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BIOTECHNOLOGY and BIOENGINEERING

Airlift Column Photobioreactors for *Porphyridium* sp. Culturing: Part I. Effects of Hydrodynamics and Reactor Geometry

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ABSTRACT: Photosynthetic microorganisms have been attracting world attention for their great potential as renewable energy sources in recent years. Cost effective production in large scale, however, remains a major challenge to overcome. It is known to the field that turbulence could help improving the performance of photobioreactors due to the so-called flashing light effects. Better understanding of the multiphase fluid dynamics and the irradiance distribution inside the reactor that cause the flashing light effects, as well as quantifying their impacts on the reactor performance, thus, are crucial for successful design and scale-up of photobioreactors. In this study, a species of red marine microalgae, *Porphyridium* sp., was grown in three airlift column photobioreactors (i.e., draft tube column, bubble column, and split column). The physical properties of the culture medium, the local fluid dynamics and the photobioreactor performances were investigated and are reported in this part of the manuscript. Results indicate that the presence of microalgae considerably affected the local multiphase flow dynamics in the studied draft tube column. Results also show that the split column reactor works slightly better than the draft tube and the bubble columns due to the spiral flow pattern inside the reactor.

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KEYWORDS: airlift column; photobioreactor; photosynthesis; microalgae; hydrodynamics; irradiance distribution

Introduction

In recent years, photosynthetic microorganisms such as microalgae and cyanobacteria have been garnering worldwide attention for their great potential as renewable energy sources to meet the increasing energy demand. Cost effectively producing microalgae/cyanobacteria in large-scale production systems such as enclosed photobioreactors or open ponds, however, remains a major challenge to overcome (Xu et al., 2009). The challenge arises from the extreme complexity of the culturing system involving various physical and chemical phenomena of multiple time and length scales. For example, the photosynthetic reactions from photon capturing to carbon fixation occur in pico- to milliseconds and in nano- to micrometers, while the time scales for mass transfer and biomass reproduction could be in minutes or days. The production systems to culture these autotrophic cells thus require careful examination for design and scale-up.

One of the main reasons for the high operational and capital costs for microalgae production is the low cell density sustainable in the culturing system, usually caused by the limited light energy that can be delivered to the microorganism cells. Unlike other substrates like water and carbon dioxide, sunlight can only be supplied via surfaces with limited penetration depth due to the shading effects from microalgae cells closer to the surfaces. This usually causes photoinhibition for the cells near the surface while the rest are starving from light. It is known to the field that the so-called flashing light effect can help reduce photoinhibition and thus enhance the efficiency in using light energy (Luo and Al-Dahhan, 2004; Nedbal et al., 1996). This flashing light effect is stemmed from the movement of the cells between the highly illuminated surface region and the dark center resulting in a highly fluctuating light history experienced by the cells. The flashing light effect is thus determined by the flow dynamics, or turbulence, and the irradiance distribution in the photobioreactor. It is therefore crucial to understand the local fluid dynamics, how light intensity distributes inside a photobioreactor and their impacts on the efficiency of photosynthesis.

A good understanding of these fundamentals could shed lights on better design and scale-up of different types of

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photobioreactors, such as the airlift columns, which have been considered as one of the most promising types of photobioreactor (Chini Zettelli et al., 2000; Garcia Camacho et al., 1999; Merchuk et al., 2000). For example, it was reported that the draft tube column performed superior to the bubble column in lab scale experiments, but performed just equally in larger scale tests (Xu et al., 2009). The disappearance of such advantage in a larger scale unit clearly indicates the existence of a scale-up issue, which is usually dominated by the difference in fluid dynamics at different scales.

The multiphase flow dynamics in an airlift column photobioreactor is governed by the interactions among three phases: gas, liquid, and microorganism cells. Due to the size (in μm) and density (very close to water) of most microorganism cells, it is reasonable to assume that the liquid and the cells form a pseudo-homogenous phase. However, the rheological properties of this pseudo-homogenous phase can be very different from those of either the liquid or the cell phases. These properties can be affected by the cell concentration, the composition of the aqueous salt solution (e.g., the electrolyte solution is well-known to hinders bubble coalescence (Chisti, 1998)), whether or not cells aggregate and form larger particles. Moreover, many microorganisms excrete viscous secondary metabolic products that turn the culture medium into a non-Newtonian fluid. These factors usually have different impacts on the multiphase flow, and thus further complicate the already complex flow dynamic characteristics in airlift column reactors.

As a result, studies on local hydrodynamic characteristics using a real microorganism system are rare (Chisti, 1998; Petersen and Margaritis, 2001). Instead, some researchers used different media to mimic the real microorganism culturing systems, such as aqueous salt solution (Posarac and Petrovic, 1991), non-Newtonian carboxymethyl cellulose solution (Li et al., 1995), or glass beads as the solid phase (Koide et al., 1992). In these studies, the effects of physical properties and operating conditions on the multiphase flow were investigated separately. Inconsistent findings have also been reported in the literature. For example, in a draft tube column reactor, Yuan et al. (1994) observed similar overall gas holdup and liquid circulation rates in an air-water system and an air-aqueous ethanol solution system, which were much larger than in an air-yeast broth system. In contrast, Fraser and Hill (1993) obtained almost identical overall gas holdups in an external-loop airlift reactor using three different media (i.e., water, aqueous salt solution, and an alga culture system). Therefore, better understanding of the local multiphase hydrodynamics in a real culturing system is necessary for better design and scale-up of photobioreactors.

