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Heat and Moisture Transfer in Soil Warming by Circulating Warm Water in a Buried Pipe Line

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In warming the soil bed for the protected cultivation of a typical water retentivity by circulating warm water, changes of temperature and moisture content distributions of the soil with time were predicted theoretically by applying Philip and deVries' model. Heat and moisture transport properties were estimated systematically, on the basis of the matric potential of soil water expressed by an approximate function of temperature and moisture content, and of the several empirical constants. Temperature and moisture content distributions were calculated by finite difference technique for the cases of 30°C, 40°C and 50°C of water temperature T_l, assuming the bare soil. It was shown that the drying rate of the soil around the warm water pipe becomes larger as T_l becomes higher, and that the dry out would be limited within an extremely narrow region around the pipe. The calculated results shown here would become useful information on planning the soil warming system in a greenhouse.

Key words: Heat transfer, Moisture transfer, Protected cultivation, Soil warming.

キーワード： 施設栽培，水分移動，熱移動，土壌加温

1. Introduction

In the regions where it is cold in winter because of low intensity of solar radiation such as Hokuriku district, soil warming is introduced to the protected cultivation in order to prevent an undesirable temperature drop in the soil. In the cultivation of plants, it is not permitted that moisture content falls extremely with warming the soil, since plants become unable to grow if the moisture content of the soil falls below the wilting point. Accordingly, in planning the operation of soil warming, it is important to predict exactly how the temperature and moisture content of the soil vary spatially with time.

Several reports (Abdel-Hadi and Mitchel, 1981; Baradi *et al.*, 1981; Radhakrishna *et al.*, 1984) were published regarding the change of moisture content around heat sources buried in the soil, however, these reports were not for the soil bed for cultivation. Shapiro (1975) investigated the problem of heat and moisture transfer in the soil with the application of power plant waste heat to warm the field soil, and predicted theoretically that the moisture content becomes lower than the wilting point for a silty loam in the plant root zone at the steady state when the volumetric moisture content is less than 15% at the bottom of the soil profile and the temperature difference between the water and soil surface is greater than 15°C. Slegel and Davis (1977) investigated the subirrigation effect of the porous pipe to prevent the soil around the pipe from drying out. These investigations were not for the protected cultivation but for the open-field culture of grains such as wheat and corn, so that the results obtained in those investigations are available almost only for a very large scale soil warming system in the open field. The decrease in moisture content with warming the soil bed would similarly occurs even in the protected cultivation, however, there has been few papers on the subject.

Among theoretical models for problems of the

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simultaneous. heat and moisture transfer in the soil, a model of Philip and deVries (1959) is the most well known, which is the basis of most of the above referenced papers. It has been pointed out that the model of Philip and deVries does not apply directly to moisture transfer in the regions considerably deeper under the ground and to moisture transfer in extremely clayey soils (Dakshanamurthy and Fredlund, 1981), however, the model would be useful to apply to moisture transfer in relatively shallow regions from the surface to the position at most 1m below the ground such as the soil bed for cultivation. In applying Philip and deVries' model, it is important to estimate the heat and moisture transport properties properly, however, a tractable estimation procedure of them has not be so far arranged satisfactorily.

From the above view point, a problem of simultaneous heat and moisture transfer in soil warming by the circulation of warm water for the protected cultivation is solved numerically by applying Philip and deVries' model. The transport properties of heat and moisture were estimated systematically by using the mathematical expression of the matric potential of soil water. Then, from the calculated results of temperature and moisture profiles in the soil, the decrease of moisture content in the soil around warm water pipe is mainly investigated.

2. Mechanism of simultaneous heat and moisture transfer in the soil and equations for estimating transport properties

According to Philip and deVries (1959), transfer of heat and of moisture in the soil are mutually influenced with each other, so that the following differential equations of moisture and heat transfer are given.

$$\frac{\partial(\rho_d w)}{\partial\theta}=\nabla\cdot(D_T\nabla T)+\nabla\cdot(D_w\nabla w)+\rho_w\frac{\partial k}{\partial z}, \tag{1}$$

$$\frac{\partial(C_p\rho T)}{\partial\theta}=\nabla\cdot(K_{eff}\nabla T)+L\nabla\cdot(\rho_{wv}D_{wv}\nabla w). \tag{2}$$

where

$$D_T=\rho_w D_{Tl}+\rho_{wv}D_{Tv}, \tag{3}$$

$$D_w=\rho_w D_{wl}+\rho_{wv}D_{wv}. \tag{4}$$

All the transport properties, that is, $k, D_{Tl}, D_{wl}, D_{Tv}, D_{wv}$ and K_{eff} in Eqs. (1) and (2), are functions of the moisture potential of soil water. If the soil water can be approximated by a pure water, in which osmotic potential can be ignored, the transport properties may be regarded as the functions of Φ_p only. Although it is desirable to predict Φ_p as a function of w and T in order to estimate the transport properties, well-established theoretical formulation on the relation between Φ_p and w, that is, moistute characteristic curve has not yet been developed. Therefore, the moisture characteristic curve of the soil must have been determined experimentally.

