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Aeration and mass transfer optimization in a rectangular airlift loop photobioreactor for the production of microalgae

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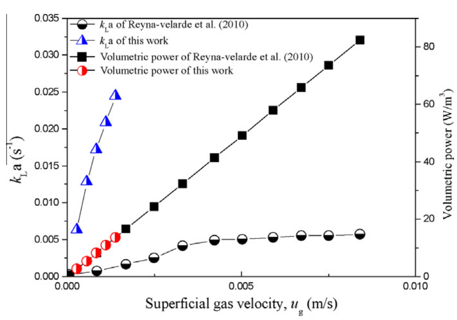
HIGHLIGHTS

- The hydrodynamics and mass transfer in a new photobioreactor are presented.
- A simple method for measuring the low gas holdup is developed.
- The influence of top clearance on the hydrodynamics is elucidated.
- A cost-effective photobioreactor is designed for microalgae cultivation.

GRAPHICAL ABSTRACT



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ABSTRACT

Effects of superficial gas velocity and top clearance on gas holdup, liquid circulation velocity, mixing time, and mass transfer coefficient are investigated in a new airlift loop photobioreactor (PBR), and empirical models for its rational control and scale-up are proposed. In addition, the impact of top clearance on hydrodynamics, especially on the gas holdup in the internal airlift loop reactor, is clarified; a novel volume expansion technique is developed to determine the low gas holdup in the PBR. Moreover, a model strain of *Chlorella vulgaris* is cultivated in the PBR and the volumetric power is analyzed with a classic model, and then the aeration is optimized. It shows that the designed PBR, a cost-effective reactor, is promising for the mass cultivation of microalgae.

1. Introduction

Microalgae are a new promising source of biodiesel and are also commercially cultivated for pharmaceuticals, nutraceuticals, cosmetics and aquaculture. The success of mass production of microalgae depends greatly on the design of an efficient photobioreactor (PBR). From the economic point of view, flat plate PBR is thought to be the most popular reactor due to its high illuminated surface-area-to-volume ratio, and easy temperature control which can be done simply by spraying water onto the surface of the reactor when the culture temperature exceeds a designated value (Dasgupta et al., 2010). In addition, airlift loop reactor (ALR) has some excellent performance on mixing and low mechanical forces on cells. A rectangular airlift loop photobioreactor (RALPBR) is vividly portrayed by taking advantage of these aspects, and it becomes one of the most promising reactor types due to many advantages such as good mixing, well-defined fluid flow

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pattern, relatively high gas–liquid mass transfer rate, and low operating costs (Meiser et al., 2004).

The RALPBR can be classified into three categories according to the geometric structures, i.e., a riser and a downcomer type (Reyna-Velarde et al., 2010), two risers and a downcomer type (Kilonzo et al., 2006), and a riser and two downcomers type (Yu et al., 2009). Before selecting a specific type, one should take many factors into consideration, for instance, characteristics of PBRs, operating costs, maintenance and cleaning, and so on. A RALPBR split in the direction of light path with one riser and one downcomer has been widely adopted to enhance the radial mixing (Reyna-Velarde et al., 2010), however the light depth is low and costs of operation, maintenance and cleaning are high for a long run. Furthermore, some of the light may be blocked by the baffle in these PBRs. It was also argued that the ALR sparged in the center produces consistently higher liquid circulation velocities than that sparged on peripheral walls (Choi et al., 1996). Therefore, a RALPBR sparged in the center with one riser and two downcomers was designed in this work to reduce the operating cost.

Designing an efficient PBR still remains a big challenge due to its complexity and difficulty in scale-up, and most of the PBRs are still designed by using semi-empirical methods (Kumar et al., 2011; Moheimani et al., 2011; Singh and Sharma, 2012). The most important factors, such as light penetration and distribution, hydrodynamics, and mass transfer inside the PBRs, which should be carefully considered in the design, are closely interrelated, further complicating the design.

Aeration rate is a key parameter to improve the growth of microalgae cell (Anjos et al., 2013). Gas is supplied to the culture to increase the mass transfer, avoid deficiency of CO_2 (Pegallapati and Nirmalakhandan, 2013), control the toxic level of dissolved oxygen and the inhibitory level of CO_2 (Acién Fernández et al., 2013; Carvalho et al., 2006; Kumar et al., 2011), reduce nutrients gradient in the culture broth, avoid cell sedimentation, emergence of dead zones, clumping of cells, and fouling in the reactor (Carvalho et al., 2006), and create an optimized light/dark cycle that can enhance the photosynthesis (Xue et al., 2013). However, excessive aeration may produce cell damage, affecting the culture performance if the microalgae are susceptible to mechanical shear forces (Acién Fernández et al., 2013). Furthermore, a high aeration rate will lead to high running costs, so that it is not recommended for mass cultivation. Therefore, it is necessary to determine the limiting factors for the growth in the cost-effective operations. To achieve high productivity, the fluid dynamic and the mass transfer must satisfy the culture requirements in addition to providing an adequate light regime for the efficient use of light. Only the adequate design and operation allow one to achieve maximum attainable productivity according to the light availability.

