論　文

農業気象 (*J. Agr. Met.*) 43 (3): 189–202, 1987

Application of Heat Generated in Compost to Soil Warming

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Abstract

A simulation model of a soil warming system with a compost heat extractor was proposed. The soil warming system for the model simulation was constituted by some compost beds for heat extraction, pipe lines for circulation of the medium water and water reservoirs. The application of the simulation model to the practical example for warming the soil bed was investigated by the analysis of the heat balance of the system, using some actual operating conditions. The heat balance in the soil warming was treated analytically and systematically, taking account of the process control of the system. The concept of the model simulation and procedure for the systematical analysis of the heat balance in the soil warming may be of use for the planning, design and operations of the actual soil warming system.

1. Introduction

It has been empirically proposed that the range of the suitable soil temperature for breeding or cultivating vegetables would be from 18 to 23°C (Itaki, 1980), though the suitable temperature of soil for cultivation is dependent upon the growing stage and the species of the vegetable.

Previously, in order to estimate the temperature profile of the soil bed around the warm water pipe buried in the soil, an analytical solution was presented and it was also available to evaluate the optimum temperature of the medium water circulated in the pipe lines within the soil bed (Seki, Komori and Kajikawa, 1986b). According to the calculated results for several illustrative examples of the soil warming, the optimum water temperature required to control the soil temperature in the range of 18 to 23°C was about 30°C and the heat flux released to the soil at the surface of the water pipe is approximately in the range of 10–15kcal/mhr.

For instance, when the quantity of heat 1000 kcal/hr is required continuously to warm a soil bed for cultivation, the total length of the pipe line buried in the soil bed will be about 100m and the volume of a compost heat generator is approximately 5.0m^3, because the rate of heat generation possible to extract from the unit volume of the compost is at most 200kcal/m^{3}hr in average (Seki and Komori, 1983, 1984a).

Supposing that the calculated results would be applied to a practical soil warming system with a compost heat extractor as a heat source, these numerical values obtained by the analytical solution may be available to decide an original planning of the process and some dimensions of devices for the soil warming system. However, these values of basic data could not give details of the process design, specifications of the device and the practical operation manuals for the soil warming.

Therefore, to get the above-mentioned detailed data for design of the process and operation of the actual soil warming, a simulation model of the soil warming system with a compost heat extractor unit was investigated by introducing a systematic heat balance method together with the concept of the process control.

Read at Annual Meeting on May 30, 1986
Received June 26, 1987

2. Systematic heat balance of a soil warming system and determination of the volume of a compost bed

A schematic representation of systematic heat balance of the soil warming system is shown in Fig. 1. The soil warming system consists of a warm water reservoir for regulating the water temperature, two compost beds for the heat source, and a pipe line unit for warming the soil bed.

Usually, the rate of heat transfer for the soil warming is proportional to the area of the soil bed and particularly, in the practical case of cultivation, a large amount of heat may be required to warm the soil bed over the wide area for a long period. According to several experimental results (Seki and Komori, 1985b), the rate of heat generation in a unit volume of the compost bed is comparatively smaller than the amount of heat for warming the soil bed per unit time, so that the activity of the microorganisms is decreased by the fall of temperature of the compost due to the extraction of heat.

Then, to reconcile the quantity of heat released to the soil with the rate of heat extraction from the compost and to maintain the activity of the microorganisms for a fairly long period, it is suggested that a periodical heat extraction from one of several compost beds combined in parallel would make a heat source sub-system most suitable by using simultaneously some reservoirs as well. Namely, for an operation of the heat source sub-system, a conversion from the heat extraction to the temperature recovery of the compost takes place alternatively at intervals of θ_{ext} or θ_{rec} in composting process, and for the purpose of a stable heat extraction, several compost beds to be extracted the heat are switched over one by one.

Fig. 2 shows an operation cycle of the heat extraction for the case of two compost beds. Details of a compost bed such as the volume, dimensions and other specifications of the compost bed, are designed so that the amount of heat required to warm the soil bed may be extracted sufficiently from a single compost bed. In Fig. 2, the range of $T_u - T_d$ is a permitted temperature limit of the compost possible to extract continuously the heat generated in the compost and θ_c is a cycle time of heat extraction.

According to the pattern of the operation cycle, as shown in Fig. 2, the extraction of heat from a compost starts at T_u, it is continued for a period θ_{ext} and the temperature of the compost recovers to the previous level T_u for a time θ_{rec} by interrupting the heat extraction at T_d.

Thus, the stable heat extraction could be obtained by overlapping of two waves of the operation cycle with the same period and temperature amplitude.

By the above operation method of the heat extraction, the flow diagram of the heat balance for the soil warming system can be drawn schematically in Fig. 3. Therefore, the systematic heat balance for one of the alternative system

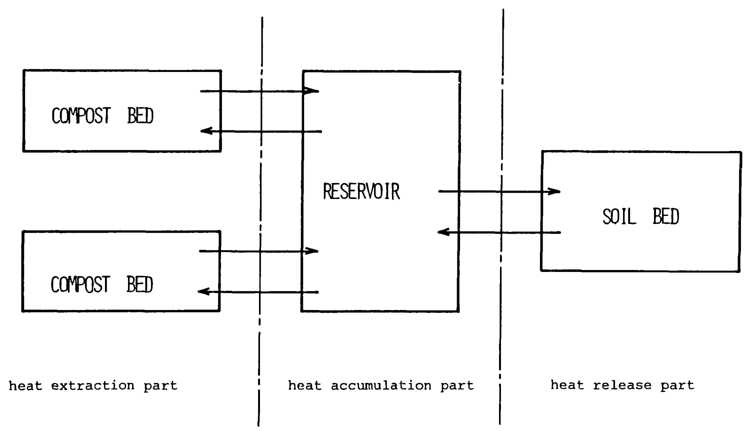

Fig. 1 Schematic representation of the systematic heat balance of the soil warming system (⟶: flow direction of heat by medium fluid)

