CHAPTER 6

TEMPERATURE ENVIRONMENT UNDER COVER

6.1. INTRODUCTION

Temperature is another important environmental condition for plant growth. The temperature of the plant environment can be modified by cover the area. In the daytime, the main energy source is, of course, the sun, and its energy is stored in the soil. The transmissivity of the film used for covering is an important factor in getting a large amount of energy into the soil surface. At night, the energy source is thus the soil layer. The main heat loss from the surface is due to long wave radiation, and the emissivity of the cover is a key factor in this.

Long wave radiation heat exchange between the sky and the soil surface is expressed by the difference between eqs. 4.4 and 4.17, where the absolute temperature of the soil surface is **AT**. Emissivities for covering materials range between 0 and 1; they are shown in Table 2.3 in Chapter 2, where emissivity is expressed as absorptivity.

6.2. EFFECT OF MULCHING

6.2.1. Experimental measurements

The effect of mulching is well appreciated, but its mechanism is not yet fully understood. Many field experiments have been conducted over a period of years. But it is rather difficult to isolate boundary conditions in field experiments, so the effect of mulching on the temperature in the surrounding environment has not been clearly explained. For example, suppose we set up three mulchings with three films with different color -- clear, black and white -- in order to examine the temperature differences in the soil layer. Even if the soil condition appears to be the same under the three coverings, the actual situation will be different. There will be slight differences in the way the coverings are placed. Air leakage through the covering affects water vapor conditions under the cover, and therefore the temperature. Measurement of soil temperature is not easy: the spacing and the placement of the sensing element at a certain point requires considerable skill. Even if thermocouples are used, they are not easy to place exactly 1 cm deep in the soil. These are all reasons to use computer simulation.

Figure 6.1 shows one of the typical results of soil temperature measurement under different mulches, and Table 6.1 lists some major components of the heat balance in these systems. These are all measured values. Soil temperatures 1 cm deep under mulchings of various materials are valuable not only as good indicators for comparison but also determining the variability of the measurements. Since details on the covering materials are not shown, quantitative comparisons cannot be made on the basis of these data. It is clear from Table 6.1 that there is some difference in latent heat transfer among these coverings. However, we cannot quantify it because of differences in the permeability of these materials and because of measurement errors. Furthermore, vapor transfer through the holes made for plants might affect the situation. In Table 6.1, albedo (reflectivity of solar radiation) is given and surface temperature is not. The techniques for making simulation models in the present chapter show that surface temperatures are easily derived and that transmissivity and absorptivity rather than albedo are needed to analyze the energy balance of these systems.

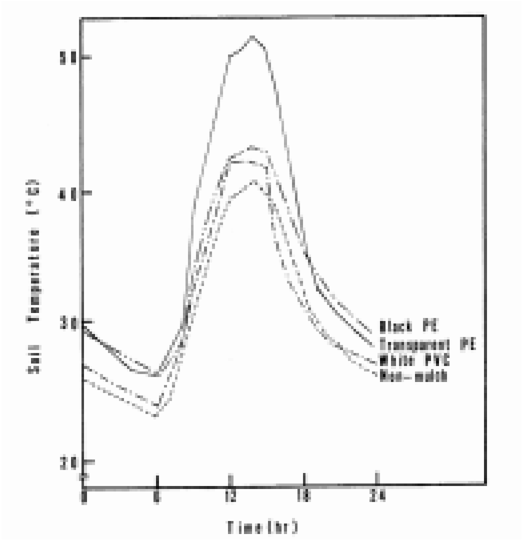

Figure 6.1. Daily variation of soil temperature at 1 cm depth under various types of mulching in Aug., 1984 (after Kwon, 1988).

Table 6.1. Some major components of heat balance under various mulchings (after Kwon, 1988).

Treatment	*Albedo (%)*	*Net radiation*	*Sensible heat*	*Latent heat*	*Soil heat flux*	*Solar radiation*	**Volumetric heat capacity*
Non-mulched	11.8	905.5	510.3	274.7	120.5 (100)	2368	1.76
Transparent PE	19.4	889.1	685.9	55.4	147.8 (123)	2368	2.10
White PVC	32.1	1100.4	978.2	37.4	84.8 (71)	2368	2.06
Black PE	4.3	779.1	621.6	45.8	111.7 (93)	2368	2.18
Straw mulch	21.4	1300.3	1077.7	136.9	85.7 (71)	2368	2.14

All units except volumetric heat capacity are Jcm^{-2}day^{-1} and were investigated on Aug. 19, 1984.