A deep knowledge of the fluid dynamics and the mass transfer is needed for the PBR rational design and optimization. It is necessary to understand the interplay among gas holdup, liquid circulation velocity, mixing, and gas–liquid mass transfer (Gourich et al., 2006). However, to the best of the authors' knowledge, limited progress on the hydrodynamics has been made for ALR (Gourich et al., 2005; Huang et al., 2010; Kochem et al., 2014), let alone the RALPBR. To date, only a few researches that cover hydrodynamics and mixing on this type of PBRs have been reported (Mudde and Van Den Akker, 2001). Since different experimental conditions lead to different flow hydrodynamics, further studies on this type of reactor are essential. It is well known that maximal productivity of a designed reactor can be obtained by applying a set of optimal operating conditions. To make a high liquid circulation velocity and prevent the depletion of CO_2 in the downcomer, the entrainment of bubbles into the downcomer, which is determined by the superficial gas velocity, is undesired. In addition, top clearance (the distance of the free surface above the baffle), an important factor in the ALRs for the controlling of shear stress in the separator and the hydrodynamics in the reactor, especially for PBRs with low superficial gas velocity, has received minimal attention. The influence of top clearance on the hydrodynamics, especially on the global gas holdup, is not well understood. Couvert et al. (1999) argued that the top clearance has negligible effect on the gas holdup. Lazarova et al. (1997), Liu et al. (2008) and Lu et al. (1994) stated that the gas voidage decreases with the increase of top clearance, while Chisti (1989), Kilonzo et al. (2006) and Kilonzo et al. (2007) drew a completely opposite conclusion. However, no further explanation has been made on it so far. It was reported that the mixing accounts for 53% of the total costs in a RALPBR (Leupold et al., 2013), and one critical challenge to algae biofuel generation was its poor energy balance due to high auxiliary energy requirements for the mixing and the mass transfer (Béchet et al., 2013). How to reduce the operating costs and make a balance between the profits and the costs for a designed PBR is a crucial issue, especially for the industry of bioenergy. Therefore, cost-effective operating conditions (including the superficial gas velocity and the top clearance) are desired.

A new, simple, and efficient airlift PBR is designed in this work, and the low gas holdup in the PBR is determined with a developed method. The hydrodynamics, mixing, mass transfer, and growth of algae cultivation are measured and evaluated; the influence of top clearance on the hydrodynamics of internal airlift loop reactor (IALR) is systematically elaborated. Additionally, cost-effective operating conditions for the mass cultivation of algae in this promising PBR are determined.

2. Methods

2.1. RALPBR and experimental apparatus

The experimental system setup is shown schematically in Fig. s1. Each of the downcomer and the riser shared a fixed straight rectangular baffle (0.005 m × 0.05 m × 0.7 m) as the barrier, and the other walls were constructed with 8 mm thick glass. The width, length and height of the RALPBR were 0.05 m, 1 m, and 1 m, respectively. The cross area of the riser was 0.7 m × 0.05 m. The baffles were fixed at 0.1 m above the bottom of the reactor, and the ratio of the cross-sectional area of the downcomers to that of the riser was equal to 0.4143.

The top clearance was varied in the range of 2–11 cm by adjusting the static liquid level. The gas sparger was a developed microporous aeration tube with an outer diameter of 15 mm and an inner diameter of 9 mm. It was fixed at the bottom of the riser and partly sealed, leaving only two slits parallel to the bottom, from which bubbles could be distributed uniformly in the riser. The experiment was done on an air-tap water system at room temperature and atmospheric pressure. The volumetric air flow rate was controlled by a regulating valve and a calibrated rotameter. The superficial gas velocity, which was based on the total cross-sectional area of the reactor, was varied over 2.78×10^{-4}–1.39×10^{-3} m/s. The signal was sampled with an A/D acquisition card and recorded online by a computer, and the data were averaged over at least three repeated experiments.

2.2. Gas holdup

Since the superficial gas velocity is very low for a cost-effective operation, the gas holdup in the reactor is low as well, less than 1% even for the biggest superficial gas velocity in this work. The difference between the ungassed and the gassed liquid level, below 1 mm in some cases, could not be measured by using the traditional volume expansion method (e.g., visual measurements of the static liquid height). Moreover, the change of absolute pressure was only about 10 Pa, within the measurement error of a conventional manometer (0.2%), thus differential pressure technique was inappropriate for the purpose.

A novel, relatively simple, and accurate, as well as economically attractive technique based on the volume expansion technique was proposed for determining the gas holdup. As illustrated in detail A of Fig. s1, a cylindrical cavity covered by permeable gauze, which was used to prevent the pulsation of free surface and the entry of gas bubbles, was inserted into the center of the gas disengagement zone. A syringe needle was fixed on the free surface of the cavity to suck the expansion liquid into a volumetric cylinder through a peristaltic pump. At the beginning, the system was operated under ungassed condition to discharge the liquid to a specified level. Then the reactor was aerated and the expansion volume of water was exhausted and measured. Hence, the average gas holdup in the reactor can be calculated by the discharged volume of water divided by the total volume of the reactor. All the measurements were carried out after the system reached a steady state when no more water could be exhausted. The repetition of experiment showed that this new technique yielded reliable data.

2.3. Liquid velocity

The liquid circulation velocity was measured using a classical tracer response technique. The tracer (saturated solution of NaCl) was instantaneously dropped onto the free surface of the downcomer which was just above the two conductivity electrodes (10) and (11) in Fig. s1, and then the conductivity was monitored by the probes with an interval of 20 cm located at the downcomer. The time interval between these two adjacent peaks is the time required for the liquid to advance within these two fixed points. Therefore, the linear liquid velocity in the downcomer can be calculated. The measurement was performed at least thirty times for each condition and the results were averaged. The average data of liquid velocities in two downcomers were employed to evaluate the performance of the PBR.

2.4. Mixing time

Mixing time was defined as the time required for the conductivity reach a homogeneity of ±5% after the injection of the tracer (Yang and Mao, 2014). Mixing time was determined by a signal-response technique using a tracer and two conductivity electrodes (12) and (13) in Fig. s1 as the detectors. The tracer of 25 ml saturated NaCl solution was poured onto the free surface adjacent to the side wall instantly, and the response of conductivity was recorded by the electrode (13) nearby and another electrode (12) at the across corners adjacent to the other side wall, respectively. Therefore, the instant of feed can be acquired by the electrode (13) nearby, and the evolution of conductivity can be obtained by the electrode (12). Finally, the moment satisfying the standard of the mixing time can also be deduced from the evolutional profile of the conductivity measured by the electrode (12). The interval of these two moments recorded by the two electrodes was regarded as the mixing time.

