Korean J. of Chem. Eng., **14**(4), 297-300 (1997)
SHORT COMMUNICATION

DEVELOPMENT OF GAS RECYCLING PHOTOBIOREACTOR SYSTEM FOR MICROALGAL CARBON DIOXIDE FIXATION

Yeoung-Sang Yun and Jong Moon Park†

Department of Chemical Engineering, School of Environmental Engineering,
Pohang University of Science and Technology, Pohang 790-784, Korea
(Received 3 May 1997 • accepted 8 July 1997)

Abstract – A gas recycling photobioreactor was developed to achieve high CO_2 conversion, in which *Chlorella vulgaris* was cultivated under various light intensities. The light intensity affected the algal growth and the CO_2 concentration in the exit gas. However, the final cell density was independent of light intensity and was limited by nitrate concentration in the medium. In the linear growth phase, the CO_2 concentration in the exit gas ranged 4.6 to 6.0 % (v/v) when 20 % (v/v) CO_2 balanced with 80 % (v/v) N_2 was introduced into the photobioreactor. The gas recycling photobioreactor developed in this work was claimed to be a useful system for microalgal CO_2 fixation.

Key words: Gas Recycling Photobioreactor, Carbon Dioxide Fixation, Photosynthesis, Microalgae, Light Intensity

INTRODUCTION

Increased concentration of carbon dioxide (CO_2) in the atmosphere is considered to be one of main causes of global warming problem [Schneider, 1989]. Among various methods for CO_2 reduction (absorption, adsorption, chemical fixation, etc.), biological CO_2 fixation by microalgal photosynthesis has been proposed as an economically feasible method [Karube et al., 1992]. However, for a practical and large scale microalgal CO_2 fixation, there are some problems to be solved such as inhibition of algal growth by high CO_2 concentration, requirement of large amount of nutrients such as nitrogen and phosphorus and low CO_2 conversion due to short gas retention time.

Since flue gases from industries such as steel-making plants and thermal power stations contain about 500 times higher concentration of CO_2 [10-20 % (v/v)] than that in the air, selection and screening of suitable algal strains having tolerance to high CO_2 concentration have been extensively carried out as an essential step for the biological CO_2 removal from flue gases [Negoro et al., 1991; Takeuchi et al., 1992; Hanagata et al., 1992; Kodama et al., 1993]. Recently, it was found that the CO_2 tolerance of *Chlorella vulgaris* was enhanced by gradual increase of CO_2 concentration [Yun et al., 1996]. In addition, simultaneous removal of CO_2 from flue gases and nutrients from wastewater was proposed as an economically feasible process [Yun et al., 1997]. However, the CO_2 conversion still remains too low to remove CO_2 practically from flue gases. In previous studies on microalgal CO_2 fixation, the CO_2 fixation rate and the conversion could not be monitored by direct measurement of CO_2 in the inlet and exit gas but have been roughly estimated from the algal growth rate and the carbon content of algal cells.

In this study, a gas recycling photobioreactor has been designed and used for algal cultivation in order to achieve high CO_2 conversion. The algal growth rates in the exponential growth and in the linear growth phase were estimated at various light intensities. The composition of exit gas from the photobioreactor and the concentration of dissolved inorganic carbon in the medium were analyzed during the culture time.

†Corresponding Author

DESIGN AND OPERATION OF PHOTOBIOREACTOR

Fig. 1 shows the schematic diagram of gas recycling photobioreactor. Dimension of culture vessel is detailed in Table 1. The inlet gas was supplied from a compressed bomb containing 20 % (v/v) CO_2 balanced with 80 % (v/v) N_2. The inlet gas was supplied to the photobioreactor by peristaltic pump at a flow rate of 0.001 $dm^3\ min^{-1}$. The gas was recycled by

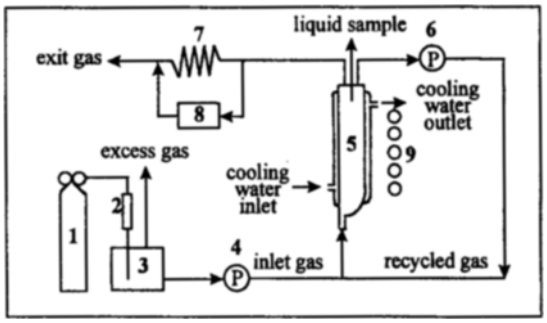

Fig. 1. Schematic diagram of gas recycling photobioreactor.