This work presents our continuing efforts to enhance the understanding of hydrodynamics and irradiance distributions and their impacts on the growth of photosynthetic microorganisms. In part I of this manuscript, a species of red microalgae, *Porphyridium* sp., was grown in three different types of airlift columns: bubble column, draft tube column, and split column. The physical properties of culture media such as viscosity and surface tension were measured. The local multiphase hydrodynamics in the draft tube column was studied using advanced experimental techniques, namely CARPT (i.e., Computer Automated Radioactive Particle Tracking) and CT (i.e., Computed Tomograph). The reactors' performances were also monitored in terms of biomass concentrations such as optical density, dry mass, cell number counts, and Chlorophyll (a). The following sections first describe the materials and methods used in the experiments, and then discuss the observations and results obtained. Please note that in Part II of this manuscript, the experimental data obtained in Part I will be further used to verify a dynamic growth rate model developed in Luo and Al-Dahhan (2004), attempting to establish a quantitative tool for photobioreactor design and scale-up.

Experiments

Microalgae Culture Preparation

A red marine microalgae, *Porphyridium* sp. (UTEX 637), obtained from the culture collections of University of Texas, was grown in an artificial seawater medium prepared according to Jones et al. (1963). The microalgae were first grown in 500 mL Erlenmeyer flasks in a shaker at 31°C and a pH of 7.6. Light was supplied by a cool white fluorescent lamp with a photon flux density (PFD) of 30 $\mu E/m^2 s$ installed on the sidewall inside the shaker. To avoid contamination to the small-scale cultures, no extra CO_2 was supplied.

Airlift Column Photobioreactors

Reactor Configurations

Three types of airlift column photobioreactors were used in this study as shown in Figure 1. They were actually the draft tube column studied in Luo and Al-Dahhan (2008a,b, 2010). This acrylic column has an outer cylinder of 0.13 m diameter and 1.5 m height with total liquid volume about 15 L. It was modified for different configurations:

- no internal was used when running as a bubble column;
- a draft tube of 0.09 m diameter and 1.05 m height was mounted coaxially with the outer cylinder when running as a draft tube column;
- a plate was inserted vertically to the reactor center forming two identical zones when running as a split column.

For the draft tube and the split columns, the top clearance, or the distance from the top edge of the internal to the static liquid level was 3 cm. As for the bottom clearance, or the distance from the column base to the bottom edge of the

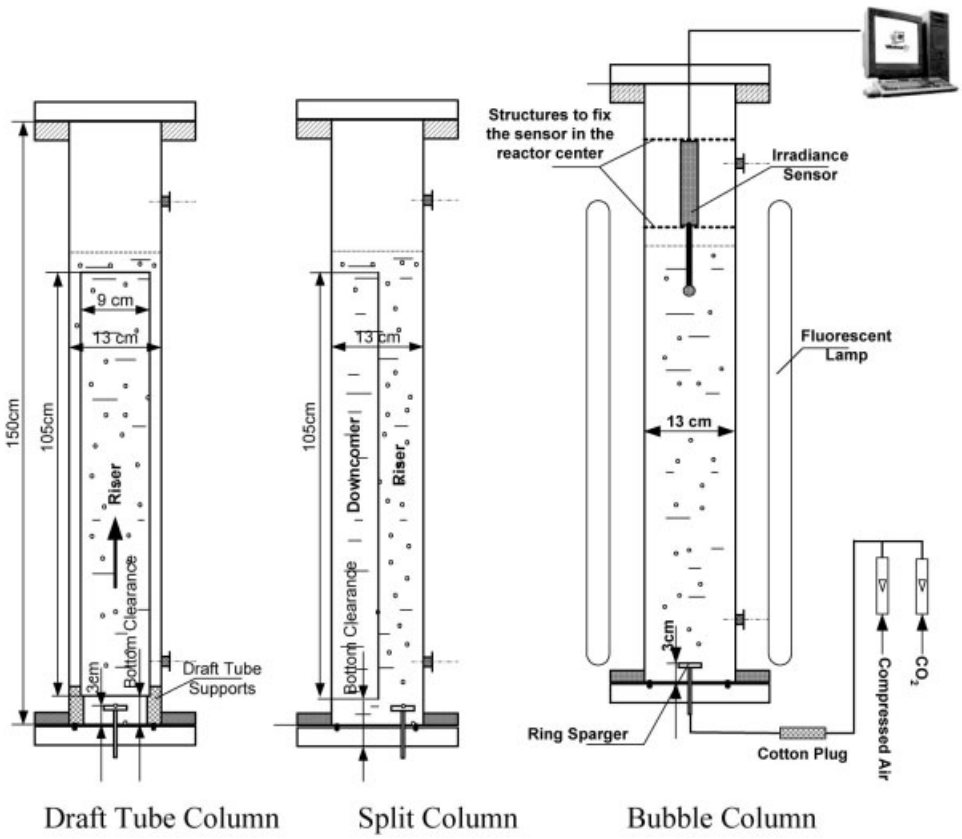

Figure 1. Schematic diagram of the experimental set up and configurations of three airlift column photobioreactors: draft tube column, split column, and bubble column.

internals for the draft tube and the split columns, it was chosen to be 5 cm to avoid potential high shear stress spots in the bottom regions as observed in Luo and Al-Dahhan (2008b). At the bottom of the column, a ring sparger was installed at the reactor center to distribute the gas phase (the sparger was moved to one side when running as a split column, so that it was still in the center of the Riser).

