CHEMICAL ENGINEERING TRANSACTIONS Volume 21, 2010
Editor J. J. Klemeš, H. L. Lam, P. S. Varbanov
 ISBN 978-88-95608-05-1 ISSN 1974-9791
DOI: 10.3303/CET1021033

Preliminary Investigation of an Integrated Photobioreactor System for Microalgal CO_2 Fixation

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This study involves an integrated carbon reduction system that encompasses a CO_2 stripper, a close-loop microalgal photobioreactor, and a membrane harvesting system. This paper reports the laboratory-scale evaluation of each unit operation, and the results were used as basis of the scale-up system, which had been installed and begun operation. The system design of the pilot-scale system is also described in the paper.

1. Introduction

The international scientific community has agreed that the excessive emission of greenhouse gases (GHGs) from anthropogenic activities exacerbated global warming. Initiative actions exemplified by the signing of the Kyoto protocol in 1997 had many developed and developing countries to voluntarily reduce the emissions of GHGs down to the levels in the early 90's before 2012. In Taiwan, the government has also vowed to "return" the CO_2 emissions back to the 2008 level by 2016, and to 2000 level by 2025.
Reduction of energy use and energy restructuring that favours the use of renewable/clean energy are the primary strategies for most of the countries to achieve carbon reduction, however such strategies are daunting tasks in themselves because of pressures such as continuing population growth, energy costs, and technological barriers. Carbon capture and storage, therefore, has also been considered as an indispensable option to reduce carbon emission. Extensive research has been conducted to evaluate the feasibility of large-scale permanent carbon storage in oil fields and ocean beds. This carbon storage process appears to be a potential solution for immediate reduction of carbon, but the cost will be undoubtedly high and its long-term stability remains questionable.
Microbial photosynthesis, particularly by microalgae, is now being reconsidered as a viable technology to reduce carbon. The conventional open-pond cultivation uses sunlight for photosynthetic uptake of CO_2, but suffers from the drawback of night-time respiration that emits the CO_2 back to the atmosphere. The "engineered" microbial photosynthesis processes are then designed to achieve faster growth rate, better carbon fixation efficiency, and greater growth density. These processes are also attractive

Please cite this article as: Den W., Wang Ch-Ch. and Yang S., (2010), Preliminary Investigation of an Integrated Photobioreactor System for Microalgal CO_2 Fixation, Chemical Engineering Transactions, 21, 193-198 DOI: 10.3303/CET1021033

because the microbial extracts may possess substantial commercial values such as dietary supplements and cosmetics components. Consequently, a number of studies involving microalgae carbon fixation have been reported (Kurano et al., 1995; Cheng et al., 2006; Chiu et al. 2008). These studies demonstrated that the microalgae had optimum growth conditions with a CO_2 concentrations in the range of 10~12 %. The carbon fixation rate was in the range between 2 and 20 g/L-day.

In the present study, we design an integrated CO_2 biofixation system that consists of three parts, namely a CO_2 scrubber system, a LED-enhanced photobioreactor system, and a submerged membrane harvesting system. A laboratory-scale system was built to investigate the technical feasibility, and a pilot-scale system has been subsequently installed on the roof of a wafer fabrication facility which uses natural gas for boiler operation. The energy input of the pilot-scale system is supported by a GaAs compound solar panel to yield net CO_2 reduction. The results of the laboratory test results are presented in this paper, and those of the pilot-scale system will be presented in the future when sufficient data is available.

2. Materials and methods

Although the pilot-scale system was designed to integrate CO_2 stripping, microalgae photobioreactor, and membrane harvesting system into a single treatment train, the laboratory-scale testing operated these units independently to evaluate the optimum conditions for each unit. For the CO_2 scrubber, the stripping liquid was a dilute sodium hydroxide (NaOH) solution to absorb CO_2 from air:

$$2NaOH + CO_2 \rightarrow Na_2CO_3 + H_2O \quad (1)$$

The solution was internally circulated at 0.6 L/min through the column filled with size-15 plastic pall rings. The stripping performance was evaluated using various air flowrates (5 to 20 L/min), NaOH concentrations (0.1 to 1.0M), and inlet CO_2 concentration (air to 0.1%) detected by a non-dispersive infrared CO_2 sensor. In addition, the total inorganic carbon (TIC) accumulated in the stripping solution was measured by a TOC analyzer (Elementar Liqui TOC).