1: Compressed gas bomb containing 20 % (v/v) carbon dioxide
2: Gas flow meter
3: Gas container
4: Inlet gas pump
5: Culture vessel
6: Gas recycling pump
7: Back-mixing prevention loop
8: Gas chromatography
9: Fluorescent tubes

Table 1. Dimension of gas recycling photobioreactor

Item	Unit	Quantity
Diameter of culture vessel	cm	2.3
Height of culture vessel	cm	44.0
Total volume of culture vessel	dm^3	0.18
Working volume	dm^3	0.12

peristaltic pump with a flow rate of 0.3 dm^3 min^{-1}. The exit gas from the photobioreactor was discharged through a loop preventing back-mixing which was made of 1 m tube in order to avoid inflow of air into the photobioreactor. Fluorescent tubes (GE, Korea) were used for one-sided illumination and the light intensity was modulated by changing the distance between the light source and the photobioreactor.

The advantages of our gas recycling photobioreactor are: (1) With the increase of gas retention time, the CO_2 concentration in the recycled gas can be maintained at the optimal range of algal photosynthesis despite the CO_2 concentration in the inlet gas is the typical CO_2 concentration in flue gases (10-20% (v/v)); (2) Therefore, algal strains without tolerance to high CO_2 concentration can be successfully cultivated without inhibition by high CO_2 concentration in the photobioreactor; (3) The high CO_2 conversion can be achieved by increasing gas retention time; (4) The high CO_2 fixation rate can be achieved by active algal photosynthesis in the gas recycling photobioreactor; and (5) The CO_2 fixation rate and the O_2 production rate can be determined directly by common methods of gas analysis and quantitative evaluation of reactor performance is possible because of high CO_2 conversion.

MATERIALS AND METHODS

1. Algal Strains, Medium and Seed Culture

A green microalga, *Chlorella vularis* UTEX 259, was obtained from the Culture Collection of Algae at the University of Texas, Austin, TX, USA [Starr and Zeikus, 1993]. Inoculum was prepared in 0.25 dm^3 bottles with 0.2 dm^3 of N8 medium [Vonshak, 1986] by successive subculture in a light incubator at 27 °C with air bubbling.

2. Cultivation in Gas Recycling Photobioreactor

The N8 medium and the photobioreactor were autoclaved separately at 121 °C for 20 min. Before inoculating algal cells, the medium in the reactor was saturated with 20% (v/v) CO_2 by bubbling for 24 hours. The characteristics of CO_2 absorption into the cell-free medium are described in Results and Discussion. The temperature was maintained at 27 °C by circulating water with constant temperature through the outer jacket of culture vessel.

3. Analyses

The algal growth was monitored by absorbance at 750 nm using a spectrophotometer (Spectronic 21, Milton Roy) which was converted into dry cell weight. Gas compositions were analyzed by a gas chromatography (GC-600D, Young-In, Korea) with a thermal conductivity detector. The total amount of dissolved inorganic carbon (TIC) was determined by a TOC analyzer (TOC-5000A, Shimatzu, Japan). Other forms of dissolved inorganic carbon (dissolved CO_2, HCO_3^-, CO_3^{2-}) were estimated by the Henderson-Hasselbach equation using equilibrium constants for pure water. The concentration of anions were analyzed by an ion chromatography (Dionex) with a conductivity detector as described previously [Yun et al., 1997]. The incident light intensity was measured at the surface of the culture vessel by a quantum sensor (LI-190SA, Licor, USA) connected to a readout instrument (L-1000, Licor, USA).

RESULTS AND DISCUSSION

1. CO_2 Permeation

Fig. 2 shows the CO_2 concentration in the exit gas when the photobioreactor was operated without algal cells. After the gas containing 20% (v/v) CO_2 was introduced into the photobioreactor, the CO_2 concentration in the exit gas increased and reached the maximum value of 15.7% (v/v) which was lower than that of inlet gas (20% (v/v)). It is probably due to permeation of CO_2 through tubes and silicon connectors used for fitting of gas lines. For the quantitative analyses of reactor performance such as CO_2 fixation rate and the CO_2 conversion, the exact amount of permeated CO_2 should be evaluated. Currently, the effect of CO_2 permeation is under investigation in our group.

2. Algal Growth and CO_2 Fixation

A typical time course of algal growth and the change of pH value in the medium are shown in Fig. 3. *C. vulgaris* grew

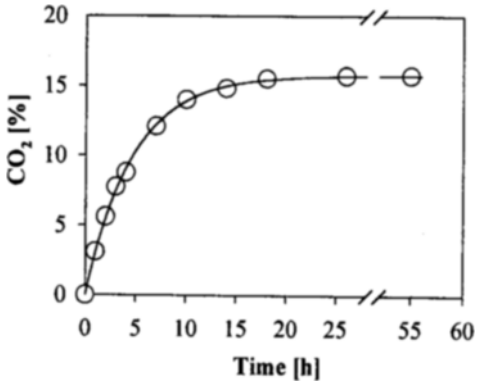

Fig. 2. Change of carbon dioxide concentration in the exit gas from gas recycling photobioreactor filled with cell-free medium.

