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# An Investigation of Practical Process Design and Control of a Soil Warming System with Heat Generated in Compost

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**Abstract**

An optimum design and a control method of a soil warming system with heat generated in compost were investigated, following a concept of process design. Provided that many of the input data such as thermal physical properties of compost bed, the amount of heat required to soil warming, and the micrometeorological condition in a greenhouse are given and that the dimensions of the tube for heat extraction is premised, there are only two decision variables to be optimized. One is the space of arrangement of the tubes for heat extraction and the other is the flow rate of medium fluid in the tubes. Optimum numerical values of the decision variables were obtained, taking account of stability in operation, increase in heat efficiency and reduction of the cost of equipments of heat source. Assuming that the system is applied to the protected cultivation in a small scale, a representative example of the flow sheet of the system was proposed, and operation manuals of the system were described. Optimum numerical values of the decision variables, operation manuals and the flow sheet proposed here would become the basis of the detailed design of equipments and devices of the system.

## 1. Introduction

In a previous paper (Seki and Komori, 1987b), a soil warming system by the alternative use of two compost bed units with the two water reservoirs was proposed, and a theoretical analysis of the heat transfer process of the system was performed by the total heat balance of the system. The procedure of computer simulation for estimating the several important characteristic values under the given practical design and operating conditions was described. From the calculated results, it was suggested that the computer simulation is applicable to the practical soil warming system.

Generally, for the practical application of the soil warming system using the heat generated in composting, the system should become most suitable not only from a theoretical view point previously described but also from view points of stability in operation, reliability and simplicity of control, and reduction of the cost required to equipments and devices of the system. According to the above idea, optimum design and operating conditions are investigated by extending the previously proposed simulation model to process design. Then, an appropriate control method for the proper operation of the system is investigated, and a flow sheet of the total system incorporating the control system for soil warming is proposed.

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## 2. Consideration of the number of compost bed units

According to the usual manner of process design, a procedure of basic process design of the soil warming system may be shown as Fig. 1. The previous theoretical investigation (Seki and Komori, 1987b) had been made supposing the alternative use of two compost bed units as a basic constitution part of the system. As pointed out previously (Seki and Komori, 1984), since the steady-high-temperature period of the compost bed is at most 2 or 3 weeks, it is practically necessary to remix or renew the compost materials at intervals in order to warm the soil bed over a long period. Therefore, some other compost bed units must be provided. An increase of the number of compost bed units $n$ is also related to the enlargement in soil warming area. If the multi-unit-compost is applied to a greenhouse of a limited floor area, there is large room for choise of units for heat extraction, and it is evident that multi-unit-compost will be useful to stabilize the operation of the system for a long period.

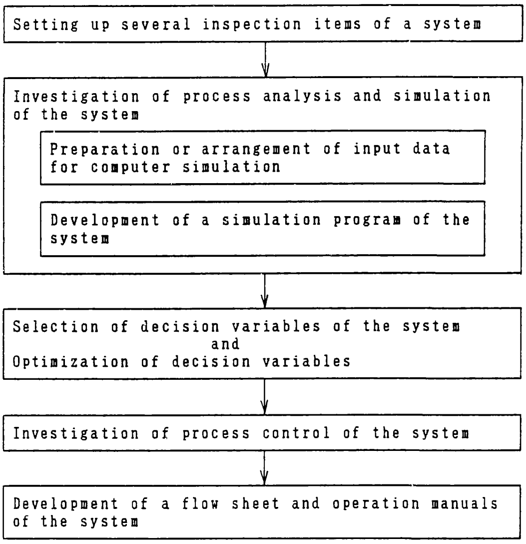


Fig. 1. Procedure of basic planning of a soil warming system

However, multi-unit-compost has the following disadvantageous points:
1) Tedious manual works such as remixing or replacing compost materials in compost containers increase in proportion to the number of compost bed units.
2) Area occupied by compost bed units and equipments is large.
3) Arrangement and connection of the tubes for heat extraction and flow control system become difficult.