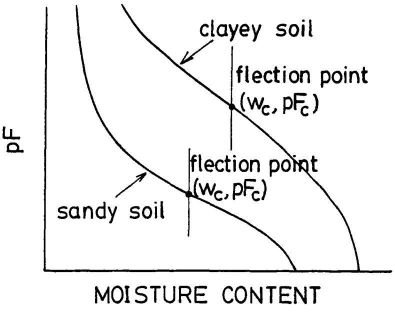


Fig. 1. Schematic illustration of the moisture characteristic curve of soil.

The moisture characteristic curve has been presented semi-empirically to be sigmoid for many types of soil as shown in Fig. 1, and it may be considered that the whole region of the curve consists of two parts separating at the flection point (w_c, pF_c). One of the parts is corresponding to the region of relatively low moisture content mainly involving adsorptive and capillary water, and the other part is corresponding to the region of relatively high moisture content primarily occupied with free water (Mitsuno, 1979). Then, considering the above general characteristics of Φ_p, the authors approximately express the matric potential of the soil water $\Phi_{pT_0}(w)$ at a representative temperature T_0 by the following exponential functions.

$$\Phi_{pT_0}(w)=\begin{cases}\Phi_{pc}(w/w_c)^{-A} & \text{for } 0<w<w_c, \quad (5)\\ \Phi_{pc}\{(w_{st}-w)/(w_{st}-w_c)\}^{(w_{st}-w_c)A/w_c} & \text{for } w_c<w<w_{st}. \quad (6)\end{cases}$$

where A is an empirical constant regarding as soil texture. Eq. (5) of the above two equations is similar to Gardner's equation (1970), which is applicable to a relatively narrow range of moisture content.

Assuming that the temperature dependence of Φ_p is determined by the temperature dependence of σ only as pointed out by Philip and deVries, Φ_p as a function of T and w is

$$\Phi_p(w,T)=\Phi_{pT_0}(w)\exp[(1/\sigma)(\partial\sigma/\partial T)(T-T_0)]\,. \tag{7}$$

Using Eq. (7), all the transport properties of heat and moisture in the soil can be obtained successively by the following procedure.

According to Green and Corey (1971), hydraulic conductivity of an unsaturated soil is given by the following function of Φ_p as illustrated in Fig. 2.

$$k_i=\frac{k_{st}}{k_{stc}}\frac{\sigma^2}{2\rho_w^2 g\nu}\frac{\Psi_{ws}}{n^2}\sum_{j=1}^{m}\{(2j+1-2i)(-\Phi_{pj})^{-2}\}\,,\quad i=1,2,\cdots,m\,. \tag{8}$$

where i = pore class of the soil, m=total number of pore classes, $n=mw_{st}/(w_{st}-w_1)$, k_{st}= measured saturated hydraulic conductivity, and k_{stc}=theoretical saturated hydraulic conductivity defined as follows:

$$k_{stc}=\frac{\sigma^2}{2\rho_w^2 g\nu}\frac{\Psi_{ws}}{n^2}\sum_{j=1}^{m}\{(2j-1)(-\Phi_{pj})^{-2}\}\,. \tag{9}$$

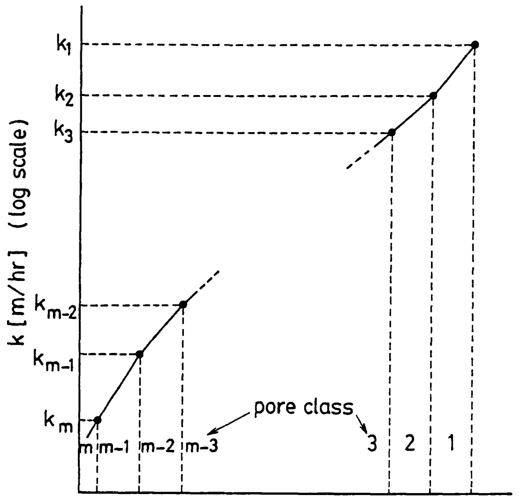


Fig. 2. Relation between hydraulic conductivity and moisture content estimated from Eq. (8) proposed by Green and Corey.