2.5. Mass transfer

The volumetric mass transfer coefficient (k_La) was determined by a traditional Na_2SO_3 feeding method (Zhang et al., 2012). The concentration of the dissolved oxygen was measured by using a polarographic dissolved oxygen electrode (9), which was located at the midpoint of h_{tc} (seen in Fig. s1). Na_2SO_3 with a concentration of 0.6 mol L^{-1} was fed into the system by a peristaltic pump (at a rate of 2.7–5.4 ml/min continuously) just 1 cm below the free surface and above the other baffle. The details of experiment can be found in Zhang et al. (2012).

2.6. Cultivation of Chlorella vulgaris

The strain of *C. vulgaris*, which was obtained from the Ocean University of China, was adopted as the model strain to assess the influence of aeration rate on the growth of microalgae. The culture medium was prepared as follows: 2 g/L KNO_3; 0.474 g/L KH_2PO_4; 0.408 g/L $MgSO_4{\cdot}7H_2O$; 0.176 g/L $CaCl_2{\cdot}2H_2O$; 0.08 g/L EDTA; 0.06 g/L $FeSO_4{\cdot}7H_2O$; 0.83 μg/L H_3BO_3; 0.95 μg/L $CuSO_4{\cdot}5H_2O$; 3.3 μg/L $MnCl_2{\cdot}4H_2O$; 0.17 μg/L $(NH4)_6Mo_7O_{24}{\cdot}4H_2O$, 2.7 μg/L $ZnSO_4{\cdot}7H_2O$ and 0.51 μg/L $CoCl_2{\cdot}6H_2O$. Two banks of fluorescent lamps (36 W) were used as the light sources giving the average photon flux density of 120.8 and 105.4 μE m^{-2} s^{-1} on the front and back surface, respectively. For the pilot experimental tests, regular tap water without sterilization was used, and air enriched with 2% CO_2 was sparged into the reactor. All experiments were carried out in a room with temperature controlled in a range of 25–30 °C, and the clear liquid height was 0.85 m. The growth of the culture was evaluated in parallel by a traditional mass weight method.

2.7. Volumetric power

A classic expression has been widely employed to estimate the volumetric power (P/V) supplied to the reactor (Kochem et al., 2014):

$$\frac{P}{V} = \frac{\rho_L g u_{gr}}{1 + A_d/A_r} \tag{1}$$

where ρ_L, g, u_{gr}, A_d, A_r, P, and V denote the liquid density, acceleration due to gravity, superficial gas velocity based on the cross area of the riser, cross-sectional area of downcomer, cross-sectional area of riser, power supplied for aeration and volume of the culture, respectively. The above equation was also adopted here to estimate the power input for the aeration.

3. Results and discussion

3.1. Hydrodynamics

The main hydrodynamic parameters in the IALR are the gas hold-up and the liquid circulation velocity. The top clearance affects the gas holdup difference between the riser and the downcomer; hence, the driving force for the liquid circulation is also affected (Kilonzo et al., 2006).

The relationship of the superficial gas velocity and overall gas holdup in the RALPBR under different top clearance is illustrated in Fig. 1, and an empirical correlation is obtained and can be expressed as follows:

$$\alpha_g = 2.3709 u_g (0.8 + h_{tc})^{-3.312} \quad R^2 = 0.99 \tag{2}$$

where α_g, u_g, h_{tc}, and R^2 are the gas holdup, the superficial gas velocity based on the cross area of the reactor, the length of the top clearance, and regression coefficient, respectively. The predicted data under different conditions are also shown in Fig. 1.

It is found by visual observation that the gas and the liquid are well separated at the degassed zone under the range of superficial gas velocities investigated. Thus, regime I (i.e., homogeneous regime with no bubble in the downcomer) in the IALR described by Heijnen et al. (1997) is obtained, and the gas holdup in the downcomer can be neglected. It can be seen in Fig. 1 that the gas holdup in the reactor increases with the increment of the superficial gas velocity under different top clearances. However, the gas

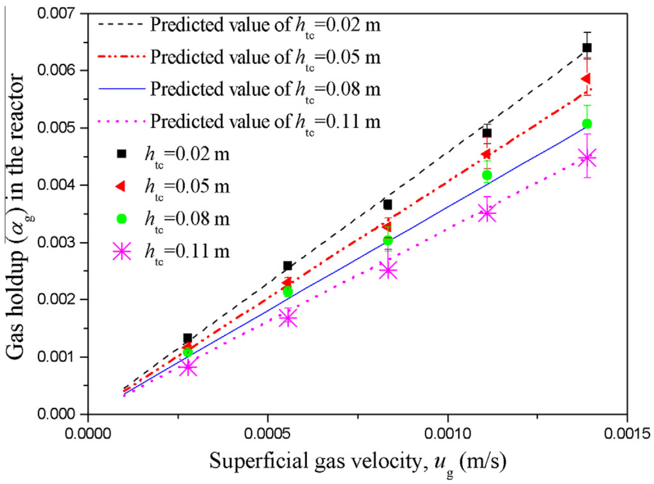

Fig. 1. Effect of the superficial gas velocity on gas holdup for different top clearances.