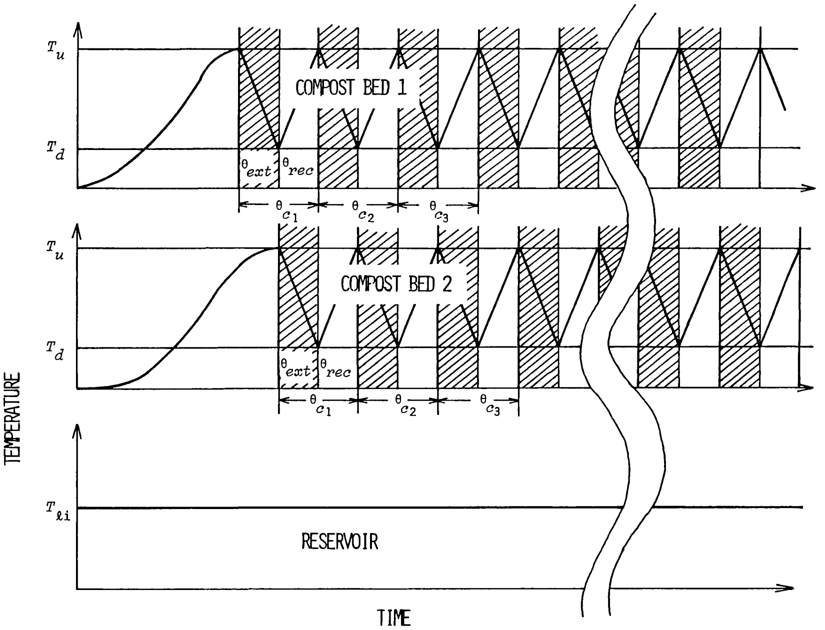

Fig. 2 Operation cycle of heat extraction for the case of two compost beds

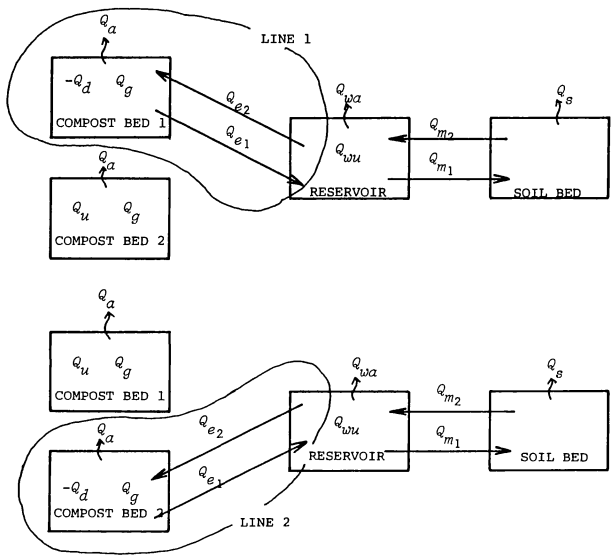

Fig. 3 Flow diagram of the heat balance for the soil warming system

lines is

$$-Q_d = Q_g - Q_a - Q_e\ , \quad (1)$$

$$Q_e = Q_{e1} - Q_{e2}\ , \quad (2)$$

and Q_u for the temperature recovery of the compost is

$$Q_u = Q_g - Q_a\ . \quad (3)$$

Now, by a suitable operation cycle shown in Fig. 2, θ_{ext} is assumed to be equal to θ_{rec}, so that Q_d for θ_{ext} may be regarded as being approximately identical with Q_u for θ_{rec}. Therefore, from Eq. (1) and Eq. (3), Q_e is defined by

$$Q_e = 2(Q_g - Q_a)\ . \quad (4)$$

Supposing that Q_{wu} is the rate of heat accumulation or heat dissipation of the water in the reservoir, a heat balance for the water reservoir is expressed by the following equation.

$$Q_{wu}=Q_e-Q_{wa}-Q_m\ , \quad (5)$$

and Q_m is

$$Q_m=Q_{m1}-Q_{m2}\ . \quad (6)$$

In Eq. (5), for the case of $Q_{wu}>0$, there is an excessive heat extraction from the compost bed and for the case of $Q_{wu}<0$, the amount of heat for the soil warming is lacking. In other words, the unbalance of Q_{wu} interferes with the stable operation of the soil warming system.

In order to make the soil warming system most suitable and stable, it is desirable to maintain at $Q_{wu}=0$. Therefore, by substituting zero for Q_{wu} in Eq. (5) and by using Eq. (4), Q_g is given by

$$Q_g=\frac{Q_{wa}+Q_m}{2}+Q_a\ , \quad (7)$$

and Q_g can be also written in a form of

$$Q_g=V_t\,G_0\ , \quad (8)$$

where G_0 is equivalent to the rate of heat possible to extract from the compost.

Supposing that the composting reactions take place uniformly in the compost bed and the compost bed is a rectangular prism $V_t/\zeta a^2$ long, ζa wide and a high, as shown in Fig. 4, Q_a may be expressed by

$$Q_a=h\,(T'-T_a)\,A=h\,(T_{av}-T_a)\,2a^2[\zeta+\frac{V_t}{a^3}(\frac{1}{\zeta}+1)]. \quad (9)$$

From Eqs. (7), (8) and (9), V_t is

$$V_t=[(\frac{Q_{wa}+Q_s}{2})+2a^2h\zeta\,(T_{av}-T_a)]$$
$$/[G_0-\frac{2h}{a}(\frac{1}{\zeta}+1)(T_{av}-T_a)]\ . \quad (10)$$

According to the experimental results obtained in previous investigations (Seki and Komori, 1985b; 1986a), Eq. (9) is held to a fairly good approximation by substituting T_{av} for T'. Since the efficiency of the heat extraction from the compost bed becomes smaller than unity (Seki and Komori, 1985b), the actual volume of the compost bed V for the practical soil warming would be larger than V_t.

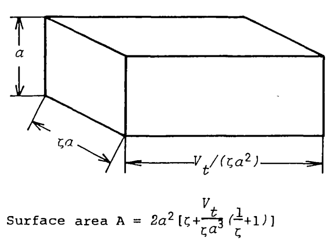

Fig. 4 Dimensions of the compost bed

3. Mathematical treatment of the heat transfer mechanism in the soil warming system

In the soil warming process, the conduction and the convection of heat are recognized to coexist together in both compost and soil beds. Particularly, for the heat extraction from the compost bed by the medium water, since the rate of heat extraction or the temperature of water at the outlet of the heat extractor varies with time, it is a difficult problem to maintain the water in the reservoir at constant temperature without a systematic control of the flow rate or the temperature of water.

Then, the original soil warming system shown in Fig. 1 is improved to an appropriate system by addition of a 2nd water reservoir, taking account of the practical optimum operation of the soil warming. Fig. 5 illustrates an improved soil warming system and Fig. 6 shows the flow diagram of the heat balance for the above alternative soil warming system. For the case of the improved soil warming system, since Q_{wa} in Eq. (10) includes two terms of heat loss, Q_{wa1} of the 1st reservoir and Q_{wa2} of the 2nd reservoir, Eq. (10) may be rewritten in a form of

$$V_t=[(\frac{Q_{wa1}+Q_{wa2}+Q_s}{2})+2a^2h\zeta\,(T_{av}-T_a)]$$
$$/[G_0-\frac{2h}{a}(\frac{1}{\zeta}+1)(T_{av}-T_a)]\ . \quad (11)$$

The system may be divided into two sub-systems by introducing a 2nd water reservoir, so that the important mathematical treatment of the soil warming would be reduced to solve the heat transfer problem for the region of the heat source sub-system. Then, two heat transfer problems for the periodical heat extraction are solved by using suitable boundary conditions upon several assumptions.

