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Carbon Dioxide Fixation by Microalgae Photosynthesis Using Actual Flue Gas Discharged from a Boiler

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ABSTRACT

To mitigate the effects of carbon dioxide discharged from a boiler in a power plant, CO_2 fixation by microalgae photosynthesis was studied. For the algae cultivation, actual flue gas from a boiler was used in two sets of small-sized raceway-type cultivators installed at Tohoku Electric Power Company's Shin-Sendai power station. Using *Nannochloropsis* sp. NANNP-2 and *Phaeodactylum* sp. PHAEO-2 strains from the SERI collection, the microalgae were cultured semicontinuously and harvested periodically. From the results of the field test, the productivity of both strains using direct flue gas was almost on a par with that of bombed CO_2 gas. Therefore, it was clarified that the direct blowing of flue gas into the cultivator did not adversely affect algal growth.

Index Entries: CO_2 elimination; actual flue gas; field test; raceway cultivator; Shin-Sendai power station.

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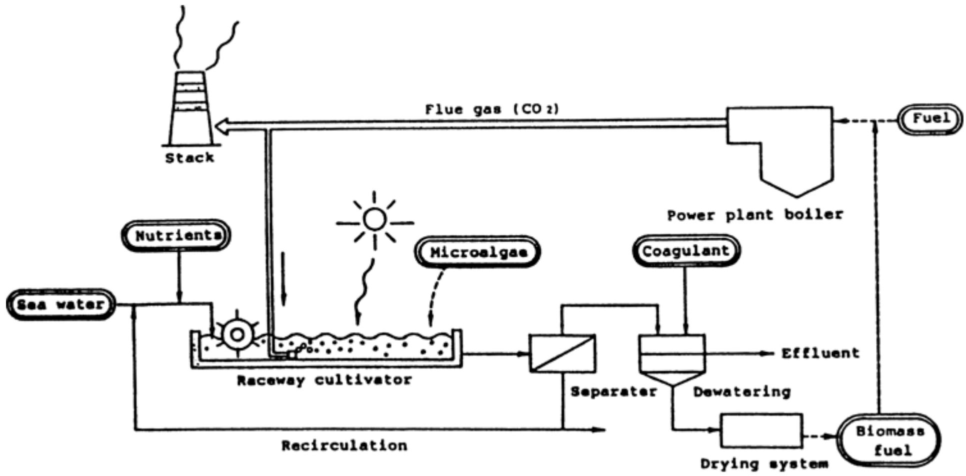

Fig. 1. Conceptual system of CO_2 fixation by microalgae.

INTRODUCTION

In recent years, worldwide studies have been made to mitigate the discharge rate of carbon dioxide, one of the suggested sources of global warming. We have been devoted to the technical development of improved thermal efficiency and utilization of natural energy to reduce consumption of fuels, such as coal and oil. Elimination of CO_2 is possible by physicochemical techniques, such as wet absorption and dry adsorption (*1*), but the fixation technology of CO_2 has not been investigated thoroughly. A study is now being undertaken to develop a system to remove and fix directly CO_2 that has been discharged from a boiler in a power plant by microalgae photosynthesis. CO_2 gas contained in the flue gas could be a useful source of carbon for the mass culture of microalgae.

The conceptual system in this study is shown in the flow sheet in Fig. 1. A part of the flue gas is directly blown into the cultivation ponds, and CO_2 is fixed on microalgae by solar energy. Produced algal cells are utilized by recycling as a biomass crude fuel for a part of the boiler fuel after harvesting processes, such as separating, dewatering, and drying, take place.

Our last papers (*2,3*) reported the experimental results in the laboratory about the growth of marine microalgae at high CO_2 concentration, the effects of SOx, NOx, and dust. Here the authors continue to report on the outdoor test results concerning the growth of microalgae in small-sized raceway ponds using actual flue gas discharged from a boiler.

The test facilities were installed and the culture test, using actual flue gas, was conducted at the Tohoku Electric Power Company's Shin-Sendai power station, located in the northern part of Japan.

