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Improvement of mixing time, mass transfer, and power consumption in an external loop airlift photobioreactor for microalgae cultures

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ABSTRACT

Longer mixing times and higher power consumption are common problems in the design of photobioreactors. In this study, a vertical triangular external airlift loop photobioreactor was designed, constructed and operated for microalgae production studies. Gas feeding was performed by two spargers: one at the bottom of the hypotenuse (downcomer) and another at the bottom of the vertical side (riser). This configuration provided more effective countercurrent liquid–gas flow in the hypotenuse. The mass transfer coefficient, gas hold-up, mixing time, circulation time, dimensionless mixing time, bubble size, and volumetric power consumption were measured and optimized using response surface methodology. Investigations were carried out on the performance of the riser (the vertical side), downcomer (the hypotenuse), and separator. The countercurrent flow in the hypotenuse provided sufficient contact between gas and liquid phases, and increased mixing and mass transfer rates, in contrast to the results of previous studies. The promising results of this geometry were shorter mixing time and a significant decrease in volumetric power consumption in comparison with other configurations for photobioreactors.

1. Introduction

Hydrodynamics and transport phenomena are crucial and complicated aspects of sparged photobioreactor cultivation of microalgae [1–3]. The level of complexity increases strongly in response to interactions between the fluid phases, biomass, and nutrients generally found in photobioreactors [4]. The growth rate of most microalgae is rapid [5–11], thus, photosynthesis in microalgae demands high CO_2 absorption and high O_2 release. Consequently, the rate of CO_2 absorption and O_2 desorption are usually limiting factors inhibiting the overall growth rate of the biomass [2,12–14]. Photosynthesis depends on sufficient mass transfer between the three phases involved; liquid culture, suspended solid biomass, and sparged gas, which is the main carbon source required for growth [13,15–17]. Superficial fluid velocity, gas hold-up, photobioreactor geometry, and mixing time influence overall mass transfer [2,10], which in turn affects biomass function and process productivity [10,16].

Microalgae are sensitive to stress [18–21] and harsh mechanical stirring may discourage growth [16,22–26]. Photobioreactors have been designed and tested to address this limitation, the majority of which are gas-lift photobioreactors [3,13,17,27]. Both the intensity and history of illumination influence the growth rate of microalgae [2,3]. Loop photobioreactors may yield better performance in this area over flat-panel or bubble column air-lift photobioreactors.

External loop airlift bioreactors show good performance at different gas velocities, good compatibility with sensitive organisms, are easy to maintain, low cost, and have low energy consumption [5,28]. They can accommodate multiphase and heterogeneous gas-liquid systems, allow once to scale-up, and provide good sterilization, making them promising candidates for microalgae cultivation [13,16,17,29].

The present study designed, built, and operated a specially shaped external loop airlift photobioreactor. The mass transfer coefficient, gas hold-up, mixing time, and circulation time were studied and correlated for the riser (vertical side), downcomer (hypotenuse), and separator. The main variables in this configuration were superficial gas velocities sparged from the bottom of the vertical side (V_{gs2}) and the hypotenuse (V_{gs1}). The results of the experimental study were compared with other configurations for bioreactors. Better results were found in all aspects, especially

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Nomenclature

1	gas feeding from bottom of the hypotenuse
2	gas feeding from bottom of the riser
A	cross-sectional area, m^2
C	concentration of dissolved oxygen, $mg\,l^{-1}$
d	bubble diameter size, mm
D	downcomer
DO	dissolved oxygen, $mg\,l^{-1}$
e	volumetric power consumption, $W\,m^{-3}$
g	global gravity acceleration, $m\,s^{-2}$
G	gas
H	height
k_La	volumetric oxygen mass transfer coefficient, h^{-1}
L	liquid
P/V	volumetric power consumption, $W\,m^{-3}$
R	riser
RSM	response surface method
S	separator
t	time, arbitrary time, h
t_0	zero time state, s
t_c	circulation time, s
t_m	mixing time, s
T	total
V_{gs}	superficial gas velocity, m/s
X_1, X_2	RSM parameters
Y	expected response value predicted from RSM, dimensionless

Greek letters

$\alpha_i, \alpha_j, \alpha_{ij}$	parameters estimated from the RSM regression
ε	gas hold-up, dimensionless
θ_m	dimensionless mixing time
ρ	liquid density, $kg\,m^{-3}$
*	saturation state
$\circ$	degree

mixing time (t_m), mass transfer coefficient (k_La), and volumetric power consumption (P/V).

