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A pond for edible *Spirulina* production and its hydraulic studies

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Introduction

In recent years, confronted with the problem of worldwide depletion of underground resources, industry has been carrying on intensive research on the production of microalgae *via* artificial processes, with a view to developing an effective means to make better use of solar energy in the production of useful materials and in photosynthetic energy conversion. Typical species which have been the focus of attention for artificial production on microalgae include *Chlorella, Spirulina, Scenedesmus, Dunaliella* and so on. The attempt at artificial production of these microalgae utilizes autotrophic or mixotrophic photosynthetic reactions. In artificial production of microalgae, cultivation-pond design is of primary importance, since much of production efficiency depends on the performance of the pond as the site of photosynthesis.

In many ponds for microalgal production, a circulation-type open-channel system is widely used, but a search of the literature reveals few studies which concern its fluid dynamics and hydraulics. However, these constitute an important subject for inquiry, as the elucidation of problems in these areas will help to delineate conditions of a stable biological environment and provide clues to efficient and economical design of cultivation ponds. In mass production of *Spirulina* in particular, the weak cell membrane dictates the exercise of meticulous care. Dainippon Ink & Chemicals, Inc. (DIC) has developed a new type of cultivation pond designed to suit the purpose of mass production of edible *Spirulina,* and we have completed hydraulic studies of the pond with a view to scale-expansion and optimization of microalgal cultivation-pond system design. This communication is a report of our results.

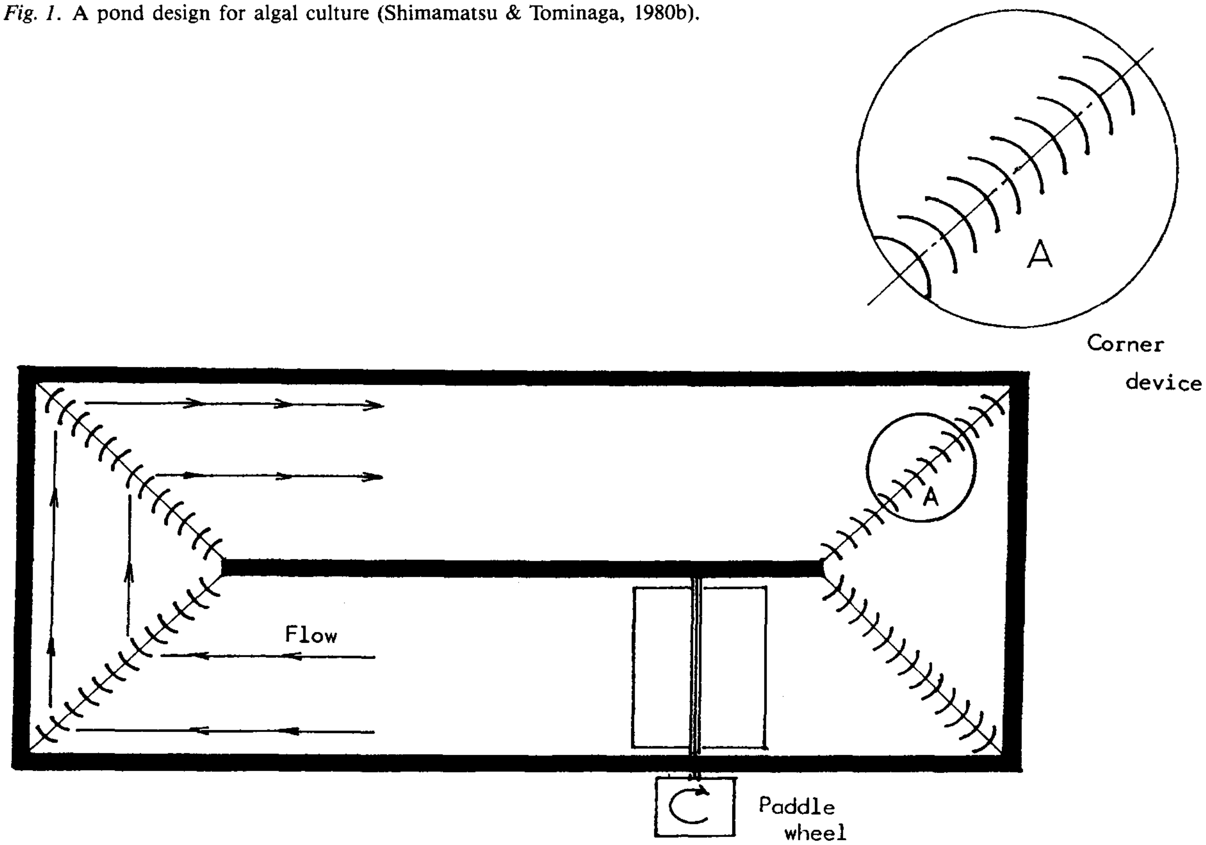
The DIC pond is an oblong open channel based on a circulation system that is provided with paddle wheels generating uniform flow (Fig. 1). Special provision is made at every corner of the pond, as shown in Fig. 2, so that the flow changes direction exactly 90 degrees at every corner. Since this circulation system gives rise to neither "partial flow" nor "stagnation", a constant flow speed, and therefore uniform mixing, can be obtained at every point in the pond. This system is described in detail in the specifications for the patents granted in Japan and the USA (Shimamatsu & Tominaga, 1980a,b).