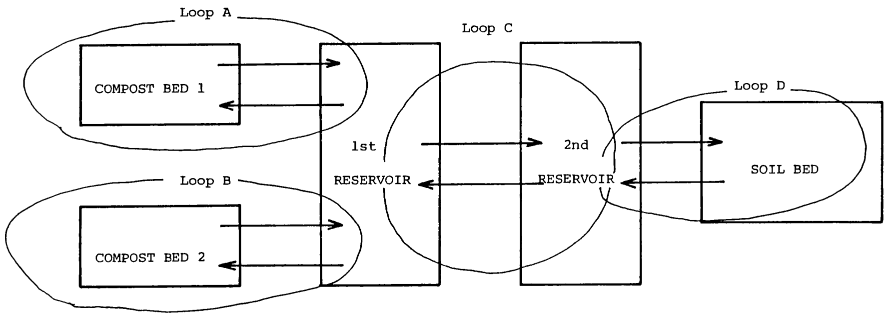

Fig. 5 Schematic representation of the systematic heat balance of an improved soil warming system (⟶: flow direction of heat by medium fluid)

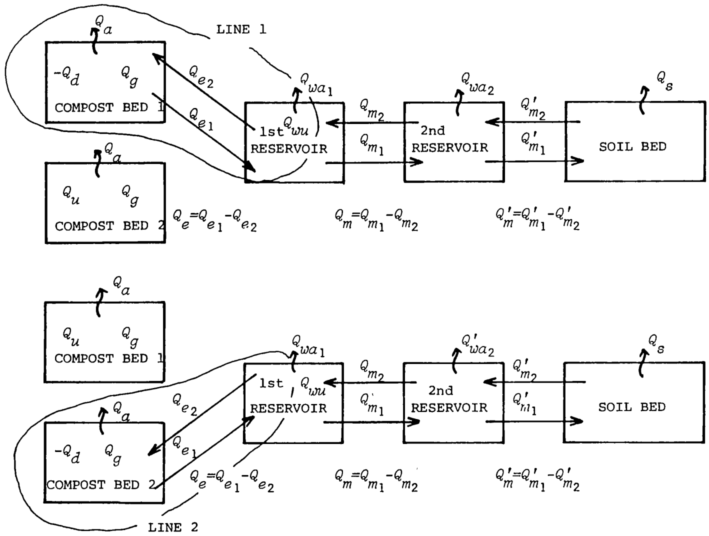

Fig. 6 Flow diagram of the heat balance for the improved soil warming system

3.1 Solutions for the heat conduction problem of the compost and the temperature of water in the heat extraction process

For simplification of the problem, the following assumptions are made.

1) Heat generation in a long core of the compost is uniform and heat is produced apparently at a constant rate G_0 in the region $r_1<r<r_2$ available for heat extraction.

2) Thermal physical properties of the compost are independent of temperature.

3) Water tubes within the compost bed are arranged in equilateral triangular pitch, and there is approximately no flow of heat at the outside of compost core $r=r_2$.

4) The heat loss between equipments to the atmosphere and the end effects due to piping works of the system can be ignored.

5) The velocity profile relation of water in the tube can be substituted by the average velocity.

In addition, according to the several experimental and calculated results obtained in the previous investigations (Seki and Komori, 1984b; 1985a), the temperature of the compost T in the core region of $r_1<r<r_2$ varied slightly with the distance of water flow z and the temperature difference $T|_{r=r_1}-T_l$ was approximately constant over the total length of the water tube, though T_l increased linearly in proportional to the distance of water flow z.

Then, integration of T and T_l with respect to z gives

$$\tilde{T}(r,\theta)=\frac{1}{l_c}\int_0^{l_c} T(r,z,\theta)\,\mathrm{d}z\,, \qquad (12)$$

$$\widetilde{T}_l(\theta)=\frac{1}{l_c}\int_0^{l_c}T_l(z,\theta)\,\mathrm{d}z\ , \qquad (13)$$

and by using the above equations, the temperature difference $T|_{r=r_1}-T_l$ is approximately

$$T|_{r=r_1}-T_l\fallingdotseq\widetilde{T}|_{r=r_1}-\widetilde{T}_l\ . \qquad (14)$$

Thus, upon these assumptions and by using Eq. (12) for manipulation of the analytical procedure, the conduction equation of $\widetilde{T}$ is given by

$$\frac{\partial\widetilde{T}}{\partial\theta}=\kappa\left(\frac{\partial^2\widetilde{T}}{\partial r^2}+\frac{1}{r}\frac{\partial\widetilde{T}}{\partial r}\right)+\frac{G_0}{C_p\rho}\qquad \text{for } r_1<r<r_2\ . \qquad (15)$$

Since the heat flux transferred to the water from the compost may be constant with respect to z approximately, by using Eqs. (12), (13) and (14), the boundary condition at $r=r_1$ is

$$K\frac{\partial\widetilde{T}}{\partial r}=U(\widetilde{T}-\widetilde{T}_l)\qquad \text{at } r=r_1\ . \qquad (16)$$

From the assumption 3), the other boundary condition at $r=r_2$ is

$$\frac{\partial\widetilde{T}}{\partial r}=0\qquad \text{at } r=r_2\ , \qquad (17)$$

and the initial condition is

$$\widetilde{T}=T_u\qquad \text{at } \theta=0\ . \qquad (18)$$

Now, the equation of heat balance for the water flowing in the tube of the heat extractor is

$$u\frac{T_{lou}-T_{l1}}{l_c}=\frac{2r_1U}{C_{pl}\rho_l r_i^2}(\widetilde{T}|_{r=r_1}-\widetilde{T}_l)\ . \qquad (19)$$

Supposing that the water in the reservoir is a well-stirred fluid, the heat balance equation of water in the 1st reservoir is

$$C_{pl}\rho_l V_{v1}\frac{\mathrm{d}T_{l1}}{\mathrm{d}\theta}=\pi r_i^2uC_{pl}\rho_l(T_{lou}-T_{l1})$$
$$-h_{v1}S_{v1}(T_{l1}-T_a)-Q_m\ . \qquad (20)$$

The heat balance of the 2nd reservoir is expressed as the following equation provided that T_{l2} is approximately at constant,

$$Q_m-h_{v2}S_{v2}(T_{l2}-T_a)-Q_m'=0\ . \qquad (21)$$

The heat balance of water circulated in the pipe lines of the soil bed is

$$Q_m'-ql_{sh}=0\ . \qquad (22)$$

Substitution of Eqs. (21) and (22) into Eq. (20) gives

$$C_{pl}\rho_l V_{v1}\frac{\mathrm{d}T_{l1}}{\mathrm{d}\theta}=\pi r_i^2uC_{pl}\rho_l(T_{lou}-T_{l1})$$
$$-h_{v1}S_{v1}(T_{l1}-T_a)-ql_{sh}-h_{v2}S_{v2}(T_{l2}-T_a)\ . \qquad (23)$$

In the right hand side of Eq. (23), the first term is the rate of heat extraction, the second term is the heat loss from the 1st reservoir to the atmosphere, the third term is the heat released to the soil bed, and the fourth term is the heat loss from the 2nd reservoir to the atmosphere.

