Nutrient Removal Rate and Heat Flux through Floating Canna Culture System in Eutrophied Water

Kunihiko HAMAGAMI*, Masayuki FUJHARA*, Edward LAPONG**

*Laboratory of Water Resources Engineering, Division of Rural Engineering, Department of Bioresource Science, Faculty of Agriculture, Ehime University, Ehime 790-8566, Japan
**The United Graduate School of Agricultural Sciences, Ehime University, Ehime 790-8566, Japan

ABSTRACT
The floating culture system is a water purification method using the ability of plants for nutrient removal. Since the appropriate management of the floating culture system in eutrophied water depends on the characteristics of the water body, like its shape or depth, it is impossible to make a general guideline. Therefore, as part of constructing a numerical prediction model of the flow and water quality in waters where the floating culture system is installed, a test tank experiment, using canna as plant, was conducted to parameterize the effect of the floating culture system, as a boundary condition, on the flow and water quality. The result of plant growth and water quality measurement shows that the growth rate of canna changes significantly with the phosphorus concentration in water; the relation between the removal rate of TP and the phosphorus concentration is unique. Regarding the DO concentration in tanks with floating culture system, it decreased because the system prevented aeration and blocked solar radiation at the water surface. Moreover, the water temperature measurement reveals that the shielding ratio of heat flux through the system depends strongly on the material of floating board and is approximately constant regardless of the plant’s growth rate. It is concluded from the result that TP removal rate can be expressed by using phosphorus concentration in the water and heat flux shielding ratio can be set as a constant, using this canna floating culture system.

Keywords: canna, floating culture system, nutrient removal rate, shielding ratio of heat flux

INTRODUCTION
The floating culture system is a soilless culture method which cultivates plants on a floating board placed on the water surface. When the plants are mowed, the nutrients, such as nitrogen and phosphorus, are also removed from the waters and, hence, the water is purified. Previous studies discussed the growth characteristics and the nutrient absorption ability of some plants used in the floating culture method (e.g. Song et al., 1994; Miyazaki et al., 1999, 2000; Mizuta et al., 2004), and considered the aspects of actual operation and management (Li et al., 2005; Kuwabara et al., 2007). However, these studies had hardly considered the physical dimension of the system, i.e. the relationship between the existence of floating matter and the flow in the waters.

Water quality deterioration in the closed body largely depends on the magnitude of vertical mixing. The vertical mixing is usually caused by wind stress and heat flux on water surface. As the floating board decreases the wind stress and the heat flux, the vertical mixing would be suppressed by the floating board. The suppressed vertical mixing could not transport the nutrients, which is often rich at the bottom, to the surface layer and thus, efficient water quality purification cannot be demonstrated (Ozaki et al., 2004; Lap and Mori, 2007). Moreover, the flow depends on the characteristics of the water body, like its shape or depth; hence, it is necessary to estimate the effect of the
floating culture system on the flow at each water body. This indicates that it is almost useless to make a general guideline of installing the floating culture system without considering the characteristics of the water body. An appropriate approach toward this problem is to construct a numerical prediction model of flow and water quality in waters where the floating culture system is installed, considering the characteristics of water body and the surrounding environment. In this case, formulation of the effect of floating culture system on both flow and water quality is the most important key point in making the model.

To take into account the effect of the floating culture system (as boundary conditions) into the prediction model, we therefore parameterize the effect of the floating culture system on the flow and water quality. And being the most important factors in water quality, the concentrations of nitrogen and phosphorus were measured, as they have influence on the photosynthetic performance of phytoplankton. This study assumed phosphorus as the limiting factor and examined the relation between the phosphorus concentration in waters and the ability of the plant used to remove phosphorus. Also, being the important factor in the flow, the thermal disturbance was determined, as it is the driving force of the flow in closed waters. Moreover, the floating board of the floating culture system would disturb the thermal transport in the water surface; hence, we also examined the change of heat flux on the water surface with the growth of plants.

