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An experimental system for the recovery, accumulation, and utilization of heat generated by bamboo chip biodegradation using a small-scale apparatus

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Abstract

We performed experiments using a small, laboratory-scale apparatus for validating a system of recovery, accumulation, and utilization of the heat generated by bamboo chip biodegradation. This system is based on the effective use of biomass resources and is needed to support industrial progress in low population regions such as Noto, Ishikawa Prefecture, Japan. This paper is the first attempt at quantifying the use of heat to warm an aquaculture pond. Although conduction is the main heat transfer mechanism in the bamboo chip pile, physical models of heat conduction are mathematically complex. Therefore, we considered the heat conduction effects concentrated around the heat extraction pipe embedded in the bamboo chip pile, and obtained relatively simple analytical solutions for the temperature in the bamboo chip pile, water reservoir for heat accumulation, and conceptual fishpond（*i.e.*, a heat utilization subsystem）. Based on the experiment's results and the simplified model, we discussed the validity of the comprehensible heat transfer model and the feasibility of the proposed system.

Key words: Bamboo chip, Biomass utilization, Composting, Heat generation, Local energy.

1. Introduction

Industrial progress has slowed in rural regions such as Noto, Ishikawa Prefecture, Japan because of depopulation and the high percentage of elderly inhabitants. Farmers in the Noto region recognized that new job development using sustainable local resources is critical and urgent（Gohma, 2013）. In addition, there is an increasing need for promoting the use of sustainable energy, which helps maintain a proper relationship between development and environment（*e.g.*, Fischer *et al.*, 2009）. In this context, we focus on the heat generated by the biodegradation of bamboo chips as a natural and local source of energy. Bamboo is primarily found in Asia, South America, and Africa, and, according to Fujii（2008）, it is a possible local energy source with the following advantages:

1．It has a higher growth rate than most plants; *i.e.*, it grows more than 10 m in 2 months.
2．It has a very short preparation period; *i.e.*, it becomes established one year after germination.
3．It is possible to achieve a stable annual increase if the number of bamboo plants harvested is balanced with that propagated.
4．It has an annual natural cycle of regeneration; therefore, reforestation is not needed.
5．It contributes to public safety; *i.e.*, bamboo rhizomes protect against mudslides.

Therefore, we designed a basic experiment for a system of recovery, accumulation, and utilization of the heat generated by bamboo chip biodegradation using a small-scale apparatus. Second, we constructed a heat-transfer model for this system and discussed its validity on the basis of the experimental results. Third, we investigated the practical potential of the proposed system by using numerical simulations of heat transfer.

To date, there are no theoretical discussions on the extraction and use of the heat generated in composting except a series of papers by Seki and Komori（1984,

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1985, 1986, 1987a, 1987b）. Even though the mathematical analysis of heat conduction in these papers was complex, a simplified model of heat transfer was proposed and its validity was discussed. In addition, this was the first attempt at quantifying the use of heat to warm an aquaculture pond.

2. Outline of the proposed system

The maximum temperature in bamboo chip composting is about 70 ℃（Seki, 2010; Gohma, 2013）; therefore temperatures higher than 70−80 ℃ generally cannot be obtained in facilities that use heat extracted from bamboo chips. However, we can use bamboo in systems that require water at temperatures below 30 ℃.

With that in mind, we propose a closed-type heat-utilizing system as shown in Fig. 1. The system consists of three subsystems: a bamboo chip container, a water reservoir, and a facility that uses the extracted heat; these subsystems correspond to the recovery, accumulation, and utilization of the heat generated during bamboo chip biodegradation. There are two water circulation routes: route 1 is for the flow between the water reservoir and bamboo chip container and route 2 is for the flow between the water reservoir and heat-utilizing facility.

Researchers have proposed several methods for the extraction of heat from compost（Gasser, 1984; Seki and Komori, 1984; Seki and Komori, 1987a; Tanaka, 1990）. From these methods, we selected a heat exchanger of the buried-tube type（Seki and Komori, 1984）on the basis of its simple assembly and inexpensive materials. In this heat-extraction system, we circulated water from the reservoir to the water pipeline in the bamboo chip container. The heat capacity of water is large enough that the extracted heat was accumulated effectively in the reservoir.

3. Mathematical model for the heat-transfer system

Conduction is the main heat-transfer mechanism in the bamboo chip pile, but physical models of heat-conduction equations are mathematically complex. Therefore we approximated that the heat conduction effects are concentrated around the heat-extraction pipe embedded in the bamboo chip pile. With this approximation, we could obtain relatively simple analytical solutions for the temperature in the bamboo chip pile, the water reservoir for heat accumulation, and the conceptual fish pond（a heat-utilization subsystem）.

3.1 Model description and mathematical treatment

Following Seki and Komori's method（1984）and assuming the heat-transfer rate in the embedded pipeline direction z is negligibly small compared to that in the radial direction r, the basic heat conduction equation in the bamboo chip pile around the pipe with heat generation is

$$\frac{\partial T}{\partial t} = \kappa\left(\frac{\partial^2 T}{\partial r^2} + \frac{1}{r}\frac{\partial T}{\partial r}\right) + \frac{R_H}{C\rho}, \qquad (1)$$

where T stands for temperature, r is the radial coordinate, t stands for time, κ is the thermal diffusivity, C is the heat capacity, ρ is the density, and R_H is the rate of heat generation.

