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Impact of Microalgae on CO_2 Bubble Growth and Detachment in Bubble Column Bioreactor

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The biological capture of carbon dioxide (CO_2) using microalgae is a promising technology and has gained a huge momentum due to its environment-friendly, low cost and high CO_2 fixation efficiency. In the applications CO_2 gas usually was pumped into photobioreactors in bubble form. The bubbles behavior significantly affects the mass transfer and distribution of the microalgae. Also the adhesion of microalgae and absorption of CO_2 at the gas-liquid interface will certainly have an important effect on the dynamics of CO_2 bubbles in bubble column bioreactor. In this work, visual experiments were conducted for studying the impacts of microalgae on CO_2 bubble growth and detachment in bubble column bioreactor. It was found that many microalgae cells adsorbed on the surface of the bubble resulting in easier detachment of bubble in microalgae suspension against with pure water. Besides, it was also found that smaller capillary radius and larger CO_2 concentration gave rise to decreasing bubble growth rate and detachment diameter which was conducive to CO_2 transportation. Moreover, a critical gas flow velocity of 1.7 m/s in capillary was achieved, which divided the bubble growth status into steady and unsteady state, and different bubble growth and detachment behaviors were observed. These findings will be beneficial for the design of aeration system of photobioreactors for microalgae cultivation to enhance the mass transport at the interface.

1. Introduction

Carbon dioxide mainly produced by burning fossil fuels has resulted in serious global warming in the last few decades. CO_2 emissions reduction has been widely studied throughout the world (Fernández et al., 2012). Among numerous techniques including physical (Grimston et al., 2001), chemical (Diao et al., 2004) and biological (Skjånes et al., 2007) techniques. CO_2 capture by microalgae is considered as one promising approach owing to its environment-friendly, low cost, high CO_2 fixation efficiency (Makareviciene et al., 2013) and ability to producing bioethanol (Gonzalez-Delgado et al., 2013). In the applications, CO_2 gas is pumped into photobioreactors in bubble form to form bubble flow. Then CO_2 molecules diffuse from the bubbles to the microalgae cells and is bio-fixed by photosynthesis. Thus, the bubbles behaviors significantly affect the CO_2 transfer in the microalgae suspension, and hence microalgae growth and CO_2 capture ability. Although many existing works have revealed the importance of two-phase flow in cultivation of algae in photobioreactors (Yang et al., 2014), most of them only focused on the turbulent mixing and CO_2 and light transport enhancement while less attention has been paid to the bubble growth and detachment in photobioreactor.

In the past decades, numerous works on air bubble growth and detachment in water have been carried out. Xie et al. (2012) investigated formation and detachment of the air bubbles developing from an immersed micro-orifice (54 μm) in water using a visualization experiment and the effect of micro-orifice and gas flow rate were also analysed. Xu et al. (2014) visually studied the bubble growth and departure behaviors in a narrow rectangular channel and theoretically predicted the bubble departure diameter by analysis of force balance of the growing bubble. They found that bubble growth force was not the main

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force acting on a bubble. Yuan et al. (2014) investigated the effect of contact angle on bubbles formation and detachment at submerged orifices theoretically and experimentally. A few researchers concentrated on the bubble growth and detachment behaviors in other mediums, such as electrolyte solutions (Fazel and Shafaee, 2010), binary mixtures (Hamzekhani et al., 2014), and so on. While the bubble growth and detachment behaviors in microalgae suspension have not been well understood. It is believed that there will be different growth and detachment behaviors of CO_2 bubbles in microalgae suspension because of its special physical properties, adhesion of microalgae at the gas-liquid interface and absorption of CO_2 bubbles by biochemical reactions.

In the present study, the research on the growth and detachment behaviors of CO_2 bubble in microalgae suspension were visually studied. The microalgae behaviors were observed and the effects of gas flow rate, CO_2 concentration and capillary radius were also investigated.