Compressed air enriched with 3% CO_2 was introduced into the reactor through the ring sparger providing both a carbon source and agitation to the photobioreactors. Light energy was supplied continuously by a bank of cool white Sylvania fluorescent lamps (four 40 W lamps with an intensity of 3,000 Lumen and eight 60 W high output lamps with an intensity of 3,281 Lumen) that were evenly distributed around the airlift column. Such a configuration of the lamp bank, as shown in Figure 2, generated a fairly uniform light intensity distribution around the illuminated column surface. Continuous illumination was applied throughout the experiments without applying day and night cycles.

Experimental Procedure and Operating Conditions

Before each experiment, the whole column was carefully washed with soap water and thoroughly rinsed with

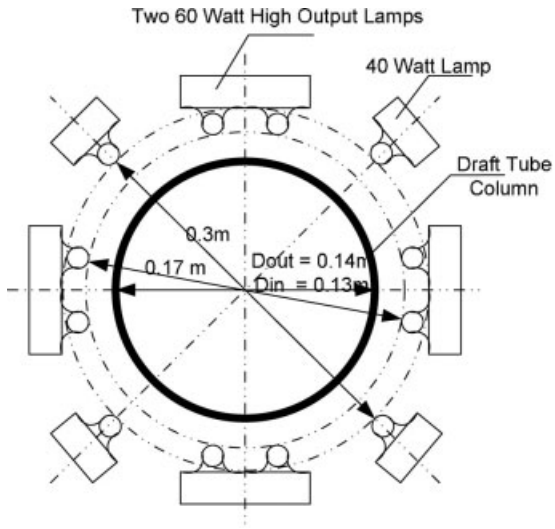

Figure 2. Arrangement of cold fluorescence lamps to illuminate the photobioreactors.

de-ionized water. To avoid contamination, all culture media were sterilized in an autoclave under pressure of 1 atm for 20 min. Furthermore, compressed air was filtered by a cotton plug before entering the column, which was loosely covered by a lid. No significant contamination was observed under a microscope in any of the experiments.

The experiments were conducted in a batch mode. The airlift column photobioreactor was first inoculated with *Porphyridium* sp. with a very low initial optical density (i.e., less than 0.01). The column was then run for 12 h under low light intensity (i.e., illuminated only by lab ceiling lamps with a Photon Flux Densities (PFD) around 26 $\mu E/m^2 s$) and low superficial gas velocity (i.e., Ug of 0.3 cm/s). This is to reduce photoinhibition and to shorten the lag time the cells needed to adept with the new environment. After that, four 40 W lamps were switched on giving a PFD around 275 $\mu E/m^2 s$ on the illuminated surface, which is close to the optimum irradiance of 250 $\mu E/m^2 s$ for *Porphyridium* sp. suggested by Wu and Merchuk (2001). When the optical density of the culture reached 1.0 (thick enough to avoid detrimental photoinhibition at very high PFD), all lamps were switched on, giving a high irradiance of ~1,850 $\mu E/m^2 s$. Finally, to test the effects of mixing intensity on the airlift column photobioreactor performance, the superficial gas velocity was increased to 1 cm/s while keep all lamps on.

Liquid Phase Physical Properties

The viscosities and the surface tension of the microalgae culturing media at different growth stages were measured without pretreatment such as filtration. This is to measure the true properties of the pseudo-homogeneous liquid/cell phase. The viscosities were measured by a viscometer (model AR2000, TA Instruments, Inc., New Castle, DE) using an aluminum cone geometry (cone diameter of 60 mm and angle of 59′49″). The surface tension was measured by a tensiometer (Sigma 701, KSV Instruments, Inc., Espoo, Finland).

Hydrodynamic Characterization Under Real Culture Conditions

To characterize the local flow structures in the draft tube airlift column photobioreactors under real microalgae culture conditions, CARPT and CT were employed in this study using the same experimental setup and procedures described in detail in Luo and Al-Dahhan (2008b, 2010). The CARPT and CT experiments were carried out at different time, as the instruments reside in different labs, and were not conducted for the bubble column and the split column photobioreactors due to time restriction. They are in consideration for future studies, though.

The CARPT experiments started after the microalgae culture reached the active growth stage with an optical density around 0.2. Experiments at a superficial gas velocity (Ug) of 0.076 cm/s were performed first, immediately followed by the experiment for Ug of 0.3 cm/s. The optical density increased to ~0.6 after these experiments in about 3 days. A similar procedure was applied to the CT experiments to measure the local gas hold up in the photobioreactor. The optical density was around 0.2–0.4 throughout the CT experiments. For each CT experiment, the local gas holdup on three cross-sections of the reactor were measured: the top scan at 110 cm above the column base, the middle scan at 67 cm above the base, and the bottom scans at 4.2 cm above the base.

Biomass Concentration measurements

To monitor the biomass concentration, a 100 mL sample was taken from the top of the airlift column (around 5–10 cm below the liquid level) at least twice a day. After taken the samples, a same amount of fresh medium was added to the reactor to keep the same overall liquid level in the reactor. This sample was divided into four parts for different biomass concentration measurements: optical density, dry biomass weight, direct cell number counting, and chlorophyll concentration. They were chosen to better monitor the biomass growth rates and to better compare with literature data. The following sections describe the details of these measurements.