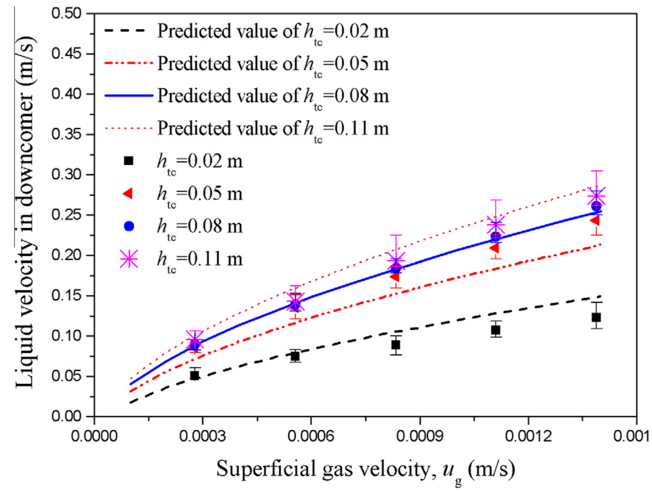

Fig. 2. Effect of the superficial gas velocity on liquid circulation velocity for different top clearances.

holdup in the reactor decreases with the increase of top clearance. The gas holdup in the reactor decreases nearly 42.9% (from 0.64% to 0.448%) when the top clearance increases from 2 cm to 11 cm at the maximum superficial gas velocity in this work. Since the bubble size distribution changes insignificant in homogeneous bubbly flow (Yang and Mao, 2014), the influence of h_{tc} on the average gas voidage can be ascribed to the fact that there is a critical value of h_{tc} for the IALR (Kilonzo et al., 2006), which is dependent on the geometric structure and the physical properties of fluids. When h_{tc} is below the critical value, the flow resistance to the reverse direction in the separator decreases with the increase of h_{tc}, and the liquid circulation velocity increases correspondingly. However, when h_{tc} is beyond the critical value, the flow resistance becomes constant, and correspondingly the liquid circulation velocity becomes almost invariable (Kilonzo et al., 2006). In the regime I and II of IALR (Heijnen et al., 1997), which are in the flow patterns with no gas recirculation, an increase of the gas velocity in the riser is resulted from the increase of liquid circulation velocity when h_{tc} is increased. Consequently, a decrease of the gas voidage in the riser is obtained at a given gas throughput. Only in the regime III where a gas recirculation exists (Heijnen et al., 1997), the gas holdup both in the riser and the downcomer can be promoted with the increase of h_{tc} (Kilonzo et al., 2006, 2007). This is why an increase of gas voidage was observed in IALR with the increase of top clearance (Chisti, 1989; Kilonzo et al., 2006, 2007) and an opposite phenomenon is seen in this work and other publications (Lazarova et al., 1997; Liu et al., 2008; Lu et al., 1994).

It is shown in Eq. (2) that the slope of the gas holdup versus the superficial gas velocity is greater than one (2.3709 in this work) and the line passes through the origin. That is also in agreement with the arguments of Thorat and Joshi (2004) in the ALR in the homogeneous regime. In addition, it is shown in Eq. (2) that the gas holdup is related to the height of the liquid level ($0.8 + h_{tc}$), and it has no direct relationship with the height of the top clearance.

The liquid circulation velocity is an important factor in the ALR. It affects the degree of mixing, the homogeneity of the reactors, and also the gas holdup. The influence of the superficial gas velocity on the average value of liquid circulation velocity with different top clearances is demonstrated in Fig. 2, and an expression is proposed here to estimate the liquid circulation velocity as follows:

$$u_{ld} = 31.4705 u_g^{0.5868} h_{tc}^{0.35412} - 0.017628 \quad R^2 = 0.94 \tag{3}$$

where u_{ld} is the liquid circulation velocity.

As seen from Fig. 2, the liquid circulation velocity in the downcomer increases with the increase of the superficial gas velocity under different top clearances. Under the same superficial gas velocity, the liquid circulation velocity increases obviously with the increase of the top clearance. The higher the superficial gas velocity, the more apparent role of the top clearance is, and the liquid circulation velocity increases almost 125% (from 0.122 to 0.274 m/s) when the top clearance increases from 2 cm to 11 cm at the maximum superficial gas velocity investigated in this work. This is due to the fact that the flow resistance to the reverse direction in the region above the upper end of the baffles is large at relatively short top clearance and it decreases with the increase of the top clearance. The argument is in accordance with the conclusions of Kilonzo et al. (2006) that the liquid circulation velocity increases when increasing the top clearance and becomes unchanged when it is beyond a critical value of 0.175 m in a reactor with the column hydraulic diameter of 0.10 m. It is evident in Fig. 2 that the liquid circulation velocity increases mildly when the top clearance is higher than 5 cm. This can be attributed to the fact that the decrease of resistance is small when the top clearance is above a certain height. Accordingly, it is consistent with the conclusions of Kilonzo et al. (2006), i.e., the flow resistance to the reverse direction in the region above the upper end of the baffles is large at relatively short h_{tc} and it decreases with the increasing h_{tc}, and the liquid circulation velocity becomes a constant when h_{tc} is beyond a critical value. For this PBR, a 10 cm length of top clearance is recommended.

The liquid circulation velocity data reveal that the gas–liquid separator is a very important factor affecting the hydrodynamic performance. In this RALPBR, the flow behaves like an external loop reactor, and relatively high liquid velocities are resulted. It is widely accepted that the top clearance has an important impact on the shear stress in the separator, and hence the top clearance should be designed large enough to avoid the presence of bubbles in the downcomer and the excessive shear stress in the PBRs.

Fouling is one of the major problems. Cells attach to the downcomer wall, reducing the light availability. Fortunately, a suitable liquid circulation velocity can avoid these problems. The optimal liquid velocity between 10 and 25 cm/s is recommended by Moheimani et al. (2011). Therefore, a minimum superficial gas velocity of 7.5×10^{-4} m/s in this RALPBR is determined according to the rules elucidated above.

3.2. Mixing time

The effect of the superficial gas velocity on the mixing time under different top clearances is depicted in Fig. 3. An empirical relationship is proposed, and the model is defined as:

$$t_{\mathrm{m}} = 0.010991u_{\mathrm{g}}^{-1.1265} + 4.4259h_{\mathrm{tc}}^{-0.79185} - 4.6045 \quad R^2 = 0.98 \qquad (4)$$

where t_{m} is the mixing time.