Consequently, it would be rather reasonable to make the number of units as small as possible within an allowable extent if the amount of heat generation in compost is balanced with the amount of heat extraction. The number of units of minimum requirement depends on the scale of the soil warming system, and can not be simply determined. However, $n \leqq 5$ would be appropriate for the soil warming system in a relatively small scale up to 500m$^2$ in floor area. For the case of $n=3$ which corresponds to the minimum possible number, arbitrary two units of the three units are to be used for heat extraction, and the other one is waiting for use. Therefore, $\theta_{ext}$ becomes equal to $\theta_{rec}$, and the previously proposed simulation model (Seki and Komori, 1987b) can be applied to estimate the values of $\theta_{ext}$, $\theta_{rec}$ and $V$ etc.

## 3. Optimization of decision variables of the system

As described in the previous investigation (Seki and Komori, 1987b), compost bed is a low level heat source, and the required number of units becomes considerably larger with increasing the area for soil warming. As pointed out in 2., it is not advisable to make $n$ so large. This may also be evident from view points of continuous supply or preparation of compost materials and the saving of the labor required for maintenance of the equipments for heat extraction. Therefore, it is not advantageous to apply compost heat source to soil warming in protected cultivation of a large scale more than 1000m$^2$. In this section, a relatively small scale soil warming system corresponding to the system in which the amount of heat required to soil warming is 1000 or 2000 kcal/hr, is supposed, and optimization of decision variables is discussed for the case of $n=3$. The floor area is estimated to be 100～250m$^2$ for soil bed for cultivation of plants and 50～100m$^2$ for soil bed for raising of seedlings, provided that the ratio of the effective area for soil warming to the floor area is about 60%. In calculating the floor area, the values obtained from the experiments by Itaki (1976) were used as the space of the pipes for soil warming, and the heat flux required to soil warming per unit pipe length was estimated from the analytical solutions by Seki *et al.* (1986).

Thermal physical properties of the compost bed are shown in Table 1. These values had been previously obtained experimentally (Seki and Komori, 1984) for the organic mixture of 60%

Table 1 Physical properties of compost bed

| Apparent density $\rho$ [kg/m$^3$] | Heat capacity $C_p$ [kcal/kg℃] | Effective thermal conductivity $K$ [kcal/mhr℃] |
|---|---|---|
| 700 | 0.76 | 0.6 |

in moisture percentage, composed of cattle feces, chicken manure, rice bran and sawdust in proportion of 12:18:19:51 by dry matter. Many of the input data for simulation of the soil warming system, that is, $G_0$, $U$, $h$, $h_{v_1}$, $h_{v_2}$, $S_{v_1}$, $S_{v_2}$, $q$, $T_a$, $Tl_1$ and $Tl_2$ are easily given from the previous theoretical and experimental investigations (Seki and Komori, 1985a; 1987b; Seki *et al.*, 1986; 1987a), as shown in the previous paper (Seki and Komori, 1987b, p.197 Tables 1 and 3). Moreover, the number of units has been given as a prior condition. Therefore, there are not so many decision variables in this system, and they would be restricted to the variables with respect to the material and arrangement of the buried tubes in compost bed, and the flow rate of water in the tube.

Material of the tube for heat extraction should be not only high in both corrosion resistance and thermal conductivity but also low in price. Stainless tubes (SUS304) used in previous investigations (Seki and Komori, 1984; 1985b) were 1mm in thickness, and their price per unit length was not so expensive. Therefore, they would be suitable for heat extraction. Because the dimensions of the tubes available are limited, the decision variables are reduced to the two variables only, that is, $p$ and $v$.

Taking the total cost of the heat source subsystem $Y_T$ as an objective function and the condition for maintaining a stable composting reaction as a constraint, optimization of $p$ and $v$ is discussed here. Supposing that $Y_T$ is the sum of the cost of equipment $Y_e$, the running cost $Y_r$ and the maintenance expenses $Y_m$, $Y_T$ is

$$Y_T = Y_e + Y_r + Y_m. \tag{1}$$

In the following discussion, $Y_m$ is to be constant for simplicity. The cost of equipment $Y_e$ including the costs of material and production is related with $l_c$ as well as $V$. It is difficult to make clear which of the two terms, $V$ and $l_c$, is more concerned with $Y_e$, but $Y_e$ would be approximately proportional to $V$ if the price of tubes for heat extraction is relatively low. In such a case, $Y_e$ is

