volume of culture from a 3.0 m^3 tubular photobioreactor. Then, it was operated in batch mode for one week. After that, the reactor was operated in semicontinuous mode at 0.2 day^{-1} this being previously demonstrated as optimal for this reactor [15]. To operate in semicontinuous mode, a fixed culture volume of 3.0 m^3 was harvested and replaced daily with fresh medium over 6 h in the middle of the daylight period. Semicontinuous operation was maintained till steady state was achieved; only data around steady-state conditions being used. Evaporation (6–10 $l/m^2\ day^{-1}$) inside the reactors was compensated by adding fresh medium, in addition to the volume of fresh medium used for the reactor’ semicontinuous operation. The culture medium was not sterilized, simply filtered before entering the reactors using 200 μm pore-size filters to remove solids.

3. Model

To model a bioprocess, both biological aspects of the microorganism and the engineering aspects of the reactor have to be considered. In this case, a biological model for a microalgae previously reported in [24], and an engineering characterization of the raceway reactor used in [14,15, 25] were used. This previous knowledge was integrated into the dynamic model of photobioreactors previously developed in [22] to obtain a complete model of raceway reactors. Moreover, since the model is developed for outdoor conditions, the classical knowledge about solar radiation availability (sun position and solar radiation as a function of location, date, day of the year and solar hour) was also incorporated.

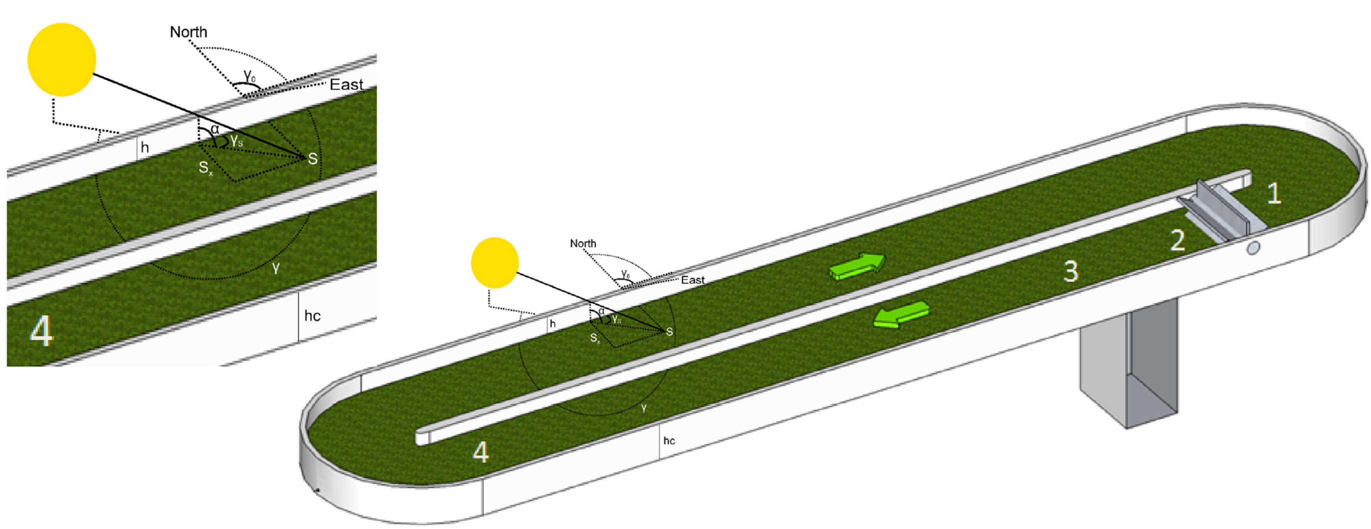

Fig. 1. Raceway reactor scheme showing dimensions, position of pH-T and DO probes used for the calibration and validation of the model, and geometric calculation of the shadow projection on the perpendicular axis of the walls. Numbers indicates the position where the probes were situated. (1) before paddlewheel, (2) after paddlewheel-before sump, (3) after sump-beginning of the channel, (4) end of the right channel.