The initial condition for the water in the 1st reservoir is

$$T_{l1}=T_{li}\qquad \text{at } \theta=0\ . \qquad (24)$$

By applying the Laplace Transformation method (Carslaw and Jaeger, 1959), the solution of $\widetilde{T}$ is given by

$$\widetilde{T}-T_u=B^*\sum_{n=1}^{\infty}f(\alpha_n,\xi)\Big[\Theta_s(T_u-T_{li})e^{-\alpha_n^2\Theta}$$
$$+\{H_v(T_u-T_a)+Q_l+A_g\Theta_s\}\frac{1-e^{-\alpha_n^2\Theta}}{\alpha_n^2}$$
$$+\frac{H_vA_g}{\alpha_n^2}\{\Theta-\frac{1-e^{-\alpha_n^2\Theta}}{\alpha_n^2}\}\Big]+A_g\Theta\ , \qquad (25)$$

where parameters and variables in Eq. (25) are

$$\Theta=\frac{\kappa\theta}{(r_2-r_1)^2}\ , \qquad (26)$$

$$\xi=\frac{r}{r_2-r_1}\ , \qquad (27)$$

$$\nu=\frac{1}{\eta_2-1}=\frac{1}{(r_2/r_1)-1}\ , \qquad (28)$$

$$N^*=\frac{N}{1+N/2}=\frac{2\pi r_1l_cU/(C_{pl}\rho_l\pi r_i^2u)}{1+\{\pi r_1l_cU/(C_{pl}\rho_l\pi r_i^2u)\}}\ , \qquad (29)$$

$$B^*=\frac{B_i}{1+N/2}=\frac{U(r_2-r_1)/K}{1+\{\pi r_1l_cU/(C_{pl}\rho_l\pi r_i^2u)\}}\ , \qquad (30)$$

$$\Theta_s=\frac{\kappa\{V_{v1}/(\pi r_i^2u)\}}{(r_2-r_1)^2}\ , \qquad (31)$$

$$H_v=\frac{h_{v1}S_{v1}}{C_{pl}\rho_l\pi r_i^2u}\ , \qquad (32)$$

$$A_g=\frac{G_0(r_2-r_1)^2}{K}\ , \qquad (33)$$

$$Q_l=\frac{ql_{sh}+h_{v2}S_{v2}(T_{l2}-T_a)}{C_{pl}\rho_l\pi r_i^2u}\ . \qquad (34)$$

In Eq. (25), the term $f(\alpha_n,\xi)$ is expressed as follows:

$$f(\alpha_n,\xi)=\frac{\begin{bmatrix}\alpha_n\{J_0(\alpha_n\xi)Y_1(\alpha_n\nu\eta_2)\\-Y_0(\alpha_n\xi)J_1(\alpha_n\nu\eta_2)\}\end{bmatrix}}{\begin{bmatrix}\alpha_n\{\nu(N^*+H_v-\alpha_n^2\Theta_s)-2B^*\Theta_s\}Z_0(\alpha_n\nu)\\-\{2\Theta_s\alpha_n^2+\nu B^*(H_v-\alpha_n^2\Theta_s)\}Z_1(\alpha_n\nu)\\+\nu\eta_2\alpha_n(N^*+H_v-\alpha_n^2\Theta_s)B_1(\alpha_n\nu)\\+\nu\eta_2B^*(H_v-\alpha_n^2\Theta_s)B_0(\alpha_n\nu)\end{bmatrix}}, \tag{35}$$

where $Z_m(x)$ and $B_m(x)$ are

$$Z_m(x)=J_m(x)Y_1(x\eta_2)-Y_m(x)J_1(x\eta_2)\ , \tag{36}$$

$$B_m(x)=J_m(x)Y_0(x\eta_2)-Y_m(x)J_0(x\eta_2)\ , \tag{37}$$

and α_n is a positive root of

$$\alpha_n(N^*+H_v-\alpha_n^2\Theta_s)B_1(\alpha_n\nu)+B^*(H_v-\alpha_n^2\Theta_s)Z_0(\alpha_n^2\nu)=0\ . \tag{38}$$

The average temperature T_{av} of the compost core is

$$\begin{aligned}T_{av}-T_{li}&=\int_{r_1}^{r_2}2\pi r(\widetilde{T}-T_u)\,dr\Big/\int_{r_1}^{r_2}2\pi r\,dr\\&=B^*\sum_{n=1}^{\infty}g(\alpha_n)[\Theta_s(T_u-T_{li})e^{-\alpha_n^2\theta}\\&\quad+\{H_v(T_u-T_a)+Q_l+A_g\Theta_s\}\frac{1-e^{-\alpha_n^2\theta}}{\alpha_n^2}\\&\quad+\frac{H_vA_g}{\alpha_n^2}\{\Theta-\frac{1-e^{-\alpha_n^2\theta}}{\alpha_n^2}\}]+A_g\Theta\ ,\end{aligned} \tag{39}$$

where the term $g(\alpha_n)$ is

$$g(\alpha_n)=\frac{-4Z_1(\alpha_n\nu)/\{\nu(\eta_2^2-1)\}}{\begin{bmatrix}\alpha_n\{\nu(N^*+H_v-\alpha_n^2\Theta_s)-2B^*\Theta_s\}Z_0(\alpha_n\nu)\\-\{2\Theta_s\alpha_n^2+\nu B^*(H_v-\alpha_n^2\Theta_s)\}Z_1(\alpha_n\nu)\\+\nu\eta_2\alpha_n(N^*+H_v-\alpha_n^2\Theta_s)B_1(\alpha_n\nu)\\+\nu\eta_2B^*(H_v-\alpha_n^2\Theta_s)B_0(\alpha_n\nu)\end{bmatrix}}. \tag{40}$$