$$Y_e = y_v V n. \tag{2}$$

The cost of the derivery power of pump would be the main part of $Y_r$. Generally, the derivery power of pump increases in proportion to $v^3$ (SCEJ, 1968), and $Y_r$ is

$$Y_r = \alpha v^3. \tag{3}$$

Substitution of Eqs. (2) and (3) into Eq. (1) gives

$$Y_T = y_v V n + \alpha v^3 + Y_m. \tag{4}$$

As pointed out previously (Seki and Komori, 1985b), temperature in the compost bed must be held higher than 40°C so as not to decrease heat generation in compost bed, and a constraint for stable heat generation is given as follows:

$$T_{avf} \geqq 40°\mathrm{C}. \tag{5}$$

It is difficult to find the values of $p$ and $v$ analytically that minimize Eq. (4) under the condition of Eq. (5), because the analytical solution of $T_{avf}$ is in a rather complicated form mathematically as shown in the previous paper (Seki and Komori, 1987b). Therefore, the optimum values are estimated here graphically on the basis of the calculated results of $T_{avf}$, $E_t$, $\theta_{ext}$ and $V$ by the computer simulation.

There are four cases for which the values of $p$ and $v$ must be optimized as shown in Table 2.

Table 2 Dimensions of the tube for heat extraction and total length of the soil warming pipe

| Case | Dimensions of the tube for heat extraction | | Amount of heat required to soil warming |
|---|---|---|---|
| | I.D. ($=2r_i$) [m] | O.D. ($=2r_1$) [m] | $ql_{sh}$ [kcal/hr] |
| 1 | 0.008 | 0.01 | 1000 |
| 2 | 0.008 | 0.01 | 2000 |
| 3 | 0.014 | 0.016 | 1000 |
| 4 | 0.014 | 0.016 | 2000 |

For each case, the soil warming process was simulated by the previously proposed simulation model (Seki and Komori, 1987b) for several practical values of $p$ and $v$ as parameters. The calculated results of $V$, $\theta_{ext}$, $T_{avf}$ and $E_t$ are illustrated in Table 3.

Fig. 2 shows the plots of $E_t$, $V$ and $\theta_{ext}$ against $p$, and Fig. 3 shows the plots of $E_t$, $V$ and $\theta_{ext}$ against $v$. Figs. 2 and 3 are for Case 1, and similar results to Figs. 2 and 3 were obtained for the other cases.

Table 3 Calculated results of the volume of the compoet bed unit $V$, the period of heat extraction $\theta_{ext}$, the average temperature in compost bed at the end of heat extraction $T_{avf}$, and the overall heat efficiency of the system $E_t$ for Case 1

| Spacing of the tube arrangement $p$ [m] | | Volumetric flow rate of water in the tube for heat extraction $v$ [$l$/min] 2.5 | 5.0 | 10.0 | 20.0 | 30.0 |
|---|---|---|---|---|---|---|
| 0.10 | $\theta_{ext}$ [hr] | 81.0 | 82.8 | 86.7 | 88.1 | 88.6 |
| | $T_{avf}$ [°C] | 36.7 | 35.4 | 34.2 | 33.7 | 33.6 |
| | $V$ [m$^3$] | 3.6 | 3.6 | 3.55 | 3.55 | 3.55 |
| | $E_t$ [−] | 0.694 | 0.694 | 0.704 | 0.704 | 0.704 |
| 0.15 | $\theta_{ext}$ [hr] | 65.5 | 68.0 | 72.0 | 73.4 | 73.9 |
| | $T_{avf}$ [°C] | 41.4 | 40.1 | 38.9 | 38.5 | 38.4 |
| | $V$ [m$^3$] | 4.0 | 4.0 | 3.95 | 3.95 | 3.95 |
| | $E_t$ [−] | 0.625 | 0.625 | 0.633 | 0.633 | 0.633 |
| 0.20 | $\theta_{ext}$ [hr] | 42.0 | 47.5 | 50.8 | 52.2 | 52.8 |
| | $T_{avf}$ [°C] | 48.8 | 46.9 | 46.0 | 45.5 | 45.3 |
| | $V$ [m$^3$] | 4.2 | 4.2 | 4.14 | 4.13 | 4.13 |
| | $E_t$ [−] | 0.595 | 0.595 | 0.604 | 0.605 | 0.605 |
| 0.25 | $\theta_{ext}$ [hr] | 17.8 | 22.2 | 25.5 | 27.2 | 27.8 |
| | $T_{avf}$ [°C] | 55.9 | 54.8 | 53.9 | 54.3 | 53.3 |
| | $V$ [m$^3$] | 4.7 | 4.7 | 4.6 | 4.6 | 4.6 |
| | $E_t$ [−] | 0.532 | 0.532 | 0.543 | 0.543 | 0.543 |