It is shown in Fig. 3 that the mixing time decreases with the increase of the superficial gas velocity, and the top clearance has a significant effect on the mixing time. The higher the top clearance, the smaller the mixing time is. The influence of the top clearance is more remarkable as the superficial gas velocity increases. The mixing time decreases nearly 68.2% (from 122.3 to 38.9 s) when the top clearance increases from 2 cm to 11 cm at the maximum superficial gas velocity investigated. However, the decrease of the mixing time by the increment of the top clearance is indistinctive when the top clearance is higher than 5 cm. This is because the mixing time is primarily controlled by the liquid turbulence and cycling frequency in the ALR, and both of which depend directly on the magnitude of the induced liquid circulation velocity. Therefore, the mixing time becomes shorter with the increase of the liquid circulation velocity.

Mixing, which governs the movement of the cells between the illuminated and the dark zones, can considerably enhance the productivity for a wide range of operational conditions, as it can create beneficial light fluctuations onto the cells. Consequently, the increase of the top clearance could yield a shorter mixing time and a higher frequency of favorable flashing light effect. It should be noted here that the mixing time is related to the light/dark cycle, but they are different due to their respective definitions.

3.3. Mass transfer coefficient

Volumetric mass transfer coefficient ($k_{\mathrm{L}}a$) is the crucial characteristic of the PBRs and determines the capability of the reactor to sustain optimum cell growth. In the cultivation of the microalgae, CO_2 from the gaseous phase transfers inside the algal cells through bulk liquid. At the same time, the released O_2 from photobioreaction is transferred from the liquid phase to the gas bubbles due to dissolved oxygen saturation. High mass transfer rate is requisite for the PBRs designed especially for CO_2 sequestration (Kumar et al., 2011).

The influence of the superficial gas velocity on $k_{\mathrm{L}}a$ with different top clearances is presented in Fig. 4. A phenomenological model is established and $k_{\mathrm{L}}a$ can be calculated as follows

$$k_{\mathrm{L}}a = 0.59535u_{\mathrm{g}}^{0.47236}h_{\mathrm{tc}}^{-0.073624} - 0.0090438 \quad R^2 = 0.99 \qquad (5)$$

where $k_{\mathrm{L}}a$ is the volumetric mass transfer coefficient. The predicted results are also shown in Fig. 4.

It can be seen from this figure that $k_{\mathrm{L}}a$ increases with the increase of the superficial gas velocity, and the value of $k_{\mathrm{L}}a$ with 2 cm top clearance increases only 3.89 times (from 6.91×10^{-3} to 2.69×10^{-2} s^{-1}) when the superficial gas velocity increases five-fold. However, the top clearance has a small effect on $k_{\mathrm{L}}a$; the value of $k_{\mathrm{L}}a$ deceases only 16.7% (from 2.69×10^{-2} to 2.24×10^{-2} s^{-1}) when the top clearance increases from 2 cm to 11 cm at the maximum superficial gas velocity investigated. All these phenomena can be ascribed to fact that $k_{\mathrm{L}}a$ is mainly determined by the gas holdup when the diameter of the bubbles is a constant. Generally speaking, the surface area of the bubbles increases with the increase of the gas holdup, and hence the value of $k_{\mathrm{L}}a$ is higher. It is noteworthy that $k_{\mathrm{L}}a$ of CO_2 can be estimated by the model given by Huang et al. (2010).

For optimal cell growth, CO_2 levels in liquid phase have to be maintained above the minimum nutritional requirements and below the inhibitory level; the range depends on the species due to its strong impact on pH. It has been reported that CO_2 is responsible for the limitation in the exponential growth phase, and the supply of CO_2 to the culture is one of the principal limitations (Pegallapati and Nirmalakhandan, 2013) at this stage. Meanwhile, the accumulation of O_2 is a serious problem and it should be kept below the toxic level. To avoid excessive oxygen level, the capacity of mass transfer must be high enough to remove O_2. The concentration of the dissolved CO_2 can be controlled by adjusting the gas flow rate and the partial pressure of CO_2 in gas. From the analysis above, there is an optima value of gas supply that ensures enough mass transfer and mixing while preventing the excessive oxygen accumulation and shear in the PBRs. It will be shown that the superficial gas velocity recommended above is large enough for O_2 removal in the designed RALPBR from our preliminary experimental results of cultivation.

3.4. Influence of hydrodynamics on the growth of microalgae

It is widely accepted that the superficial gas velocity has a great impact on the growth of microalgae in the ALRs. The increase of the

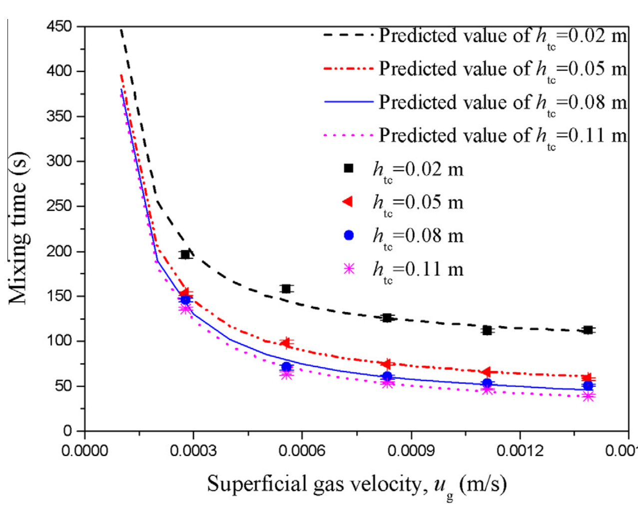

Fig. 3. Effect of the superficial gas velocity on mixing time for different top clearances.