Table 1
Specification and Conditions of Test Facilities

Cultivator pond	Type: Raceway with four ways (two sets) Size: 1×2×0.3 m (width) (length) (depth) Material: PVC resin (8-mm thickness) Mixing: Propeller stirrer (two sets/pond)
CO_2 supply method	Case I: Direct supply of actual gas Case II: Bombed 12% CO_2 gas Case III: De-SOx gas
Sea-water supply	Raw water: Near-shore sea water Treatment: Filtration by 10-μm filter
Other conditions	Cultivator temperature: Controlled with a chiller unit Cultivator ponds: Installed in a glass greenhouse

MATERIALS AND METHODS

Algal Strains

Nannochloropsis salina NANNP-2 and *Phaeodactylum tricornutum,* PHAEO-2 were cultured in this test. These were obtained from the Solar Energy Research Institute (SERI), Golden, CO (4). These species were selected on the basis of salinity tolerance, stable growth at high CO_2 level, and calorific value of the biomass.

Test Facilities and Conditions

The specification and conditions of the test facilities are shown in Table 1. The cultivator pond is a small-sized, raceway-type with four channels (1 m width×2 m length×0.3 m depth) and is made of poly vinyl chloride resin. Two propellers were used for mixing and stirring of the culturel medium. About 12% CO_2 compressed gas in a bottle (bombed gas) without impurities and an absorber with 3% hydrogen peroxide to remove SOx, from the flue gas were prepared to compare with actual flue gas. Near-shore sea water was introduced into the pond with nutrients (N and P).

This was treated by passing through a 10-μm-sized cartridge filter. Flue gas was divided by vinyl tubes and blown into the pond by dispersing nozzles. The cultivator temperature was controlled by indirect heat exchange with a chiller unit. Two sets of raceway cultivator, as shown in Fig. 2, were installed in a glass greenhouse sized 4 m width×4 m length×3 m height.

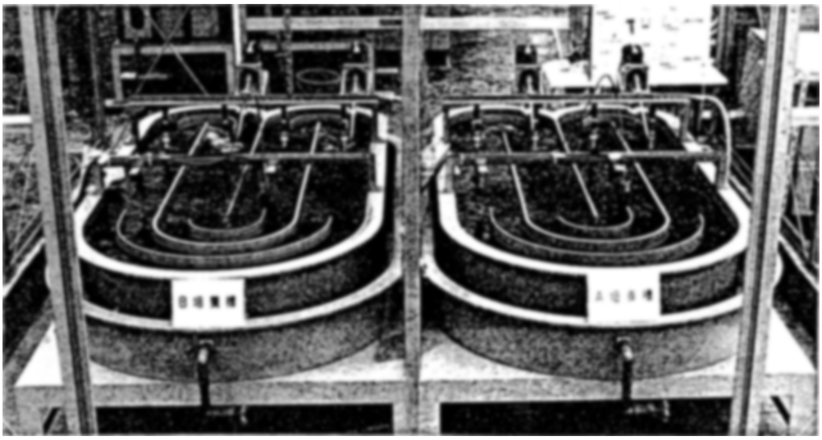

Fig. 2. Raceway cultivator ponds in a glass greenhouse.

Culture Methods and Conditions

The medium for stock cultures and cultivation in the pond was a modification of the f/2 sea-water medium, in which nitrogen and phosphorus were enriched fourfold as 300 mg of $NaNO_3$ and 20 mg of NaH_2PO_4. The increase in nutrients was accounted for by the deficiency of N and P on photosynthesis in the high concentration of CO_2 (12%). The flow velocity of water was 20-30 cm/s, and the gas supply rate was approx 1 L/min. Regarding the concentrations of SOx, NOx, and CO_2 contained in the flue gas in the test period, the range of CO_2 concentration was 10–12%, and that of SOx and NOx 70-90 ppm. The temperature of the culture medium in the test period was 20–27°C, and the value of the pH was 6.6–7.2. Microalgae were cultured semicontinuously and harvested periodically, referred to as the fill-and-draw operating procedure. Specifically, it was decided that the harvesting amount of the biomass be <30%/1 or 2 d.

RESULTS AND DISCUSSION

Growth Curve in Flue Gas

In this test series, the test period of one run was in 2–3 wk to investigate the possibility of cultivation using actual flue gas containing impurities, such as SOx, NOx, and dust. The long-term operation was not carried out.