**MATERIALS AND METHODS**

**Experimental set-up**

The experiment was conducted using six adjacent concrete test tanks in a vinyl greenhouse (Fig. 1). The test tanks have a surface dimension of 200 cm × 93 cm and depth of 110 cm. The plant used was canna (Canna generalis B.) which has been reported as a suitable plant for the floating culture (Matsuda et al., 1995; Arima et al., 1999). Two floating boards (90 cm × 90 cm × 5 cm) made of styrofoam were set on the water surface and canna were bed out in a sponge with 9 hills per square meter (18 hills in each tanks).

The floating culture experiment was conducted with various phosphorus concentrations. Slow-release fertilizer (4.0% N; 6.0% P; 1.0% K) was applied on the base of root in the sponge at a rate of 0.3 g/hill at the time of plant transfer and there was no additional fertilization during the experiment. The experimental conditions are shown in Table 1. Phosphorus concentration is the limiting factor in the experiment with values set from 0.01 mg/L to 1.0 mg/L. The sixth test tank (Tank F) served as the control and both the nitrogen and potassium concentrations were constant and sufficient. The phosphorus

Fig. 1 - Experimental set-up and equipment
concentration was controlled by applying horticultural liquid fertilizer and the shortfalls of nitrogen and potassium were filled in by applying water-soluble fertilizers. Since the test tanks were relatively small, the water in the tank was refilled every two weeks to keep the nutrients at the controlled concentration. The lower part of the vinyl greenhouse was opened to let air through and prevent high-temperature injury on the plants. The commercial bulbs of canna were grown in individual pots until they became seedlings and were bed out on June 25th when the required number of plants was completed. The observation period ended on October 1st when leaf death had been pronounced.

Measurement factors
Meteorological factors such as solar radiation and air temperature were measured every 5 minutes by pyranometer and thermometer, respectively. The water quality parameters, i.e. pH, dissolved oxygen (DO), conductivity, turbidity, total dissolved solids (TDS) and oxidation-reduction potential (ORP) were measured by the multi-sensor probe (W-22XD, HORIBA, Japan) every 2 days. The measurement was done in three points on the vertical direction of the tank and the average value was computed. In addition, total nitrogen (TN), nitrate-nitrogen (NO₃-N), total phosphorus (TP) and phosphate-phosphorus (PO₄-P) were measured before and after refilling the tanks; the decreasing rate at each interval was calculated. Moreover, the numbers of leaves per hill were counted and the area of each leaf was measured, assuming that the leaf shape is ellipsoidal. As for the growth rate of canna, the total leaf area per hill was calculated based on the individual leaf area instead of weighing the dry canna—due to paucity of samples. On the other hand, in order to examine the thermal characteristics, thermocouples were set vertically at 10 cm intervals in Tanks E and F; the water temperatures at each depth were measured every 5 minutes.

RESULTS AND DISCUSSION

Growth rate of canna
Figure 2 shows the average number of leaves per hill, the average leaf area per hill, the average total leaf area per hill, the standard deviation of the number of leaves, the standard deviation of the leaf area and the standard deviation of the total leaf area in each test tank. The average number of leaves and the average leaf area per hill in all tanks were almost the same at the time of plant transfer, but the rate of increase of the values varied at each tank due to the difference in phosphorus concentration. The average leaf area per hill increased significantly after the plants were transferred into the high phosphorus concentration tanks and the difference of the average number of leaves