As described in the previous paper (Seki and Komori, 1987b), the relation between $E_t$ and $V$ is

$$E_t = \frac{q\, l_{sh}}{n G_0 V}\ . \tag{6}$$

According to Eq. (6) and Fig. 2, increase of $E_t$ is equivalent to decrease of $V$, and is related to reduction of energy cost as well as $Y_e$, and is pertaining to the less number of switching the water flow path for heat extraction, since $\theta_{ext}$ becomes larger with increasing $E_t$.

It is found that $E_t$ decreases with increasing $p$ from Fig. 2 and that $E_t$ is almost independent of $v$ for $v \geqq 10 l$/min from Fig. 3. Therefore, $E_t$ may be approximately expressed by the following function of $p$ only:

$$E_t = f(p), \tag{7}$$

where $f(p)$ is a monotonously decreasing function of $p$.

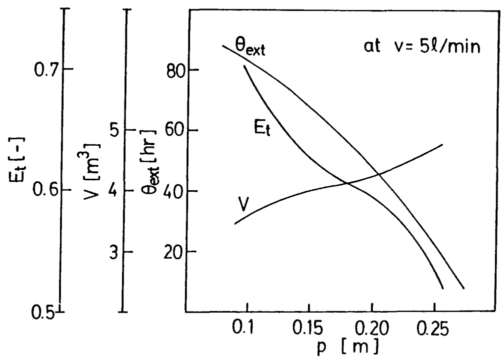


Fig. 2. Plots of $E_t$, $V$ and $\theta_{ext}$ against $p$

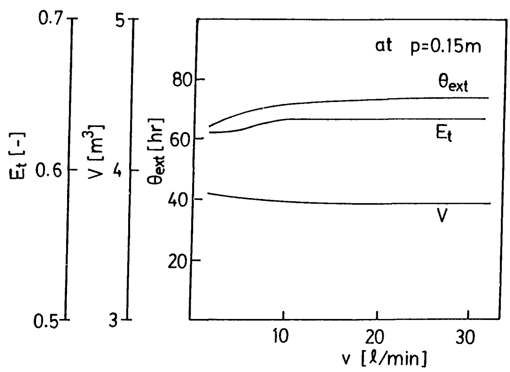


Fig. 3. Plots of $E_t$, $V$ and $\theta_{ext}$ against $v$

Combination of Eq. (6) with Eq. (7) gives

$$nV = \frac{ql_{sh}}{f(p)} \; . \tag{8}$$

By substituting Eq. (8) into Eq. (4), $Y_T$ is expressed by the following function of $p$ and $v$.

$$Y_T = y_v \frac{ql_{sh}}{f(p)} + \alpha v^3 + Y_m . \tag{9}$$

From Eq. (9), it is clear that both $p$ and $v$ should be made as small as possible to reduce $Y_T$ as far as Eq. (5) is satisfied.

Fig. 4 shows the change of $T_{avf}$ with $p$ and $v$. By Eq. (5), the allowable extents of $p$ and $v$ are limited within the regions indicated by ///// in Fig. 4. As mentioned above, since $E_t$, $\theta_{ext}$ and $V$ do not change much for $v \geqq 10l$/min, $10l$/min would be the most suitable value of $v$ for all cases in Table 2, taking account of reduction of the derivery power of pump.

Next, the minimum values of $p$ satisfying Eq. (5), that is, the optimum values of $p$ under the condition of $v = 10l$/min are estimated from Fig. 4 to be 0.16m for Case 1, 0.15m for Case 2, 0.185m for Case 3 and 0.175m for Case 4. As a whole, the most suitable value of $p$ would be 0.15～0.20m.