The growth curve of NANNP-2 is shown in Fig. 3. This test was conducted during the period of September 18 to October 4, 1991 as run no. 3. In this test run, the growth curve using direct flue gas was compared with that of SOx gas removed by chemical absorption. Algal biomass increased to about 200 mg/L in a week and at this time, the produced algal cells

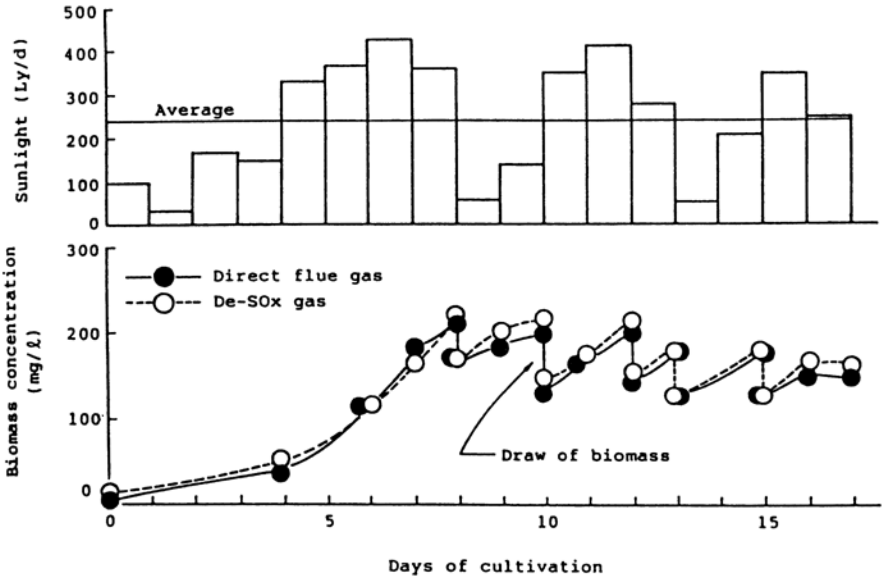

Fig. 3. Biomass concentration of NANNP-2 and sunlight.

were harvested. The authors decided to drawn the algal cells at this time from the results of the pretest; that is, it was found that the efficiency of light utilization decreased, and the activity of microalgae turned down on the conditions of <400 Ly/d sunlight and over 200 mg/L biomass. In this test run, sunlight changed day by day, and the average value was approx 240 Ly/d as shown in the figure. A biomass amount of <30% was drawn per 1–2 d, and the same amount of fresh sea-water medium was supplied. The algae were cultured semicontinuously by repeating this operation. From this test result, the growth curves of both cases show no particular differences.

Chemical Analysis of Harvested Algae

The components by elemental analysis and the total calorific value measured of the harvested dried algal cells are shown in Table 2. NANNP-2 had a calorific value of 5180 kcal/kg, almost the same value as PHAEO-2. These values were used to calculate the photosynthesis efficiency afterward. The components of NANNP-2 and PHAEO-2 were similar to the general microalgae, known as the chlorella species.

Numerical Analysis of Algal Productivity

The photosynthesis reaction rate is generally expressed as shown in Fig. 4. It shows the dependency of light intensity on the growth curve of microalgae. With increasing light intensity, the rate of that reaction increases proportionally, but the rate becomes constant over a certain intensity. This intensity is called the saturation point. On the other hand, the

Table 2
Chemical Analysis of Harvested Algae

Item	NANNP-2	PHAEO-2
Total calorific value	5180 kcal/kg	5090 kcal/kg
Ash	7.0 wt%	9.5 wt%
Carbon (C)	47.5 wt%	46.2 wt%
Hydrogen (H)	6.57 wt%	6.47 wt%
Oxygen (O)	28.0 wt%	*
Nitrogen (N)	8.31 wt%	7.97 wt%
Sulfur (S)	1.82 wt%	*
Phosphorus (P)	0.61 wt%	*

*Not measured.

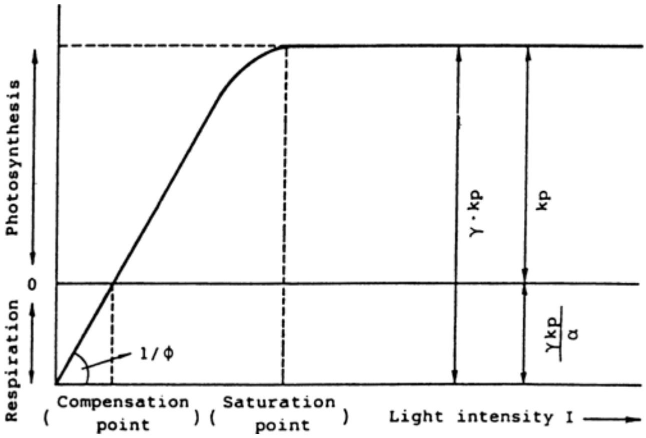

Fig. 4. Dependency of light intensity on growth curve of algae.