2. Materials and Methods

2.1 Microalgae and culture medium

Microalgae used in this work was Chlorella pyrenoidosa, which purchased from Institute of Hydrobiology, Chinese Academy of Sciences (Wuhan, China). Chlorella pyrenoidosa was cultivated in the SE (Brostol's solution) medium, 1 L of which contained the following elements: 0.25 g $NaNO_3$, 0.075 g K_2HPO_4, 0.098 g $MgSO_4$•$7H_2O$, 0.025 g $CaCl_2$•$2H_2O$, 0.175 g KH_2PO_4, 0.025 g NaCl, 0.05 g $FeCl_3$•$6H_2O$, 1 mL EDTA-Fe, 1 mL Trace mental solution and 40 mL soil extraction solution. 1 L of EDTA-Fe solution was composed of 41 mL HCL, 9.306 g EDTA-Na_2 and 45.05 g $FeCl_3$•$6H_2O$. 1 L of trace mental solution contained 2.86 g H_3BO_3, 1.86 g $MnCl_2$•$4H_2O$, 0.22 g $ZnSO_4$•$7H_2O$, 0.39 g Na_2MO_4•$2H_2O$, 0.08 g $CuSO_4$•$5H_2O$ and 0.05 g $Co(NO_3)2$•$6H_2O$. The cells were cultivated at 25 °C under an illumination of fluorescent lamps with 160 μmol/m^2•s.

2.2 Experimental system

The experimental system for studying the impact of microalgae on CO_2 bubble growth and detachment in bubble column bioreactor is shown in Figure 1, which consists of a gas mixing system, a gas injection system and data acquisition system. During the working process, pure CO_2 (99.99 %vol) and air from the tanks were completely mixed in the gas mixer, and the concentration of CO_2 and flow rate of the mixed gas were adjusted by the mass flow controllers. Then, the mixed gas was injected into the photobioreactor through by a syringe pump (LSP02-1B) through a glass capillary with the inner diameter d_0. The photobioreactor was fabricated by PMMA and its dimensions were 100 mm × 100 mm × 200 mm (Length × Width × Height). Thereafter, the dynamic behaviors of the bubbles growth and detachment in the photobioreactor were characterized by a data acquisition system consisting of a high speed camera (Phantom V5.1 at the shooting speed of 5,000 fps.) and a data storage system. The recorded bubble images were processed and analyzed by the self-developed software using MATLAB software (Xie et al. 2012). Optical density (OD) of microalgae suspension was measured by a UV-visible spectrophotometer (TU1901, China) at a wavelength of 680 nm. Surface tension of microalgae suspension was measured using GBX3S (France) tensiometer.

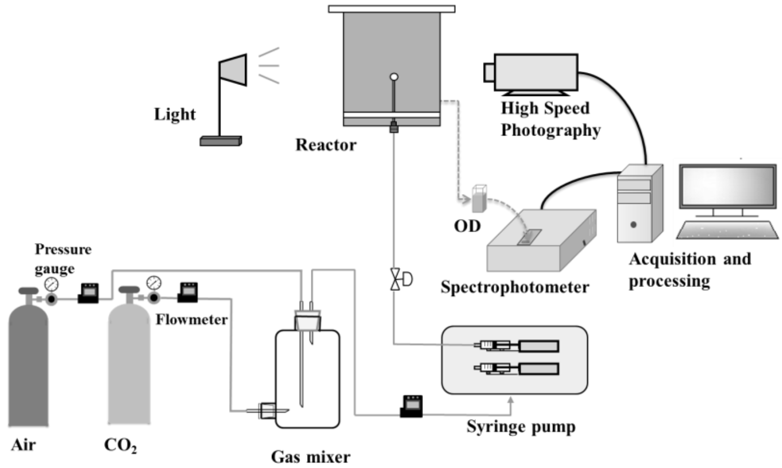


Figure 1: The experimental system

3. Results and Discussion

3.1 Microalgae behaviours and distribution at the gas-liquid interface

Figure 2 plots the microalgae behaviours and distribution at the gas-liquid interface. It can be seen in Figure 2 that many microalgae cells tended to move to and adsorbed on the bubble surface. This is because CO_2 was the only carbon source which diffused from bubble to the suspension in this experiment. Thus, microalgae cells in suspension would like to gather at the bubble surface with the highest CO_2 concentration due to chemotactic migration. Moreover, many microalgae cells collided to the bubble surface due to bubble surface expansion or were carried to the bubble surface by the liquid flow with the vortexes near the bubble during bubble growth. Then the microalgae cells were captured by capillary force and adsorbed on the bubble surface. Thus, it can be observed that the microalgae cells concentration at the gas-liquid interface was much greater than in the suspension. Table 1 shows the surface tension coefficient σ of microalgae suspension with different OD_{680nm}. It can be seen that the surface tension coefficient σ of microalgae suspension decreased with increasing of OD_{680nm}. This is because the adsorption of microalgae cells on the bubble changed the bubble surface characteristics and then may affect the bubble growth and detachment behaviours.