## 4. Process control and operation manuals of the system

### 4.1 Process control method

Since all the characteristic values of the soil warming system including decision variables were determined in section 3, a process control method must be investigated for proper operation of the system. The following six control routines will be needed in process control of the soil warming system.

(1) A control routine for changing the combinations of compost bed units for heat extraction

For the case of three units in total number, there are three possible combinations made of two arbitrary unit. Since the steady-high-temperature period in compost bed is at most 2～3 weeks, a period to use any one of combinations should be limited within 7～10 days, as illustrated in Fig. 6. Therefore, the number of cycles of heat extraction during the above period $m$ is given by

$$m = \mathrm{INT}[(7 \sim 10) \times 24/\theta_c] \, , \tag{10}$$

where INT(X) means to take integer part of X, and $\theta_c = \theta_{ext} + \theta_{rec}$. At the end of the $m$-th cycle of heat extraction, a combination of the units must be changed with any one of the two other combinations.

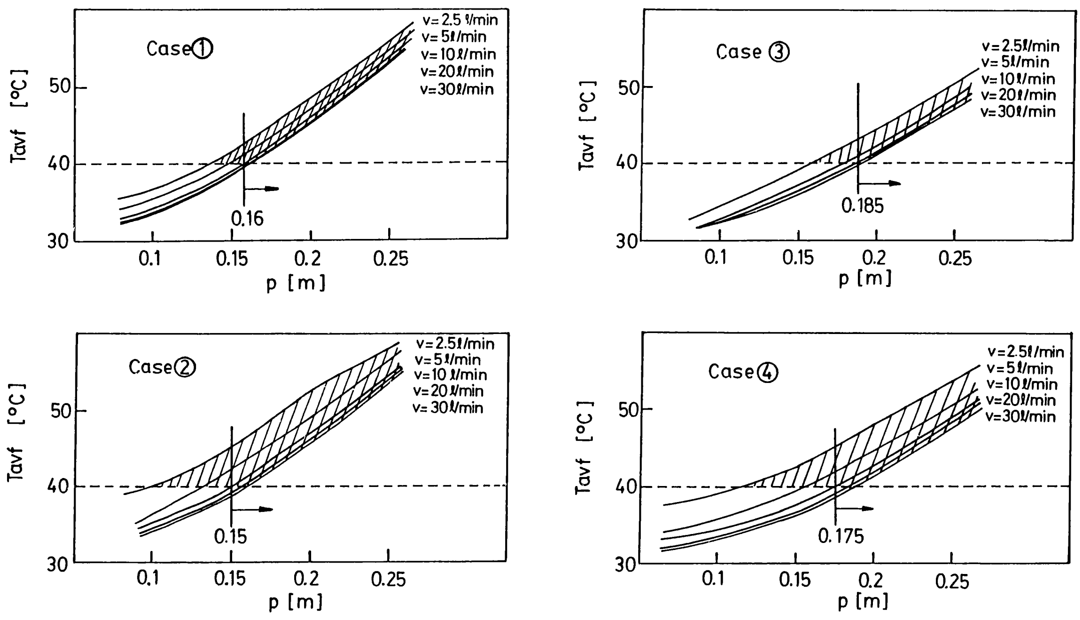


Fig. 4. Relation between $T_{avf}$ and $p$

(2) A control routine for switching the flow pathes of heat extraction

In each combination of compost bed units, two units are used alternatively to extract heat. When $T_{l_1}$ decreases to 30°C, the flow path of heat extraction is switched with the other flow path by this control routine.

(3) A control routine to hold $v$ constant

(4) A control routine to hold $T_{l_2}$ constant

(5) A control routine to hold $H_1$ constant

(6) A control routine to hold $H_2$ constant

Generally, there are two types of process control systems, that is, an analog system without a computer and a digital system involving a computer (Kozai, 1980). Provided that the control system for soil warming is independent of the other control systems incorporated in a greenhouse, the analog system may be recommended of the two types of control systems for soil warming in a relatively small scale, because the number of control routines is small. Accordingly, the construction of the control system is described assuming that the analog system is introduced. All the control routines except (1) are 'feed back control routines', and of which construction elements are illustrated by Table 4.

