FOOD PRODUCTION and GAS EXCHANGE SYSTEM using BLUE-GREEN ALGA (SPIRULINA) for CELSS

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ABSTRACT

In order to reduce the cultivation area required for the growth of higher plants in space adoption of algae, which have a higher photosynthetic ability, seems very suitable for obtaining oxygen and food as a useful source of high quality protein.

The preliminary cultivation experiment for determining optimum cultivation conditions and for obtaining the critical design parameters of the cultivator itself has been conducted.

Spirulina was cultivated in the 6-liter medium containing a sodium hydrogen carbonate solution and a cultivation temperature controlled using a thermostat. Generated oxygen gas was separated using a polypropyrene porous hollow fiber membrane module. Through this experiment, oxygen gas (at a concentration of more than 46%) at a rate of 100 ~ 150 ml per minute could be obtained.

INTRODUCTION

To support the long duration stay of human beings in space, technology to recover O_2 gas from CO_2 gas exhaled by human beings and a continuous food production system must be established. Environmental control system hardware for supporting life science experiments plans to use solid amine for removing excessive CO_2 gas and some kind of salcomine for recovering excessive O_2 gas produced by higher plants and algae. Otherwise, Sabatier or Bosch method is also planned to be used for reduction from CO_2 gas to O_2 gas. Though these physico-chemical methods are very effective for gas exchanges, they have no ability to producing foods.

The utilization of biological methods in space is advantageous for producing food and also for conducting gas exchange simultaneously. However, there are various problems with this method. If we plan to conduct the gas exchanges using only higher plants a very large cultivation area is required. The required quantity of O_2 gas per day for supporting a crew is about 0.9 kg. Harvesting of 1.0 kg dry weight of leaf vegetables such as lettuce through about 3 month cultivation time requires about 1.6 kg of CO_2 gas and produces 1.2 kg of O_2 gas. To get 0.9 kg of O_2 gas, for example, cultivation area where produces 70 kg of lettuce is required. Therefore, another bio-species such as algae having higher photosynthetic ability is profitable to be adopted in Controlled Ecolgical Life Suppord Systems (CELSS).

UTILIZATION OF ALGAE AS FOOD RESOURCE

To use algae as food, it is desirable to establish the following conditions; ① Mass production ability. ② High quality protein and mineral biomass. ③ Lower production costs. ④ No toxicity. ⑤ Acceptable taste.

Chlorella, a green alga, has been studied for about 30 years and could be used as the protein source, but utilization of Chlorella as food in CELSS seems very difficult for following reasons; ① A high speed centrifugal separator which needs very high energy consumption must be used for harvesting because of its very small size (nearly 5 μm). ② Since the cell wall consists of crude fiber, it is indigestible by the human body without pulverization. ③ Contamination by a virus or a bacillus occurs easily because the nutrient solution is weakly acidic.

Then, Spirulina, a kind of blue-green alga, has been proposed because of the following distinctive features; ① Harvesting is very easy because the size is about 100 times that of Chlorella. ② Cell is made of viscous polysaccharide and is very easily digested. ③ Contamination seldom occures because the medium is heavily alkaline.

These characteristics cover most of the weak points of Chlorella and furthermore, the protein contained in Spirulina is high quality. About 30 kinds of Spirulina have been found, but only several species among these have good properties with high protein, no toxicity, high propagating ability and big size for harvesting. Especially, Spirulina platensis and Spirulina maxima are the well-known species produced in industrial scale. Since the range of the suitable cultivation temperature for Spirulina is from 30 to 40 °C, the waste heat from other facilities in CELSS can be used.

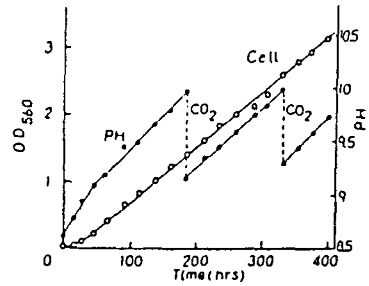
As shown in Fig. 1b the alkaline medium, range of its pH is from 9 to 12, has a very high utilization efficiency of CO_2 /1/. Spirulina utilizes sodium hydrogen carbonate ($NaHCO_3$) as the source of CO_2 necessary for photosynthetic reactions. $NaHCO_3$ is dissociated into HCO_3^- or CO_3^{2-} in the solution as shown in Fig. 1. When the photosynthetic reaction of Spirulina proceeds, the concentration of CO_3^{2-} increases relatively. The rise of pH value as shown in Fig. 1a results from the progress of this reaction /2/. To maintain continuous cultivation, pH value must be held within some range (i.e. 9~10). If pH value goes over the limit value, CO_2 must be provided in the culture solution to reduce pH value. These operations are shown as the discontinuous broken lines of pH in Fig. 1a. On the other hand, since the medium for Chlorella is weakly acidic, solubility of CO_2 are not so high, therefore, it is very difficult to increase the concentration of CO_2 in the culture solution. To use Spirulina in CELSS seems more suitable than Chlorella from comparing these characteristics of Chlorella and Spirulina.