decomposition reaction of algae occurs at low light intensity by respiration loss. This intensity is called the compensation point. Now, the photosynthesis rate is given as Eq. (1), in which *kp* is a function of light intensity, *I*. The first term is based on photosynthesis, and the second term is based on respiration loss (5).

$$kp = \gamma \cdot Kp\,[(I / I + \phi) - (1 / \alpha)] \tag{1}$$

where kp = photosynthesis rate (1/h), γ = conversion coefficient (kg − cells/ mL − O_2), Kp = productivity constant (mL − O_2/kg − cells·h), I = light intensity (lux), ϕ = light dependency constant (lux), and α = respiration constant (− 1).

Light intensity, *I*, is a function of algal biomass and water depth, and is expressed as Eq. (2), called Beer's law.

$$I = I_o \cdot \exp(-\epsilon\, C\, \ell) \tag{2}$$

where I_o=light intensity on the surface (lux), ϵ=extinction coefficient (1/[m·kg − cells/m³]), ℓ=water depth from the surface (m), and C=concentration of algal biomass (kg − cells/m³).

Algal productivity per unit surface area of a cultivator pond is expressed as Eq. (3).

$$P_T = 10^3 \times C\,t \int_0^{\ell} kp\, d\,\ell \quad (3)$$

$$= 10^3 \times C\,t\,\gamma\,Kp \int_0^{\ell} [(I / I + \phi) - (1/a)]\, d\,\ell \quad (4)$$

where P_T=algal productivity (g/m²d) and t=daylight hours (h/d). From Eq. (2):

$$(d\,I / d\,\ell) = -\epsilon\, C\, I_o \exp(-\epsilon\, C\, \ell) = -\epsilon\, C\, I \quad (5)$$

Therefore, the solution of Eq. (4) becomes the following:

$$P_T = (10^3 \times t\,\gamma\,Kp / \epsilon)\,\{\ln[(I_o + \phi / I_H + \phi)] - (1/a)\ln[(I_o / I_H)]\} \quad (6)$$

where:

$$I_H = I_o \exp(-\epsilon\, C\, H) \quad (7)$$

The photosynthesis efficiency is calculated by the next equation.

$$\eta = (100 \times P_T \times Q / 10^4 \times E \times a) \quad (8)$$

where η=photosynthesis efficiency (% visible), Q=total calorific value (cal/g), E=total solar energy (Ly/d) or (Ly/h), a=visible light ratio (−)=0.45.

The efficiency η is based on the visible light of solar energy and is expressed as the ratio of output energy to input energy. In Eq. (8), the denominator indicates the visible light energy of sunlight as the input energy, and the numerator indicates the algal productivity by calorific value as the output energy.

Productivity in Flue Gas

NANNP-2 and PHAEO-2 were cultured by blowing bombed CO_2 gas and de-SOx gas to compare with direct flue gas as shown in Table 1. The comparison between these cases was described as the values of productivity, which were calculated from the growth curve data.

Figure 5 shows the producivity of NANNP-2 in the case using direct flue gas compared with bombed CO_2 gas. The values of productivity were calculated from the growth curve as shown in Fig. 3. This test run 1 was conducted in the period of July 19 to August 8, 1991. The dotted values are experimental, and the two straight lines are the correlation calculated by the least-squares method. Although the points are highly scattered, there is little difference between the two lines. The difference in the two results could not be regarded as significant on the whole.