In the analog system, it is important to select the types or specifications of controllers. The controllers used in the soil warming system would be similar to those generally used in chemical plants (Tamaki and Tamaki, 1983), and the selection of controllers will be easy. However, the values of several regulating parameters such as proportionality sensitivity or integration time for individual controllers must be obtained after investigating or examining the characteristics of dynamic behavior of individual control routines theoretically and experimentally. For the control routine (1), sequential control method with a timer set may be useful, however, hand control method is rather appropriate practically for the stability and reliability of operation.

Fig. 5 shows an example of the flow sheet of the soil warming total system involving the analog control system. The symbols in Fig. 5 are after those commonly used by process system engineers (SCEJ, 1973).

**4.2 Operation manuals of the soil warming system**

Fig. 6 illustrates the periodic changes of $T_{av}$, $T_{l_1}$ and $T_{l_2}$ in order to show the operation manuals of the system clearly. It is required 4～5 days until $T_{av}$ becomes sufficiently high (50～60°C) to extract heat (Seki and Komori, 1984). It is inadequate to use the compost beds as heat source in this temperature increasing period, and then soil warming is started by applying the supplementary energy source specially prepared as illustrated by Fig. 5. The temperature of soil bed

Table 4 Constitutions of the feed back control routines

| Control routine | (2) | (3) | (4) | (5) | (6) |
|---|---|---|---|---|---|
| controlled object | compost bed | tube for heat extraction | 2nd water reservoir | 1st water reservoir | 2nd water reservoir |
| controlled variable | $T_{l_1}$ | $v$ | $T_{l_2}$ | $H_1$ | $H_2$ |
| primary means | thermocouple | flow meter | thermocouple | level gauge | level gauge |
| controller | temperature controller | flow rate controller | temperature controller | flow rate controller | flow rate controller |
| desired variable | $T_{l_1} \geqq 30$°C | $v = 10 l$/min | $T_{l_2} = 30$°C | $H_1$ = const. | $H_2$ = const. |
| final control element | valve (three directional) | valve | valve | valve | valve |
| manipulated variable | flow rate of water in tube (0 or $10 l$/min) | amount of water supply into tube | amount of water supply from 1st to 2nd reservoir | amount of water supply from 2nd to 1st reservoir | amount of water supply from 1st to 2nd reservoir |