Optical Density

Optical densities of the microalgae samples were usually measured at 10 AM and 10 PM using a spectrophotometer (Spectronic Genesys 8, Thermo Spectronic Instruments, Inc., Waltham, MA) with cuvettes of 1 cm path length at wavelength of 663 nm (Merchuk et al., 2000). For each measurement, an average of three samples was used, although the standard deviation was usually quite low. When the biomass concentration was very high, the samples were diluted with de-ionized water before the measurement for better accuracy.

Dry Biomass Weight

The dry biomass weight was measured twice a day with two samples each time. Initially, 20 mL of each sample was filtered through a 0.8 μm filter paper (GC/G, Fisher Healthcare Co., Pittsburgh, PA) and washed with a few milliliters of de-ionized water. When the cell concentration was high which requires a very long filtration time, the sample volume was reduced while the total dry biomass weight was kept about the same. The filter paper with microalgae was then oven dried (105°C) for 24 h and weighed. An average of the two samples was taken as the dry biomass weight.

The dry biomass is usually proportional to the measured optical density as shown below ($R^2 = 0.946$):

$$\text{Optical Density (dimensionless)} = 0.4777 \times \text{Dry Biomass (g/L)} \quad (1)$$

Cell Number Counting

Cell numbers were counted using a counting chamber (Bright-line counting chamber, Fisher Healthcare Co.) under a microscope (Olympus 324, Olympus, Inc., Center Valley, PA) with 400× zoom. A calibration curve gives a linear relationship between the cell numbers and the optical densities ($R^2 = 0.995$):

$$\text{Optical Density (dimensionless)} = 0.0435 \times \text{Cell Number } (10^6 \text{ cells/mL}) \quad (2)$$

The morphology of the microalgae was also routinely checked under the same microscope.

Concentration of Chlorophyll (a)

Chlorophyll (a) concentration was measured once a day with two samples each time. To measure the concentration of chlorophyll (a), two samples of 20 mL algae (or 5 mL when the concentration was high) were first filtered through a 0.8 μm filter paper (GC/F, Fisher Healthcare Co.) under dim light as soon as the samples were collected (the samples were always covered with aluminum foils to prevent pigment changes during transportation). The filter papers with algae were then placed in vials and frozen in a refrigerator. When enough samples (usually 8) were collected, these samples were analyzed all at one time following the method described in Clesceri et al. (1998). The chlorophyll on the filter paper was extracted overnight by 10 mL 90% aqueous acetone solution containing trace magnesium carbonate in the dark at 4°C. The extraction solution was then clarified by a 0.4 μm syringe filter with its volume also measured.

The optical densities of the extract under different wavelengths (i.e., OD750, OD664, OD647, and OD630) were determined in a spectrophotometer (Spectronic Genesys 8, Thermo Spectronic Instruments Inc.). The concentration of chlorophyll (a) was then calculated by (Clesceri et al., 1998):

$$\text{Ca} = 11.85(\text{OD664}) - 1.54(\text{OD647}) - 0.08(\text{OD630}) \quad (3)$$

$$\text{Chlorophyll (a), mg/L} = \frac{\text{Ca} \times \text{extracted volume, L}}{\text{volume of sample, L}} \quad (4)$$

where Ca is the concentrations of chlorophyll (a), and OD664, OD647, and OD630 are optical densities at respective wavelengths corrected by OD750 (e.g., OD664 is the optical density at 664 nm less the optical density at 750 nm).

Results and Discussions

Physical Properties of the Culture Medium

The physical properties of the culture medium, mainly the viscosity and the surface tension, have important effects on the fluid dynamics in the reactor, and in turn on the overall reactor performance. Microalgae *Porphyridium* sp. is encapsulated within sulfated cell-wall polysaccharides and is a well-known polysaccharide producer (Eteshola et al., 1996; Gu and Liu, 2001). These polysaccharides accumulate in the culture medium especially at the stationary growth stage, and significantly affect the culture medium's rheological properties (Eteshola et al., 1996, 1998; Geresh et al., 2002).

Figure 3 shows the measured viscosities of the culture medium at different biomass concentrations. Initially, when the biomass concentration was very low, the medium's viscosity was similar to that of water. However, the medium soon became Non-Newtonian as the biomass concentration increased. It showed a typical shear-thinning character with apparent viscosity decreased exponentially as shear stress increased. Increasing the biomass concentration also increased the apparent viscosities significantly in the low shear stress range, but was quite constant in the high shear stress range. These results are consistent with the literature (Eteshola et al., 1996, 1998) and confirm that the polysaccharides produced by microalgae cells have significantly impact on the viscosity of the culture medium.

On the other hand, the surface tension of the culture medium was found to be constant and close to that of pure water. The measured surface tension for a sample with an optical density as high as 4.0 was 72.18×10^{-3} N/m, very close to the surface tension of pure water (i.e., 71.94×10^{-3} N/m at 25°C). The reason for the small change in surface tension is not clear, and surface tension measurements have rarely been reported in the literature.

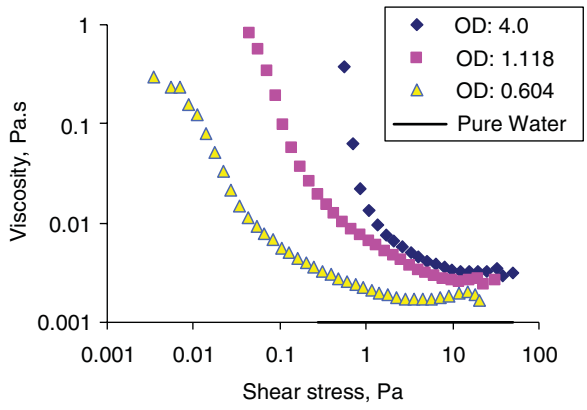

Figure 3. Apparent viscosity of the culturing media at different biomass concentrations.