This equation can be solved analytically with the necessary boundary and initial conditions（Shibata, 2011）. However, its mathematical treatment is complicated; therefore, the solution may not be appropriate in

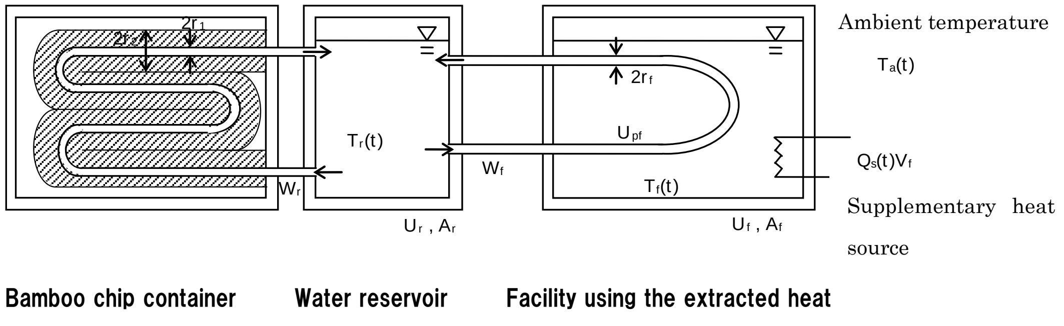

Fig. 1. Survey view of the proposed closed-type heat-utilizing system.

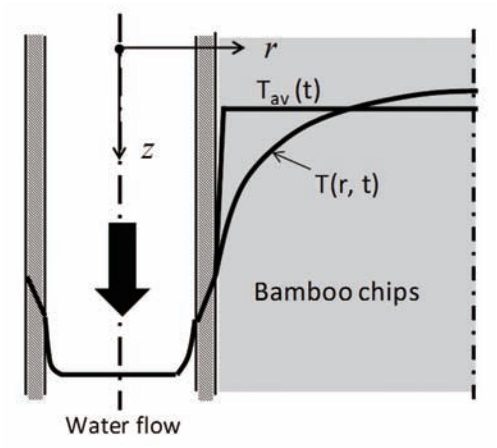

Fig. 2. Temperature profile near the pipe for heat extraction.

practice.

It is useful in practical calculations, however, if we can directly obtain the solution for T_{av}, which is the spatially averaged temperature over direction r. Thus, we propose one such approximation technique. By considering the heat resistance $1/U_c$ to heat conduction in the bamboo chip region concentrated around the pipe surface, as shown in Fig. 2, we obtain the following relationship:

$$\frac{1}{U'}=\frac{1}{U}+\frac{1}{U_c}, \tag{2}$$

where the total heat resistance $1/U'$ is the sum of the overall heat resistance $1/U$ between water flowing in the pipeline and the bamboo chips, and the heat resistance $1/U_c$ due to the heat conduction in the bamboo chip. Applying the analytical solution of the bamboo chip temperature to steady-state heat conduction with heat generation（Seki *et al.*, 2011）, the mathematical expression for $1/U_c$ is

$$\frac{1}{U_c}=\frac{r_1}{K}\left\{\frac{\eta^2}{\eta^2-1}\left(\frac{\eta^2}{\eta^2-1}\ln\eta-\frac{1}{2}\right)-\frac{1}{4}\right\}, \tag{3}$$

where K is the thermal conductivity of the bamboo chips, $\eta\ (=r_2/r_1)$ is the parameter for the piping interval, r_1 is the outer radius of the pipe, and r_2 is the effective radius of the bamboo chip bed to heat extraction. In this case, the basic equation for T_{av} :

$$T_{av}=\frac{1}{\pi\left(r_2^2-r_1^2\right)}\int_{r_1}^{r_2}2\pi rT\,dr, \tag{4}$$

is given by

$$C\rho\frac{dT_{av}}{dt}=-\frac{2\pi r_1 lH}{\pi r_1^2\left(\eta^2-1\right)l}\left(T_{av}-T_r\right)+R_H, \tag{5}$$

where l is the pipe length and T_r is the temperature in the water reservoir. H is the parameter that includes a “number of transfer units”（NTU）for heat transfer N:

$$H=U'\frac{1-e^{-N}}{N}, \tag{6}$$

$$N=\frac{2\pi r_1 U' l}{C_{pl}W}, \tag{7}$$

where C_{pl} is the specific heat of water and W is the mass flow rate of water circulated between the bamboo chip pile and water reservoir.