<table>
<thead>
<tr>
<th>Tank</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floating culture system</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Nitrogen (mg/L)</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
<td>5.0</td>
</tr>
<tr>
<td>Phosphorus (mg/L)</td>
<td>0.1</td>
<td>0.0</td>
<td>0.5</td>
<td>0.1</td>
<td>1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>Potassium (mg/L)</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
<td>0.5</td>
</tr>
</tbody>
</table>
between the low and high P concentration tanks became larger after mid-August. The average leaf area tended to decrease starting the end of July. This is because bigger hills tended to have more young leaves. However, the total leaf area in the high phosphorus concentration tank continued to increase until the beginning of September. The total leaf area in the low phosphorus concentration tank decreased after mid-August because leaf death begins earlier compared to that of the high phosphorus concentration tank. These observations, as reflected in the figure, indicate that the growth rate of canna changed with the change of phosphorus concentration in the tank. Moreover, it also reveals that canna can grow abundantly and uninhibitedly in conditions with high nutrient concentration and, thus, is suitable for eutrophied waters. In addition, the coefficient of variation of the growth rate has been low in tanks of high nutrient concentration throughout the whole period.

**Removal rates of phosphorus and nitrogen**

Figure 3 shows the removal rates of phosphorus and nitrogen during the observation period. The removal rates of TP and PO₄-P differ in each tank. As the phosphorus concentration increased, its removal rate increased within the range set in the experiment. The removal rate of phosphorus in Tank F, which had no floating culture system, was higher than Tank C (whose phosphorus concentration was the same as in Tank F) and other lower concentration tanks. This is thought to be effected by algae

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**Fig. 2 - Growth rate and standard deviation of canna with respect to the number of leaves, leaf area and total leaf area**

- Average number of leaves (piece)
- Average leaf area (cm²)
- Average total leaf area (cm²)
- Coefficient of variation of the number of leaves
- Coefficient of variation of leaf area
- Coefficient of variation of total leaf area
which proliferated in Tank F due to receipt of solar radiation and which used up phosphorus and settled at the bottom of the tank. Although the removal rates of TN and NO$_3$-N were high in the high concentration tanks throughout the whole period, the difference among them was smaller compared with the removal rate of phosphorus. In contrast to phosphorus, a significant quantity of nitrogen was removed regardless of the phosphorus concentrations.

The relation between the removal rate of TP and the phosphorus concentration (the limiting factor) during the observation period is shown in Fig. 4. This figure indicates that the removal rate of TP and the phosphorus concentration were strongly correlated and had a unique relationship throughout the plant’s growth stage. The datum far from the regression line was obtained just after plant transfer, hence, it is surmised that the plant required a certain time to be firmly fixed at the floating board and get used to the new environment. With this, it is concluded that the removal rate of total phosphorus could be determined using a simple expression with phosphorus concentration as the independent variable, as it was the limiting factor.

As for nitrogen, Fig. 5 shows the removal rates of TN and NO$_3$-N during the entire experiment period. This figure illustrates that the removal rate of TN per hill was around 30.0 mg/day when the phosphorus concentration was less than 0.1 mg/L (Tanks A, B and C). Although it is expected that the removal rate of nitrogen also depends on the growth rate of canna as affected by the phosphorus concentration, the ratio of nitrogen removal rate to phosphorus concentration was not constant. Considering that DO linearly decreased in the tanks with floating culture system (refer to Fig. 6), we could not deny the possibility of denitrification which removed nitrogen. In addition, the nitrogen concentration was set constant in this experiment, under the assumption that it is always sufficient. Thus, it is necessary to conduct supplementary experiment involving nitrogen, since nitrogen is a possible limiting factor in actual waters.
Other water quality parameters
The time series of pH, conductivity, turbidity, TDS, ORP and DO from 7th to 14th of August are shown in Fig. 6. Although long-term observation was not conducted because the water in the tank was being refilled every 2 weeks, some significant changes of water quality were observed even within a short period. For most factors, Tank F had a different tendency from the other five tanks. This indicates that the variation of water quality was largely effected by the existence of floating culture system. The floating culture system blocked most of the solar radiation in the water surface, caused water temperature variation due to solar radiation during daytime, and limited radiation cooling during nighttime.