Fluid Dynamics of the Draft Tube Photobioreactor

To characterize the local flow dynamics in a *Porphyridium* sp. culturing system, both CARPT and CT experiments were implemented in the draft tube photobioreactor during the active growth stage, when the optical density increased from 0.2 to 0.6. Please note that, since the cultures were at the active growth stage in a batch mode, the optical density was rising during the experiments. The culturing medium's physical properties were certainly changing too. Therefore, exact matches of conditions for the CARPT and CT measurements were not possible. This situation hindered a more thorough analysis of the obtained multiphase fluid dynamics data.

Figure 4 displays the CARPT and CT results obtained in this work, together with the results obtained from an air-water system reported earlier (Luo and Al-Dahhan, 2008b, 2010). Figure 4a shows the radial profile of the normalized occurrence density, or the number of times the tracer were detected in a certain radial position per unit volume. As can be seen, the profiles in the middle of the riser and downcomer regions are flat as in the air-water system. But the tracer particle or cells in a real culturing system have less chance to visit the outer wall regions than those in the

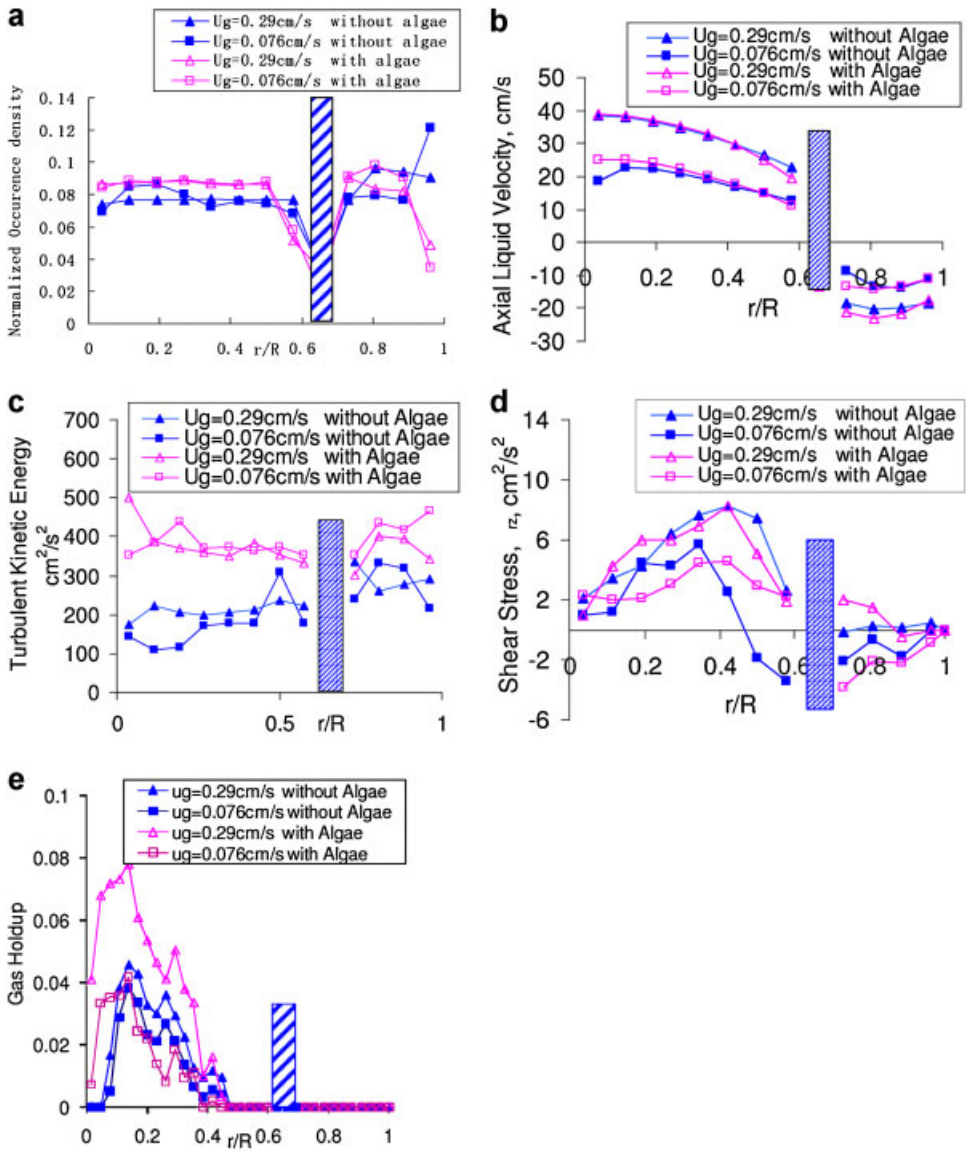

Figure 4. Comparison of the local hydrodynamic characteristics in the draft tube column between the real alga culture system obtained in this work and the air-water system obtained in Luo and Al-Dahhan (2004). **a**: Radial profile of the occurrence density normalized by the total number of occurrences; (**b**) axial liquid velocity profiles; (**c**) turbulent kinetic energy profiles; (**d**) profiles of the Reynolds shear stress, τ_{rz}; (**e**) gas holdup profiles at the middle level ($H = 67$ cm). Operating conditions: bottom clearance = 5 cm and top clearance = 3 cm (for Ug = 0.076 cm/s in the air-water system, the top clearance is 0 cm).

air-water system. This is likely due to the increase of the viscosity in the real culturing system as shown in Figure 3. Increasing the liquid viscosity enlarges the turbulent sub-layer, where the particle or the cells have difficulty to access. Since the outer cylinder wall is the illuminated reactor surface, this phenomenon reduces the light availability delivered to the interior cells, and thus affects the reactor performance.