The ratio k_{st}/k_{stc} is a matching factor, which is expressed here briefly by a symbol β . Eq. (8) gives a good approximation of k if $m>10$. The value of k at a certain moisture content between w_i and w_{i+1} was estimated here by linear interpolation between the values of k_i and k_{i+1} obtained from Eq. (8) on a semi-logarithmic paper as shown by Fig. 2. According to Raudkivi and U'u (1976), since the temperature dependence of k is governed by the temperature dependence of ν in many types of soil, k may be approximately given by the following function of w and T.

$$k(w,T)=k_{T_0}(w)\exp[-(1/\nu)(\nu/T)(T-T_0)]\,. \tag{10}$$

Then, using Eqs. (7) and (10), D_{Tl} , D_{wl} , $\rho_{wv}D_{Tv}$ and $\rho_{wv}D_{wv}$ defined by Philip and deVries (1959), are

$$D_{Tl}=k\partial\Phi_p/\partial T=k(1/\sigma)(\partial\sigma/\partial T)\Phi_p\,, \tag{11}$$

$$D_{wl}=k\partial\Phi_p/\partial w=k\exp\{(1/\sigma)(\partial\sigma/\partial T)(T-T_0)\}\,d\Phi_{pT_0}/dw\,, \tag{12}$$

$$\rho_{wv}D_{Tv}=D_v\alpha\eta\rho_0 h(d\rho_0/dT)\xi\zeta\,, \tag{13}$$

$$\rho_{wv}D_{wv}=D_v\alpha\eta\rho_0(dh/dw)\xi\,. \tag{14}$$

There are several methods for estimating K_{eff}, of which the following equation (Seki and Komori, 1984) that had been slightly simplified the series-parallel-combined model by Krischer (1963) was used here.

$$K_{eff}=1/\{(1-B)/K_1+B/K_2\}\,, \tag{15}$$

where

$$K_1=(1-\Psi)K_s+\Psi_w K_w+(\Psi-\Psi_w)(K_a+K_{dif})\,, \tag{16}$$

$$K_2=1/\{(1-\Psi)/K_s+\Psi_w/K_w+(\Psi-\Psi_w)/(K_a+K_{dif})\}\,. \tag{17}$$

The foregoing equations, Eqs. (5)−(15), were not obtained through the purely theoretical consideration, so that the several empirical constants, A in Eqs. (5) and (6), β, that is, k_{st}/k_{stc} in Eq. (8) and B in Eq. (15), are involved. Therefore, the constants must be given experimentally in advance. The systematic estimation procedure of transport properties proposed here requires not so many empirical constants, and would be available for practical calculation of heat and moisture transfer in the soil.

3. A problem of simultaneous heat and moisture transfer in soil warming

Suppose that the pipes for soil warming are arranged within the soil bed in a greenhouse at a constant depth a below the surface of the soil with an equal space p as shown in Fig. 3.

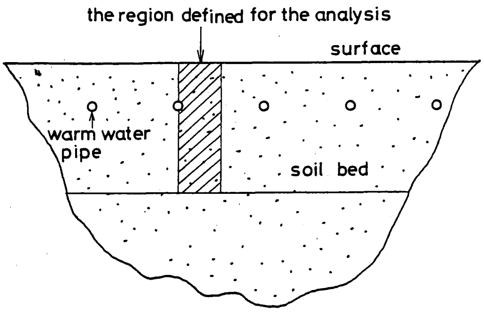


Fig. 3. Schematic representation of the pipe arrangement and the region defined for the analysis of heat and moisture transfer.

In the soil warming system, flow rate of water circulated in the pipe is usually set large enough to make the temperature difference of water between the inlet and outlet of the pipe as small as possible. Therefore, a two dimensional analysis with respect to the soil profile perpendicular to the pipes may be available to give a good approximation of the temperature and moisture content distributions in the soil. In treating the problem mathematically, the following several assumptions for simplification are made.

(1) The soil does not shrink during the soil warming process, and ρ_d is held constant.

(2) The hysteresis in the relation between Φ_p and w is not taken into account because the soil warming is related to the drying process only.

(3) A bare soil is assumed here, and the effect of suction of water in the plant root zone can be ignored.

(4) Since the difference of T_l between the inlet and outlet of the pipe is relatively small under the usual operating conditions of soil warming, T_l is regarded to be constant approximately.

(5) The temperature and moisture content at the bottom of the soil profile are held constant during the soil warming process.

(6) Thermal resistance at the interface between the warm water pipe and soil can be ignored.

(7) The temperature and moisture content are uniform initially.

