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Numerical and experimental study on the CO_2 gas–liquid mass transfer in flat-plate airlift photobioreactor with different baffles

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ABSTRACT

A flat-plate airlift photobioreactor with two types of baffles, named flat baffle and waved baffle, were investigated for their performance of carbon dioxide mass transfer by the experimental and numerical methods. The model for mass transfer was verified and validated, and the predicted mass transfer coefficient obtained by the CFX® software agrees well with the experimental data. Using the numerical approach, four structural parameters of baffles, i.e., baffle number, downcomer-to-riser cross-section area ratio (Ad/Ar), wave number (n) and wave amplitude (A), were employed and the influence of these parameters on the mass transfer was simulated. Results showed that with the increase of Ad/Ar the overall volumetric mass transfer coefficient (k_La) increased firstly and then decreased for single baffle. While for double baffles, it decreased with the increase of Ad/Ar. In addition, the waved baffle could have higher mass transfer coefficient only at lower Ad/Ar than flat baffle for the baffle numbers investigated. The effects of wave number and wave amplitude on mass transfer coefficient are related to Ad/Ar.

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1. Introduction

A photobioreactor is a bioreactor which is used to cultivate phototrophic microorganisms. These microorganisms build their own biomass from light and carbon dioxide by photosynthesis process, with each kilogram of dry cell weight fixing 1.83 kg carbon dioxide. One important criterion for optimized photobioreactors is sufficient mass transfer of carbon dioxide from the gas phase into the microorganism suspending in the gas–liquid dispersion [1–4].

Airlift bioreactors are extensively studied during the past decades, due to their low energy consumption, good flow mixing, good gas–liquid mass transfer, easy to scale up and so on [5–8]. The mass transfer of oxygen from gas phase into liquid phase in different airlift bioreactors were researched, such as internal-loop bioreactor [9–13], external-loop bioreactor [4,14,15] and bubble column [16,17]. Recently, the computational fluid dynamics (CFD) was used to aid bioreactor design and scale-up [18–20]. Due to their lower cost and shorten design period, the CFD method is more and more popular for the investigation of the hydrodynamic, gas holdup, and mass transfer in airlift bioreactors and significant success had been achieved [21–23].

According to literatures, the mass transfer was affected by reactor geometry, gas holdup, superficial gas velocity and phase properties [24]. In order to improve the performance of airlift bioreactor, the effect of baffle on mass transfer was investigated, such as horizontal baffle [3,25] and vertical baffles [9–15,26]. For vertical baffles, Li et al. [27] reported that the flat-plate airlift photobioreactor with double waved baffles could improve the oxygen mass transfer at downcomer-to-riser cross-section area ratio (Ad/Ar > 1), when compared with the flat baffles. Based on Li's experiment, the effects of the ratio of waved baffle height to wave length (L/λ) and the ratio of wave amplitude to wave length (A/λ) on mass transfer in airlift bioreactor were simulated [28], and the results showed that the waved baffles could improve mass transfer for 10% at Ad/Ar = 1.62, $A/\lambda = 0.8$ and $L/\lambda = 0.4$, since the average turbulent kinetic energy was enhanced by waved baffles. However, both of these researchers ignored the condition of Ad/Ar < 1, although the results clearly demonstrated that the waved baffle could enhance the gas–liquid mass transfer in airlift photobioreactor.

To date, the influence of baffles on the performance of mass transfer is still not thoroughly understood. In this paper, we focus on the effect of flat and waved baffles on the mass transfer of carbon dioxide in flat-plate airlift photobioreactor. Since the effects of the bottom and top baffle clearances on mass transfer in internal-loop airlift reactor was presented by Kilonzo et al. [26], four structural parameters of baffles, i.e., baffle number, downcomer-to-riser

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Nomenclature

A	Wave amplitude, cm
Ad, Ar	Cross-section area of downcomer and riser, m^2
a	Specific interfacial area per unit liquid volume, m^{-1}
C_T, C_T^*	Instantaneous and saturation concentrations of total inorganic carbon, $mol\,m^{-3}$
C_s	Concentration of solids in suspension, dry wt./vol.%
d_B	Mean bubble diameter, m
D	Diffusion coefficient, $m^2\,s$
g	Acceleration due to gravity, $m\,s^{-2}$
k_L	Overall mass transfer, $m\,s^{-1}$
k_La	Overall volumetric mass transfer coefficient, s^{-1}
t	Time, s
U_{GR}	Superficial gas velocity in riser, $m\,s^{-1}$

Greek letters

ε	Turbulent energy dissipation rate, $m^2\,s^{-3}$
ε_g	Gas holdup,%
μ_L	Kinematic viscosity of liquid, $kg\,m^{-1}\,s^{-1}$
ρ_L	Density of liquid, $kg\,m^{-3}$
σ	Surface tension, $N\,m^{-1}$

cross-section area ratio (Ad/Ar), wave number (n) and wave amplitude (A) were used in this study. CFD software (ANSYS CFX) was also used to simulate the gas–liquid mass transfer in flat-plate airlift photobioreactor.