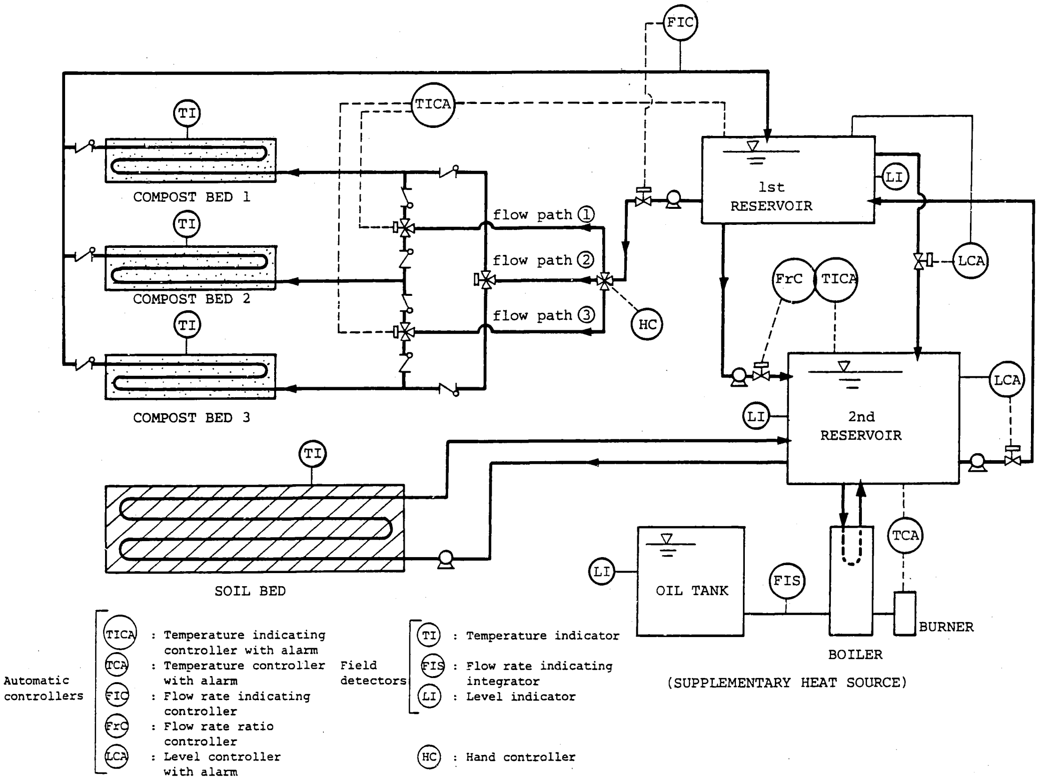


Fig. 5. A flow sheet of the soil warming system with the heat generated in composting

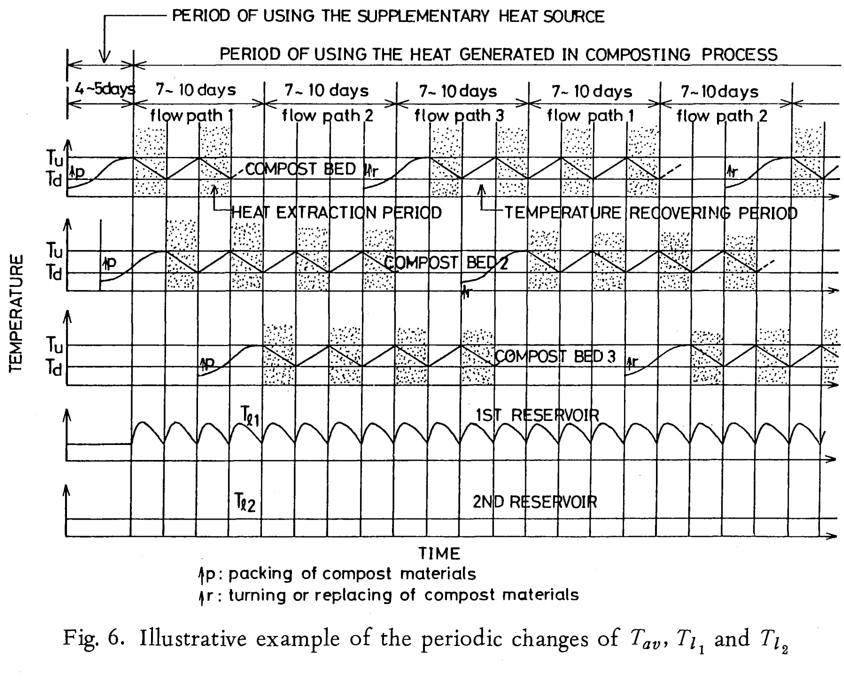


Fig. 6. Illustrative example of the periodic changes of $T_{av}$, $T_{l_1}$ and $T_{l_2}$

gradually rises and reaches the steady state in 4～5 days, when the heat flux required to soil warming becomes constant and stable. Since the compost beds have also arrived at the steady-high-temperature period by this time, the supplementary energy source is shifted to the compost heat source. Then, two units of all the three units are used alternately for heat extraction. The other unit is not in operation during the use of the above two units, but the compost materials in this unit must be remixed or renewed. Then, the combination of the units for heat extraction is changed with the other combination when the $m$-th cycle of heat extraction is ended. With the repetition of the above procedure, it will be possible to continue the operation of soil warming over a long period.

## 5. Conclusions

Optimization of design and operating conditions, and process control for the soil warming system with the heat generated in compost were investigated. The results obtained are summarized as follows:

1) It will be effective to use several numbers of compost bed units one by one to make the stable operation of soil warming for a long period. Provided that the system is applied to the protected cultivation in a relatively small scale, the optimum number of the units would be 3～5, taking account of saving of mannual works, reduction of space occupied by heat source units and simplicity of process control. The optimization of the system were discussed here for the case of three units in total number.