NUTRITIVE VALUES AND PRACTICAL USE OF SPIRULINA IN CELSS

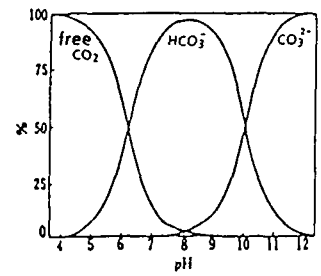
The nutritive values and components of Spirulina are very important factors to use it as food. The organic components of Spirulina have the following distinctive features;
① Abundant protein content. ② Carbohydrate consists of glycogen (so called animal starch). ③ Containing linoleic acid and linolenic acid (unsaturated fatty acids). ④Containing an abundant vitamin complex, in comparison with another algae, especially vitamin B_{12} and vitamin E. ⑤ Containing pigments such as chlorophyll and carotenoid (β-Carotene) which changes into vitamin A. ⑥ Containing many mineral components.

As to protein, not only quantity but also quality is very important factors to keep animal's lives. The quantity of essential amino acids of Spirulina nearly satisfies the values recommended by the FAO (Food and Agriculture Organization) except for lysine and cystine /3/. Furthermore, the human body needs digestible and absorbable proteins. Fig. 2 shows the comparison of digestibility by pepsin /2/. It is clear from the data shown in Fig. 2 that Spirulina has better digestion properties in comparison to Chlorella.

When human and animals stay in the micro gravity environment for a long time, the phenomena such as calcium decrease in bones and the deterioration of muscular function are reported. Fig. 3 shows the clinical examples for the changes of values of calcium and potassium in blood electrolyte when Spirulina was given every day on the ground /5/. Since these data show the increasing tendencies of calcium and potassium in blood, it is expected some effects to prevent the occurence of these harmful phenomena. From the data described



1a. Production of S. platensis by PH - control



1b. The Effect of Existing Conditions of Carbonate in the Medium on PH

$$NaHCO_3 \rightleftharpoons Na^+ + HCO_3^-$$

$$HCO_3^- \rightleftharpoons \frac{1}{2}(CO_2 \cdot CO_3^{2-} + H_2O)$$

$$CO_2 + H_2O \xrightarrow{h\nu} (CH_2O) + O_2$$

Fig. 1. Utilizaiton Efficiency of Carbon Dioxide on Spirulina Cultivation

above, Spirulina seems a good candidate for food in CELSS.

OXYGEN GAS RECOVERING EXPERIMENT

To cultivate algae in the micro gravity environment, many technical problems must be solved. One of those problems is to establish an effective method to gather and recover O_2 gas which is generated by algae and remains in the medium. To separate oxygen gas from the medium, it is not suitable to use a centrifugal separator which would disturb other experimental equipment. Therefore, a membrane separation technique which works without mechanical moving components seems more suitable. As for the membranes, various properties regarding permeability of gas are affected by shapes or material composition of membranes.

Table 1 shows the properties of representative membranes /5/. Plain membrane has a good property for gas permeability, but it has a demerit in mechanical strength if the membrane thickness is reduced in order to get higher permeability. In the result, some compromising between both characteristics is required. Usually O_2 gas generated by algae remains in the form of bubble that is gas itself, in the medium solution. Then, utilization of the porous membrane enabling to pass gas only seems to be better than the plain membrane. Table 1 shows that the membrane made from silicone has a superior property for gas permeation, but, Table 2 /5/ shows that porous type membranes have much better gas permeation characteristics than plain silicone membranes.