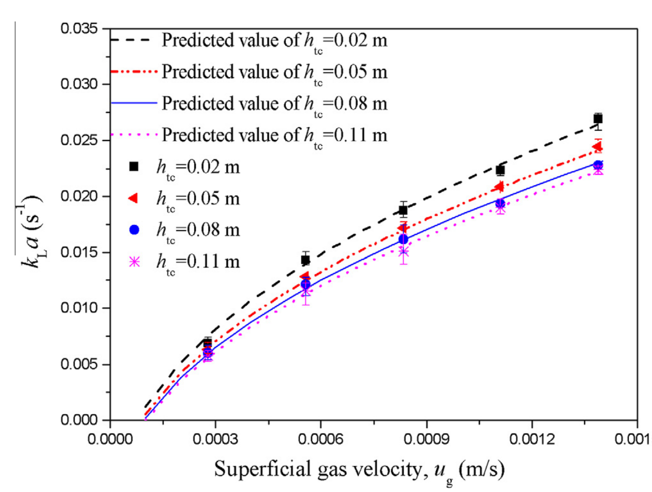

Fig. 4. Effect of the superficial gas velocity on mass transfer coefficient for different top clearances.

superficial gas velocity not only enhances the mixing and the light–dark cycle of microalgae, but also increases the rate of shear in the reactor, which is harmful when it is beyond a critical shear stress. Since the dissolved CO_2 concentration is higher than 10 ppm and less than 40 ppm when the 2% CO_2 is aerated in all the tested cases, the deficiency and inhibitory of CO_2 can be avoided in this work. Additionally, the dissolved oxygen concentration in all the experiments is stable (9–19 ppm) due to high mass transfer efficiency of the reactor, the toxicity of dissolved oxygen can also be prevented. The evolutions of microalgae concentration at five different superficial gas velocities are illustrated in Fig. 5.

Fig. 5 presents that the superficial gas velocity exerts a decisive influence on the growth of microalgae, and the final difference between the maximum biomass and the minimum biomass can be as high as twofold (3.96 and 1.97 g/L, respectively). The influence of superficial gas velocity behaves with a non-monotonic pattern. The growth curves show that a significant increase of culture concentration is obtained when the value of the superficial gas velocity increases from 2.778×10^{-4} to 8.333×10^{-4} m/s. However, with the subsequent increase of the superficial gas velocity, the rate of growth decreases and lower biomass weight is acquired due to excessive shear stress in the reactor. It shows that although the increase of the superficial gas velocity makes valuable contributions to the light/dark cycle in the PBR, an increase of harmful shear stress is also resulted. Therefore, the mixing and the shear stress should be balanced carefully when a suitable superficial gas velocity is adopted. The optimal superficial gas velocity of 8.333×10^{-4} m/s for the cultivation of the *C. vulgaris* strain in this PBR is also confirmed.

3.5. Energy analysis

The ALRs are considered one of the most promising designs in the direction of increasing mass transfer rate and at the same time minimizing the energy consumption. It requires further researches to investigate the relationship between the mixing intensity and the productivity for a designed reactor so that the energy input can be minimized. Through optimizing the superficial gas velocity used in the RALPBR, the energy requirement for the operation can be dramatically reduced; the optimal productivity can be achieved and the energy balance for the potential algal of biofuel-energy can also be shifted.

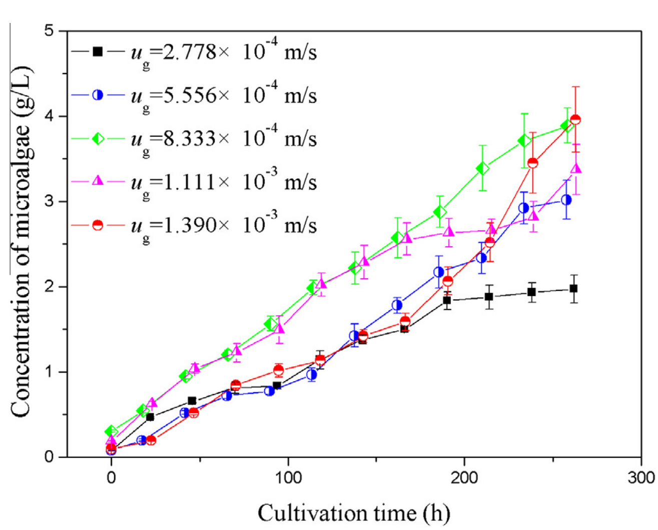

Fig. 5. Evolution of concentrations in the reactor at five different superficial gas velocities.

The influences of the superficial gas velocity on the volumetric power and the mass transfer coefficient are shown in Fig. 6, and an example of RALPBR with one riser and one downcomer provided by Reyna-Velarde et al. (2010) is also illustrated here for comparison. It shows that the mass transfer coefficient in this work is an order of magnitude higher than that of Reyna-Velarde et al. (2010) at the same superficial gas velocity due to the produced small bubbles (Sauter mean diameter d_{32} in this reactor is about 2.5–3.25 mm). Since the superficial gas velocity is low, a highly efficient RALPBR with high performance of mass transfer and low power supply is obtained.

It is shown that at the normal operating condition (i.e., the superficial gas velocity of 8.3×10^{-4} m/s and 4.2×10^{-3} m/s in this work and Reyna-Velarde et al. (2010), respectively), the power supply in this work (about 8 W/m^3) is only a quarter of that in Reyna-Velarde et al. (2010). In addition, the energy consumption is only one-sixth or one-ninth of the current operating guidelines (50–70 W/m^3) in the bubble column and the ALRs (Béchet et al., 2013; Kumar et al., 2011; Lehr and Posten, 2009; Singh and Sharma, 2012), and it compares favorably with 7.5 W/m^3 obtained in a cylindrical column reactor with a long height (2 m height × 0.19 m internal diameter) (Béchet et al., 2013). Therefore, the PBR designed in this work is an economic reactor for the cultivation of the microalgae.