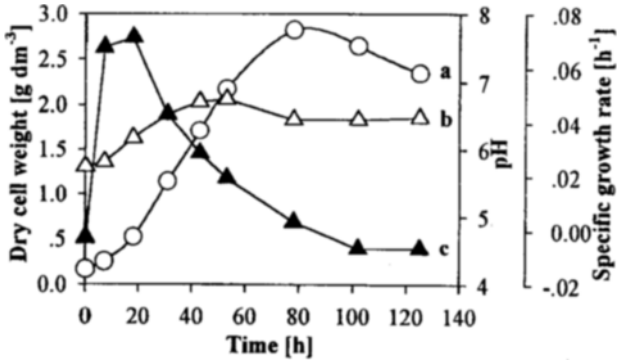

Fig. 3. Algal growth in the gas recycling photobioreactor.
a: dry cell weight, b: pH, c: specific growth rate.

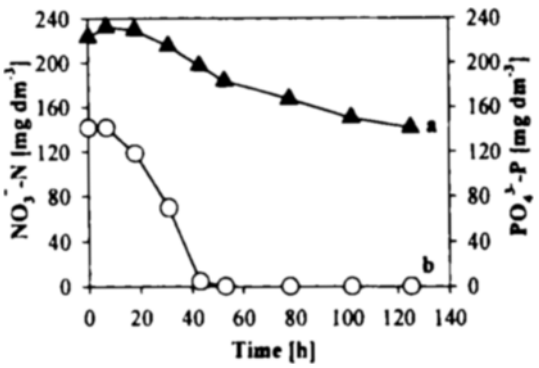

Fig. 4. Consumption of nutrients by algal culture in the gas recycling photobioreactor.
a: phosphate, b: nitrate.

almost linearly after a short period of exponential growth phase and the specific growth rate showed a typical decreasing pattern in the linear growth phase. The maximum cell density was 2.82 g dm^{-3} and was limited by NO_3^- which was depleted after 53 hours of culture time (Fig. 4). The pH value in the algal culture increased at the early growth phase mainly because of assimilation of NO_3^- as a nitrogen source and remained constant after the depletion of NO_3^-.

As shown in Fig. 5, the change of concentration of CO_2 and O_2 in the exit gas showed a symmetric pattern and this indicated that the alga grew photoautotrophically in the photobioreactor. The CO_2 concentration in the exit gas dropped sharply according to algal growth and reached a minimum value of 4.6% (v/v) which corresponded to the volumetric CO_2 fixation rate of 0.14 g CO_2 dm^{-3} h^{-1}. In the linear growth phase where most of growth occurred, the CO_2 concentration ranged between 4.6 and 6.0% (v/v) which is near optimum concentration of CO_2 for the photosynthesis of *C. vulgaris* [Yun et al., 1996].

The concentration of total inorganic carbon increased during the algal growth although the inorganic carbon was actively fixed by algal photosynthetic activity because the carbonate equilibrium was shifted into HCO_3^- by increase of the pH value in the algal culture (Fig. 6). The dissolved CO_2 concentration remained constant in the linear growth phase.

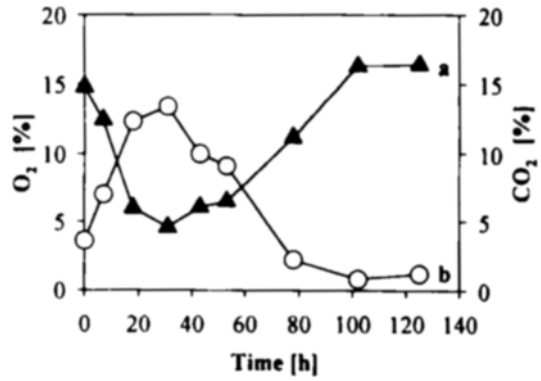

Fig. 5. Carbon dioxide fixation and oxygen production by algal culture in the gas recycling photobioreactor.
a: carbon dioxide, b: oxygen.

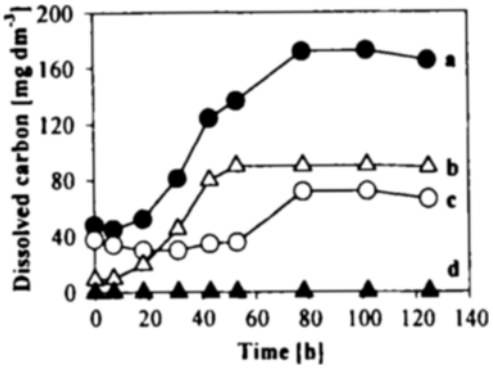

Fig. 6. Dissolved inorganic carbons in the algal culture.
a: total inorganic carbon, b: bicarbonate, c: dissolved carbon dioxide, d: carbonate.