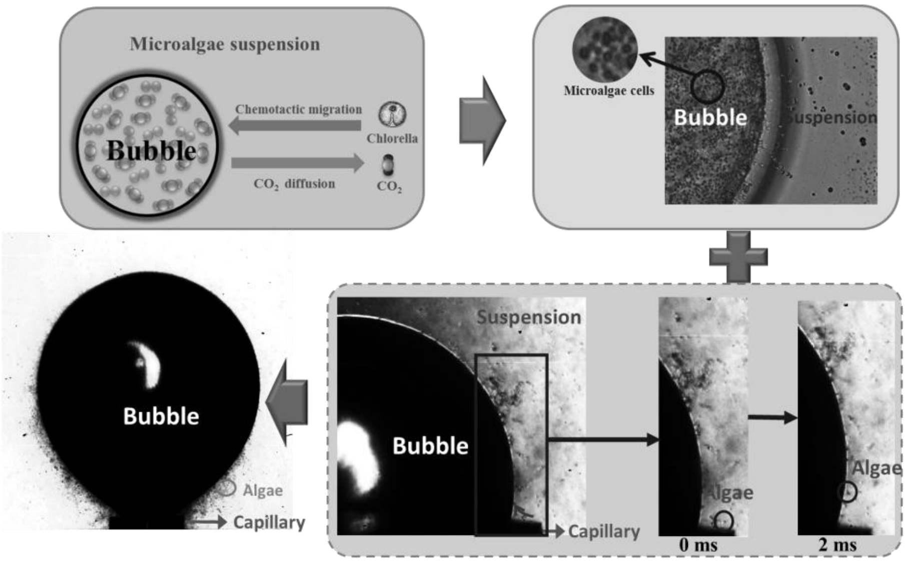


Figure 2: Microalgae behaviors and distribution at the gas-liquid interface

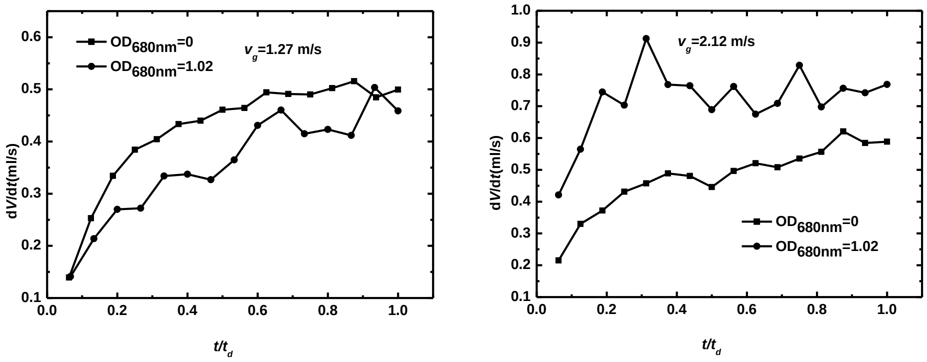
Table 1: Surface tension coefficient σ of microalgae suspension

OD_{680nm}	0	0.51	0.98	1.61	1.93
σ (10^{-2}N/m)	7.21	6.94	6.78	6.44	6.31

3.2 Effects of gas flow velocity

In this section the effects of gas flow velocity on the bubble growth and detachment was investigated, shown in Figure 3 and 4 (d_0=0.5 mm, CO_2 concentration is 10 %vol). Figure 3 plots the variations of bubble volume growth rate with time before detachment, which were recorded starting at the moment when the gas–liquid interface just broke through the orifice. t_d is defined as the moment when the bubble started to detach. It can be seen in Figure 3 that the bubble volume growth rate gradually increased in the first half period of bubble growth and tended to a constant in late growth period. This is because bubble surface area increased with the growth of bubble, and more microalgae cells were absorbed on the surface. All this facilitated transportation and consumption of CO_2 through the interface. Figure 3(a) also plots that when gas flow velocity was small (v_g = 1.27 m/s), CO_2 bubble had lower volume growth rate in microalgae suspension (OD_{680nm} = 1.02) than in pure water (OD_{680nm} = 0). While opposite results can be achieved when the gas flow velocity was large (v_g = 2.12 m/s), shown in Figure 3(b). This is because when gas flow velocity was small (v_g =1.27 m/s), the bubbles grew slowly both in microalgae suspension and pure water, and less interface fluctuations was observed. The steady growth of bubble facilitated enrichment and adsorption of microalgae cells at gas-liquid interface, which was beneficial to CO_2 transportation and consumption. Thus, smaller bubble volume growth rate was achieved in microalgae suspension. While when gas flow velocity was large (v_g = 2.12 m/s), the bubbles grew fast and obvious interface fluctuations was observed, which was not facilitated enrichment and adsorption of microalgae cells at gas-liquid interface, and then lowered the CO_2 transportation and consumption. Moreover, bubble had smaller surface tension coefficient in microalgae suspension than in pure water facilitating bubble growth. Thus, larger bubble volume growth rate was achieved in microalgae suspension.