Figures 4b–e further shows the radial profiles of the axial liquid velocity, the turbulent kinetic energy, the Reynolds shear stress (τ_{rz}), and the local gas holdup at the middle of the column, respectively. These results indicate that the presence of microalgae slightly changes the axial liquid velocities and the shear stress, but noticeably enhances the gas holdup and the turbulent kinetic energy. They suggest that the multiphase flow structures are quite different between a real culture system and an air-water system. Such differences will be further discussed in Part II of this manuscript, when the hydrodynamic data obtained in this part will be used to predict the bioreactor performance.

As reported in the literature, increasing viscosity reduces the terminal velocity of bubbles in the liquid phase, and thus tends to increase the gas holdup in the reactor. Moreover, the bubble size distribution can also be very different. The electrolyte solution usually inhibits bubbles' coalescence (Chisti, 1998), and the polysaccharide produced by *Porphyridium* sp. cells can also significantly promote or inhibit bubbles' coalescence (a small amount of foaming was observed on the top of the culture at the early active growth stage, which became significant as biomass concentration increases). The effects of the shear-thinning nature of the fluids on the bubbly dynamics are not clear either. Since the rising bubbles in the airlift reactors are the driving force of the bulk liquid circulation, the changes in bubble size distribution have significant effects on the multiphase flow dynamics, such as the turbulent kinetic energy. However, how the bubble size distribution changes is not clear, which requires further study of the bubble dynamics under real culturing conditions.

It should be pointed out that the flow dynamics was measured at fairly low biomass concentrations. When the cell culture reaches the stationary stage with higher biomass concentration, the apparent viscosity can be much larger, as shown in Figure 3. Under such conditions, the multiphase flow dynamics, especially the local structures, could be much more complex. Indeed, both tiny and very large bubbles (in centimeters by visual observations) were observed at the end of the cultures, resulting in a wide range of bubble size distribution. Foaming was also observed at the end of the experiments. Moreover, the small-scale turbulence with low shear rates could also be greatly damped out due to the high apparent viscosity. These phenomena could certainly reduce the light fluctuations the microorganism cells experienced in the photobioreactor and enhance photoinhibition. These analyses, based on fluid dynamic principles, provide a knowledge base to understand the photobioreactor's performance.

Performance of the Draft Tube Column Photobioreactor

The performance of the draft tube airlift column on *Porphyridium* sp. culturing is shown in Figure 5. It showed the evolution of the culture medium's optical density, the dry biomass concentration, the chlorophyll (a) concentration, and the measure irradiance in the reactor center. A long lag time of 70 h was observed, suggesting the big differences between the environments before and after the inoculums.

After the cells have adapted to the new environment, the culture entered the active growth stage. The optical density, the dry biomass concentration, and the chlorophyll (a) concentration increased almost linearly with time. Correspondingly, the light intensity in the reactor center also decreased linearly, suggesting photolimitation started to dominate the cellular growth. Under such conditions, the flashing light effects are not prominent due to the low illuminating light intensity used. The overall growth rate of the reactor was nearly proportional to the total light energy supplied too. At this stage, most of the *Porphyridium* sp. cells were quite small as observed under a microscope (comparing to the later growth stages).

To investigate the photoinhibition and the flashing light effects on the photobioreactor performance, eight high output fluorescence lamps were switched on after the culture's optical density reached one. This gave a total PFD on the illuminated surface as high as 1,850 $\mu E/m^2 s$. As shown in Figure 5, the overall growth rate and the dry biomass concentration increased considerably due to the higher light availability. However, the chlorophyll (a) concentration dropped radically, which was recovered somewhat later. Since the chlorophyll contents reflect the strategies adopted by the microorganisms in handling the light intensity stress (Falkowski and Raven, 1997), the rapid drop of chlorophyll contents demonstrated the existence of photoinhibition in the reactor under high PFD.

To further investigate the effects of the mixing intensity on the reactor performance, the superficial gas velocity was increased to 1 cm/s when the medium's optical density reached about 2.5. As shown in Figure 5a, this resulted in a small jump in the optical density, which, however, did not last long. Such a jump was hardly observed from the dry biomass weight profiles as shown in Figure 5b, probably due to the larger experimental error. Nevertheless, these results imply that increasing the superficial gas velocity at a high biomass concentration has minor effects on the reactor performance.