For these reasons, we carried on the O_2 gas recovering experiment using a porous hollow fiber membrane module, manufactured by Mitsubishi Rayon Co., Ltd., as the gas separator. The characteristics of this module are shown in Table 3 and the pictures of scanning electron micrographs of hollow fiber are shown in Fig. 4 /6/. One of the hollow fibers is small in inside diameter, and wall thickness. Then, the module which is composed of bundles of hollow fiber is designed very compact. The dimension of this module is 215 mm (L) × 40 mm (D).
A very large membrane area can be obtained by using hollow fiber membranes. Fig. 5 shows the block diagram of the O_2 gas recovering experiment equipment now being used in our laboratory. O_2 gas blown into the cultivation tank is carried to the membrane module along the water flow and a part of the O_2 gas permeates the membrane, therefore, for clearing the permention property of the membrane, the quantity and concentration of permeated O_2 gas are measured by the oxygen gas analyzer.

The cultivation tank is made from acrylic resin and has a round shaped top in order to collect oxygen gas concentratively and also has an inner volume of about 0.009 m³. For the permeation ability estimation of the membrane, pure water was used and its temperature was set at 30 °C (same condition as Spirulina cultivation) and also 99.99% high purity O_2 gas was used instead of the O_2 gas generated by Spirulina.

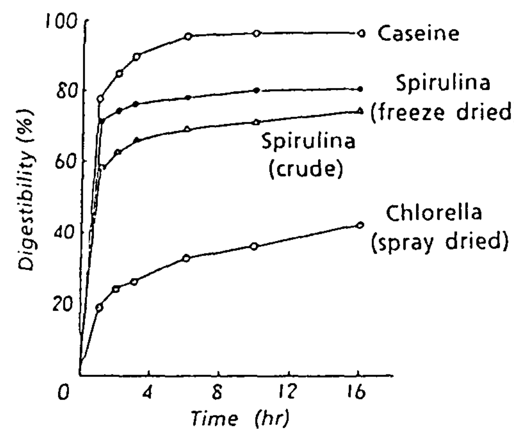


Fig. 2. Digestibility Test by Pepsine

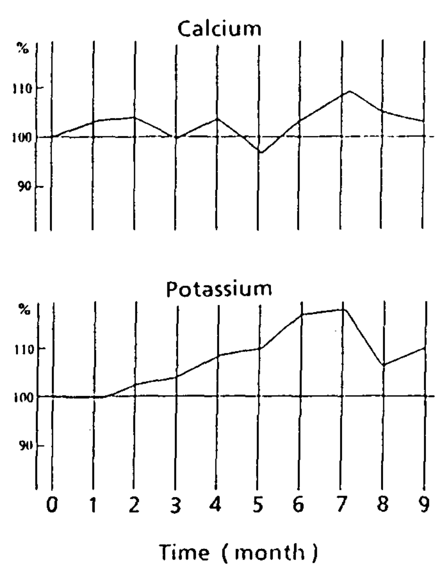


Fig. 3. Variation of Blood Electrolyte

One of the experimental data for O_2 concentration variation of recovered gas is shown in Fig. 6. For determining the accurate dissolved O_2 gas quantity, the dissolved O_2 concentration in pure water was reduced to about 1.7 ~ 1.8 ppm before the experiment. The flow rate of pure O_2 gas from O_2 bottle was 50 cc / min. and the flow time was set for 10 minutes. O_2 gas which permeated the membrane was continuously collected by the suction pump and its concentration was measured by the oxygen gas analyzer. During 4 ~ 5 minutes from the start of the experiment, the concentration of O_2 gas did not change, but after that it rapidly increased. The flow rate of O_2 gas at the membrane module was about 30 ~ 45 cc / min.. Three kinds of membrane area, such as 0.3, 0.5, and 1.0 m^2 were tested, but there appeared only small differences between them.

As shown in Fig. 6, the maximum value of O_2 concentration is about 73%. It took about four hours until the dissolved O_2 concentration went down to the value of the start time. From these results, it is clarified that the membrane module works effectively to recover not only the bubbled but also the disolved O_2 gas.