DIC has two factories for mass production of *Spirulina* in Bangkok, Thailand, and California, USA; these have been in operation since 1978 and 1983, respectively. In Thailand, DIC has been operating a cultivation pond of this type, achieving stable and efficient production of *Spirulina* over many years. Accumulated scientific evidence indicates that the system under discussion is one of the cultivation ponds of high utility.

Experimental

Mainly two cultivation ponds, a concrete pond 2 000 m^2 in area (20×100 m) and a plastic-lined pond 1 000 m^2 in area (9×111 m), that DIC has in Bangkok and California, respectively, were used in the experiment. The shapes and dimensions of these ponds are given in Fig. 3. These ponds are provided with a paddle wheel and liquid flow-

Fig. 1. A pond design for algal culture (Shimamatsu & Tominaga, 1980b).



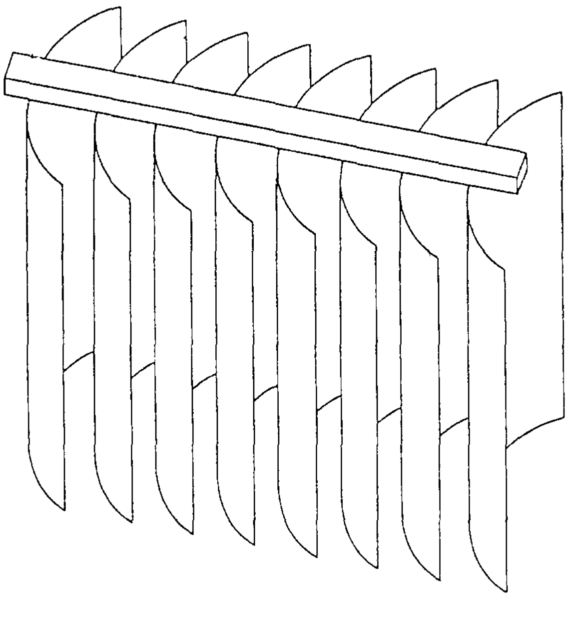


Fig. 2. Corner device of algal pond.

direction rectifier, called a "corner device", at each corner. This device is made of cut pieces of pipe which are arranged to suit the intended purpose.

The dynamic behavior of water in the circulation pond was investigated, particularly the relationship between velocity of flow and the potential energy of the water. For calculations of potential energy, water depths were measured at various points (A–G, Fig. 3) in the pond while water was circulating, and compared with depths at the same points when water was not circulating. This was done in three representative cases of water depth, *i.e.,* 0.15, 0.20 and 0.25 m, using a stilling pot and a precision level meter accurate to ±1 mm. Flow speed was measured using a Syston Donner flow meter, and paddle-wheel revolutions per unit time were recorded.

Examples of results are presented in Table 1.