Indeed, under conditions of high biomass concentration, the light energy is concentrated in the highly illuminated wall region. This region lies in the turbulent sub-layer and is low in turbulent intensity. Moreover, the liquid phase becomes non-Newtonian with a high apparent viscosity at low shear rate as mentioned above, which could further damp out the turbulent intensity in the wall region. Therefore, although increasing the superficial gas velocity enhances the turbulent intensity in the wall region and thus improves the overall growth rates, such effects cannot last

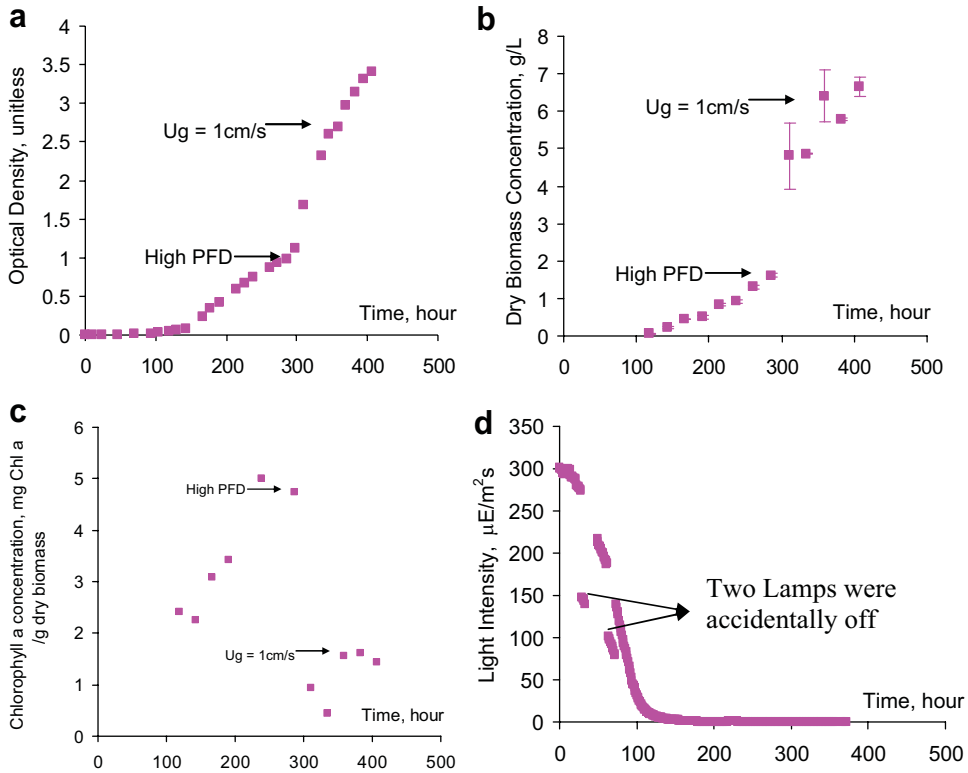

Figure 5. Biomass concentration evolution in the draft tube airlift column photobioreactors for *Porphyridium* sp. culturing. **a**: Evolution of the culture medium's optical density; (**b**) evolution of the dry biomass concentration; (**c**) evolution of the normalized chlorophyll (a) concentration by the dry biomass concentration; (**d**) evolution of irradiance in the reactor center.

long, as the medium's apparent viscosity also increases fast due to the growth. Moreover, as observed in the experiments, increasing superficial gas velocity at the late growth stage generated a large amount of foaming, which carried liquid phase out of the column. When the liquid dynamic level of the liquid phase decreased, the experiment eventually failed and the biomass concentration in culture dropped suddenly (not shown in the figure).

Effects of Reactor Geometry on Performance

Figure 6 exhibits the effects of reactor geometry on the photobioreactor performance. Please note that, due to the different lag times observed, the biomass evolution curves were shifted to match the same point when all lamps were switched on. This helps to better compare the reactor performances at different growth stages.

As shown in Figure 6a, the measured optical densities for the studied photobioreactors increased almost linearly in the active growth stage at an optical density in the range of 0.1–1.0. The optical density profile of the split column has a higher slope than the other columns as further demonstrated in Figure 7, indicating a higher growth rate. When all lamps were switched on, the optical densities for the draft tube and the bubble columns increased exponentially, while the optical density for the split column was still increasing almost linearly. However, the optical densities for all three columns eventually reached a level very close to each other at about the 320th hour. When superficial gas velocity increased to 1 cm/s, the biomass concentration in the bubble column soon reached a plateau while the concentrations in the draft tube column and the split column kept increasing to a higher level. These trends are not clear from Figure 6b due to the higher variance for the dry biomass concentration measurements.

The observed faster growth rate in the split column at low PFD stage can be further proofed by the normalized chlorophyll (a) concentration profile as shown in Figure 6c. The normalized chlorophyll (a) concentration of the split column is considerably lower than that of the other columns. Based on photosynthetic principles (Falkowski and Raven, 1997), such lower pigment contents suggest that the cells in the split column face higher light stress. This implies that these cells have more chance to visit the wall regions, resulting in a better performance. These results are consistent with the observed spiral movement of tracer particles in split column observed by Luo et al. (2003). In the split column, as cells move up and down spirally in the riser or downcomer, the cells' accessibility to the outer wall region