On the other hand, the solution of T_{l1} is

$$\begin{aligned}T_{l1}-T_{li}&=\frac{N^*}{\Theta_s}\int_0^{\theta}\{\widetilde{T}(\nu,\tau)-A_g\tau\}e^{-\frac{\theta-\tau}{\Theta_s}(N^*+H_v)}d\tau\\&\quad+[N^*(T_u-T_{li})-H_v(T_{li}-T_a)-Q_l]\frac{1-e^{-\frac{\theta-\tau}{\Theta_s}(N^*+H_v)}}{N^*+H_v}\\&\quad+\frac{N^*A_g}{N^*+H_v}[\Theta-\frac{\Theta_s}{N^*+H_v}\{1-e^{-\frac{\theta-\tau}{\Theta_s}(N^*+H_v)}\}]\ .\end{aligned} \tag{41}$$

3.2 Solution of the time required to recover the temperature of the compost core

Supposing that the temperature recovery of the compost core starts at $T_{av}=T_d$ by interrupting the heat extraction, the heat transfer problem of the compost in the period of the temperature recovery is reduced to a heat conduction problem with heat generation by internal source.

As described in the previous investigation (Seki and Komori, 1986a), it is considered that the temperature recovery of compost bed is schematically performed in the two steps. In the first step, inhomogeneous temperature distribution in the compost bed is made for $0<\theta<\theta_{recn}$, and in a period of the second step θ_{rech}, the temperature distribution is approximately uniform and dependent on time only after $\theta=\theta_{recn}$. θ_{recn} is estimated from the numerical solution of the temperature profile of the compost bed by using the finite difference technique.

According to the experimental results (Seki and Komori, 1986b), θ_{recn} is the maximum limit within 5hrs, and is relatively smaller than θ_{rech}. Therefore,

$$\theta_{rec}=\theta_{recn}+\theta_{rech}=5+\theta_{rech}\ . \tag{42}$$

θ_{rech} is estimated from the analytical solution of the average temperature in the compost bed, and the analytical solution is given by the following equation.

$$T_{av}=(T_{ri}-T_a-\frac{G_0V}{hA})\exp(-\frac{hA}{C_p\rho V}\theta)+\frac{G_0V}{hA}+T_a\ , \tag{43}$$

where T_{ri} is the average temperature of the compost at $\theta=\theta_{recn}$. Therefore, θ_{rech} may be calculated by substituting T_u for T_{av} in Eq. (43).

4. Considerations of the calculated results by the computer simulation

4.1 Procedure for the computer simulation of the soil warming

For the computer simulation of the soil warming, the important experimental results, the analytical solutions and actual operating conditions are used. To develop the procedure for the computer simulation, the physical properties of the compost and soil, some meteorological data and the practical operational conditions of the soil warming system must be provided initially. Usually, since the above basic data can be estimated by many experimental results or measured values, the determination of these values would not be so serious. Accordingly, the design of the heat

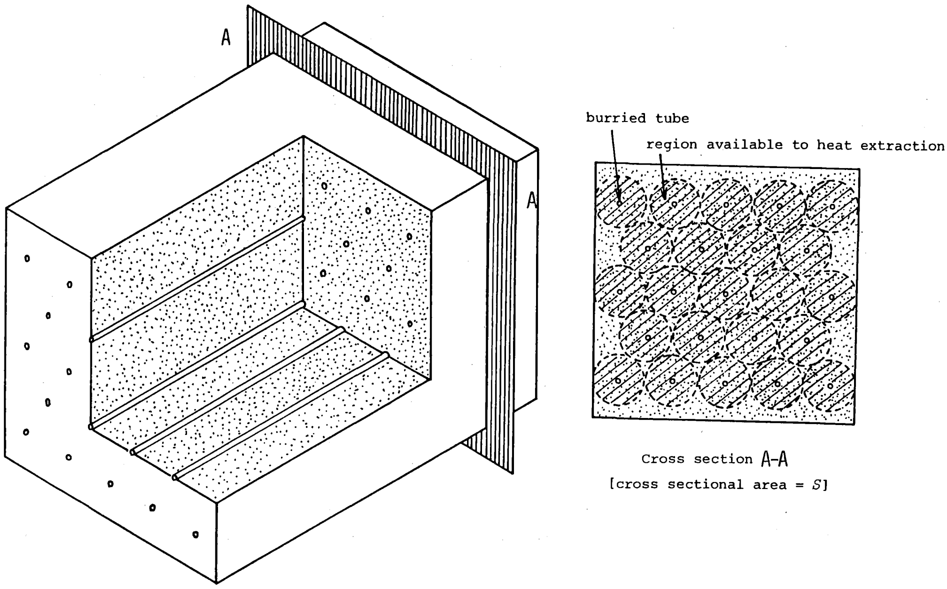

Fig. 7 Arrangement of water tubes within the compost bed

source sub-system comes up as an important problem and the following inspections are instructed.

(1) A stable heat extraction is closely related with the volume of the compost core available for heat extraction V_{eff} which is inevitably determined from the arrangement and specifications of the water tube buried in the compost bed. Then, it is desirable to estimate the diameter of the water tube and V_{eff} in the region of $V_{eff}/V=0.7-0.8$, assuming the arrangement of water tubes within the compost and the base area of the compost bed S (Fig. 7).

(2) The theoretical volume of the compost V_t can be calculated by Eq. (11). The approximate total length of the water tube l_c is obtained from V_t and S for an arbitrary average temperature of the compost T_{av}. The available value of T_{av} to estimate the approximate value of l_c is 50°C, taking account of the stable operation of the heat source sub-system.

(3) θ_{ext} is calculated from Eq. (41) by using the approximate value of l_c, and substitution of 60°C for T_{av} in Eq. (43) gives the value of θ_{rec} also.

According to the typical operation cycle for the heat extraction, as described in Section 2, since $\theta_{ext}=\theta_{rec}$, l_c is determined so that the relation, $\theta_{ext}=\theta_{rec}$, holds by the trial method.