2. Experiment

2.1. Experiment apparatus setup

The flat-plate airlift photobioreactor and flow scheme used are illustrated in Fig. 1. The main dimensions of the airlift photobioreactor are 320 mm width, 110 mm depth and 400 mm height. The flat-plate airlift photobioreactor which are made of acrylic glass. The cross-section of the split flat-plate airlift photobioreactor was divided by a vertical baffle to create riser and downcomer zones.

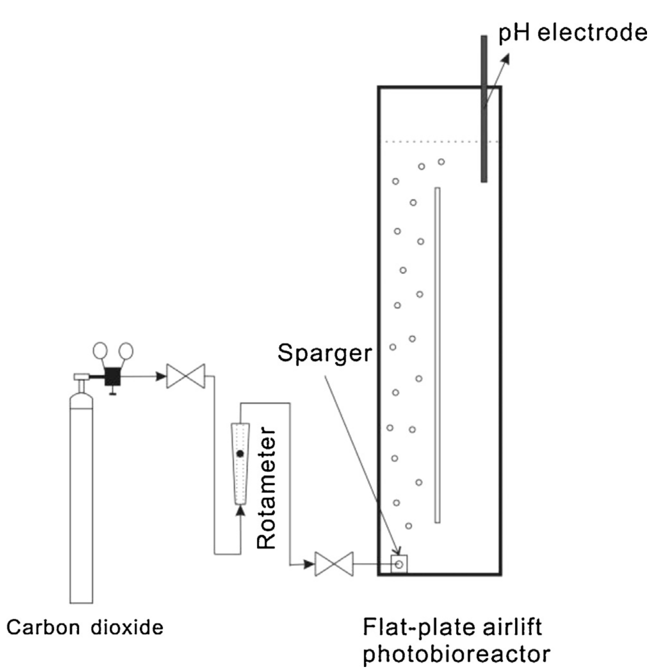

Fig. 1. Schematic diagram of the flat-plate airlift photobioreactor.

The central flat-plate airlift photobioreactor has two vertical baffles which divide reactor into two downcomers and one riser. All the vertical baffles (3 mm thickness and 250 mm height) had a clearance space of 50 mm from the bottom of airlift photobioreactor. The initial height of the gas/liquid dispersion is 350 mm. The airlift photobioreactor with different baffle number and structure were investigated in this study (Fig. 2).

A pH electrode (AZ8601, Taiwan), which is 300 mm away from the bottom of the photobioreactor, was located at the upper part of the downcomer of reactor [29]. For bubbling, a gas distributor (300 mm width, 12 mm depth and 16 mm height), which was made of a porous material, with a plate sparger in the upper surface was located at the bottom of the riser. The volumetric flow rate of carbon dioxide was controlled by a regulating valve and a calibrated rotameter (See Fig. 1). The injected carbon dioxide flow rate were conducted for 1–6 $L\,min^{-1}$. All experiments are performed with a carbon dioxide/tap water system at a temperature 26 ± 0.5 °C.

2.2. Measurement methods

The overall volumetric mass transfer coefficient, k_La, was measured by dynamic method.

$$\frac{dC_T}{dt} = k_La \times \left(C_T^* - C_T\right) \tag{1}$$

where $C_T$and C_T^* are the instantaneous and saturation (or equilibrium) concentrations of the total inorganic carbon in the liquid respectively. Since the dissolved oxygen can be directly measured by dissolved oxygen electrode, the carbon dioxide was replaced by oxygen for the investigation of the mass transfer in photobioreactor. In order to investigate the carbon dioxide mass transfer, the concentration of the dissolved inorganic carbon was measured in this paper.

The dissolved carbon dioxide in microalgae cultures is in equilibrium with carbonate and bicarbonate species. And these equilibriums are pH dependent. The relevant equilibrium and the corresponding equilibrium constants can be determined by [30]:

$$H_2O \leftrightarrow H^+ + OH^- \quad K_W = \left[H^+\right] \times \left[OH^-\right] = 10^{-14} \tag{2}$$

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \quad K_1 = \frac{[HCO_3^-] \times [H^+]}{CO_2} = 10^{-6.381} \tag{3}$$

$$HCO_3^- \leftrightarrow CO_3^{2-} + H^+ \quad K_2 = \frac{\left[CO_3^{2-}\right] \times \left[H^+\right]}{\left[HCO_3^-\right]} = 10^{-10.377} \tag{4}$$

The total concentration of inorganic carbon and hydrogen ion are given by

$$[C_T] = [CO_2] + \left[HCO_3^-\right] + \left[CO_3^{2-}\right] \tag{5}$$

$$\left[H^+\right] = \left[OH^-\right] + \left[HCO_3^-\right] + \left[CO_3^{2-}\right] = 10^{-pH} \tag{6}$$

Combining Eqs. (2)–(6), the relationship between total concentration of inorganic carbon and pH can be obtained. Because the initial pH of tap water is 6.11, and the percentage of $\left[CO_3^{2-}\right]$ in $[C_T]$ is small, the concentration of $\left[CO_3^{2-}\right]$ was ignored.

3. CFD simulation

3.1. Mass transfer modeling

The overall volumetric mass transfer coefficient (k_La) is the product of the overall mass transfer (k_L) and the specific interfacial area per unit liquid volume (a). Because of the difficulties of

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