Heat-balance equations for the water in the reservoir and for the water in the conceptual fish pond are

$$\begin{aligned}C_{pl}\rho_l V_r\frac{dT_r}{dt}&=C_{pl}W\left(1-e^{-N}\right)\left(T_{av}-T_r\right)\\&\quad-C_{pl}W_f\left(1-e^{-N_f}\right)\left(T_r-T_f\right)\\&\quad-U_rA_r\left(T_r-T_a\right),\end{aligned} \tag{8}$$

$$\begin{aligned}C_{pl}\rho_l V_f\frac{dT_r}{dt}&=C_{pl}W_f\left(1-e^{-N_f}\right)\left(T_r-T_f\right)\\&\quad-U_fA_f\left(T_f-T_a\right)+Q_sV_f.\end{aligned} \tag{9}$$

In the above equations, V_r is the volume of water in the water reservoir, U_r is the overall heat transfer coefficient concerning heat loss from the water reservoir to the ambient environment, A_r is the wall area of the water reservoir, T_f is the temperature in the conceptual fish pond, V_f is the volume of the conceptual fish pond, W_f is the mass flow rate of water circulating between the water reservoir and bamboo chip container, U_f is the overall heat transfer coefficient concerning heat loss from the fish pond, A_f is the wall area of the fish pond, T_a is the ambient temperature, and Q_s is the heat supply rate from a supplementary heat source per unit volume of the fish pond. N_f is another NTU relating to the heat exchange between the water reservoir and the fish pond:

$$N_f = \frac{2\pi r_f U_{pf} l_{pf}}{C_{pl} W_f}, \qquad (10)$$

where r_f is the radius of the pipe set in the fish pond, l_{pf} is the total length of the pipe set in the fish pond, and U_{pf} is the overall heat transfer coefficient between water in the fish pond and water circulating in the pipe for heat exchange. The initial conditions are

$$t = 0; \quad T_{av} = T_i, T_r = T_{ri}, T_f = T_{fi}. \qquad (11)$$

By solving Eqs.（5）,（8）, and（9）with initial conditions from Eq.（11）, the analytical solutions for T_{av}, T_r, and T_f are

$$\begin{aligned} T_{av} = {} & T_i\Phi_1(t) + \int_0^t \frac{R_H(\tau)}{C\rho}\Phi_1(t-\tau)d\tau + T_{fi}AB_f\Phi_2(t) \\ & + A\int_0^t T_a(\tau)\Phi_3(t-\tau)d\tau + T_{ri}A\Phi_4(t) \\ & + AB_fG_f\int_0^t Q_s(\tau)\Phi_2(t-\tau)d\tau, \end{aligned} \qquad (12)$$

$$\begin{aligned} T_r = {} & T_{ri}\Phi_5(t) + \int_0^t T_a(\tau)\Phi_6(t-\tau)d\tau + T_{fi}B_f\Phi_7(t) \\ & + T_{fi}B_f\Phi_4(t) + B_fG_f\int_0^t Q_s(\tau)\Phi_7(t-\tau)d\tau \\ & + B_r\int_0^t \frac{R_H(\tau)}{C\rho}\Phi_4(t-\tau)d\tau, \end{aligned} \qquad (13)$$

$$\begin{aligned} T_f = {} & T_{ri}\Phi_8(t) + \int_0^t T_a(\tau)\Phi_9(t-\tau)d\tau \\ & + G_f\int_0^t Q_s(\tau)\Phi_{10}(t-\tau)d\tau + T_iB_rE_r\Phi_2(t) \\ & + T_{ri}E_r\Phi_7(t) + B_rE_r\int_0^t \frac{R_H(\tau)}{C\rho}\Phi_2(t-\tau)d\tau. \end{aligned} \qquad (14)$$

In the above equations, the parameters are A, B_r, B_f, D, E_r, F_f, and G_f, and the functions are ϕ_1 through ϕ_{10}. Table 1 presents the parameters and functions.

3.2 Validity of the parameter concentration model

To validate the parameter concentration model, we first compared T_{av} values calculated by a parameter distributed model（heat conduction model）and those obtained from the parameter concentration model. Then we considered the heat-transfer process from the bamboo chips to the water flowing in the embedded pipe, where the water temperature is held constant at T_l. The boundary and initial conditions for T are

$$r = r_1; \quad K\frac{\partial T}{\partial r} = U(T - T_l), \qquad (15)$$

$$r = r_2; \quad \frac{\partial T}{\partial r} = 0, \qquad (16)$$

$$t = 0; \quad T = T_i. \qquad (17)$$

The analytical solution for Eq.（1）that satisfies Eqs.（15）-（17）can be derived by applying the Laplace transformation method（Carslaw and Jaeger, 1959）. The solution for T_{av} obtained after substituting this solution of T into Eq.（4）is