In particular, the value of DO in Tank F increased after water refilling; but it decreased in other tanks. Also, the value of DO in Tank F was higher than the DO saturation value during daytime. This is because many phytoplankton grew and photosynthesized excessively under sufficient solar radiation. As for tanks with floating culture system, the DO concentration decreased gradually after water refilling because the tanks lack air supply and solar radiation due to the existence of floating board. It became almost zero after a week as the water surface was already completely covered by the growing plants. The DO decrease due to floating board was already reported in a previous study (Agata et al., 1996).
Shielding ratio of heat flux on the water surface

The shielding ratio of heat flux through the water surface by the floating board was calculated to examine its effect on the flow in the waters. Figure 7 shows the time series of solar radiation, heat quantity and heat flux through the water surface in Tanks E and F for 1 week—from 9th to 15th of August. The heat quantity \( Q \) in the column of water with depth \( h \) in unit area was calculated as follows,

\[
Q = \int_0^h \rho c T_z dz
\]  

(1)

where, \( \rho \) is the water density, \( c \) is the specific heat of water, and \( T_z \) is the water temperature at the depth \( z \). Moreover, under the assumption that heat was transported only through the water surface, the heat flux \( F \) was calculated as follows,

\[
F = \frac{\Delta Q}{\Delta t}
\]  

(2)

where, \( \Delta Q \) is the variation of \( Q \), and \( \Delta t \) the measurement time interval.

The heat quantity in the tanks continuously increased in this period due to fine weather. The change rate of heat quantity in Tank F, which had no floating board, was larger than in Tank E—both during daytime and nighttime. In other words, the heat flux in Tank E
which had floating boards was lower throughout the whole period. Moreover, the phase of daily cycle wave of heat flux in Tank E shifted late compared with that in Tank F. The shifting time of these waveforms calculated by cross-correlation was about 2 hours.

The comparison of the heat flux between Tank E and F considering the shifting time is shown in Fig. 8. Figure 8(a) indicates that the shielding ratio of heat flux through the water surface with floating board made of 5cm-thick styrofoam was about 0.29 during the 1 week observation from 9th to 15th of August. In other words, the floating board interrupted about 71% of the heat flux at the water surface. Since canna can reach a height of 2 m when it grows abundantly, it is predicted that the shielding ratio of heat flux changes with the growth rate of canna. However, this was not actually the case as indicated by the comparison of heat flux on each month.

Figure 8(b) shows the shielding ratio of heat flux in each month. The 5-minute interval data are plotted for 2 days every month and represents the initial growth stage on July 17th - 18th, the abundant growth stage on August 17th - 18th, and the leaf death stage on September 17th - 18th. As observed, the height of canna was small on 17th - 18th of July, so the growth rate was significantly different from the other periods. The figure indicates that the shielding ratios of heat flux were generally similar at the growth stages, with value ranging from 0.22 to 0.27.

However, the values of the shielding ratios have hardly depended on the growth stages. This result reveals that the shielding ratio of heat flux actually depends on the material of the floating board and is approximately constant regardless of the growth stage and growth rate of the plant.
CONCLUSIONS

As part of construction of the flow and water quality prediction model in the waters with the floating culture system, a test tank experiment using canna was conducted to examine the effect of floating board, as the boundary condition, on the flow and water quality. The following results were obtained:

1. The growth rate of canna changes with phosphorus concentration in waters. Moreover, canna can grow abundantly and uninhibitedly in conditions with high nutrient concentration.
2. The relation between removal rate of TP and the phosphorus concentration is unique, in which case phosphorus concentration is the limiting factor.
3. In tanks with floating culture system, the DO concentration decreases because the system prevents aeration and blocks solar radiation in the water surface.
4. The shielding ratio of heat flux greatly depends on the material of floating board and is approximately constant regardless of the plant’s growth stage and growth rate.

From the above results, it is concluded that TP removal rate can be expressed by using phosphorus concentration in the water and heat flux shielding ratio can be set as a constant, using this canna floating culture system.

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