Upon these assumptions, a mathematical treatment of this problem may be defined only for the region indicated by //// in Fig. 3. The differential equations for w and T are

$$\rho_d \frac{\partial w}{\partial \theta} = \frac{\partial}{\partial x}\left(D_T \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(D_T \frac{\partial T}{\partial z}\right) + \frac{\partial}{\partial x}\left(D_w \frac{\partial w}{\partial x}\right) + \frac{\partial}{\partial z}\left(D_w \frac{\partial w}{\partial z}\right) + \rho_w \frac{\partial k}{\partial z}, \tag{18}$$

$$\frac{\partial (C_p \rho T)}{\partial \theta} = \frac{\partial}{\partial x}\left(K_{eff} \frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_{eff} \frac{\partial T}{\partial z}\right) + L \frac{\partial}{\partial x}\left(\rho_{wv} D_{wv} \frac{\partial w}{\partial x}\right) + L \frac{\partial}{\partial z}\left(\rho_{wv} D_{wv} \frac{\partial w}{\partial z}\right). \tag{19}$$

The boundary conditions at the surface of the soil are heat and moisture balance equations at the soil surface. According to the assumptions (5) and (6), the boundary conditions at the bottom of the soil profile and at the surface of the pipe are easily given. Moreover, the other boundary conditions are also given easily, taking account of the symmetry of T and w at the both sides of the soil profile.

Since Eqs. (18) and (19) are non-linear equations, it is difficult to obtain the analytical solutions of T and w. Therefore, in calculating the temperature and moisture content distributions, the soil profile is divided into a number of square parts as shown in Fig. 4, and the differential equations and boundary conditions are rewritten into the difference forms. Using the difference-form-equations, T and w at the individual grid points are calculated every small increment of time $\Delta\theta$ successively from the initial values T_i and w_i. In the numerical calculation, the value of $\Delta\theta$ against Δz or Δx is determined to be $0.1(\Delta z)^2/\kappa$ or $0.1(\Delta x)^2/\kappa$, taking account of the stability of the numerical solutions.

4. Physical properties of the soil and operating conditions

The basic physical properties of the soil for cultivation are assumed as shown in Table 1 with reference to the experimental results reported previously (Maeda and Matsuo, 1974; Kasubuchi and Miyazaki, 1979). Based on the basic physical properties, heat and moisture transport properties of the soil were estimated from Eqs. (5)−(17). Several empirical constants necessary for estimation of the transport properties are shown in Table 2. The value of A was determined so that the curve expressed by Eqs. (5) and (6) coincides the primary and permanent wilting points and the point of field capacity for the soil for cultivation of typical in Japan (SAMJ, 1986). Fig. 5 shows the calculated results of pF againts w and the experimental results by the thermocouple psychrometer (Wescor, HR-33T) for a sample soil for cultivation. The experimental results are scattered to some extent, however, the calculated results are relatively in good agreement with the experimental results, and the value of A would be available. The value of B in Eq. (15) was estimated from the experimental results of K_{eff} under both the saturated and completely dried conditions. The value of β, which was estimated from the measured value of the saturated hydraulic conductivity of the sample soil by permeability test by falling head, varies from 0.0032 to 0.0315 with a slight difference in packing condition of the sample soil into a sample container. For the densely packed soil, β becomes smaller. The order of magnitude of the saturated hydraulic conductivity of the soil sample k_{st} was $10^{-1}-10^{-2}$ m/hr. Using the empirical constants, K_{eff}, k, D_T and D_w were calculated

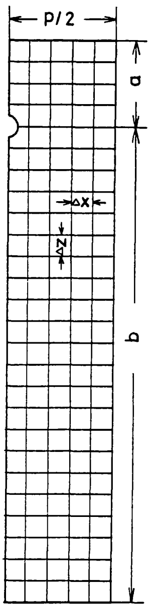


Fig. 4. Grid network for the numerical solution.

Table 1 Specifications of the pipe arrangement.

Depth of the buried pipe from the soil surface a [m]	Distance between the buried pipe and the bottom of soil bed b [m]	Distance between pipes p [m]	Outer radius of the buried pipe R [m]
0.152	0.836	0.19	0.019

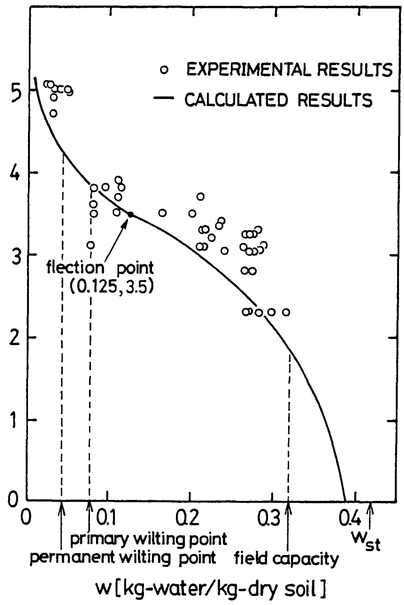


Fig. 5. Comparison of the calculated results of pF $-w$ relationship with the experimental results for the soil sample (ρ_s=2500kg/m^3; ρ_d=1256kg/m^3).