$$\begin{aligned} T_{av} = {} & \frac{R_H}{2K}\left[\frac{r_2^4}{r_2^2 - r_1^2}\ln\left(\frac{r_2}{r_1}\right) - \frac{3}{4}r_2^2 + \frac{1}{4}r_1^2\right] + \frac{R_H}{2Ur_1}\left(r_2^2 - r_1^2\right) + T_l \\ & + \frac{R_H}{K}\frac{4r_1}{\left(r_2^2 - r_1^2\right)}\left(\frac{U}{K}\right)^2 \sum_{n=1}^{\infty} \frac{Z_{01}(\alpha_n r_1)e^{-\kappa\alpha_n^2 t}}{\alpha_n^4\left[r_1\left(\alpha_n^2 + (U/K)^2\right)Z_{01}(\alpha_n r_1) + r_2\alpha_n\left\{\alpha_n Z_{10}(\alpha_n r_1) + (U/K)Z_{00}(\alpha_n r_1)\right\}\right]} \\ & - (T_i - T_l)\frac{4r_1}{\left(r_2^2 - r_1^2\right)}\left(\frac{U}{K}\right)^2 \sum_{n=1}^{\infty} \frac{Z_{11}(\alpha_n r_1)e^{-\kappa\alpha_n^2 t}}{\alpha_n^2\left[r_1\left(\alpha_n^2 + (U/K)^2\right)Z_{01}(\alpha_n r_1) + r_2\alpha_n\left\{\alpha_n Z_{10}(\alpha_n r_1) + (U/K)Z_{00}(\alpha_n r_1)\right\}\right]}, \end{aligned} \qquad (18)$$

where

$$Z_{mi}(\alpha_n r_1) = J_m(\alpha_n r_1)Y_i(\alpha_2 r_2) - Y_m(\alpha_n r_1)J_i(\alpha_n r_2). \qquad (19)$$

$J_j(X)$ and $Y_j(X)$ are the first- and second-kind Bessel functions of the j-th order, respectively. The value of α_n（n being a natural number）is a positive root of the following equation:

$$\alpha_n Z_{11}(\alpha_n r_1) + (U/K)Z_{10}(\alpha_n r_1) = 0. \qquad (20)$$

A corresponding solution for the parameter concentration model is obtained by

$$\begin{aligned} T_{av} = {} & T_l + \frac{r_1\left(\eta^2 - 1\right)}{2U'}R_H \\ & + \left\{T_i - T_l - \frac{r_1\left(\eta^2 - 1\right)}{2U'}R_H\right\}e^{-\frac{2U'}{r_1\left(\eta^2 - 1\right)C\rho}t}. \end{aligned} \qquad (21)$$

Equation（21）is equal to Eq.（12）under the conditions that 1）R_H and T_a are constant; 2）$T_r = T_{ri} = T_l$ =

constant; 3）$Q_s = 0$; and 4）H approaches U' because N approaches zero.

Figure 3 shows the calculation results for T_{av} in the bamboo chip bed using the proposed parameter concentration model with the calculation results for the bamboo chip temperature by the distributed parameter model over time. Both agree with each other. Therefore, the simple model proposed here can be considered appropriate for estimating the value of T_{av}.

Table 1. Parameters and functions used in the analytical solutions of T_{av}, T_r, and T_f.

- Parameters:

$$A = \frac{2\pi r_1 H}{\pi r_1^2(\eta^2 - 1)},\quad B_r = \frac{C_{pl} W(1 - e^{-N})}{C_{pl}\rho_l V_r},\quad B_f = \frac{C_{pl} W_f (1 - e^{-N_f})}{C_{pl}\rho_l V_r},\quad D = \frac{U_r A_r}{C_{pl}\rho_l V_r},$$

$$E_r = \frac{C_{pl} W_f (1 - e^{-N_f})}{C_{pl}\rho_l V_f},\quad F_f = \frac{U_f A_f}{C_{pl}\rho_l V_f},\quad G_f = \frac{V_f}{C_{pl}\rho_l V_f}.$$

- Functions:

$$\Phi_1(t) = \sum_{i=1}^{3} \frac{\alpha_i^2 + (B_r + B_f + D + E_r + F_f)\alpha_i + (B_r + D)(E_r + F_f) + B_f F_f}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},$$

$$\Phi_2(t) = \sum_{i=1}^{3} \frac{1}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},\quad \Phi_3(t) = \sum_{i=1}^{3} \frac{D\alpha_i + D(E_r + F_f) + B_f F_f}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},$$

$$\Phi_4(t) = \sum_{i=1}^{3} \frac{\alpha_i + E_r + F_f}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},\quad \Phi_5(t) = \sum_{i=1}^{3} \frac{\alpha_i^2 + (A + E_r + F_f)\alpha_i + A(E_r + F_f)}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},$$

$$\Phi_6(t) = \sum_{i=1}^{3} \frac{D\alpha_i^2 + \{D(A + E_r + F_f) + B_f F_f\}\alpha_i + A\{D(E_r + F_f) + B_f F_f\}}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},$$

$$\Phi_7(t) = \sum_{i=1}^{3} \frac{\alpha_i + A}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},\quad \Phi_8(t) = \sum_{i=1}^{3} \frac{\alpha_i^2 + (A + B_r + B_f + D)\alpha_i + A(B_f + D)}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},$$

$$\Phi_9(t) = \sum_{i=1}^{3} \frac{F_f \alpha_i^2 + \{F_f(A + B_r + E_r + D) + DE_r\}\alpha_i + A\{F_f(B_f + D)\}}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t},$$

$$\Phi_{10}(t) = \sum_{i=1}^{3} \frac{\alpha_i^2 + (A + B_r + E_r + D)\alpha_i + A\{B_f + D\}}{[3s^2 + 2A^* s + B^*]_{s=\alpha_i}} e^{\alpha_i t}.$$