Fig. 8 shows a flow chart of the calculation

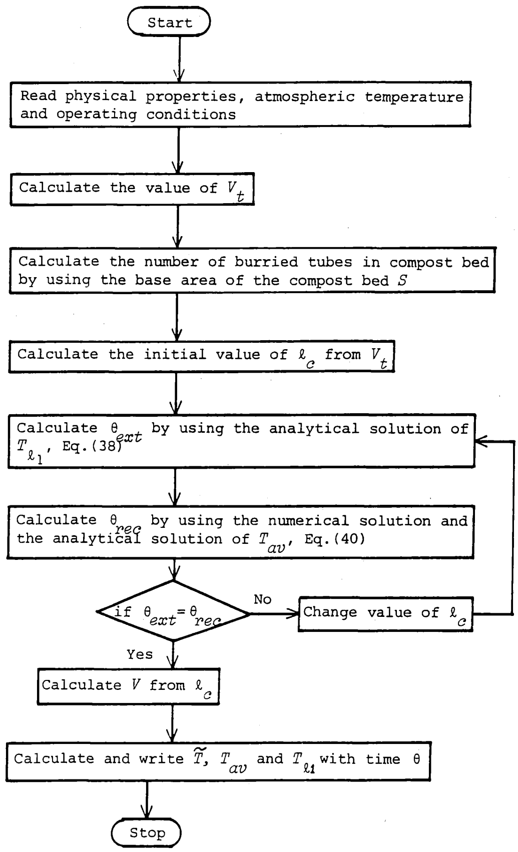

Fig. 8 Flow chart for the computer simulation of the soil warming system

procedure for the computer simulation of the soil warming system. Table 1 shows the operating conditions and specific values of several characteristic parameters for the computer simulation, thermal physical properties of the compost, soil and medium water are listed in Table 2 and some specifications or dimensions of main devices constituting the soil warming system are illustrated in Table 3.

4.2 Calculated results by the computer simulation and evaluation of the results

In this investigation, to evaluate the calculated results for the soil warming system, the numerical calculations of two illustrative examples were performed. Table 4 shows the calculated results of V_t, l_c, θ_{ext}, V and V_{eff}. The actual volume of the compost per heat source unit V is about 40% larger than V_{eff} and V_{eff} is fairly good agreement with V_t estimated by Eq. (11). Therefore, it is suggested that V may be also determined by using a criterion term V_t/V instead of V_{eff}/V mentioned in Section 4.1 Item (1) (Inspection Item (1)).

The heat balance for the soil warming system of Run 1 is shown in Fig. 9 and the calculated results of the heat balance for illustrative examples are summarized in Table 5. These results are also useful for evaluating the heat efficiency of the system.

Fig. 10 shows the variation of T_{av} and T_{l1} with time θ. T_{l1} decreases linearly with time and temperature difference $T_{av}-T_{l1}$ is approximately

Table 1 Operating conditions and specific values of several characteristic parameters for the computer simulation

Maximum temperature in compost bed T_u [°C]	Initial water temperature in 1st reservoir T_{li} [°C]	Water temperature in 2nd reservoir T_{l2} [°C]	Atmospheric temperature T_a [°C]	Apparent rate of heat generation in compost bed G_o [kcal/m³hr]	Overall heat transfer coefficient U [kcal/m²hr°C]	Inner radius of the burried tube in compost bed r_i [m]
60	30	30	5	200	40	0.004
Outer radius of the burried tube in compost bed r_1 [m]	**Effective radius for heat extraction r_2 [m]**	**Heat transfer coefficient h [kcal/m²hr°C]**	**Heat transfer coefficient h_{v1} [kcal/m²hr°C]**	**Heat transfer coefficient h_{v2} [kcal/m²hr°C]**	**Volumetric flow rate of water in tube v [l/min]**	**Heat transfer rate per unit pipe length q [kcal/mhr]**
0.005	0.1	0.2	0.35	0.35	5	10

Table 2 Thermal physical properties of the compost, soil and medium water

Thermal conductivity of compost bed K [kcal/mhr°C]	Heat capacity of compost bed C_p [kcal/kg°C]	Apparent density of compost bed ρ [kg/m³]	Thermal conductivity of soil bed K_s [kcal/mhr°C]	Heat capacity of soil bed C_{ps} [kcal/kg°C]	Apparent density of soil bed ρ_s [kg/m³]	Heat capacity of water C_{pl} [kcal/kg°C]	Density of water ρ_l [kg/m³]
0.6	0.76	700	0.6	0.47	1130	1.0	1000

Table 3 Specifications or dimensions of main devices constituting the soil warming system

RUN	Height of compost bed a [m]	Horizontal length of compost bed perpendicular to the tube ζa [m]	Surface area of 1st reservoir S_{v1} [m²]	Surface area of 2nd reservoir S_{v2} [m²]	Length of soil warming pipe l_{sh} [m]
1	1	1	0.96	3.28	100
2	1	2	1.60	5.21	200

Table 4 Calculated results of V_t, l_c, θ_{ext} and V_{eff}

RUN	Theoretical volume of compost bed V_t [m^3]	Length of burried tube in compost bed l_c [m]	Cycle time of heat extraction θ_{ext} [hr]	Cycle time of temperature recovery in compost bed θ_{rec} [hr]	Volume of compost bed V [m^3]	Volume of compost core available to heat extraction V_{eff} [m^3]
1	3.3	4.15	47.5	47.5	4.15	2.9
2	6.2	4.1	38.5	38.5	8.2	5.9

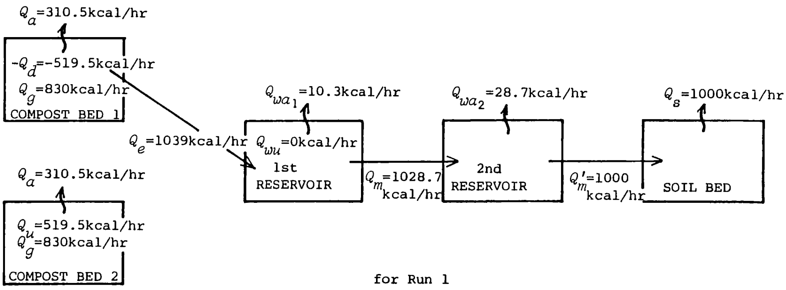

Fig. 9 Heat balance for the soil warming system of Run 1

Table 5 Calculated results of heat balance for illustrative examples

RUN	Amount of heat generated apparently in compost bed per unit time Q_g [kcal/hr]	Enthalpy decrease in compost bed per unit time Q_d [kcal/hr]	Enthalpy increase in compost bed per unit time Q_u [kcal/hr]	Amount of heat loss from compost bed to atmosphere per unit time Q_a [kcal/hr]	Amount of heat extracted from compost bed per unit time Q_e [kcal/hr]	Enthalpy increase in 1st reservoir per unit time Q_{wu} [kcal/hr]	Amount of heat released from 1st reservoir to atmosphere per unit time Q_{wa_1} [kcal/hr]	Amount of heat flow by medium from 1st reservoir to 2nd reservoir per unit time Q_m [kcal/hr]	Amount of heat released from 2nd reservoir to atmosphere per unit time Q_{wa_2} [kcal/hr]	Amount of heat flow by medium from 2nd reservoir to soil bed per unit time Q'_m [kcal/hr]	Amount of heat released from water pipe to soil bed per unit time Q_s [kcal/hr]
1	830	519.5	519.5	310.5	1039	0	10.3	1028.7	28.7	1000	1000
2	1640	1031	1031	609	2062	0	16.2	2045.6	45.6	2000	2000