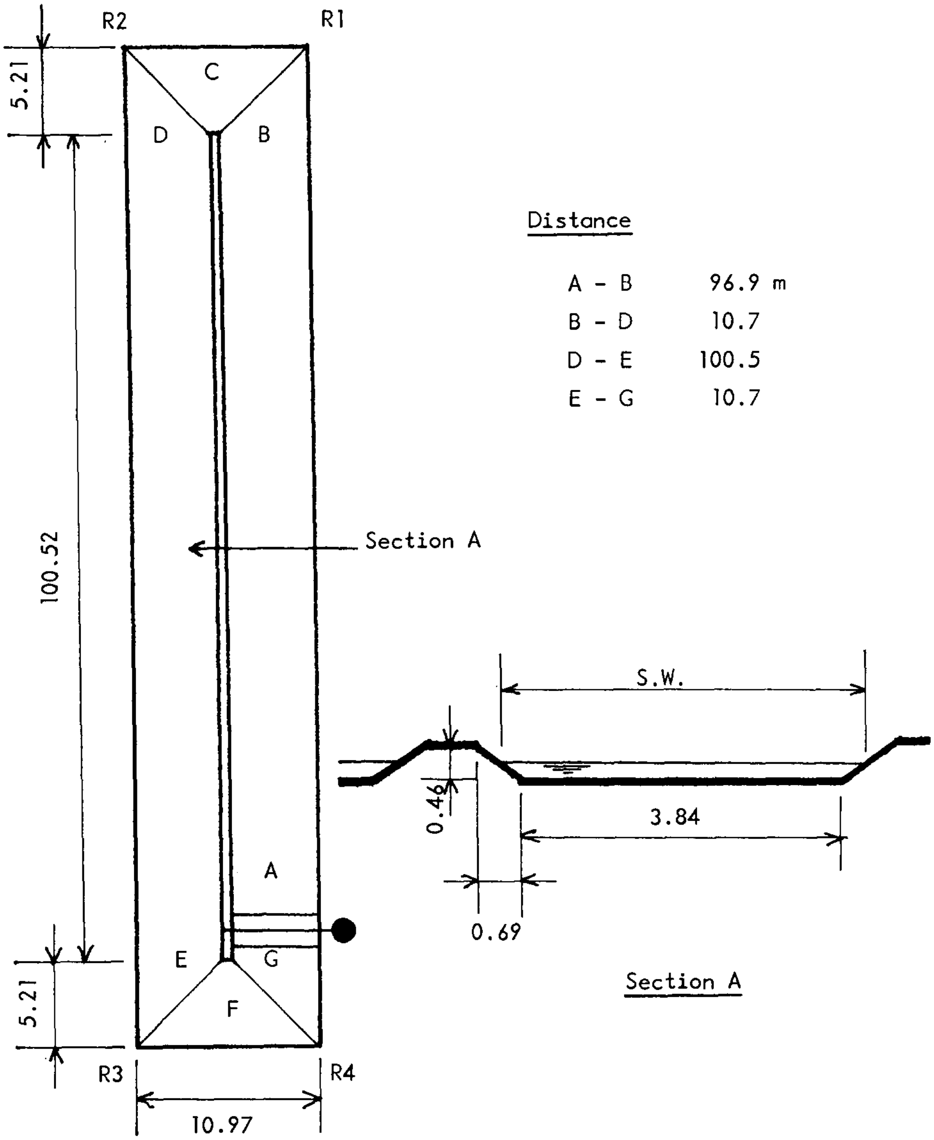


Fig. 3. Schematic design of 1000-B pond.

Results and discussion

The hydraulic concept in the open-channel circulation-type pond is basically that the potential energy provided by the paddle wheel is used as the driving force for circulating the water in the pond, and that the energy is consumed as the water overcomes various forms of friction which are caused by the resistance between the water and the pond wall. In the case of the open channel considered, the total energy loss is divided into two portions; loss sustained in the straight part of the channel and loss incurred when flow changes direction at the corners of the pond.

Formula for calculating the mean flow speed in the straight open channel

Chézy-Kutter's and Manning's formulas, widely

Table 1. Results of measurement (data on water depths 15 cm and 26 cm are omitted).

1000 B pond							
Water depth = 20.2 cm (mean)							
20.0 cm for D – E							
Test No.	1	2	3	4	5	6	7
R.P.M. of P.W.	0	7.2	7.8	9.3	12.5	15.4	18.3
Fluid velocity	0.0	25.1	26.4	29.4	33.5	35.9	35.9 ($cm \cdot s^{-1}$ at D – E)
Relative water level							(cm)
A point	0.0	(1.36)	(1.48)	(1.73)	(2.08)	(2.2)	(2.2)
B point	0.0	0.4	0.45	0.55	0.7	0.7	0.7
D point	0.0	-0.2	-0.2	-0.2	-0.3	-0.4	-0.4
E point	0.0	-1.4	-1.5	-2.0	-2.8	-3.2	-3.2
G point	0.0	-2.2	-2.4	-3.2	-4.7	-5.6	-5.6
ΔH (D – E)	0.0	1.2	1.3	1.8	2.5	2.8	2.8 (cm)
Inclination		1/8377	1/7732	1/5584	1/4021	1/3590	1/3590
W. depth (D – E)	20.0	19.2	19.15	18.9	18.45	18.2	18.2 (cm)

used in hydraulic studies, are well-known as equations for calculating the flow speed of liquids in straight channels. As shown below, these formulas comprise such variables as wall-material roughness, mean hydraulic depth and water-surface inclination.