** Unit is Jcm^{-3}°C^{-1} and was investigated at soil depth between 10 and 20 cm on Oct. 11, 1984.

6.2.2. A model to simulate temperature regime under mulching **(CUC20)**

A computer simulation enables us to isolate boundary conditions and idealize the situation. Let us look at a model that compares the three colors of mulching: clear, black, and white. The main part of the model is depicted in Fig. 6.2. This part is the surface of the soil layer where film mulching has been used. The air gap between the film and the soil surface is enlarged in order to show the energy exchange in this layer clearly.

It is assumed that the air temperature in this layer is the arithmetic mean of the film temperature (**TC**) and the soil surface layer temperature (**TF**) and that the air layer is at the same temperature as the surface of the soil which is saturated with water vapor. All energy terms involved in the energy balance of the film to determine its temperature are shown in the Figure. They include direct solar radiation (**RAD**), diffuse radiation (**RADS**), long wave radiation from both sides of the film surface **(EPSC*SIG*TC4)**, thermal radiation from the soil surface **(EPSF*SIG*TF4)** and from the sky **(EPSA*SIG*TO4)**, convective heat transfer from both sides of the film **HO*(TC-TO)** and **HI*(TC-TI)**, and energy-related condensation of water vapor at the inside surface (**HWT**). Evaporation from the soil surface is expressed in a way similar to that in Chapter 4, but a factor (0.0 - 1.0) to reduce the saturated humidity ratio (Greenhouse Soil Index; GSI) is introduced. The thermal radiation from the film to the soil surface and then reflected back from the soil surface is also considered.

The program of the model for mulching is shown in Figs. 6.3a, b and Figs. 6.4a, b and the simulation results are given in Figs. 6.5, 6.6 and 6.7. Enter ‘cuc20(n)’ in the Command Window of **MATLAB** to run this model. Within the parentheses, n = 1 is for selecting clear mulch, n = 2 for black and n = 3 for white mulch. The user can run these options one by one or enter ‘cuc20(1); cuc20(2); cuc20(3)’ followed by the Enter to run three options in a row. Entering ‘cuc20’ along will assume n = 1. This part of the program was done by checking the number of arguments (**nargin** is a reserved word of **MATLAB**). If no argument exists, the program will assign 1 to the parameter **out**.

Fig. 6.3a shows the branching function **switch…case ….end** both before and after the line containing the **ode23t** function. The former **switch** is used to choose the type of film and the latter part is to draw the corresponding Figure of the chosen film. A stiff solver is suggested when solving simultaneous ordinary differential equations (ode) of this model. Function **ode23t** provides the shortest execution time.

Fig. 6.3b shows the ‘**soil20.m**’ subprogram containing all the simultaneous equations related to the energy balance of the cover, inside air layer, soil surface and soil layers. The main part of the model is depicted in Fig. 6.2.

In the present model, function **FRSNL** (listed in Fig. 6.4a**)** is defined to calculate transmissivity and absorptivity of the film and direct and diffused solar radiation for clear PE film, and function **FRSNLa** (listed in Fig. 6.4b**)** is for black and white PE films.

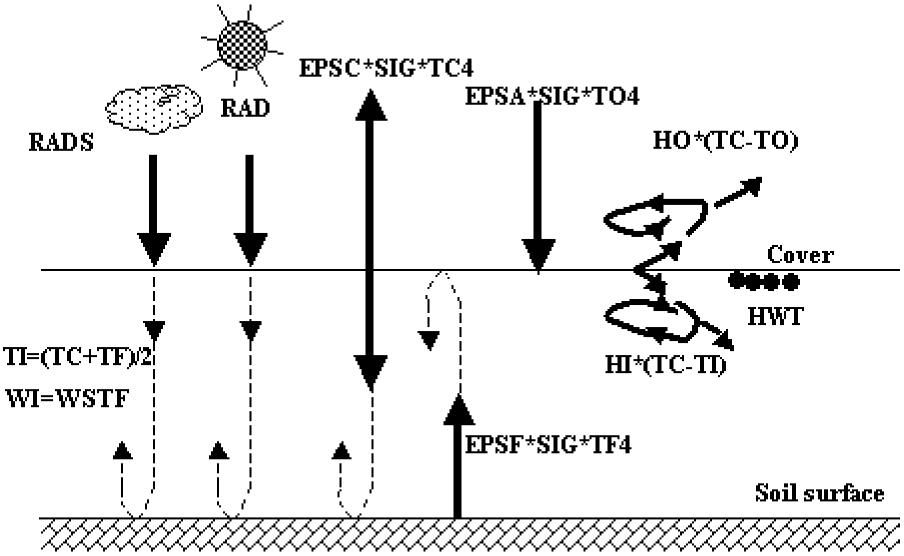

Figure 6.2. Energy balance of mulching.

