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Analysis of mass transfer capacity in raceway reactors

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ABSTRACT

In the present work, a methodology is proposed to determine the mass transfer capacity in existing microalgae raceway reactors to minimize excessive dissolved oxygen accumulation that would otherwise reduce biomass productivity. The methodology has been validated using a 100 m^2 raceway reactor operated in semi-continuous mode. The relevance of each raceway reactor section was evaluated as well as the oxygen transfer capacity in the sump to different air flow rates. The results confirm that dissolved oxygen accumulates in raceway reactors if no appropriate mass transfer systems are provided. Therefore, mass transfer in the sump is the main contributor to oxygen removal in these systems. The variation in the volumetric mass transfer coefficient in the sump as a function of the gas flow rate, and therefore the superficial gas velocity in the sump, has been studied and modelled. Moreover, the developed model has been used to estimate the mass transfer requirements in the sump as a function of the target dissolved oxygen concentration and the oxygen production rate. The proposed methodology allows us to determine and optimize the mass transfer capacity in the sump for any existing raceway reactor. Moreover, it is a powerful tool for the optimization of existing reactors as well as for the design optimization of new reactors.

1. Introduction

Raceway reactors have been used since the 1950s for the industrial production of microalgae. Today, > 90% of worldwide microalgae biomass production is carried out using these types of reactors [1]. The major advantage of raceway reactors is their simplicity and low construction cost. However, these reactors have certain problems related to their low productivity, high risk of contamination and poor control of growing conditions, in addition to their low mass transfer capacity. It has been demonstrated that the mass transfer capacity in these reactors is limited and must be improved to allow significantly increased biomass productivity [2]. In this regard, improvements are necessary in the fluid dynamics, the related CO_2 absorption and the oxygen desorption to enhance productivity in these systems [1–3]. Moreover, models are required that allow us to determine the mass transfer capacity and overall performance of these reactors for the scaling-up of any reactor type.

To maximize the performance of any microalgae strain, the culture conditions prevailing inside the reactor must be as close to optimal as possible for that strain. Any deviation from optimal culture conditions in outdoor cultures reduces productivity by > 50% compared to indoor production, even when using closed tubular photobioreactors. These deviations and losses in productivity are still higher in raceway reactors where there is less control of the culture conditions [4,5]. By providing the most suitable culture conditions possible, we can increase biomass productivity, thus reducing the production costs per biomass unit as well as ensuring efficient and stable biomass production. Concerning CO_2 transfer, some works have been carried out optimizing the utilization of the supplied CO_2 to save costs; this is because CO_2 can contribute up to 30% of the total biomass production cost [6,7]. Nonetheless, much less attention has focused on dissolved oxygen accumulation in the system. It is commonly believed that oxygen is naturally desorbed to the atmosphere without the need for specific desorption systems. However, this is erroneous and the negative effect of dissolved oxygen accumulation on biomass productivity in raceway reactors has already been proven, with values surpassing 300 %Sat. reported [2,9]. In this regard, to ensure that dissolved oxygen accumulation does not diminish biomass productivity in raceway reactors, it is imperative to improve the reactor design as well as the operational conditions, especially the mass transfer capacity.

Although the utilization of raceway reactors for the production of microalgae was first proposed in the 1960s, only recently has its design

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been revised, both from the fluid-dynamic and mass transfer capacity points of view [3,8–12]. Most of the studies focus on improving fluid dynamics to minimize power consumption, especially in biofuels production, whereas others focus on CO_2 transfer to make more efficient use of this expensive raw material. However, only a few studies have focused on oxygen removal and its improvement. Nonetheless, it was reported that reducing dissolved oxygen below 250 %Sat. by injecting flue gases as a source of CO_2 leads to an increase in biomass productivity above 30% compared to cultures operated with pure CO_2, in which dissolved oxygen increases above 300 %Sat. [3]. Thus, it was concluded that being able to manipulate the mass transfer capacity of raceway reactors in order to maintain the dissolved oxygen content below inhibitory values is a challenge.

In this paper, the mass transfer capacity of a pilot-scale raceway reactor is studied to identify the major phenomena taking place, the oxygen accumulation and the contribution of each reactor section to the mass transfer capacity of the entire reactor. The objective is to be able to fit the mass transfer capacity to that required for the productivity or photosynthesis rate of the specific biomass. To do this, a simple novel methodology has been developed using online dissolved oxygen sensors that do not disturb the reactor's normal operation; these can be used to audit any raceway reactor. The methodology has been validated and utilized to estimate the optimal operating conditions in an existing raceway reactor, making it a useful tool for improving this reactor type.

2. Materials and methods

2.1. Microorganism and culture conditions

The microalgae strain *Scenedesmus almeriensis* (CCAP 276/24) was used. Inoculum for the raceway reactor was produced in a 3.0 m^3 tubular photobioreactor under controlled conditions: at pH = 8 and at a temperature ranging from 18 to 22 °C using freshwater and Mann & Myers medium prepared using fertilizers: (0.14 $g \cdot L^{-1}$ $K(PO_4)_2$, 0.18 $g \cdot L^{-1}$ $Mg(SO_4)_2$, 0.9 $g \cdot L^{-1}$ $NaNO_3$, 0.02 $mL \cdot L^{-1}$ Welgro, and 0.02 $g \cdot L^{-1}$ Kalentol) [15]. In addition, $NaHCO_3$ was provided once a week to maintain the medium's alkalinity at the optimum 7 mM.