Chézy-Kutter's formula:

$$w = \sqrt{2g/\lambda'}\sqrt{mi} = C\sqrt{mi}$$

where w = mean velocity ($m \cdot s^{-1}$), λ' = friction coefficient, m = mean hydraulic depth (m), i = inclination of the water surface, and C = velocity coefficient. (Ganguillet-Kutter's formula):

$$C = \frac{23 + (1/n) + (0.00155/i)}{1 + \{23 + (0.00155/i)\}(n/\sqrt{m})}$$

where n = wall material roughness factor.

Manning's formula:

$$w = (1/n)m^{2/3}i^{1/2}.$$

It was first examined whether the cultivation ponds under consideration had fluid-dynamic and hydraulic characteristics such that the formulae of Chézy-Kutter and Manning would apply. As shown in Fig. 4, good agreement was found between the results obtained by the two formulae, thus confirming that they are suitable for fluid-dynamic and hydraulic studies of the straight open channels as cultivation ponds. Accordingly, it was decided that Chézy-Kutter's formula would be used in the present study.

Energy loss at the corner of the pond

When determining energy loss due to the resistance of the corner device, an attempt was made to divide it into two losses, loss due to flow deflection in the corner device and loss due to the resistance of the narrow passage in the corner device:

$$\text{Total loss of energy } H_t = f_t \cdot \frac{w^2}{2g} = (f_1 + f_2) \cdot \frac{w^2}{2g}$$

where H_t = total loss (m), w = mean flow speed ($m \cdot s^{-1}$), g = acceleration of gravity ($m \cdot s^{-2}$), f_t = total friction loss coefficient, f_1 = coefficient of friction loss due to 90-degree flow deflection, and f_2 = coefficient of friction loss due to narrow passage resistance.

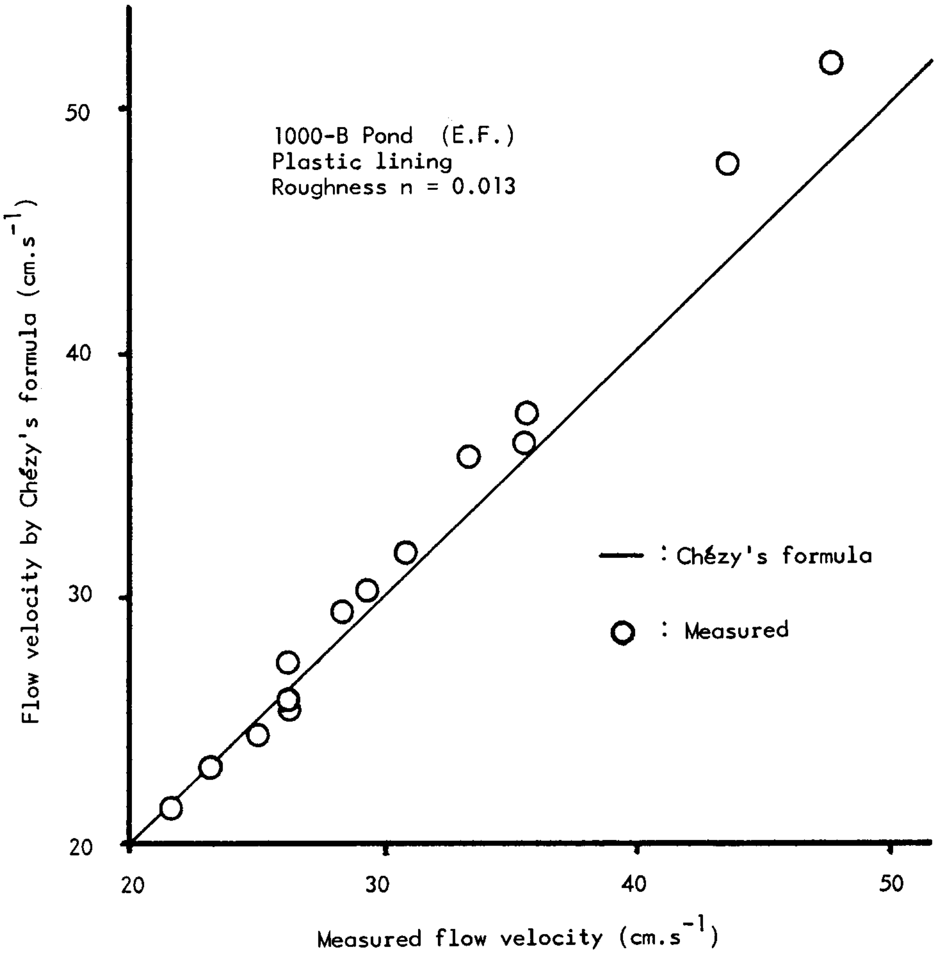


Fig. 4. Coincidence of flow velocity between measured and calculated by Chézy's equation.