The bottleneck for the production of energy or commodities with the microalgae is to develop more productive photobioreactor systems while reducing their cost dramatically. In some cases, the superficial gas velocity can be as high as 0.013 m/s, corresponding to a flow rate of 1.5 vvm (Cuaresma et al., 2009). Even for the ALR, the energy of mixing could represent 30% of the biochemical energy harvested during photosynthesis (Lehr and Posten, 2009). The power consumption must be sharply reduced for the actual production systems to become energetically positive.

It can be seen that the cost for mixing would be reduced to 16.3% of the total costs and only account for a 6.54% of the harvested biochemical energy share if this plot RALPBR is used. This is essential for the production of energy, and the cost may be reduced even further when the height is greater. It is argued that air enriched with 5% or 10% (v/v) CO_2 at rates of 0.025–1 vvm is cost effective for mass culture (Zhang et al., 2002). Moreover, an optimum aeration rate of 0.05 vvm has been proposed sufficient to improve the mixing and the mass transfer in flat panel PBRs (Sierra et al., 2008) and also been confirmed in this work (corresponding to the superficial gas velocity of 8.3×10^{-4} m/s in this PBR). Therefore, an aeration rate of 0.05 vvm, which is appropriate

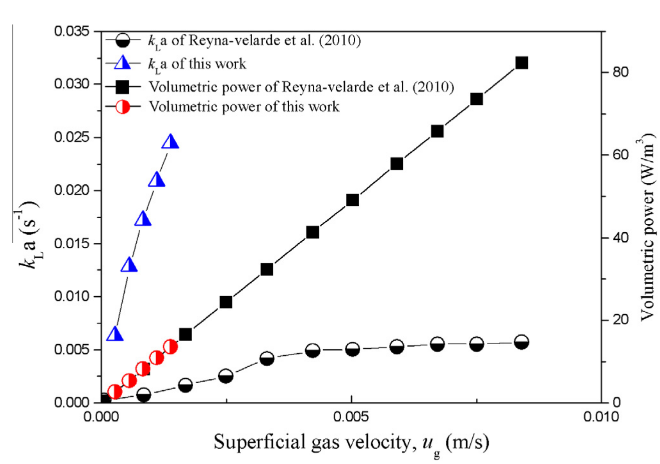

Fig. 6. Influence of the superficial gas velocity on the mass transfer coefficient and the power supply.

for the cell production, is recommended here for an efficient PBR. It should be noted that the concentration of the dissolved CO_2 can be effectively controlled by changing the percentage of CO_2 in the air stream to avoid large amount of waste at the initial stage or depletion at the exponential growth phase.

4. Conclusions

A new RALPBR for the mass cultivation of microalgae is designed. The fluid dynamics, mixing, mass transfer, and growth of *C. vulgaris* strain are investigated; the power supply is analyzed and optimized. Additionally, a novel technique is put forward for determining the low gas holdup in the PBR, and the influence of the top clearance on the hydrodynamics of the IALRs has been elucidated. It shows that this cost-effective PBR can be seen as a promising reactor for the mass cultivation of microalgae, especially for the algae biofuel.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.biortech.2015.04.077.