Where

$$A^* = A + B_r + B_f + D + E_r + F_f,\quad B^* = A(B_f + D) + E_r(A + B_r + D) + F_f(A + B_r + B_f + D),$$

$$C^* = A(E_r D + F_f B_f + F_f D),$$

α_1, α_2, and α_3 are the roots of the following equation:

$$s^3 + A^* s^2 + B^* s + C^* = 0$$

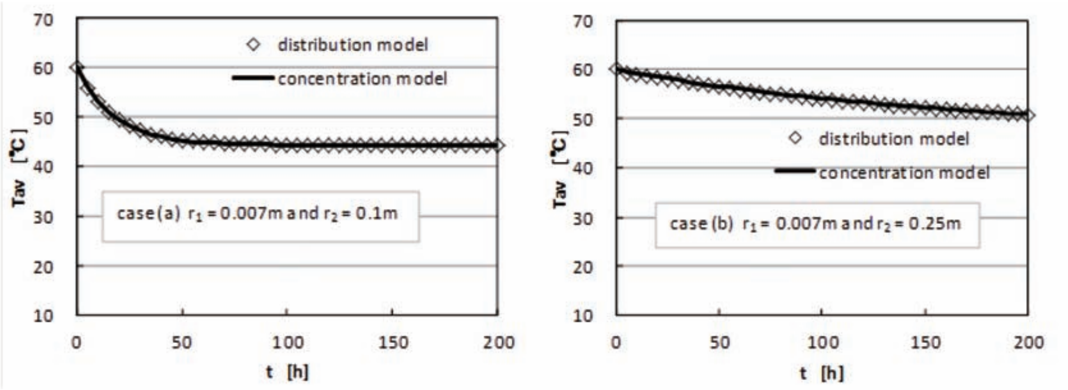

Fig. 3. Calculated T_{av} in the bamboo chip bed by the parameter concentration model and calculation results for the bamboo chip temperature by the distributed parameter model over time.

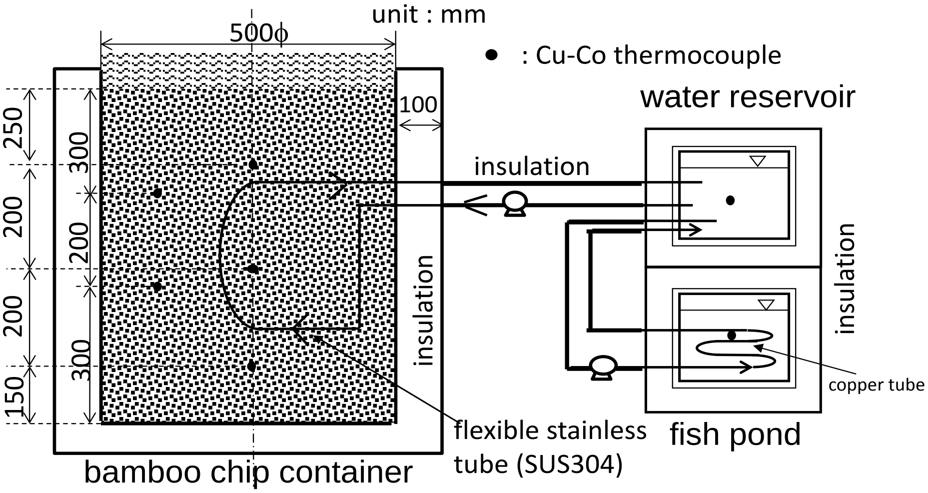

Fig. 4. Experimental apparatus.

4. Experiment

Figure 4 illustrates a small, laboratory-scale experimental apparatus. The volume of the bamboo chip container is 0.157 m^3. The volumes of cubic water reservoir and conceptual fish pond containers are 0.0156 m^3 each. All three containers are insulated with 50-mm-thick styrofoam resin to prevent heat loss. A 0.9-m-long flexible stainless tube（SUS304）is set in the bamboo chip container for heat extraction. Eight pairs of thermocouples are distributed in the system—（five pairs in the bamboo chip container, one pair in the water reservoir, one pair in the fish pond, and one pair in the room for experiment）for temperature measurement. Heat-tolerant pumps are set in the two water channels. In the fish pond, a 2-m-long copper tube（8-mm inner diameter, 1-mm thick）is arranged for heat exchange to warm the water in the fish pond.

The bamboo chips are produced in advance by grinding harvested bamboo trees grown naturally in the Kakuma campus of Kanazawa University. Table 2 lists the properties of the bamboo chips. According to a report on its calorific value, the main constituent in bamboo is carbohydrates（Fujita, 1993）. The thermal conductivity, K, is estimated from the empirical equation of water content w:

$$K = 1.36w + 0.126, \tag{22}$$

Table 2. Properties of the bamboo chip used.

item	Run 1	Run 2
Ignition loss [%]	90.9	89.7
Higher calorific value (dry base) [kJ/kg]	18200	18800
Moisture content [%]	45.9	46.9
Specific heat C_p [kJ/（kg ℃）]	2.62	2.65
Thermal conductivity K [kJ/（m h ℃）]	0.74	0.76
Density ρ [kg/m^3]	332	363

Table 3. Experimental conditions.