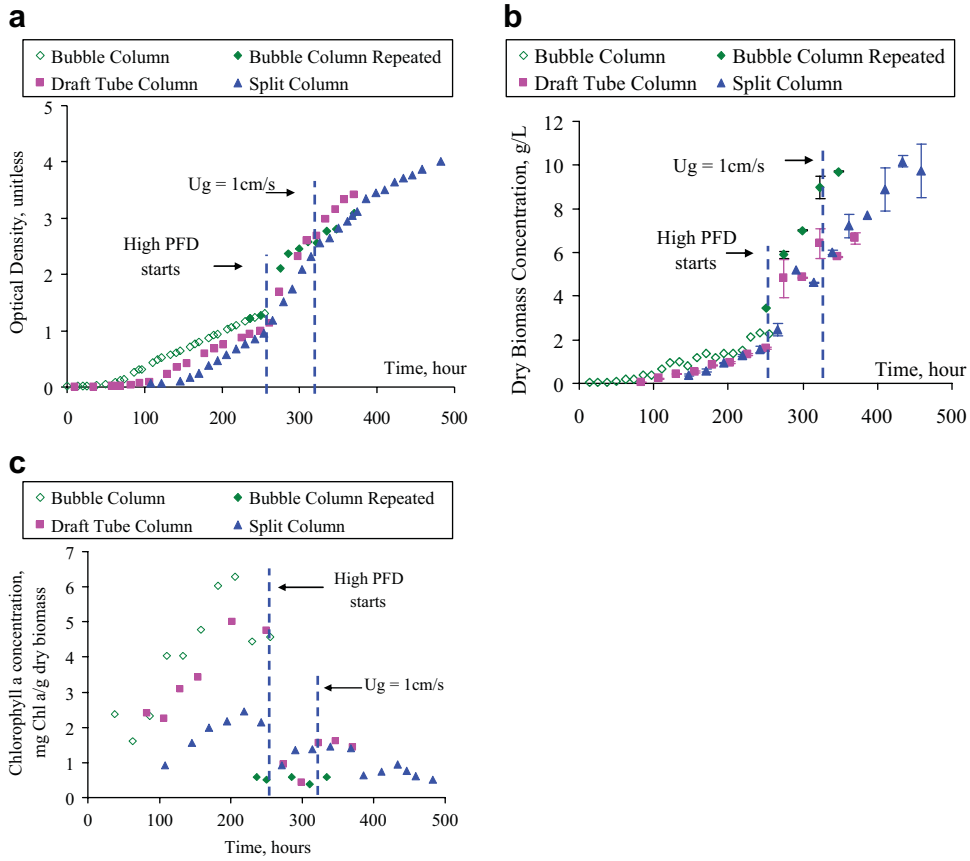

Figure 6. Biomass concentration evolutions in three airlift column photobioreactors for *Porphyridium* sp. culturing. **a**: Evolution of the culture media's optical density; (**b**) evolution of the dry biomass concentration; (**c**) evolution of chlorophyll (a) concentration normalized by the dry biomass concentration. Please note that the culture in the bubble column failed due to overheating after the high light intensity lamps were switched on (halogen lamps was used in the first trial). The experiment with high PFD in the bubble column therefore was repeated using fluorescent lamps as described in the Experiments Section.

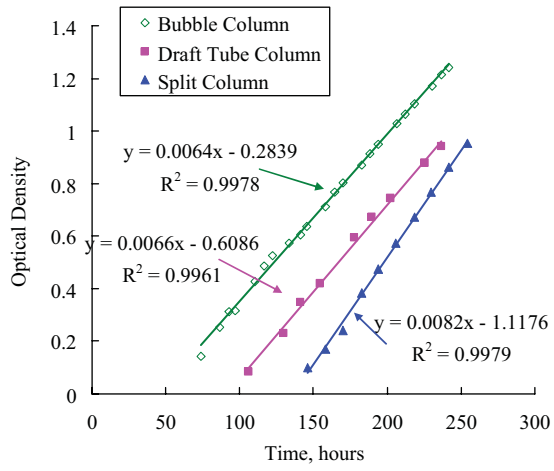

Figure 7. Evolution of the optical density in the studied photobioreactors for *Porphyridium* sp. culturing at the active growth stage.

where light is abundant is enhanced, promoting the light fluctuations experienced by the cells, and thus improving the reactor performance.

When all lamps were switched on, a sudden drop of the chlorophyll (a) concentration was observed for all the studied columns, indicating photoinhibition became prominent. Moreover, the chlorophyll (a) concentrations of the split and the draft tube columns eventually settled to a similar level, which was higher than that of the bubble column. Unfortunately, the experiment for the bubble column failed initially, and was later resumed. Because of that, it is not clear the lower pigment concentration presented in the bubble column was a result of the experimental error or due to more prominent photoinhibition effects.

These results suggest that the reactor geometry can affect the reactor performance. More comprehensive studies are required, though, to better understand the effects of the reactor geometry, and thus the local flow dynamics, on the photobioreactor performance.

Summary

In this work, a red alga, *Porphyridium* sp., was cultured in three airlift column photobioreactors. The physical properties of the liquid phase, the local flow dynamic characteristics, and the biomass concentration in the reactors were studied. The following conclusions can be drawn from this work:

- *Porphyridium* sp. excretes polysaccharides, which significantly changed the culture medium into a typical shear-thinning fluid. The surface tension of the medium however remained constant;
- The presence of microalgae considerably affected the local multiphase flow dynamics in the studied draft tube column comparing to that in an air-water system: the cells has less chance to reach the wall regions; the liquid phase turbulent kinetic energy and the local gas holdups in the fully developed flow zone increased appreciably; while the overall liquid circulation velocity and the shear stress changed slightly;
- Comparing to the bubble column and the draft tube column, the split column reactor works slightly better at the active growth stage and had the lowest photoinhibition effects. At high PFD, photoinhibition is significant and increasing the superficial gas velocity had limited effects on the reactor performance.

Nomenclature

Ca	concentrations of chlorophyll (a), g/mL
OD	optical densities
Ug	superficial gas velocity, cm/s

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