TABLE 1 O_2 and CO_2 Permeability on Various Polymer

Polymer	O_2 Permeability	CO_2 Permeability
Polyvinyliden Chloride	16	13
Polyester	176	304
Cellulose Acetate	1,705	8,680
Polyethylene	3,500	15,965
	3,200	5,390
	8,800	27,000
Polypropylene	2,900	9,905
Polystyrene	4,850	23,790
Polytetrafluoroethylene	17,600	48,000
Ethyl Cellulose	25,600	104,000
Silicone Elastmer	1,568,000	8,040,000

Membrane thickness 25μ conversion, 25°C, $cm^3/m^2 \cdot atom \cdot 24hr$

TABLE 2 Property of Membrane for Artificial Lung

Polymer	Structrue	Total thickness (μ) / Thickness of membrane (μ)	Gas permeability	
			O_2	CO_2
Silicone Elastmer	polyester reinforcement	190/160	140	770
Polysiloxanepolycarbonate	uniformalized	50/50	170	730
Polyalkylsulfon	applied porous polypropylene menbrane	25/2.5	1100	4600
Ethylcelluloseperfluorobutylete	applied polyolefin cloth	175/2.5	880	4700
Polypropylene membrane	porous	25/25	very good	very good
Teflon membrane	porous	500/500	very good	very good

permeability : $cm^3 / min. m^2$ atom

TABLE 3 Characteristics of Porous Hollow Fiber Module

Material	Polypropylene
Inner diameter	200 μm
Wall thickness	22 μm
Porosity	45 %
Pore Size	0.036 μm
Gas flux	7×10^4 l/m^2 hr 0.5atm
Bubble point	12.5 kg/cm^2
Effective area	0.3, 0.5, 1.0 m^2

GAS CLOSED EXPERIMENT

It was clear that O_2 gas has been obtained from the solution by using the porous hollow fiber membrane module. Then, we have carried out gas closed experiments using the Spirulina cultivator and a fish breeding tank. O_2 gas generated from Spirulina is provided to Tilapia (a kind of tropical fresh water fish) and CO_2 gas exhausted from Tilapia is supplied to Spirulina, through the membrane gas separator and the artificial lung that is the hollow fiber membrane module.

We have shown the block diagram of this experiment system in Fig. 7. Algae cultivator is made from acrylic resin with 180 mm diameter and 300 mm length. The species used in these experiments are Spirulina oscillatoria and Spirulina platensis. The medium solution contained mainly $NaHCO_3$ and its temperature was controlled at 30 °C by thermostat. Light energy was supplied through optical fibers or fluorescent lamp into the cultivator. The time to reach saturation in culture of Spirulina was 7 ~ 10 days in several experiments.

The airtight fish breeding tank is 280 mm diameter × 500 mm length and three Tilapias (length of 15 cm and weight of 160 g) have been bred in it. We plan to use Tilapia as protein supply resource in CELSS and have researched on developing a breeding technology and equipment which works well in micro gravity environment. O_2 gas for Tilapia was supplied through an artificial lung which is the same as the gas seperator and the variation of DO_2 was monitored for this gas closed experiment. The differences of DO_2 values supplied by room air and O_2 from Spirulina cultivator are shown in Fig. 8. The experiment started when the value of DO_2 went down to 0.1 ppm from about 4 ppm. Water circulation rate was 2.0 liter/min. and O_2 gas supply rate was 100 cc/min.. Fig. 8 shows that Spirulina has a good O_2 supply ability.
When using Spirulina, the maximum value of O_2 gas concentration reached 46.0 ~ 50.2 %.

CONCLUSIONS

A long term experiment to cultivate Spirulina for more than one month was successfully conducted. Successively, in order to examine the quantity of O_2 gas generated by Spirulina, the closed gas circulation experiment combined the algae cultivator and the breeding tank with three adult Tilapias. The experiment term reached 32 days and it was clean that the continuous experiment operation time depended on the life time of the gas separator.
The ability of the separator was decreased by algae which covered the surface of the membranes. To conduct long term experiments, this problem must be solved, for example, to wash out adhesive Spirulina on the surface of fibers.

Further work is required to establish the technologies to harvest algae automatically, to develop long life gas separators and artificial lungs and to conduct an experiment including not only gas circulation but also food supply to fishes or animals in the complete closed system.