2. Materials and methods

2.1. Photobioreactor

The 63 l Plexiglas (with PVC joints and separator) photobioreactor is a hybrid of an external loop and a vertical isosceles triangle configuration (45°) in which gassed liquid moves up the vertical side and comes down the hypotenuse. To provide better mixing (low t_m), a countercurrent flow was introduced into the hypotenuse by gas feeding at the bottom of the photobioreactor. Achieving a high mixing rate in the hypotenuse was essential to the geometry. A schematic diagram of the photobioreactor is illustrated in Fig. 1. The volume of the separator (No. 1) was 18 l and the combined volume of the vertical (No. 2) and horizontal (No. 3) sides was 8.9 l. The diameter of the hypotenuse (No. 4) was 14 cm and the diameter of other two sides was 7 cm. The hypotenuse had a length of 234 cm and the lengths of other two sides, including joints, were 170 cm each. The diameter of separator was 20 cm.

In earlier photobioreactors, the downcomers (No. 5) have demonstrated poor mass transfer and gas hold-up, which limits the residence time of air bubbles (No. 6) in the downcomer. In the present study, the creation of a high countercurrent flow and vortices in the downcomer increased the performance of the mixing process and decreased t_m, eliminating this limitation. The

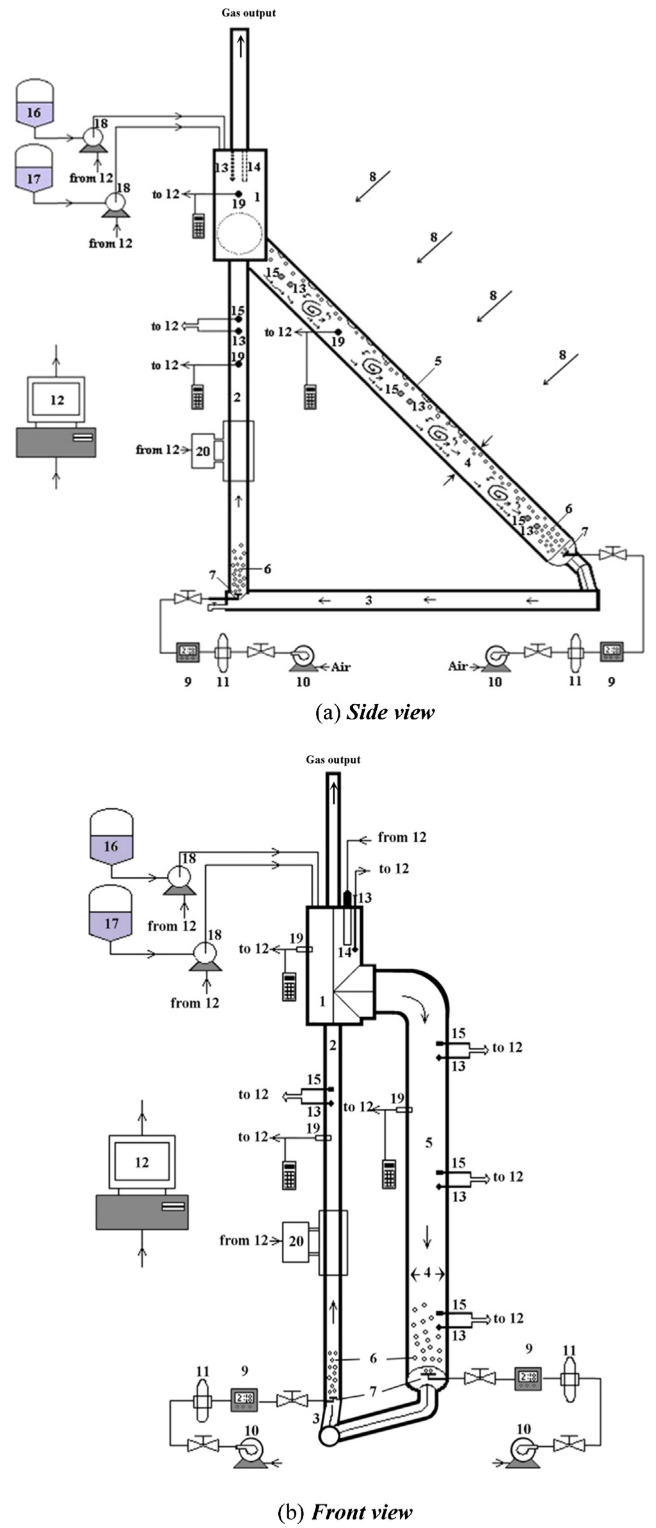

Fig. 1. Schematic of external airlift loop photobioreactor. 1: Separator; 2: Vertical side, riser; 3: Horizontal side; 4: Diameter of hypotenuse; 5: Hypotenuse, downcomer; 6: Bubble; 7: Bubble sparger; 8: Light source; 9: Digital gas flow meter; 10: Compressor; 11: Gas sterilizer, filter; 12: PC; 13: Thermometer; 14: Heater; 15: pH probe and controller; 16: NaOH solution; 17: HCl solution; 18: Dozing pump; 19: Dissolved oxygen (DO) sensor; 20: Heat exchanger.