Figure 4 shows the effect of gas flow velocity on bubble detachment. Here, d_m was bubble detachment diameter in microalgae suspension. And d_w/d_m was the ratio of bubble detachment diameter in water to in microalgae suspension. It can be seen in Figure 4 that bubble detachment diameter increased slowly with increasing gas flow velocity when the gas flow velocity was smaller than 1.7 m/s, while dramatically increased when the gas flow velocity was larger than 1.7 m/s. This is because it can be observed in the experiment that when the gas flow velocity was smaller than 1.7 m/s, bubble grew steadily and less interface fluctuations was observed. While when the gas flow velocity was larger than 1.7 m/s obvious interface fluctuations was observed, and unsteady growth of bubble was achieved. It can also be seen in Figure 4 that in steady state d_w/d_m was larger than 1, which indicated bubble had smaller detachment diameter in microalgae suspension than in pure water due to smaller surface tension coefficient. While in unsteady state d_w/d_m was less than 1, which indicated bubble had larger detachment diameter in microalgae suspension than pure water due to bubble inrush phenomenon.



(a) (b)

Figure 3: Variations of bubble volume growth rate with time before detachment: (a) v_g=1.27 m/s; (b) v_g=2.12 m/s

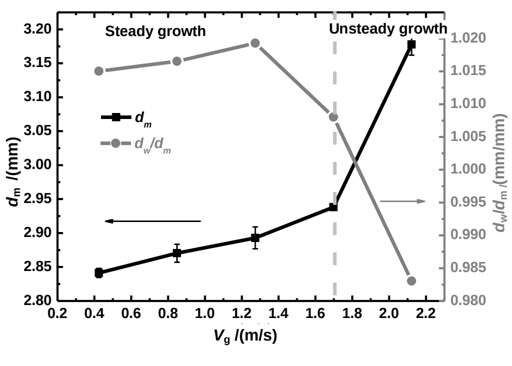
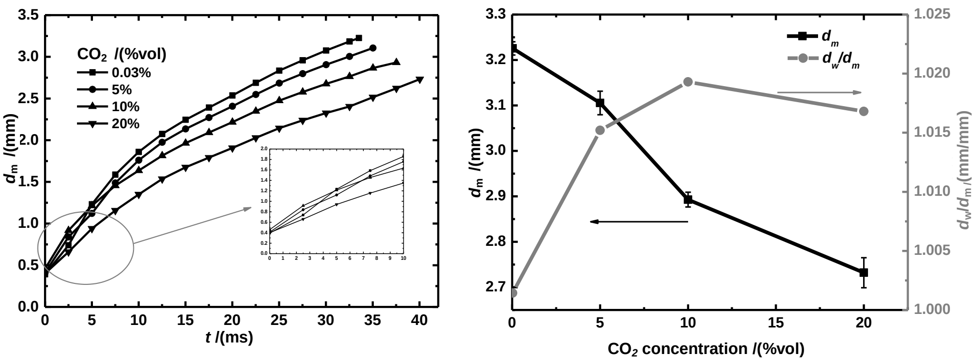


Figure 4: Effect of gas flow velocity on bubble detachment

3.3 Effect of CO_2 concentration

In this section, the effect of CO_2 concentration on the bubble growth and detachment in microalgae suspension was investigated, shown in Figure 5 (d_0 = 0.5 mm, v_g = 1.27 m/s, OD_{680nm} = 1.02). It can be seen in Figure 5(a) that larger CO_2 concentration resulted in lower bubble growth rate and longer bubble growth time. This is because larger CO_2 concentration supplied more CO_2 diffused into microalgae suspension due to improved concentration gradient between the bubble and the microalgae suspension which slowed down the bubble growth. In addition, because of chemotactic migration, more microalgae cells adsorbed on the surface of the bubble which has a higher levels of CO_2, this further promoted CO_2 transportation and consumption. Figure 5(a) also reveals that in the first 5 ms of bubble growth, the bubble growth rate increased with increasing CO_2 concentration when the CO_2 concentration was less than 10 %vol. This is because at the beginning of bubble formation, the expansion of gas-liquid interface was mainly limited by bubble surface tension. Moreover, more microalgae cells adsorbed on the bubble surface changed the bubble surface characteristics and reduced the bubble surface tension. Thus, larger CO_2 concentration caused faster bubble growth in the first 5 ms when the CO_2 concentration was less than 10 %vol. However, when the CO_2 concentration increased to 20 %vol, bubble growth rate decreased due to more amount of CO_2 in bubble diffused into microalgae suspension. Figure 5b plots the effect of CO_2 concentration on the bubble detachment. It can be seen that larger CO_2 concentration resulted in smaller bubble detachment diameter in microalgae suspension, due to smaller surface tension caused by more microalgae cells adsorption on the bubble surface. It can also be seen in Figure 5b that d_w/d_m increased with the increasing CO_2 concentration when CO_2 concentration was less than 10 %vol. When the CO_2 concentration reached 20 %vol, d_w/d_m was slightly lower but still greater than 1, which indicates increasing CO_2 concentration resulted in easier bubble detachment in microalgae suspension than water.