Table 2 Physical properties of the typical soil for cultivation.

Density of a soil particle ρ_s [kg/m^3]	Dry density of soil ρ_d [kg/m^3]	Saturated moisture content w_{st} [kg-water/kg-dry soil]	Moisture content corresponding to field capacity w_f [kg-water/kg-dry soil]	Heat capacity of soil C_p [kcal/kg°C]
2400	1200	0.417	0.32	$0.2+0.8w/(1+w)$

from Eqs. (10)–(15), and the calculated results of them are illustrated in Figs. 6 and 7. Table 3 shows the dimensions of the soil profile and specifications of the soil warming pipes. The values listed in Table 3 would be the representative ones, which were determined with reference to the previous repoets (Itaki, 1976; Okada, 1980).

The soil warming pipes are to be the plastic pipes made of P.V.C., of which dimensions are 30 mm in I.D. and 38mm in O.D. Table 4 shows the practical operating conditions of the soil warming process. In Table 4, T_0 is the average over the winter season in Hokuriku district, and w_0 is corresponding to the field capacity of the typical soil for cultivation. h_s and k_s were estimated from the empirical equations for natural convective transfer of heat and moisture in air layer near the ground (Seki and Komori, 1985), and h_r was calculated upon Stefan-Boltzman's law.

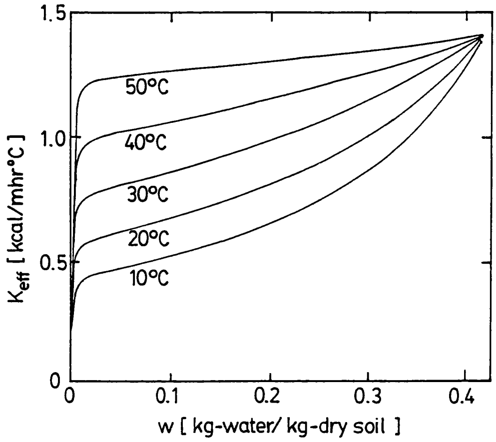


Fig. 6. Plots of the calculated results of K_{eff} against w.

5. Calculated results and discussion

As is evident from Eqs. (11) and (12), β is related not only with k but also with D_{wl} and D_{Tl}, so that β is the most important factor affecting the moisture transfer in the soil. Therefore, to

Table 3 Values of several empirical constants for estimation of heat and moisture transport properties.

A [–]	β [–]	B [–]	K_s [kcal/mhr°C]
1.47	0.0032 ~ 0.0315	0.202	2.783

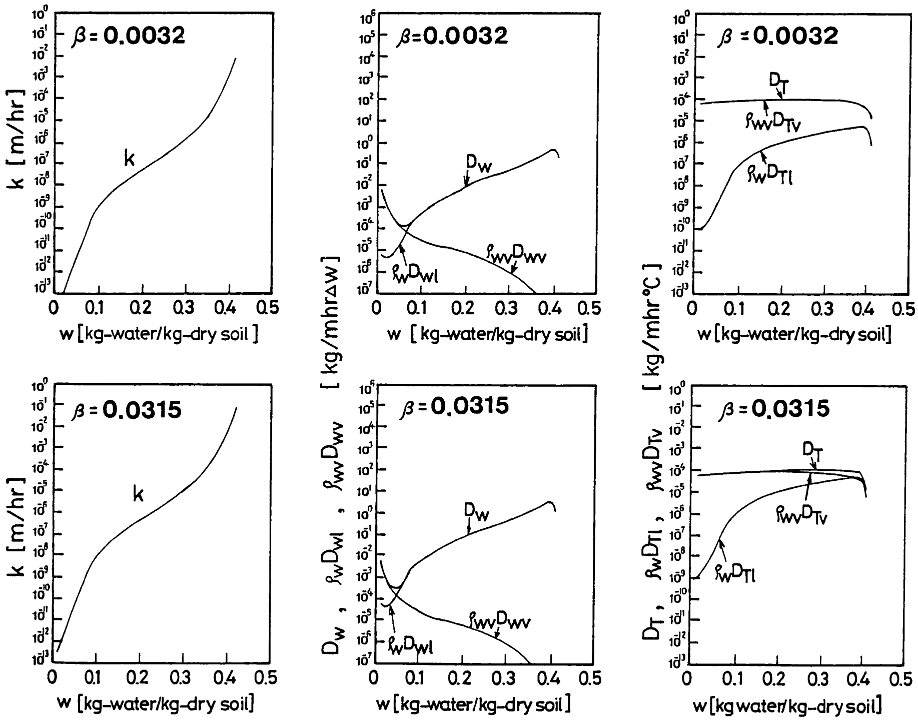


Fig. 7. Plots of the calculated results of k, D_T and D_w against w at T=20°C.