2.2. Raceway reactor design and operational conditions

The raceway reactor is located at the "Las Palmerillas" Research Centre, 36° 48′N–2° 43′W, part of the Cajamar Foundation (Almería, Spain). The reactor consists of two 50 m long channels (0.46 m high × 1 m wide), both 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 along one of the channels (Fig. 1) [17]. The pH, temperature and dissolved oxygen in the culture were measured at three different places along the reactor length using appropriate probes (5083 T and 5120, Crison, Barcelona, Spain), connected to an MM44 control-transmitter unit (Crison Instruments, Spain), and data acquisition software (Labview, National Instruments) providing complete monitoring and control of the installation. It was previously confirmed that no vertical or transversal gradients of pH, dissolved oxygen and biomass concentration existed, only longitudinal gradients, so the probes were located in the middle of both the culture depth and the channel. The gas flow rate entering the reactor was measured by a mass flow meter (PFM 725S-F01-F, SMC, Tokyo, Japan). The pH of the culture was controlled at 8.0 by on-demand injection of CO_2, whereas temperature was not controlled; it ranged ± 5 °C with respect to the daily mean air temperature, which varied from 12 °C in winter to 28 °C in summer. Air was supplied to the reactor from a blower providing 350 mbar overpressure, through a fine bubble diffuser AFT2100 (ECOTEC, Spain) providing bubbles with a diameter smaller than 2 mm at the minimum pressure drop; the estimated residence time of the bubbles in the sump ranged from 5 to 10 s [3]. The culture received continuous air injection, regardless of the CO_2 demand. The demand for carbon was supplied by the injection of pure CO_2 using an event-based pH controller at pH 8 [13]. The raceway reactor was inoculated and operated in batch mode for one week, after which it was operated in semi-continuous mode at 0.4 day^{-1} at a culture depth of 0.15 m. Only data corresponding to steady-state conditions were used. Evaporation inside the reactor was compensated for by the daily addition of fresh medium.

2.3. Experimental design

To study the mass transfer capacity in the raceway reactor, experiments were performed in different seasons (spring, summer, autumn and winter) modifying the gas flow rate into the sump (0, 100, 160, 185, 200 and 350 L min^{-1} so the superficial gas velocity was 0.0, 0.0021, 0.0033, 0.0039, 0.0042, 0.0073 m s^{-1}), and the L/G ratio (0.0, 18.0, 12.0, 9.7, 9, 5.1 $L \cdot L^{-1}$), while the culture was operated in semi-continuous mode. In this way, we could study the oxygen produced by photosynthesis as well as that removed in the different parts of the reactor under the different culture conditions imposed (Fig. 1). These experiments allowed us to quantify the different phenomena taking place and to measure the mass transfer coefficient as a function of the culture conditions.

The reactor was operated throughout all the tests under the same

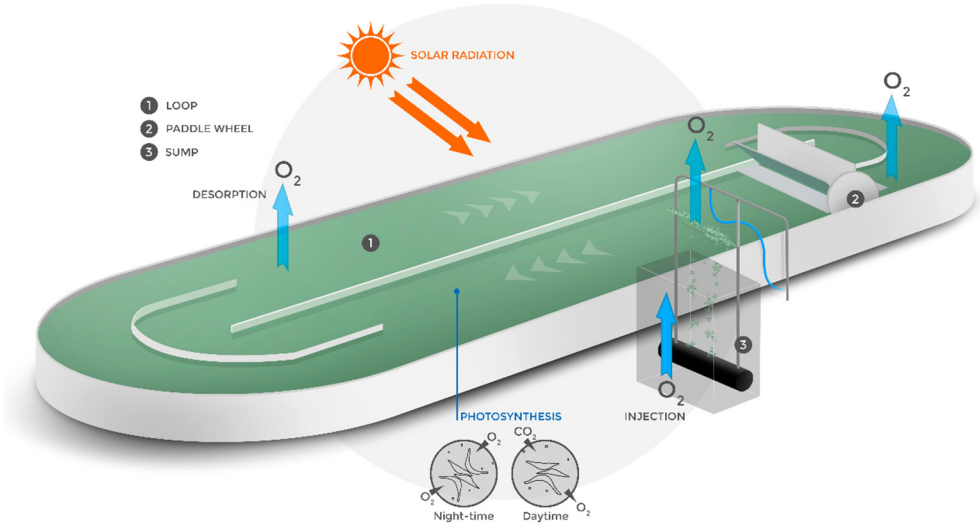

Fig. 1. Scheme of the 100 m^2 raceway reactor used to study this type of system and the mass transfer capacity, indicating the major phenomena taking place.