References

Acién Fernández, F.G., Fernández Sevilla, J.M., Molina Grima, E., 2013. Photobioreactors for the production of microalgae. Rev. Environ. Sci. Biotechnol. 12, 131–151.
Anjos, M., Fernandes, B.D., Vicente, A.A., Teixeira, J.A., Dragone, G., 2013. Optimization of CO_2 bio-mitigation by *Chlorella vulgaris*. Bioresour. Technol. 139, 149–154.
Béchet, Q., Muñoz, R., Shilton, A., Guieysse, B., 2013. Outdoor cultivation of temperature-tolerant *Chlorella sorokiniana* in a column photobioreactor under low power-input. Biotechnol. Bioeng. 110, 118–126.
Carvalho, A.P., Meireles, L.A., Malcata, F.X., 2006. Microalgal reactors: a review of enclosed system designs and performances. Biotechnol. Progr. 22, 1490–1506.
Chisti, M.Y., 1989. Airlift Bioreactors. Elsevier Applied Science, London, England and New York.
Choi, K.H., Chisti, Y., Moo-Young, M., 1996. Comparative evaluation of hydrodynamic and gas–liquid mass transfer characteristics in bubble column and airlift slurry reactors. Chem. Eng. J. Biochem. Eng. J. 62, 223–229.
Couvert, A., Roustan, M., Chatellier, P., 1999. Two-phase hydrodynamic study of a rectangular air-lift loop reactor with an internal baffle. Chem. Eng. Sci. 54, 5245–5252.
Cuaresma, M., Janssen, M., Vilchez, C., Wijffels, R.H., 2009. Productivity of *Chlorella sorokiniana* in a short light-path (SLP) panel photobioreactor under high irradiance. Biotechnol. Bioeng. 104, 352–359.
Dasgupta, C.N., Jose Gilbert, J., Lindblad, P., Heidorn, T., Borgvang, S.A., Skjanes, K., Das, D., 2010. Recent trends on the development of photobiological processes and photobioreactors for the improvement of hydrogen production. Int. J. Hydrogen Energy 35, 10218–10238.
Gourich, B., Azher, N.E., Vial, C., Soulami, M.B., Ziyad, M., 2006. Study of hydrodynamics, mixing and gas–liquid mass transfer in a split-rectangular airlift reactor. Can. J. Chem. Eng. 84, 539–547.
Gourich, B., El Azher, N., Soulami Bellhaj, M., Delmas, H., Bouzidi, A., Ziyad, M., 2005. Contribution to the study of hydrodynamics and gas–liquid mass transfer in a two- and three-phase split-rectangular airlift reactor. Chem. Eng. Process. 44, 1047–1053.
Heijnen, J.J., Hols, J., van der Lans, R.G.J.M., van Leeuwen, H.L.J.M., Mulder, A., Weltevrede, R., 1997. A simple hydrodynamic model for the liquid circulation velocity in a full-scale two- and three-phase internal airlift reactor operating in the gas recirculation regime. Chem. Eng. Sci. 52, 2527–2540.
Huang, Q., Yang, C., Yu, G., Mao, Z.-S., 2010. CFD simulation of hydrodynamics and mass transfer in an internal airlift loop reactor using a steady two-fluid model. Chem. Eng. Sci. 65, 5527–5536.
Kilonzo, P.M., Margaritis, A., Bergougnou, M.A., Yu, J., Qin, Y., 2006. Influence of the baffle clearance design on hydrodynamics of a two riser rectangular airlift reactor with inverse internal loop and expanded gas–liquid separator. Chem. Eng. J. 121, 17–26.
Kilonzo, P.M., Margaritis, A., Bergougnou, M.A., Yu, J., Ye, Q., 2007. Effects of geometrical design on hydrodynamic and mass transfer characteristics of a rectangular-column airlift bioreactor. Biochem. Eng. J. 34, 279–288.
Kochem, L.H., Da Fré, N.C., Redaelli, C., Rech, R., Marcílio, N.R., 2014. Characterization of a novel flat-panel airlift photobioreactor with an internal heat exchanger. Chem. Eng. Technol. 37, 59–64.
Kumar, K., Dasgupta, C.N., Nayak, B., Lindblad, P., Das, D., 2011. Development of suitable photobioreactors for CO_2 sequestration addressing global warming using green algae and cyanobacteria. Bioresour. Technol. 102, 4945–4953.
Lazarova, V., Meyniel, J., Duval, L., Manem, J., 1997. A novel circulating bed reactor: hydrodynamics, mass transfer and nitrification capacity. Chem. Eng. Sci. 52, 3919–3927.
Lehr, F., Posten, C., 2009. Closed photo-bioreactors as tools for biofuel production. Curr. Opin. Biotechnol. 20, 280–285.
Leupold, M., Hindersin, S., Kerner, M., Hanelt, D., 2013. The effect of discontinuous airlift mixing in outdoor flat panel photobioreactors on growth of *Scenedesmus obliquus*. Bioprocess Biosyst. Eng. 36, 1653–1663.
Liu, M., Zhang, T., Wang, T., Yu, W., Wang, J., 2008. Experimental study and modeling on liquid dispersion in external-loop airlift slurry reactors. Chem. Eng. J. 139, 523–531.
Lu, W.-J., Hwang, S.-J., Chang, C.-M., 1994. Liquid mixing in two- and three-phase airlift reactors. Chem. Eng. Sci. 49, 1465–1468.
Meiser, A., Schmid-Staiger, U., Trösch, W., 2004. Optimization of eicosapentaenoic acid production by *Phaeodactylum tricornutumin* the flat panel airlift (FPA) reactor. J. Appl. Phycol. 16, 215–225.
Moheimani, N.R., Isdepsky, A., Lisec, J., Raes, E., Borowitzka, M.A., 2011. Coccolithophorid algae culture in closed photobioreactors. Biotechnol. Bioeng. 108, 2078–2087.
Mudde, R.F., Van Den Akker, H.E.A., 2001. 2D and 3D simulations of an internal airlift loop reactor on the basis of a two-fluid model. Chem. Eng. Sci. 56, 6351–6358.
Pegallapati, A.K., Nirmalakhandan, N., 2013. Internally illuminated photobioreactor for algal cultivation under carbon dioxide-supplementation: performance evaluation. Renew. Energy 56, 129–135.
Reyna-Velarde, R., Cristiani-Urbina, E., Hernández-Melchor, D.J., Thalasso, F., Cañizares-Villanueva, R.O., 2010. Hydrodynamic and mass transfer characterization of a flat-panel airlift photobioreactor with high light path. Chem. Eng. Process. 49, 97–103.
Sierra, E., Acién, F.G., Fernández, J.M., García, J.L., González, C., Molina, E., 2008. Characterization of a flat plate photobioreactor for the production of microalgae. Chem. Eng. J. 138, 136–147.
Singh, R.N., Sharma, S., 2012. Development of suitable photobioreactor for algae production – a review. Renew. Sustain. Energy Rev. 16, 2347–2353.
Thorat, B.N., Joshi, J.B., 2004. Regime transition in bubble columns: experimental and predictions. Exp. Therm. Fluid Sci. 28, 423–430.
Xue, S., Zhang, Q., Wu, X., Yan, C., Cong, W., 2013. A novel photobioreactor structure using optical fibers as inner light source to fulfill flashing light effects of microalgae. Bioresour. Technol. 138, 141–147.
Yang, C., Mao, Z.-S., 2014. Numerical Simulation of Multiphase Reactors with Continuous Liquid Phase. Elsevier Academic Press, London, United Kingdom.
Yu, G., Li, Y., Shen, G., Wang, W., Lin, C., Wu, H., Chen, Z., 2009. A novel method using CFD to optimize the inner structure parameters of flat photobioreactors. J. Appl. Phycol. 21, 719–727.
Zhang, K., Kurano, N., Miyachi, S., 2002. Optimized aeration by carbon dioxide gas for microalgal production and mass transfer characterization in a vertical flat-plate photobioreactor. Bioprocess Biosyst. Eng. 25, 97–101.
Zhang, Q., Wang, Z., Wen, S., Liu, G., Wu, X., Cong, W., 2012. Gas–liquid mass transfer characteristics in a rotating-drum bioreactor. Chem. Eng. Technol. 35, 1842–1848.