r_1 = 0.007 m
r_2 = 0.1 m
ρ_l = 1000 kg/m^3
l = 0.9 m
C_{pl} = 4.2 kJ/（kg ℃）
U = 120 kJ/（m^2 h ℃）
V_r = 0.015 m^3

A_rU_r = 2.14 kJ/（h ℃）
U_{pf} = 1100 kJ/（m^2 h ℃）
l_f = 1.5 m
A_fU_f = 2.31 kJ/（h ℃）
V_f = 0.015 m^3
Q_s = 0 kJ/（m^3 h）

item	Run 1	Run 2
T_i [℃]	49.5	52.4
T_{ri} [℃]	29.3	29.2
T_{fi} [℃]	26.7	29.2
W [kg/h]	79.3	67.4
W_f [kg/h]	66.5	65.3

which was obtained in advance by a unsteady-state heat conduction experiment using the sample bamboo chips set in a small cylindrical container（Kunugida and Tone, 1975）. The specific heat is estimated from the following empirical equation obtained by Seki（1990）for livestock and farmyard solid waste:

$$C = 2.91w + 1.30. \qquad (23)$$

Table 3 shows the operating conditions for the experiment.

First, the bamboo chips are placed in the container. Empirical data on bamboo chip biodegradation suggests that aerobic and anaerobic fermentation proceed simultaneously（Seki, 2010）. As a result, we did not attempt to externally aerate in this experiment. Consequently, the temperature in the container gradually increases. When the temperature reaches 50−60 ℃, the extraction, accumulation, and utilization of the generated heat is initiated by circulating the water in the reservoir and fish pond. The flow rate is controlled by a manual voltage inverter connected to the pump. When the temperatures in the three subsystems dropped to within a 5 ℃ difference of each other, little additional heat was extracted. Then, the water circulation was stopped and the experiment was terminated.

5. Results and discussion

5.1 Experimental results

The experiments were performed twice. The first experiment（Run 1）started at t = 50 h and ended at t = 220 h. The second experiment（Run 2）started at t = 330 h and ended at t = 480 h. Figure 5 shows the experimental results for temperatures in the container, the water reservoir, and the fish pond over time for Run 1. After t = 24 h, the temperature rapidly rose and reached 45–55 ℃ by t = 50 h. Then we began extraction and used the generated heat in the bamboo chip container by circulating the water through the flexible stainless pipe（SUS304）set in the container and through the copper-tube line between the water reser-

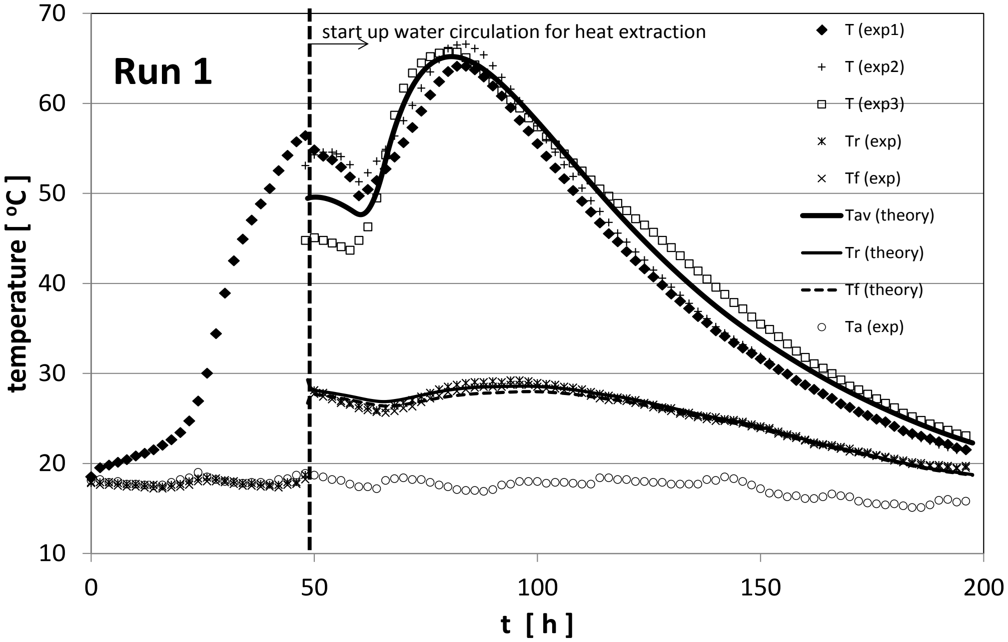

Fig. 5. Experimental results for the temperature in the container, the water reservoir, and the fish pond over time for Run1.

voir and fish pond. The temperatures in the water reservoir and fish pond dropped by 2 ℃ after 24 h, while the temperature in the bamboo chip container dropped by about 5 ℃. Subsequently, the temperature in the container began to rise again and reached 50–65 ℃ at t = 90 h. During this period, the water temperatures in the reservoir and fish pond also increased with increasing bamboo chip temperature. After t = 90 h, the temperature in the water reservoir and fish pond gradually decreased. At t = 220 h, the temperatures in the three subsystems fell and approached an approximately identical value. Then we stopped the water circulation and terminated the experimental run.