Table 4 Operating conditions for the soil warming process.

Moisture content at the bottom of the soil	Temperature at the bottom of the soil	Atmospheric temperature in a greenhouse	Humidity in a greenhouse	Sensible heat transfer coefficient at the soil surface	Long wave radiative heat transfer coefficient at the soil surface	Mass transfer coefficient at the soil surface	Solar radiation to the soil surface in a greenhouse
w_0	T_0	T_∞	H_∞	h_s	h_r	k_s	q_r
[kg-H_2O/ kg-dry soil]	[°C]	[°C]	[kg-H_2O/ kg-dry air]	[kcal/m^2 hr°C]	[kcal/m^2 hr°C]	[kg/m^{2}hr]	[kcal/m^{2}hr]
0.32	10	5	0.0032	1.3	4.3	4.0	40

inverstigate the moisture transfer with soil warming, the two limiting values of β, that is, the minimum value of 0.0032 and the maximum value of 0.0315, were chosen here, and the temperature and moisture content distributions in the soil profile were calculated. Actual temperature and moisture content distributions would lie between the calculated results obtained under the above two limiting situations. Fig. 8 shows the calculated results of temperature and moisture content distributions for $\beta = 0.0032$, where $T_l = 30$°C, 40°C or 50°C, which is the ordinary value for soil warming in a protected cultivation (Okada, 1980). According to Fig. 8, it is found that w decreases gradually with time around the warm water pipe and near the soil surface. The decrease of w near the pipe is because the outward moisture flux from the pipe due to temperature gradient $-D_T \nabla T$ is larger than the inward moisture flux to the pipe due to moisture gradient $-D_w \nabla w$. For higher value of T_l, temperature gradient around the warm water pipe becomes larger, and $-D_T \nabla T$ becomes larger, so that a considerably larger drop of w occurs near the pipe. For $T_l = 30$°C, $-D_T \nabla T$ is not so large near the pipe, and there is not a considerable decrease of w. Even in the case of $T_l = 40$°C and 50°C, however, the region in which w becomes smaller than the primary wilting point is limited within a narrow annular region within almost 2cm from the outer surface of the pipe.

The calculated results of T gradually increase with time, and would reach the quasi-steady atate in 5 days. In the case of $T_l = 40$°C or 50°C, however, there is a continuous increase of T during $\theta = 5-10$days especially in the upper region of the soil profile as shown in Fig. 8 (b), (c). The continuous increase of T is related with the gradual decrease of w in the upper region, because C_p and ρ decreases with decreasing w. However, since a suitable amount of water will be adequately sprinkled to the surface of the soil in a conventional protected cultivation, such an undesirable temperature rise in the upper region may not be possibly induced practically.

The calculated results of T and w for the case of $\beta = 0.0315$ were not shown here on account of limited space. A summary of the calculated results for $\beta = 0.0315$ is as follows: 1) There was not a significant drop in w near the warm water pipe even in the case of $T_l = 40$°C or 50°C; 2) The calculated results of T were not so different from those for $\beta = 0.0032$ except the results at 10 days in the case of $T_l = 40$°C or 50°C.

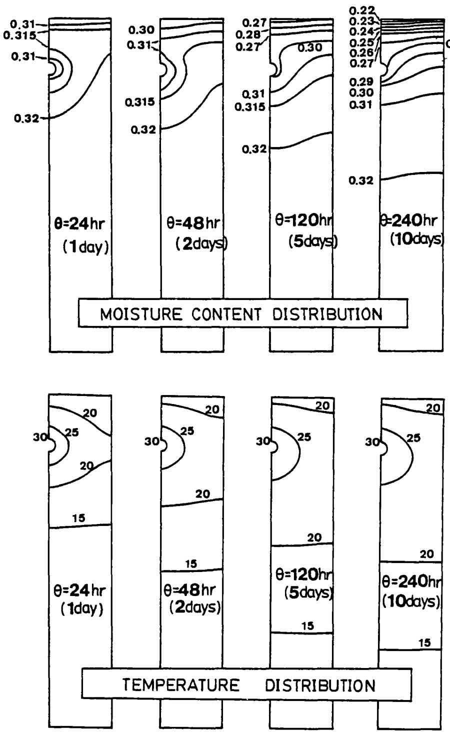
From the above results, it is suggested that moisture transfer does not influence so much on heat transfer around the pipe for warming the bare soil in a greenhouse, and that temperature distributions in the soil may be calculated practically with disregard of the moisture transfer if a suitable amount of water is continuously or intermittently supplied to the soil surface so as not to decrease w near the soil surface.