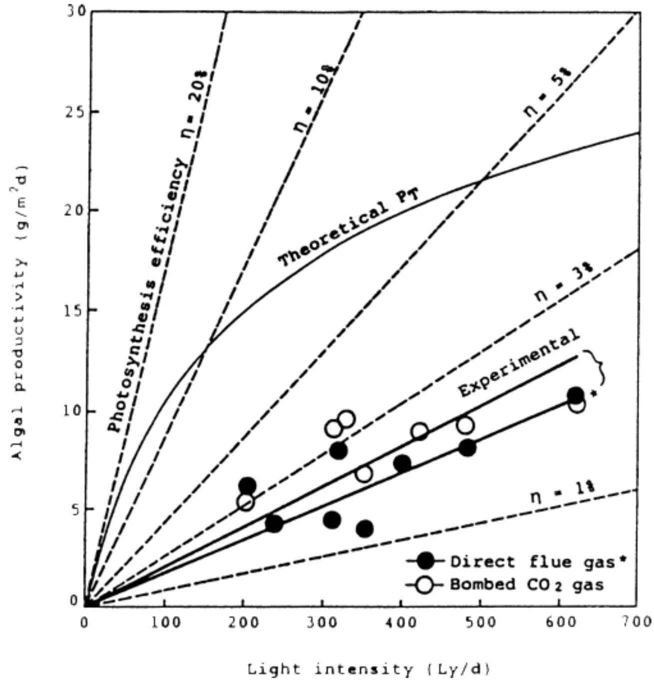

Fig. 5. Comparison between direct flue gas and bombed CO_2 gas.

The smooth curve shows the theoretical productivity calculated by Eq. (6), and the dotted lines show the theoretical photosynthesis efficiency calculated by Eq. (8). The values of algal properties used in the calculation were $Kp = 1.13 \times 10^5$, $\gamma = 8 \times 10^{-7}$, $\epsilon = 130$, $\phi = 2400$, $\alpha = 10$ for NANNP-2. The productivity based on experimental data was about 8–10 g/m^2d at 500 Ly/d of sunlight. That value was lower and only half of that of the theoretical value P_T. Also, the photosynthesis efficiency, η, was about 2–2.5%, which was lower than our expectations.

Figure 6 shows the productivity of NANNP-2 and PHAEO-2 using direct flue gas. This test run 2 was conducted from August 23 to September 8, 1991. As shown in this figure, there was no notable difference in productivity between the two strains. In this case, the productivity was also about 8–9 g/m^2d at 500 Ly/d, and the photosynthesis efficiency was about 2%.

Figure 7 shows the comparison between direct flue gas and de-SOx gas. This test run 3 was conducted last autumn and described previously. The values of productivity in both cases were similar. That of direct flue gas was about 10 g/m^2d at 400 Ly/d, and the photosynthesis efficiency was about 3%. Next, the productivity per hour was examined in the daytime. This experiment was conducted in 1 d during test run 3.

Figure 8 shows the growth curve of NANNP-2 and the light intensity in the daytime, and also shows the comparison between experimental and theoretical on the productivity and photosynthesis efficiency. The

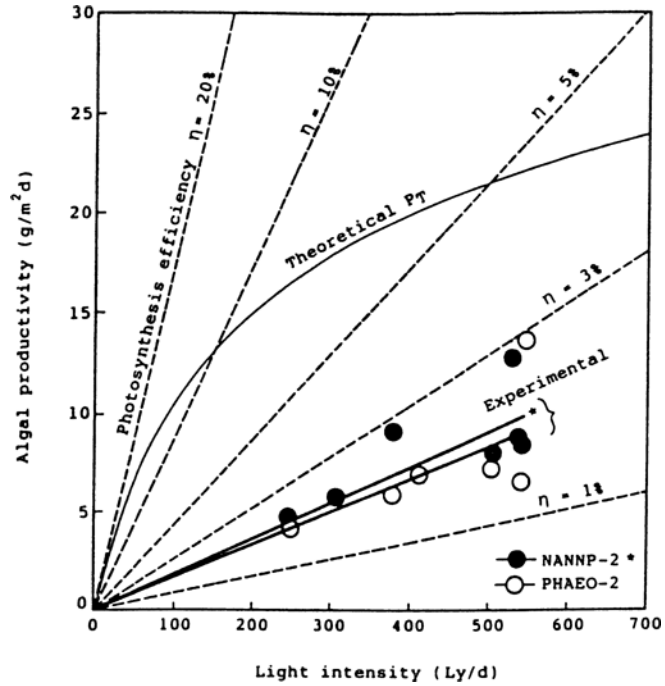

Fig. 6. Comparison between NANNP-2 and PHAEO-2.