Calculated coefficients **TDS** and **TLV** are transmissivity of the film for diffuse solar radiation and long-wave radiation, respectively. The amount of condensation at the inside surface of the film is calculated in the '**% inside air layer**' section as shown in Fig. 6.3b. In this section, the saturated humidity ratio at the inside air temperature is compared with that at the film temperature. The amount of condensed water is **TW**, and its latent heat transfer is **HWT**.

The soil surface is assumed sealed by a thin film. No air leakage from air space between the film and soil surface is assumed, and therefore the air gap is saturated by water vapor. Heat transfer in this air gap is also assumed to take place by conduction only.

The thickness of the covering film (**FL**) is assumed to be 1 mm and is defined as a **global** variable in this program as listed in subprograms shown in Figs. 6.3b, 6.4a and 6.4b. Normal thickness is about one tenth of the thickness used in this program. The reason for this change is simulation stability. If the film is thinner than 1 mm, it is difficult to obtain a stable solution by numerical iteration. On the other hand, it is clear that the resistance at both film surfaces mostly governs heat transfer through thin film and the effect of the difference in film thickness can be neglected if the film is less than several millimeters thick. This can be verified by the fact that the thickness of normal glass for greenhouses is 3-4 mm and there is no difference between glasshouses and plastic film houses attributable to the difference in covering thickness.

```
%  Temperature regime in soil under CLEAR/BLACK/WHITE              CUC20.m
%       PE Mulching.  Latent heat transfer is involved
%  function required: soil20.m
function cuc20(out)
global colr;
if nargin==0, out=1;end
switch out
case 1
   clc
   colr='clear';opt='Clear PE Mulch';
case 2
   colr='black';opt='Black PE Mulch';
case 3
   colr='white';opt='White PE Mulch';
end
disp(opt);
tic
t0=1; tfinal=48;
y0=[10; 10; 20; 20; 20; 20];
%   TC, TF, T1, T2, T3, T4   (Initial condition)
%
[t,y]=ode23t('soil20',[t0 tfinal],y0);
%
% Use Stiff Solver, time required to run
% ode23t < ode15s  < ode23tb < ode23s
% Use Non-stiff Solver
% ode23, ode45 and ode113 will take too long to solve
%
switch out
case 1
   h1=findobj('tag','cuc20_part1');  close(h1);
   figure('tag','cuc20_part1','Resize','on','MenuBar','none',...
     'Name','CUC20.m (Figure 1)','NumberTitle','off',...
     'Position',[140,120,520,420]);
case 2
   h1=findobj('tag','cuc20_part2');  close(h1);
   figure('tag','cuc20_part2','Resize','on','MenuBar','none',...
     'Name','CUC20.m (Figure 2)','NumberTitle','off',...
     'Position',[180,80,520,420]);
case 3
   h1=findobj('tag','cuc20_part3');  close(h1);
   figure('tag','cuc20_part3','Resize','on','MenuBar','none',...
     'Name','CUC20.m (Figure 3)','NumberTitle','off',...
     'Position',[220,40,520,420]);
end
plot(t,y(:,1),'kh-',t,y(:,2),'mo--',t,y(:,3),'rx-',t,y(:,4),...
   'c+-',t,y(:,5),'gs-',t,y(:,6),'b*-');
% 'kh-' : black,   hexagram, solid  line for curve TC
% 'mo-' : magenta, circle,   solid  line for curve TF
% 'rx-' : red,     x-mark,   solid line for curve T1
% 'c+-' : cyan,    plus,     solid line for curve T2
% 'gs-' : green,   square,   solid line for curve T3
% 'b*-' : blue,    star      solid  line for curve T4
grid on;
titcont=['Cover and soil temperatures under ' opt];
title(titcont);      xlabel('time  elapsed, hr');
ylabel('Temperature, ^oC'); legend('TC','TF','T1','T2','T3','T4');
toc
% 'tic'&'toc' are pair of functions to measure run time.
%
```

```
if out==3
  disp('Thank you for using CUC20:’);
  disp('      Temperatures under CLEAR/BALCK/WHITE PE mulch');  disp(' ');
end
```