Just after stopping the experimental run, we took the bamboo chips out of the container. After turning them, we repacked them in the container as soon as possible and started the temperature measurement at t = 240 h. The bamboo chip temperature gradually recovered and reached about 50 ℃ at t = 330 h before starting the second experiment for extraction and utilization of the generated heat（Run 2）. The bamboo chip temperature slowly decreased as the heat extraction progressed, but the temperatures in the water reservoir and fish pond were maintained at greater than 23 ℃ for about 150 h. At t = 480 h, when the temperatures in the three subsystems fell and approached an approximately identical value, the experimental run was terminated.

5.2 Comparison of the theoretical and experimental results

The rate of heat generation R_H in the bamboo chip pile was estimated on the basis of the experimental data of the temperature change. Because the parameter concentration model is valid, as explained in Section 3.2, R_H in the composting bamboo chips was estimated first by applying the temperature change over every 0.5-h time increment to the finite difference form of Eq.（5）. Fig. 6 shows the estimated results of R_H with time. The initiation of heat extraction thermally shocks the microorganisms. As a result, R_H decreased from its initial maximum value of 1200 kJ/（m^3 h）as the microbial activity decreased. Subsequently, as the microbial activity recovered, R_H recovered to 3000 kJ/（m^3 h）. However, after t = 90 h, R_H gradually decreased with decreasing temperature. Assuming that R_H obeys a first-order delay system（*e.g.*, Inoue *et al.*, 1960）for the decreasing temperature phase, and a second-order delay system（*e.g.*, Inoue *et al.*, 1960; Yagi and Nishimura, 1969）for the increasing temperature phase,

R_H may be expressed for different values of t as follows:

$$
\begin{aligned}
&t = 50 \sim 60h;\ R_H = 1200e^{-0.04(t-50)},\\
&t = 60 \sim 67h;\ R_H = R_H\big|_{t=60} + 4600\\
&\quad \times \left\{1 - e^{-0.24(t-60)} - 0.24(t-60)e^{-0.24(t-60)}\right\}, \qquad (24)\\
&t = 67h \sim\ ;\ R_H = R_H\big|_{t=67}\, e^{-0.031(t-67)}.
\end{aligned}
$$

The results of R_H calculated from Eq.（24）are shown as the solid line in Fig. 6. These results agree with the results estimated experimentally.

Fig. 5 also plots the calculated T_{av}, T_r, and T_f from Eqs.（5）,（8）, and（9）using Eq.（24）. These results also agree with the experimental results. Thus, the proposed heat-transfer model is deemed appropriate.

We define the efficiency of heat utilization as the ratio of the total amount of heat supplied to the fish pond, which is nearly equal to the amount of heat loss from the wall of the fish pond, to the total amount of heat generated in the region and substantially contributing to the heat extraction in the bamboo chip container $\{= \pi(r_2^2 - r_1^2)l\}$. The average value was 65 %（71 % for Run 1 and 59 % for Run 2）, which is favorable for practical applications.

5.3 Computer simulation for discussing the possibility for practical application

The mathematical model was deemed valid; therefore we used computer simulations and assumed a larger-size system in considering its applicability. The utilization of heat to warm an aquaculture pond is one potential practical application. This is a closed-type heat-transfer system in which the heat generation rate R_H and the atmospheric temperature T_a are assumed constant, and the time courses of T_{av}, T_r, and T_f are calculated from Eqs.（12）,（13）, and（14）. The volume of the bamboo chip pile is assumed 50 m^3 and Table 4 lists the rest of the calculation conditions. Fig. 7 plots the simulated results.

In cases 1, 2, and 3, where V_f is 2 m^3, T_{av} increases（Case 1）, remains constant（Case 2）, or gradually decreases（Case 3）. T_r and T_f increased and gradually approached a constant value equal to or greater than 30 ℃. T_{av} may not recover in case 3 because R_H is smaller than in cases 1 and 2 and the amount of heat recovery is too large owing to the narrow piping interval.

In cases 4, 5, and 6, where V_f is 5 m^3 and larger than in cases 1, 2, and 3, the temperatures of all the subsystems（T_{av}, T_r, and T_f）are lower than in cases 1, 2, and 3 because of the larger heat load than cases 1, 2, and 3. T_f is held at 20−30 ℃（Case 4）, 20−24 ℃（Case 5）, and 18−23 ℃（Case 6）. Summarizing these results, we discover that if we pay attention to the piping interval and use a composter equal to or greater than 50 m^3,

1）temperatures as high as 50−60 ℃ can be maintained;