6. Conclusions

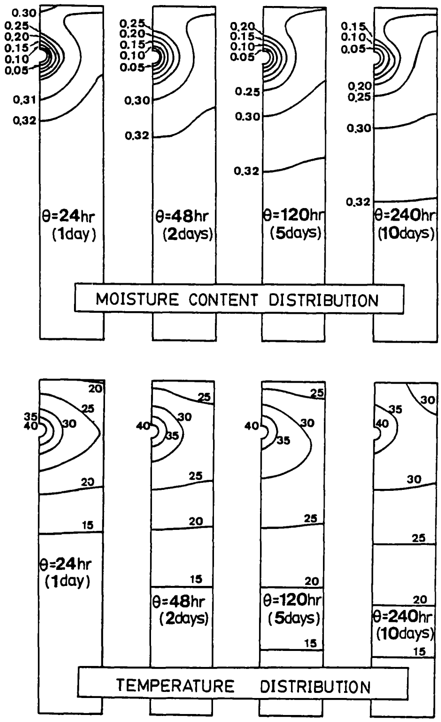
Temperature and moisture content distributions in warming the soil for the protected cultivation of a typical water retentivity, were calculated numerically. The results obtained are summarized as follows:

1) Several empirical constants are necessary to estimate the properties of heat and moisture transfer in the soil, and it is important to get the empirical constants properly. Especially, a matching factor of the hydraulic conductivity of the soil β is the most important factor affecting the moisture content distribution.

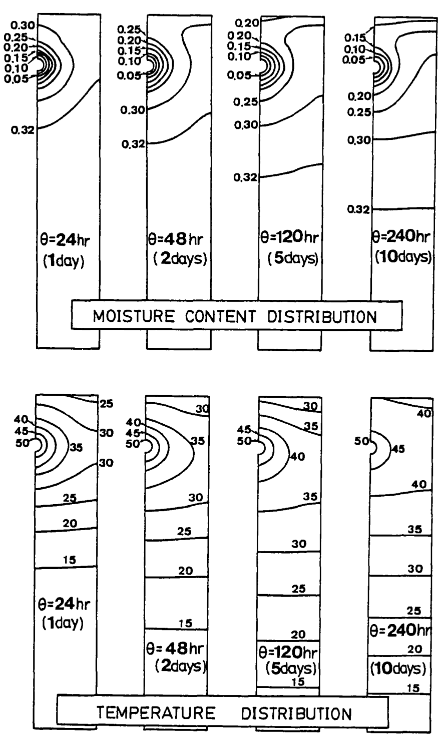
2) The soil of relatively high order value of k_{st}, 10^{-1} m/hr, which corresponds to the case $\beta =$



(a) for T_l =30°C



(b) for T_l =40°C



(c) for T_l =50°C

Fig. 8. Calculated results of the temperature and moisture content distributions for the case of $\beta = 0.0032$.

0.0315, would not be dried out near the warm water pipe, while that of relatively low order value of k_{st}, 10^{-2} m/hr, which corresponds to the case of $\beta = 0.0032$ may possibly be dried out if T_l is equal to or greater than 40°C. However, even in the case of the soil of relatively low order value of k_{st}, the dry out by warming would be limited within the narrow annular region almost near the warm water pipe.

3) The influence of the moisture movement around the warm water pipe on the temperature distribution of the soil is relatively small, and it is suggested that the temperature distribution would be approximately calculated by solving the heat conduction problem ignoring the moisture movement.

4) According to the above two items 2) and 3), the drop of soil moisture content with soil warming would not be so serious, and it seems rather plausible for the protected cultivation, since the soil moisture control is easier in a greenhouse than in an open field.

The authors would like to acknowledge Dr. S. Takami for his helpful advice.