Accordingly, f_t can be derived from the total head loss, f_2 is given by Chézy-Kutter's formula, and f_1 is the difference between f_t and f_2.

As shown in Tables 2 and 3, therefore, coefficient f_1 of energy loss due only to 90-degree flow defection can be shown to be a nearly independent constant which has little to do with water velocity or depth.

These results are summarized in Table 4.

Conclusions

The whole aspect of the hydraulics by which energy is lost during the time the water requires to make the circuit of the DIC system cultivation pond was elucidated in the present study. In the case of a cultivation pond of this type, therefore, given the shape and size of the pond together with a water velocity required for a suitable biological environment, the potential energy that is required from the paddle wheel can be calculated to design the most efficient paddle wheel possible. Further, since our procedures established in this study can be considered to apply for cultivation ponds of any large size, they will yield information required for optimization of microalgal production ponds, as well as for their scale expansion.

Artificial production of microalgae is expected to develop with vigor by way of effective utilization

Table 2. Friction coefficient of 1000 B rectifier (B – D).

W. depth Variator Corner	Depth at rectifier cm	Velocity at rectifier $m \cdot s^{-1}$	Hydraulic mean depth at rect. m	Friction coefficient		
				f_t Total at rectifier	f_1 90° turn	f_2 Friction at rectifier
15-0.3-BD	11.12	0.277	0.0631	0.567	0.450	0.117
0.4	11.145	0.294	0.0632	0.548	0.435	0.113
0.5	11.145	0.326	0.0632	0.608	0.496	0.112
20-0.23-BD	16.045	0.300	0.0764	0.507	0.421	0.086
0.25	16.07	0.315	0.0765	0.546	0.461	0.085
0.3	16.12	0.345	0.0766	0.512	0.428	0.084
0.4	16.145	0.383	0.0767	0.565	0.482	0.083
0.5	16.095	0.406	0.0766	0.553	0.470	0.083
26-0.23-BD	22.145	0.325	0.0880	0.473	0.404	0.069
0.25	22.045	0.350	0.0878	0.554	0.485	0.069
0.3	22.045	0.400	0.0878	0.530	0.462	0.068
0.4	22.095	0.475	0.0879	0.486	0.418	0.068
0.5	22.095	0.510	0.0879	0.487	0.421	0.066

Table 3. Friction coefficient of 1000 B rectifier (E – G).

W. depth Variator Corner	Depth at rectifier cm	Velocity at rectifier $m \cdot s^{-1}$	Hydraulic mean depth at rect. m	Friction coefficient		
				f_t	f_1	f_2
15 – 0.3-EG	9.295	0.332	0.0569	0.574	0.444	0.130
0.4	8.995	0.364	0.0557	0.585	0.452	0.133
0.5	8.245	0.421	0.0527	0.641	0.497	0.144
20-0.23-EG	14.945	0.323	0.0739	0.599	0.502	0.097
0.25	14.295	0.354	0.0722	0.547	0.455	0.092
0.3	13.645	0.407	0.0705	0.553	0.458	0.095
0.4	12.495	0.495	0.0673	0.591	0.492	0.099
0.5	11.845	0.552	0.0654	0.597	0.495	0.102
26-0.23-EG	20.545	0.350	0.0853	0.526	0.454	0.072
0.25	20.07	0.385	0.0845	0.514	0.442	0.072
0.3	19.395	0.455	0.0833	0.501	0.429	0.072
0.4	17.495	0.600	0.0795	0.504	0.427	0.077
0.5	16.245	0.694	0.0769	0.561	0.481	0.080

Table 4. Total head loss for DIC pond.

Loss at:		Estimated by:
1. Straight part of the channel		Chézy's or Manning's
2. Corner device		
	2a. Narrow path	Chézy's or Manning's
	2b. Changing	$\Delta H_l = f_l \cdot w^2/2g$
		$f_l \approx$ constant

Total head loss = Σ head loss 1 (straight channel) + Σ head loss 2 (2a + 2b; corner device).

of solar energy. For algal cultivation on experimental levels to develop and expand into an industry, it is hoped that further engineering studies will be done extensively concurrently with the biological investigations.

References

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