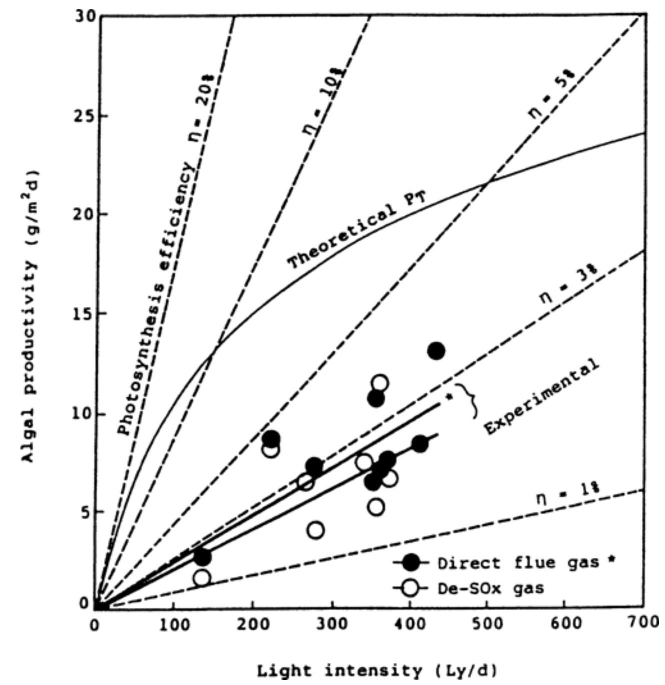

Fig. 7. Comparison between direct flue gas and de-SOx gas.

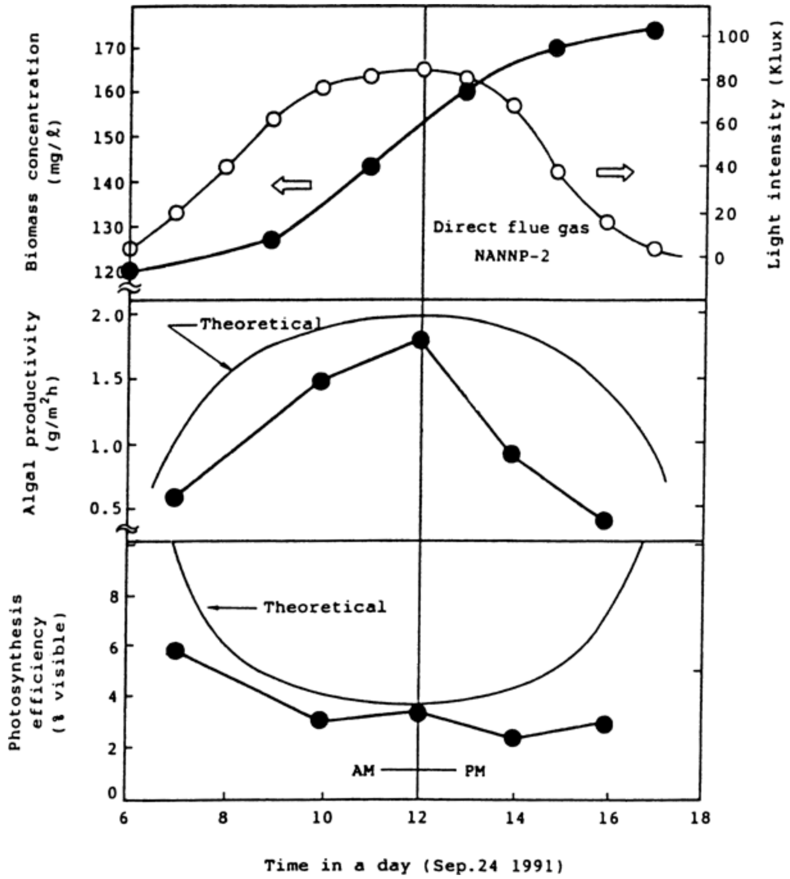

Fig. 8. Sunlight intensity and algal productivity in a day.

productivity per hour increased to the maximum value, and reached nearly the theoretical value at noon. However, the photosynthesis efficiency was not higher, in spite of the sufficient daylight intensity. In this test, the productivity per day that was accumulated from 07:00 to 16:00 was about 10 g/m^2d at 400 Ly/d. The photosynthesis efficiency was about 3%, the same value as in Fig. 7. From the results of a series of tests, it was clarified that the direct blowing of flue gas did not adversely affect algal growth.

CONCLUSIONS

The productivities of NANNP-2 and PHAEO-2 using actual flue gas were almost on a par with that of bombed CO_2 gas. The growth of algae was barely influenced by impurities such as SOx, NOx, and dust contained in the flue gas. The productivity of both strains is about 10 g/m^2 in outdoor conditions using a small-sized, race-way cultivator pond. That is half the value obtained in the laboratory last year. The suspected causes are such problems as changing of sunlight and insufficient mixing of the medium. However, direct blowing of the flue gas into a cultivator pond did not adversely affect algal growth.

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