Nomenclature

A = empirical constant defined by Eqs. (5) and (6) [−]
B = empirical constant defined by Eq. (15) [−]
a = depth of the buried pipe from the soil surface [m]
b = distance between the buried pipe and the bottom of soil bed [m]
C_p = heat capacity of soil bed [kcal/kg°C]
C_{ps} = heat capacity of a soil particle [kcal/kg°C]
C_{pw} = heat capacity of water [kcal/kg°C]
D_T = water conductivity due to temperature gradient [kg-water/m hr°C]
D_{Tl} = liquid water diffusivity due to temperature gradient [m^2/hr°C]
D_{Tv} = water vapor diffusivity due to temperature gradient [m^2/hr°C]
D_v = water vapor diffusivity in air [m^2/hr]
D_w = water conductivity due to moisture gradient [kg-water/mhr Δw]
D_{wl} = liquid water diffusivity due to moisture gradient [m^2/hr Δw]
D_{wv} = water vapor diffusivity due to moisture gradient [m^2/hr Δw]
g = gravitational acceleration [m/hr^2]
H = humidity in the soil bed [kg-H$_2$O/kg-dry air]
H_∞ = humidity of the atmosphere [kg-H$_2$O/kg-dry air]
h = relative humidity [−]
h_r = radiative heat transfer coefficient [kcal/m^2 hr°C]
h_s = free convective heat transfer coefficient [kcal/m^2 hr°C]
K_a = thermal conductivity of air [kcal/mhr°C]
K_{dif} = thermal conductivity equivalent to vapor diffusion [kcal/mhr°C]
K_{eff} = effective thermal conductivity of soil bed [kcal/mhr°C]
K_s = thermal conductivity of a soil particle [kcal/mhr°C]
K_w = thermal conductivity of water [kcal/mhr°C]
k = hydraulic conductivity [m/hr]
k_s = mass transfer coefficient [kg/m^2 hr]
k_{st} = measured saturated hydraulic conductivity [m^2/hr]
k_{stc} = theoretical saturated hydraulic conductivity [m^2/hr]
L = latent heat of vaporization of water [kcal/kg]
p = distance between pipes [m]
q = heat flux in the soil bed [kcal/m^2 hr]
q_r = intensity of solar radiation to the surface of soil bed [kcal/m^2 hr]
R = outer radius of the soil warming pipe [m]
T = temperature of the soil bed [°C]
T_i = initial temperature of the soil bed [°C]
T_l = temperature of water flowing in the pipe [°C]
T_0 = temperature at the bottom of soil bed [°C]
T_∞ = atmospheric temperature [°C]
w = moisture content of the soil bed [kg-H$_2$O/kg-dry soil]
w_i = initial moisture content of the soil bed [kg-H$_2$O/kg-dry soil]
w_c = moisture content at the flection point [kg-H$_2$O/kg-dry soil]
w_f = moisture content corresponding to field capacity [kg-H$_2$O/kg-dry soil]
w_{st} = saturated moisture content [kg-H$_2$O/kg-dry soil]
x = horizontal distance [m]
z = vertical distance [m]
Ψ = porosity [−]
Ψ_w = volumetric moisture content [−]
Ψ_{ws} = saturated volumetric moisture content ($=\Psi$) [−]
Φ_p = matric potential of soil water [cmH$_2$O]
θ = time [hr]
κ = effective thermal diffusivity of soil bed [m^2/hr]
σ = surface tension of water [kg/hr^2]
ν = kinematic viscosity of water [m^2/hr]
β = matching factor ($=k_{st}/k_{stc}$) [−]
ξ = effective fraction of porosity available for vapor transfer [−]
ζ = ratio between the average temperature gradient in the particles and that in the medium [−]
η = mass flow factor [−]
ρ = apparent density of soil bed [kg/m^3]
ρ_d = dry density of soil bed [kg/m^3]
ρ_s = density of a soil particle [kg/m^3]
ρ_w = density of water [kg/m^3]
ρ_{wv} = density of water vapor [kg/m^3]

ρ_0 = saturated vapor water density [kg/m^3]

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温水循環方式による土壌加温時の熱及び水分移動

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要　約

代表的な保水性を有する温室土壌を温水循環方式によって加温する場合，土壌内の温度及び含水比分布が時間的にどのように変化するかをPhilip & deVriesモデルに基づいて理論的に予測した。熱・水分の移動物性値は，温度と含水比の近似関数で表した土中水のマトリックポテンシャルと幾つかの実験定数に基づいて系統的に推算した。無栽植条件の下で，温水温度T_lを30℃，40℃，50℃として数値シミュレーションを行ったところ，T_lが高いほど温水管付近の乾燥速度が大きくなること，乾き上がりは管壁のごく近傍に限られることが予測された。ここに示した計算結果は，温室土壌の加温計画立案のための有用な情報となるであろう。