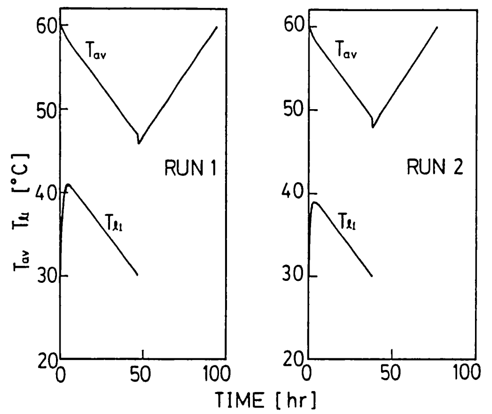

Fig. 10 Calculated results of T_{av} and T_{l_1} with time θ

constant except the beginning of the heat extraction. T_{av} also decreases linearly with time and falls slightly at the moment when interrupting the heat extraction, due to an instantaneous heat transfer from the compost to the water filled in the tube.

Fig. 11 shows the temperature profile of the compost core during both heat extraction and temperature recovery. These results of the temperature profile were obtained by Eqs. (25) and (43). From the above results, there is not an excessive heat extraction from the compost and it is suggested that the stable operation of the heat source sub-system may be maintained continuously.

4.3 Heat efficiency of the soil warming system

The soil warming system is a closed system. The compost bed may be regarded to be a heat generator with a biochemical reaction due to the

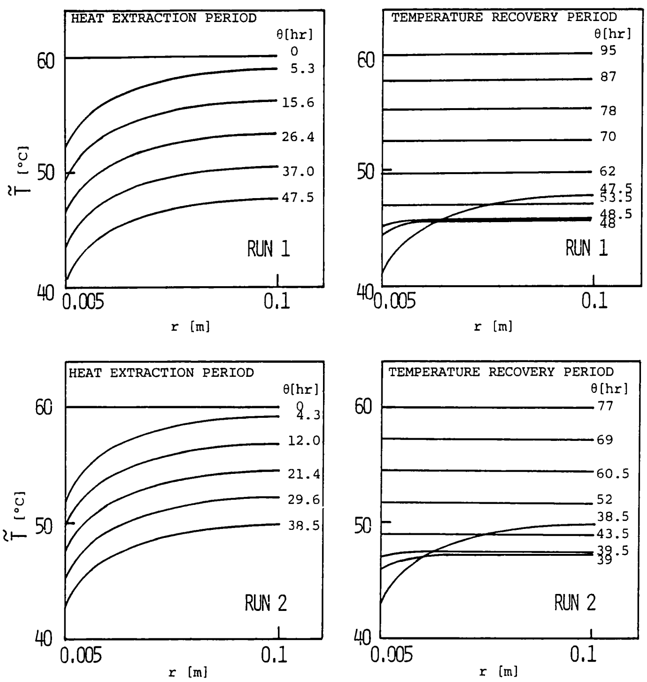

Fig. 11 Calculated results of temperature profile of the compost core during both heat extraction and temperature recovery

metabolism of micro-organisms and some others such as reservoirs are also important mechanical equipments taking part in performance of heat utilization of the system, so that the heat efficiency of the soil warming system must be investigated by the heat balance in the system.

Supposing that the soil warming system may be separated into two sub-systems, that is, the heat source sub-system for heat extraction and the heat release sub-system for warming the soil bed, the overall heat efficiency of the system and the partial heat efficiencies for two sub-systems can be evaluated by the following algebraic treatment.

In the heat source sub-system, the local heat efficiency of the heat generator is

$$E_g = Q_e / n Q_g \ . \tag{44}$$

This equation means the efficiency of heat extraction from the compost bed, as described in the previous investigation (Seki and Komori, 1986a).

From the heat balance of the system, the local heat efficiency of the 1st water reservoir is

$$E_{r1} = Q_m / Q_e \ . \tag{45}$$

Therefore, the partial heat efficiency of the heat source sub-system can be expressed as follows:

$$E_{ex} = E_g \cdot E_{r1} = Q_m / n Q_g \ . \tag{46}$$

On the other hand, the local heat efficiency of the 2nd water reservoir is

$$E_{r2} = Q'_m / Q_m \ , \tag{47}$$

and assuming that the total amount of heat released by the water pipe as a radiator is dissipated, warming the soil or releasing the heat at the surface of the soil bed, the local heat efficiency of the water pipe becomes to be unity, that is,

$$E_s = Q_s / Q'_m = 1 \ . \tag{48}$$

Therefore, the partial heat efficiency of the heat release sub-system can be represented by Eq. (47).

Now, for the practical case, since the 1st water reservoir would be installed close to the 2nd water reservoir so as to reduce the heat loss between the reservoirs, in the limit when the heat loss between 1st and 2nd reservoirs approaches to zero, the overall heat efficiency may be expressed as follows:

$$E_T = E_g \cdot E_{r1} \cdot E_{r2} = Q_s / n Q_g \ . \tag{49}$$

The calculated results of E_g, E_{r1}, E_{r2} and E_T for

Table 6 Calculated results of E_g, E_{r1}, E_{r2} and E_T

RUN	Overall heat efficiency for the system E_T [-]	Heat efficiency for heat generator E_g [-]	Heat efficiency for 1st reservoir E_{r1} [-]	Heat efficiency for 2nd reservoir E_{r2} [-]
1	0.602	0.626	0.990	0.972
2	0.610	0.629	0.992	0.978

two illustrative examples are summarized in Table 6. The range of these calculated results by the computer simulation was from an overall heat efficiency 0.6 to 0.61. E_{r1} and E_{r2} depend on the heat loss at the wall of the reservoir. E_T is dominated mainly by the efficiency of heat extraction from the compost, provided that the thermal insulation of the water reservoir is excellent.

5. Conclusions

Mathematical treatments for the planning and the design manuals of the soil warming system were proposed and application of the procedure to the practical case was investigated by the computer simulation of two illustrative examples. A summary of the calculated results may be described below.

1) The soil warming for raising of seedlings or for the cultivation of vegetables requires a very large amount of heat energy with a low level in temperature. In this sense, the heat generated in the compost, which is a soft heat energy, would be available for the soil warming, and application of the heat extracted from the compost to the soil warming would reduce the running cost or the expense of some equipments for the system.