Table 2. The algal growth and CO_2 conversion at different light intensities

Item	Unit	Light intensity [μE m^{-2} s^{-1}]		
		200	130	70
μ^a	h^{-1}	0.071	0.056	0.042
r_X^b	g dw dm^{-3} h^{-1}	0.047	0.36	0.028
X_{max}^c	g dm^{-3}	2.80	2.79	2.81
CO_2^d $(g)_{min}$	%	4.6	6.7	8.2
O_2^e $(g)_{max}$	%	13.4	9.6	7.1

[a]specific growth rate in the exponential growth phase.
[b]volumetric growth rate in the linear growth phase.
[c]maximum cell density.
[d]minimum CO_2 concentration in the exit gas.
[e]maximum O_2 concentration in the exit gas.

The concentration of CO_3^{2-} was negligible compared to other forms of inorganic carbon.

3. Effect of Light Intensity

C. vulgaris was cultivated in the photobioreactor at various light intensities (Table 2). The specific growth rate in the exponential growth phase and the volumetric growth rate in the linear growth phase were dependent on light intensity. However, the maximum cell density was independent of light intensity but determined by NO_3^- concentration in the medium as mentioned previously. The minimum CO_2 concentration and the maximum O_2 concentration were found in the early linear growth phase which were affected by light intensity.

CONCLUSIONS

By cultivating of *C. vulgaris* in the gas recycling photobioreactor, the CO_2 concentration in the exit gas was maintained at the optimal range of the algal growth despite 20% (v/v) CO_2 was introduced into the photobioreactor. In addition, the remarkable reduction of CO_2 concentration made a quantitative measurement of CO_2 consumption possible by a gas chromatography. This is usually impossible in conventional photobioreactor where the difference of CO_2 concentration between inlet and outlet gas is too narrow to detect. The light intensity affected the algal growth and the CO_2 concentration in the exit gas. Based upon these results, it was

concluded that our gas recycling photobioreactor developed in this work could be a useful system for microalgal CO_2 fixation.

ACKNOWLEDGEMENT

This research was supported in part by grants from the School of Environmental Engineering, POSTECH and Automation Research Center, POSTECH.

REFERENCES

Hanagata, N., Takeuchi, T., Fukuju, Y., Barnes, D. J. and Karube, I., "Tolerance of Microalgae to High CO_2 and High Temperature", *Phytochemistry,* **31**, 3345 (1992).

Karube, I., Takeuchi, T. and Barnes, D. J., "Biotechnological Reduction of CO_2 Emissions", *Adv. Biochem. Eng./Biotechnol.,* **46**, 63 (1992).

Kodama, M., Ikemoto, H. and Miyachi, S., "A New Species of Highly CO_2-tolerant Fast-growing Marine Microalga for High Density Culture", *J. Mar. Biotechnol.,* **1**, 21 (1993).

Negoro, M., Shioji, N., Ikuta, Y., Makita, T. and Miura, Y., "Growth of Microaglae in High CO_2 Gas and Effect of SO_x and NO_x", *Appl. Biochem,. Biotechnol.,* **28/29**, 877 (1991).

Schneider, S. H., "The Greenhouse Effect: Science and Policy", *Science,* **243**, 771 (1989).

Starr, R. C. and Zeikus, J. A., "UTEX: the Culture Collection of Algae at the University of Texas at Austin", *J. Phycol.,* **29** (suppl.), 1 (1993).

Takeuchi, T., Utsunomiya, K., Kobayashi, K., Owada, M. and Karube, I., "Carbon Dioxide Fixation by a Unicellular Green Alga *Oocystis* sp.", *J. Biotechnol.,* **5**, 261 (1992).

Vonshak, A., "Laboratory Techniques for the Cultivation of Microalgae", Handbook of Microalgal Mass Culture, Richmond, A., ed., CRC Press, FL, 1986.

Yun, Y.-S., Lee, S. B., Park, J. M., Lee, C.-I. and Yang, J.-W., "Carbon Dioxide Fixation by Algal Cultivation Using Wastewater Nutrients", *J. Chem. Technol. Biotechnol.,* **69**, 451 (1997).

Yun, Y.-S., Park, J. M. and Yang, J.-W., "Enhancement of CO_2 Tolerance of *Chlorella vulgaris* by Gradual Increase of CO_2 Concentration", *Biotechnol. Tech.,* **10**, 713 (1996).