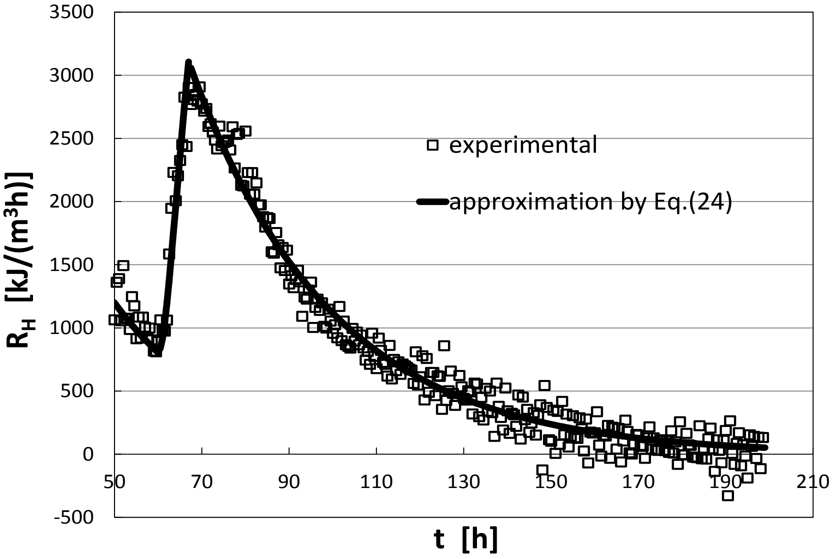

Fig. 6. Comparison of the results of R_H calculated from Eq .（24）with the results estimated experimentally.

Table 4. Calculation conditions for simulating a practical scale system.

$r_1 = 0.007$ m
$r_2 = 0.25$ m
$l = 100$ m
$\rho = 500$ kg/m^3
$C_p = 3.0$ kJ/（kg ℃）
$K = 0.94$ kJ/（m h ℃）
$\rho_l = 1000$ kg/m^3
$C_{pl} = 4.2$ kJ/（kg ℃）
$W = 100$ kg/h
$W_f = 1000$ kg/h
$U = 120$ kJ/（m^2 h ℃）

$V_r = 2$ m^3
$A_r = 10$ m^2
$U_r = 3$ kJ/（m^2 h ℃）
$r_f = 0.007$ m
$U_{pf} = 1100$ kJ/（m^2 h ℃）
$Q_s = 0$ kJ/（m^3 h）
$T_{ri} = 20$ ℃
$T_{fi} = 20$ ℃
$T_{avi} = 60$ ℃
$T_a = 5$ ℃

item	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
R_H [kJ/（m^3 h）]	200	150	100	200	150	100
U_f [kJ/（m^2 h ℃）]	8	8	8	10	10	10
A_f [m^2]	8	8	8	14	14	14
V_f [m^3]	2	2	2	5	5	5
l_f [m]	20	20	20	50	50	50

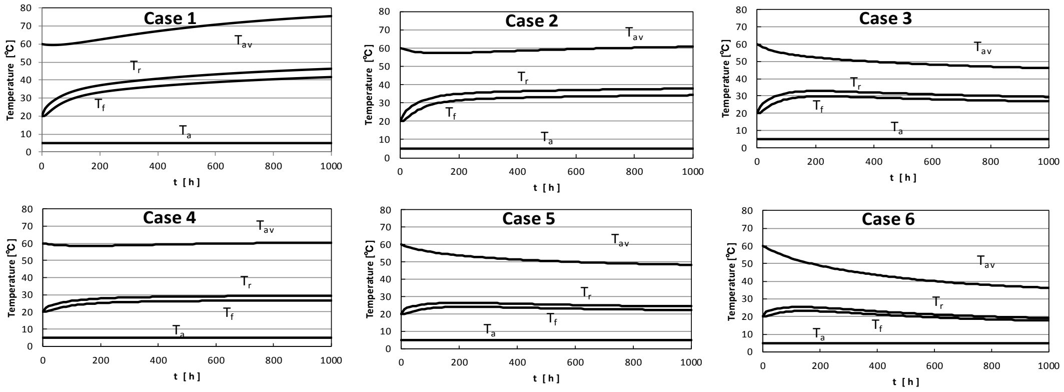

Fig. 7. Simulated results under practical conditions.

2）it is possible to extract and utilize the generated heat for up to 1000 h;

3）R_H is not necessarily larger than approximately 200 kJ/（m^3 h）.

A T_f of about 20 ℃ may be maintained even if T_a is as low as 5 ℃, indicating good potential for warming this aquaculture system by using the heat generated by bamboo chip biodegradation.

The numerical simulations suggest that the proposed system is possible, but its feasibility should be confirmed by a pilot plant-scale experiment. The main part of the energy required to run the system is the power to flow water as the heat transfer medium. If this energy can be naturally supplied by a solar battery or a small-scale hydropower system, for example, then the feasibility of the system is high and is something that we will discuss in the near future.

6. Conclusions

We performed basic experiments for a system of recovery, accumulation, and utilization of heat generated by bamboo chip biodegradation using a small, laboratory-scale apparatus and considering the effective use of biomass resources. Then we developed a heat-transfer model and discussed its validity by comparing the theoretical results for the temperature in the bamboo chip container, water reservoir for heat accumulation, and the conceptual fish pond with the experimental results. Subsequently we discussed the applicability of the proposed system using this heat-transfer model. The proposed system aimed at considering the potential for applying currently unused but locally generated energy based on the classical heat-transfer technique. It is desirable to perform a pilot plant-scale experiment of this system to confirm the simulated results for practical application, and a simple control algorithm must be constructed to realize this inexpensive heat-utilization system.

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