2) The procedure for the computer simulation and the calculated results give important inspections for the design or the determination of details of equipments included in the soil warming system. In order to make a full scale soil warming system most suitable, it is advisable that a mutual relationship between theory and application is investigated sufficiently by the results or the actual phenomena obtained from some preliminary experiments of a pilot scale system. However, the results and observations obtained in this investigation are very useful to design a small scale soil warming system such as a facility for raising of seedlings.

3) The overall heat efficiency would be an available index for the most suitable design as well as evaluation of the soil warming system. In the practical case of a small scale system, at the lowest estimate, the overall heat efficiency of the system above 50% may be obtained by the sufficient thermal insulation of equipments.

4) To magnify the soil warming system and to maintain the stable operation of the heat source sub-system, enlargement of a compost bed size or multiplying the compost unit is one of advantageous methods, though there are several serious problems such as some tedious works for preparations of the compost bed and the requirement of a wide space for setting up the compost unit.

5) Introduction of a systematic process control system appropriate for the soil warming scale is essential to obtain the stable operation of the system. To design a suitable process control system for practical application, some reasonable controlled variables and manipulated variables should be chosen, moreover, further investigation is necessary.

Nomenclature

A = surface area of compost bed [m^2]
a = height of a rectangular prism of compost bed [m]
C_p = heat capacity of compost bed [kcal/kg°C]
C_{pl} = heat capacity of water [kcal/kg°C]
E_{ex} = heat efficiency of heat source sub-system [−]
E_g = heat efficiency of heat generator [−]
E_{r1} = heat efficiency of 1st reservoir [−]
E_{r2} = heat efficiency of 2nd reservoir [−]
E_s = heat efficiency of water pipe [−]
E_T = overall heat efficiency [−]
G_0 = apparent rate of heat generation in

compost bed [kcal/m^{3}hr]

h = heat transfer coefficient at the wall of compost container [kcal/m^{2}hr°C]

h_{v1} = heat transfer coefficient at the wall of 1st reservoir [kcal/m^{2}hr°C]

h_{v2} = heat transfer coefficient at the wall of 2nd reservoir [kcal/m^{2}hr°C]

K = effective thermal conductivity of compost bed [kcal/mhr°C]

l_c = length of the tube buried in compost bed [m]

l_{sh} = total length of the water pipe in soil bed [m]

n = number of tubes buried in compost bed [−]

Q_a = amount of heat loss from compost bed to atmosphere per unit time [kcal/hr]

Q_d = amount of enthalpy decrease in compost bed per unit time during the heat extraction period [kcal/hr]

Q_e = amount of heat extracted from compost bed per unit time [kcal/hr]

Q_g = amount of heat generated apparently in compost bed per unit time [kcal/hr]

Q_m = amount of heat exchanged by medium between 1st and 2nd reservoirs [kcal/hr]

Q_{m1} = amount of heat flow by medium from 1st reservoir to 2nd reservoir [kcal/hr]

Q_{m2} = amount of heat flow by medium from 2nd reservoir to 1st reservoir [kcal/hr]

Q_s = amount of heat released from water pipe to soil bed per unit time [kcal/hr]

Q_u = amount of enthalpy increase in compost bed per unit time during the temperature recovery period [kcal/hr]

Q_{wa} = amount of heat released from water reservoir to atmosphere per unit time [kcal/hr]

Q_{wa1} = amount of heat released from 1st reservoir to atmosphere per unit time [kcal/hr]

Q_{wa2} = amount of heat released from 2nd reservoir to atmosphere per unit time [kcal/hr]

Q_{wu} = amount of enthalpy increase in 1st reservoir per unit time [kcal/hr]

q = amount of heat required to warm the soil bed per unit length of the water pipe per unit time [kcal/hr]

r = radial distance [m]

r_i = inner radius of the tube buried in compost bed [m]

r_1 = outer radius of the tube buried in compost bed [m]

r_2 = outer radius of compost core [m]

S = cross sectional area of compost bed [m^2]

S_{v1} = surface area of 1st reservoir [m^2]

S_{v2} = surface area of 2nd reservoir [m^2]

T = temperature of compost bed [°C]

$\widetilde{T}$ = temperature of compost bed averaged over the axial direction of the buried tube [°C]

T' = temperature of compost bed at the inside of the compost container [°C]

T_a = atmospheric temperature [°C]

T_{av} = average temperature of compost bed [°C]

T_l = temperature of water passing through the tube buried in compost bed [°C]

$\widetilde{T}_l$ = average value of T_l over the axial direction of the buried tube [°C]

T_{lou} = temperature of water at the outlet of the buried tube [°C]

T_{l1} = water temperature in 1st reservoir [°C]

T_{l2} = water temperature in 2nd reservoir [°C]

T_{li} = initial temperature of water in 1st reservoir [°C]

T_u = maximum temperature of compost bed [°C]

T_d = minimum temperature of compost bed [°C]

U = overall heat transfer coefficient [kcal/m^{2}hr°C]

u = average velocity of water passing through the tube buried in compost bed [m/hr]

V = actual volume of compost bed [m^3]

V_{eff} = volume of compost core available to heat extraction [m^3]

V_t = theoretical volume of compost bed [m^3]

V_{v1} = volume of water in the 1st reservoir [m^3]

z = distance in axial direction of the buried tube [m]

Θ = dimensionless time [−]

θ = time [hr]

θ_{ext} = cycle time of heat extraction [hr]

θ_{rec} = cycle time of temperature recovery in compost bed [hr]

θ_{recn} = period of 1st step for recovering temperature of compost core [hr]

θ_{rech} = period of 2nd step for recovering temperature of compost core [hr]

ρ = apparent density of compost bed [kg/m^3]
ρ_l = density of water [kg/m^3]
κ = apparent thermal diffusivity of compost bed [m^2/hr]
ξ = dimensionless value of distance in r direction [−]
ζ = dimensionless parameter of the length [−]

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堆肥発酵熱の土壌加温システムへの応用

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要 約

堆肥発酵熱を利用した土壌加温システムを提案し，その熱的シミュレーション・モデルを検討した。シミュレーションを行うために想定した土壌加温システムは，発酵熱抽出器としての数基の堆肥そう，熱媒体用の水を循環させる配管系及び蓄熱のための貯水そうから成る。幾つかの実際的な操作条件を用いてシステムの熱収支を解析することによりシミュレーション・モデルの実際例への応用を検討した。システムの熱収支はプロセス制御を考慮して解析的かつ系統的に取り扱った。ここに示した土壌加温のモデル・シミュレーションと熱収支の系統的な解析手順の概念は，実際の土壌加温システムの基本計画，設計，操作方法を検討するに当って有用であろう。