2) Since many of the input data for simulation of the soil warming system have been obtained, the decision variables of the system are only two, that is, $p$ and $v$, assuming that the material and dimensions of the tube for heat extraction are given. For the case of relatively small expense of the tubes for heat extraction, the most suitable values of $p$ and $v$ are estimated to be 0.15～0.20m and 10$l$/min, respectively, from the following view points: i) increase of heat efficiency, ii) stability of operation, and iii) reduction of the total cost of equipments for heat extraction including running cost.

3) If the control system for soil warming is independent of the other control systems incorporated in a greenhouse, it is recommended to introduce the analog system for soil warming. Several field detectors and controllers are necessary to the individual control routines of the analog system. For evaluating the regulating parameters of controllers, i.e., proportionality sensitivity and integration time, it is advisable to investigate the dynamic response of the individual control routines.

4) An illustrative example of the flow sheet of the soil warming total system incorporating process control system was proposed and the operation manuals were described concretely and clearly. This flow sheet would be useful to the detailed design of equipments in the system.

## Nomenclature

$C_p$ = heat capacity of compost bed [kcal/kg°C]
$E_t$ = overall heat efficiency of the system [−]
$G_0$ = apparent rate of heat generation in compost bed [kcal/m$^3$hr]
$H_1$ = water level of the 1st reservoir [m]
$H_2$ = water level of the 2nd reservoir [m]
$h$ = heat transfer coefficient at the wall of compost container [kcal/m$^2$hr°C]
$h_{v_1}$ = heat transfer coefficient at the wall of 1st reservoir [kcal/m$^2$hr°C]
$h_{v_2}$ = heat transfer coefficient at the wall of 2nd reservoir [kcal/m$^2$hr°C]
$K$ = effective thermal conductivity of compost bed [kcal/mhr°C]
$l_c$ = total length of the tube buried in compost bed [m]
$l_{sh}$ = total length of the water pipe buried in soil bed [m]
$n$ = number of compost beds [−]
$p$ = space of tube arrangement buried in compost bed [m]
$q$ = amount of heat required to soil warming [kcal/mhr]
$S_{v_1}$ = surface area of 1st reservoir [m$^2$]
$S_{v_2}$ = surface area of 2nd reservoir [m$^2$]
$T_a$ = atmospheric temperature [°C]
$T_{av}$ = average temperature of compost bed [°C]
$T_{avf}$ = $T_{av}$ at the end of heat extraction [°C]
$T_d$ = minimum temperature in compost bed [°C]
$T_{l_1}$ = water temperature in 1st reservoir [°C]
$T_{l_2}$ = water temperature in 2nd reservoir [°C]
$T_{li}$ = initial temperature of water in

1st reservoir [°C]

$T_u$ = maximum temperature in compost bed [°C]

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

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

$v$ = volumetric flow rate of water in the tube for heat extraction [$l$/min]

$Y_e$ = cost of equipment [¥]

$Y_m$ = maintenance expenses [¥]

$Y_r$ = running cost [¥]

$Y_T$ = total cost of heat source sub-system [¥]

$y_v$ = cost of equipment per unit volume of compost bed [¥/m$^3$]

$\alpha$ = constant [¥m$^3$/$l^3$]

$\rho$ = density of compost bed [kg/m$^3$]

$\theta_c$ = cycle time of heat extraction [hr]

$\theta_{ext}$ = period of heat extraction [hr]

$\theta_{rec}$ = period of temperature recovery in compost bed [hr]

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# 堆肥発酵熱を利用した土壌加温システムの実際的なプロセス設計・制御に関する研究


関　平和

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## 要　約


堆肥発酵熱を利用した土壌加温システムの最適設計・制御の方法を，プロセス設計の概念に基づいて検討した。混合素材の熱的物性値，土壌加温に必要な熱量，温室内微気象条件などが前提条件として与えられ，熱抽出管の規格が決められているとき，最適化によって決定すべき決定変数は，熱抽出管の配管間隔と熱抽出管内の通水量の二つで，操作の安定性，熱効率の向上，熱源装置の設備費軽減の観点からそれらの最適値が求められた。更に，本システムを小規模施設へ適用することを前提に，土壌加温トータルシステムのフローシートの一例を示し，操作要領を記述した。ここで得られた決定変数の数値，操作要領，フローシートは機器設備の詳細設計を行う際の基礎となるだろう。