A culture of *Spirulina maxima* was obtained from Taiwan Fisheries Research Institute (Tung-Kang, Taiwan), and was used as the primary microalgae for carbon fixation. The cell of *S. maxima* was cultured in the modified f/2 medium (per liter) that includes 1.25 g $NaNO_3$, 0.6 g NH_4NO_3, 0.5 g K_2HPO_4, 1.0 g K_2SO_4, 1.0 g NaCl, as well as 16 g $NaHCO_3$ as the added carbon source. The cultures were placed at room temperature under continuous exposure of fluorescent light, with continuously aeration at a rate of 250 mL/min. The cell density was measured by an UV-VIS spectrophometer at an absorbance wavelength of 680 nm, which provided a linear correlation with dry biomass density up to an optical density of 1.0.

Seven days after inoculation, the microalgae were harvested by membrane filtration which was effectively a typical membrane bioreactor with a proprietary flat circular discs membrane module (NCM Co., Taiwan). The PVDF ultrafiltration (UF) membrane has a nominal pore size of 0.03 μm, and the testing module contained 15 pieces of UF discs (effective area of 0.36 m^2). The permeate flux and the transmembrane pressure (TMP) were continuously recorded to observe the membrane fouling condition. Theoretically, if the membrane did not experience significant fouling, then the retained

solution would accumulate biomass continuously, hence achieving the purpose of harvesting biomass from liquid.

3. Results and Discussion

3.1 CO_2 stripping efficiency

The effect of different NaOH concentrations (0.1, 0.5, and 1.0 M) in the scrubbing solutions is shown in Figure 1(a). Evidently, CO_2 stripping with water was not effective, with only 2% reduction. Increasing the NaOH dosage would significantly enhance the CO_2 stripping efficiency, attaining as high as 64% reduction efficiency even with a low inlet CO_2 content (air ~400 ppmv). Following Eq. (1), the CO_2 stripped from air yielded sodium carbonate in the solution, lowering the solution pH that eventually reaches the pKa of carbonate system near the neutral range which becomes suitable for microalgal photosynthetic growth. In practical applications, one must also consider that NaOH becomes corrosive as its dosage exceeds 0.5 M even though it was more effective in CO_2 stripping. Consequently, a NaOH dosage of 0.1 M was used in the tests hereafter.

We also observed that an optimum air flowrates existed during CO_2 stripping process under a fixed liquid circulation rate (0.6 L/min). For example, the CO_2 reduction efficiency was lower for air flowrate at 5 L/min than those at 10 L/min and 20 L/min. However the air CO_2 reduction efficiency as well as the dissolved TIC concentration in the stripper solution, was lower for air flowrate at 20 L/min than those at 10 L/min. These results reveal that a balance between the mass transfer driving force and the air/liquid contact time must have existed, suggesting that the optimum air-to-liquid flowrate should be determined for a given system. Furthermore, experimental results demonstrated that the scrubber was much more effective for air containing higher CO_2 concentration (1.61%) as compared to ambient condition (~400 ppmv).