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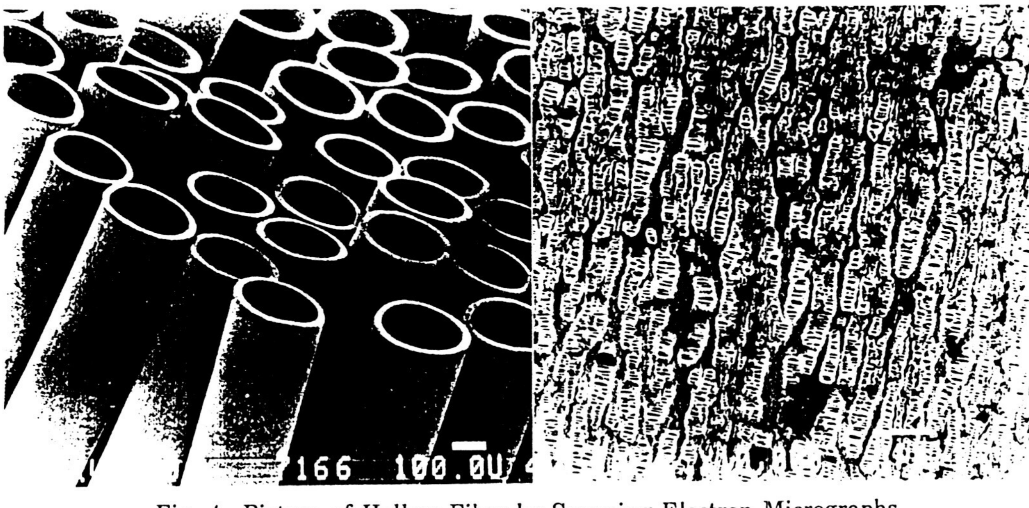

Fig. 4. Picture of Hollow Fiber by Scanning Electron Micrographs

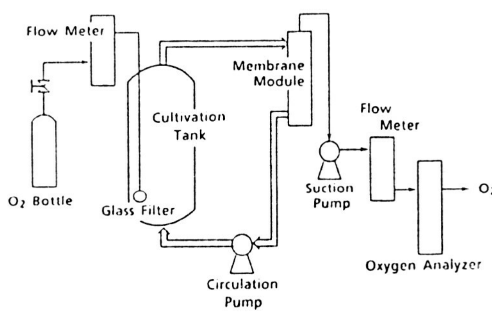

Fig. 5. Block Diagram of O_2 Recovering Experiment System

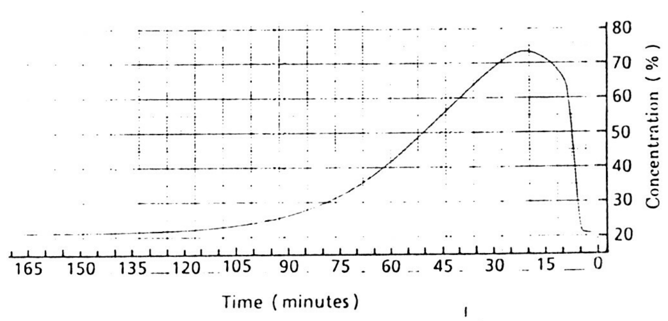

Fig. 6. Concentration of Recovered O_2 Gas

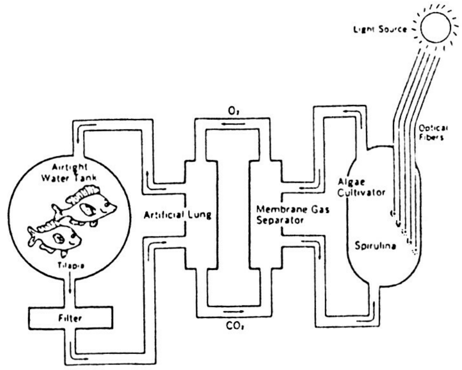

Fig. 7. Block Diagram of Gas Closed Experimental System

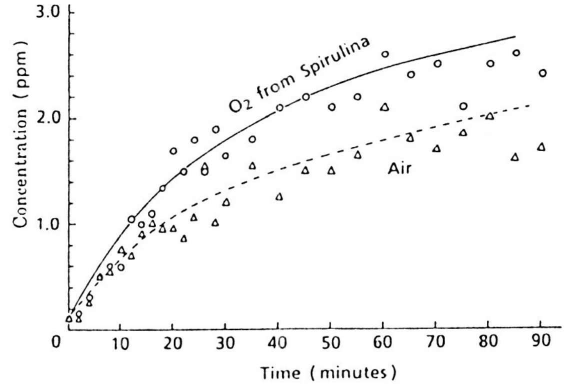

Fig. 8. Concentration of Dissolved Oxygen in Tilapia Breeding Tank