(a) (b)

Figure 5: Effect of CO_2 concentration on the bubble growth and detachment (d_0=0.5 mm, v_g=1.27 m/s): (a) Variations of bubble diameter with time; (b) Detachment diameter

3.4 Effect of capillary radius

In this section, the effect of capillary radius on the bubble growth and detachment was studied, shown in Figure 6 (v_g = 1.27 m/s, CO_2 concentration is 10 %vol). Figure 6(a) plots the variations of bubble diameter with time before detachment. It can be seen that larger capillary radius resulted in faster bubble grew rate. When capillary radius was small (d_0 = 0.3 mm), bubble grew faster in microalgae suspension (OD_{680nm} = 1.02) than in pure water (OD_{680nm} = 0) at the beginning (t<10 ms) for smaller surface tension coefficient. As time progresses, the effect of surface tension on bubble growth gradually decreased and bubble showed a smaller growth rate in microalgae suspension than in pure water due to the larger CO_2 transportation and consumption rate. When capillary radius was large (d_0 = 1 mm), bubble had smaller surface tension, and CO_2 bubble growth slower in microalgae suspension than in pure water due to the consumption of CO_2 by microalgae cells. Figure 6(b) plots the effect of capillary radius on the bubble detachment. It can be seen that d_m and d_w/d_m increased with increasing capillary radius due to increased triple-phase contact line and surface tension.

4. Conclusions

Great impact of microalgae on the bubble growth and detachment behaviors was achieved due to the adsorption of microalgae cells on the bubble surface and consumption of CO_2 by photosynthesis. And the different effects of microalgae were obtained when gas flow velocity, CO_2 concentration and capillary radius changed. It was found that many microalgae cells adsorbed on the surface of the bubble resulting in easier detachment of bubble in microalgae suspension against with pure water. Besides, it was also found that smaller capillary radius and larger CO_2 concentration gave rise to decreasing bubble growth rate and detachment diameter which was conducive to CO_2 transportation. Moreover, a critical gas flow velocity of 1.7 m/s in capillary was achieved, which divided the bubble growth status into steady and unsteady state.

These findings can give a guide to enhance the mass transport at the gas-liquid interface and design the aeration system of photobioreactors.

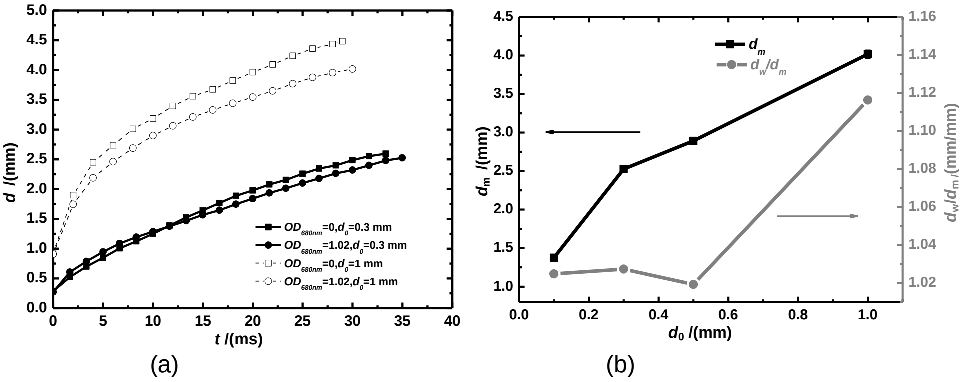


Figure 6: Effect of capillary radius on the bubble growth and detachment (v_g=1.27 m/s, CO_2 concentration is 10 %vol): (a) Variations of bubble diameter with time; (b) Detachment diameter

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