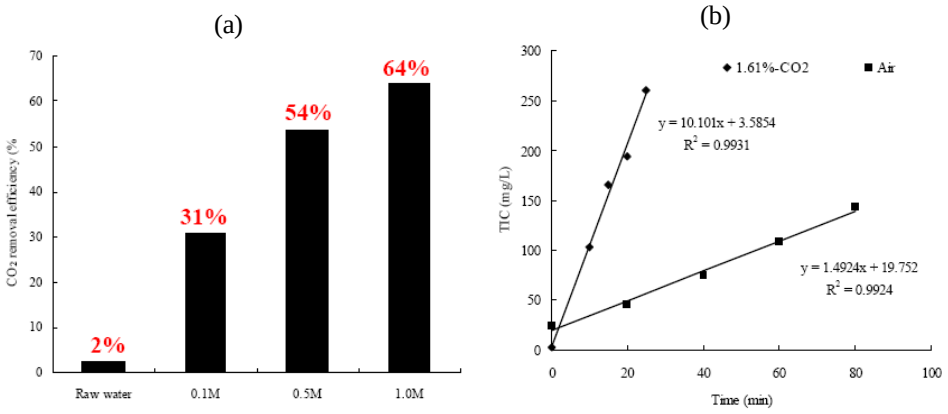

Figure 1: (a) CO_2 stripping efficiency with different NaOH concentration (CO_2 inlet ~ 400 ppmv, air flowrate = 20 L/min); (b) the accumulated dissolve inorganic carbon (TIC) in stripping solution at two CO_2 concentrations.

3.2 Microalgal cultivation and growth conditions

Figure 2 shows the various growth conditions of *S. Maxima* tested in this study, including aeration in combination with dosing with $NaHCO_3$, as well as aeration with CO_2-enhanced air with or without dosing with $NaHCO_3$. The *Spirulina* did not exhibit significant growth with only air aeration without additional carbon source (data not shown). In general, under aeration, higher *Spirulina* growth was observed when the cultivation solution contained greater amount of $NaHCO_3$. When the air was conditioned with 0.5% CO_2 for aeration, but with no addition of $NaHCO_3$ in the solution, one could still observe clear growth, although the rate of growth within the initial 5 days was substantially slower than those with $NaHCO_3$ addition. Furthermore, when providing both CO_2 (2 %) and $NaHCO_3$, the *Spirulina* growth characteristics became similar to those with large dosing levels of $NaHCO_3$. These results indicated that the *Spirulina* can grow either with $NaHCO_3$-enhanced medium or with CO_2 dissolved in the solution, but only if sufficient CO_2 concentration is present. It was not yet clear whether the *Spirulina* prefers $NaHCO_3$ medium or dissolved CO_2, considering the two conditions yield different aqueous carbonate systems. Multiple tests are currently being conducted to verify the growth curves and to clarify the preferred growth conditions.

We had also conducted parallel studies with a *Chlorella* species, another commonly cultivated micro alga with multiple commercial uses. The *Chlorella sp*. exhibited completely difference growth condition, as it clearly preferred dissolution of CO_2 from air, and showed no significant growth with dosing carbonates. Therefore, the fact that the *Spirulina* indeed utilized dosed carbonates verified that the CO_2 stripping solutions could be used to cultivate the microalgae, and was deemed suitable for our engineered process.

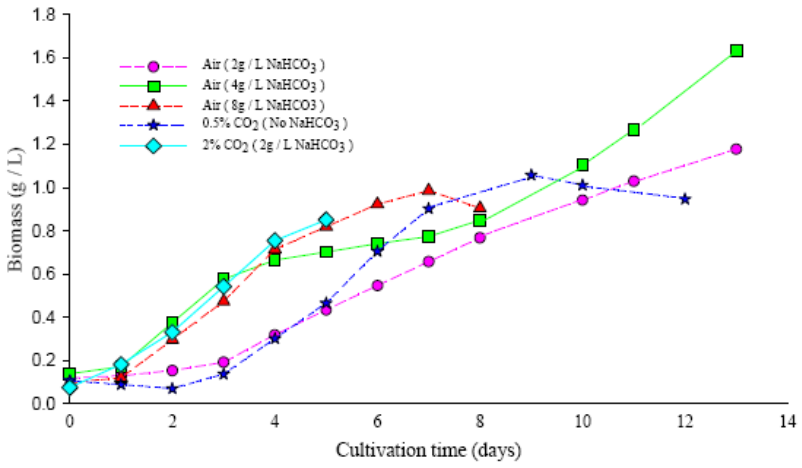

Figure 2: S. maxima growth curves with various carbon sources.

3.3 Membrane harvesting study

Membrane harvesting study was conducted with *Spirulina* as the targeted species. Since the pore size of the UF membrane virtually guaranteed that the microalgae would be completely separated from the water, this part of the study intended to clarify whether

the density of the retained biomass was proportional to the volume of water treated, and whether a constant flux could be sustained with effective membrane cleaning. It should be noted that high-speed centrifugation still represents the mainstream microalgae harvesting process by virtue of its effectiveness. Centrifugation, however, is energy intensive, and thus becomes a less desirable option as part of the carbon reduction process. Membrane filtration is also effective in separating biomass, though system design to harvest dense biomass remains to be improved.

Figure 3(a) shows the permeate flux and the corresponding TMP over the test period. The initial liquid flux was set at 0.88 m^3/day (100 LMH), and the permeate flux gradually decreased over the course of filtration. At the same time, the TMP rapidly built up and reach a test ceiling of 0.26 kg/cm^2, indicating that a dense layer of biomass was rapidly developing on the surface of the membrane. Aeration was an important factor, as the permeate flux was 25 % higher than that without aeration (data not shown), and a slower buildup of TMP. Consequently, backwashing was performed when the permeate flux reached 0.20 m^3/day using a small volume of the permeate water. The design of the disc membrane configuration makes the backwashing mechanism unique: with no chemical addition, the permeate water is reversed, filling and "ballooning" the discs such that the surface cake quickly detach from the surface, with the aid of continuing aeration to induce shear force on the surface. The backwash was effective, as the initial flux could be completely restored. Figure 3(b) shows the accumulated volume of filtration converted from the operating condition exemplified in Fig. 3(a). The resulting accumulation of biomass in the filtration tank matched well with the filtration volume (i.e., tank volume/filtrate volume ~ biomass accumulation factor). The aforementioned result can serve as a useful design parameter for scale-up membrane filtration process.

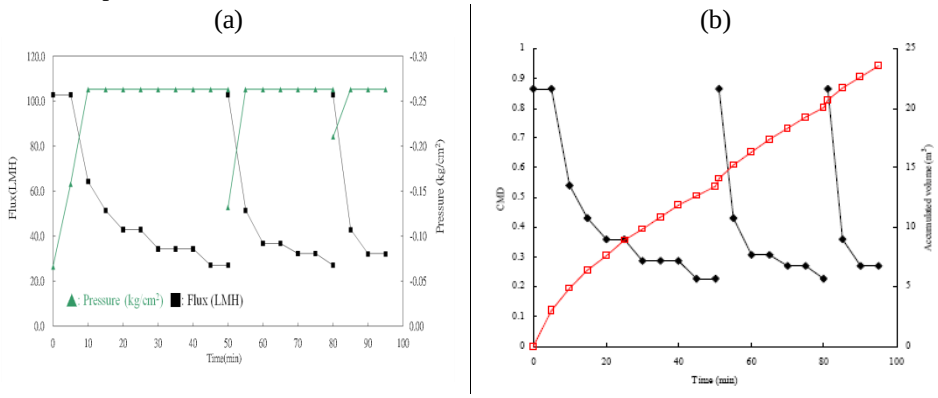

Figure 3: (a) Change of permeate flux and TMP with filtration time; (b) the accumulated filtrate volume. The test specie was S. maxima.

3.4 Pilot-scale system

Figure 4 shows the images of the pilot-scale system operated on the roof of a wafer fabrication plant using natural gas boilers. The exhaust temperature fluctuates between 50 and 60 °C, and the CO_2 content was rather consistent at 16.1 %. A fraction of the exhaust was redirected to the CO_2 stripping column as shown at the forefront of Fig. 4(a)

equipped with a pre-cooling sprayer. The endpoint of the NaOH-containing stripping water was set up a pH 8.0, after which the stripped water is stored and used as the cultivation liquid. Ten parallel photobioreactors (total volume of 2 m^3), each equipped with an aeration apparatus to enhance mixing, were installed, as shown in Fig. 4(b). The photobioreactors were equipped with LED lighting on both sides of the wall to provide night-time light source for continuing photosynthesis. Each batch of cultivation lasts five days, after which the culture was pumped into a storage tank for the ensuing membrane filtration. The system had been continuously running for nearly a month, and the preliminary data will be presented in the conference.

Figure 4: Pilot-scale integrated system: (a) site layout showing the scrubber, and a series photobioreactors; (b) photobioreactors in operation with microalgae; (c) membrane harvesting.

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