Figure 6.3a. Program to calculate cover and soil temperatures under mulch **(CUC20.m)**.

```
%  Function to be used with CUC20.m                            soil20.m
%  Also involves functions FRSNL.m, FRSNLa.m, FWS.m, TABS.m
%
function dy = soil20(t,y)
global FL;
global colr;
T0=15.0; TU=5.0; TBL=20.0;% Temp (C)
TD=8;                     %outside dew point temperature, in degree C
KS = 5.5; CS= 2.0E+3;
% KS (kJ/m/C/hr) and KS/3.6 (W/m/C) also CS (kJ/m3/C)
CA=1.164; CC=50.0;
RHO=1.164;
GSI=1.0;   % Greenhouse Soil Index, dryness of soil surface (01-1.0)
SIG= 20.4; % Stefan-Boltzmann constant (kJ/m2/K4/hr) = 5.67(W/m2/K4)
HI=7.2;    HO= 25.4;
Z0=0.01;   Z1=0.05;   Z2=0.1;    Z3=0.2;
Z4=0.5;    % Depths of soil layer (m)
ALC=0.1;   ALF=0.7;   RMC=0.1;
RMSC=0.05; EPSC=0.15; EPSF=0.95;
EPSA = 0.711+(TD/100)*(0.56+0.73*(TD/100));
HLG=2501.0;LE=0.9;
KM=3.6*HI/LE/CA*RHO;
FL=1;DEX=0.001*FL; %Thickness in mm and m
% EPSA:Emissivity of air layer
WO=FWS(TD);                          % calling function FWS()
TDS=1-ALC-RMSC;
TLV=1-EPSC-RMC;
%
clk = mod(t,24);
if colr=='clear'
  [TRAN,ABSO,RAD,RADS]=FRSNL(clk);   % calling function FRSNL()
   [TRAN,ABSO,RAD,RADS]=FRSNLa(clk); % calling function FRSNLa()
end
OMEGA=2*pi/24;                       % Time (hr)
TO = T0 + TU*sin(OMEGA*(clk-8));
%---------------------------------------------------------------------
TC=y(1); TF=y(2);T1=y(3);T2=y(4);T3=y(5);T4=y(6);
% At Cover -----------------------------------------------------------
TO4=TABS(TO);  TC4=TABS(TC);  TF4=TABS(TF);  % calling function TABS()
%  calculating HWT
HWT=0;
WSS=FWS(TC);          % Calling function FWS()
%  Inside air layer --------------------------------------------------
TI=(TC+TF)/2;
WSTF=FWS(TF);         % calling function FWS()
WI=WSTF;
if WSS < WI
  TW=WI-WSS;          % amount of water condensed
  WI=WSS;
  HWT=TW*HLG*KM;      % Energy required to condense water
end
%
```

```
ITC=(RAD*ABSO+RADS*ALC+(1-ALF)*(RADS*TDS+RAD*TRAN)*ALC+...
   SIG*EPSC*(EPSF*TF4+ EPSA*TO4+((1-EPSF)-2)*TC4)-...
   HO*(TC-TO)-HI*(TC-TI)+HWT)/DEX/CC;
% At soil surface ---------------------------------------------------
ITF=(ALF*(RADS*TDS+RAD*TRAN)-KS*(TF-T1)*2/(Z0+Z1) ...
   -HI*(TF-TI)+HLG*KM*(WI-GSI*WSTF)...
   -SIG*EPSF*((1-RMC)*TF4-EPSA*TLV*TO4-EPSC*TC4))/CS/Z0;
% In soil layers ----------------------------------------------------
IT1 = (KS*(TF - T1)*2.0/(Z0+Z1)+KS*(T2 - T1)*2.0/(Z1+Z2))/CS/Z1;
IT2 = (KS*(T1 - T2)*2.0/(Z1+Z2)+KS*(T3 - T2)*2.0/(Z2+Z3))/CS/Z2;
IT3 = (KS*(T2- T3)*2.0/(Z2+Z3)+ KS*(T4 - T3)*2.0/(Z3+Z4))/CS/Z3;
IT4 = (KS*(T3 - T4)*2.0/(Z3+Z4)+KS*(TBL - T4)*2.0/Z4)/CS/Z4;
dy=[ITC; ITF; IT1; IT2; IT3; IT4];
return
```

Figure 6.3b. One of the subprograms of CUC20 model **(soil20.m)**.

6.2.3. Same model for black or white mulch

Transmissivity and absorptivity of clear film are calculated by the equations given in the preceding section, and source codes listed in function **FRSNL** can be found in Fig. 6.4a. For opaque black and white films transmissivity and absorptivity are given by interpolation functions based on experimental observations. Source codes listed in function **FRSNLa** can be found in Fig. 6.4b. As shown in the source code, type of mulching is assigned to the parameter **colr**, which decide the proper data set for the interpolation of the calculation of **TRAN** and **ABSO** in function **mulching**.

Film properties such as transmissivity and absorptivity of black and white opaque films are given in function **mulching(colr),** which is in the last part of **FRSNLa.m** (Fig. 6.4b).

```
% Function for Clear PE Mulching to be used in CUC20 model       FRSNL.m
% Also involves functions: RADcal.m, RFcal.m
%
function [TRAN, ABSO, RAD, RADS]=FRSNL(clk)
global FL pp ARTO
LATD=35.68;LGT=139.77; LGTstd=135;conv=pi/180;
%  LATD: latitude 35 deg 41 min is f(location)
%  LGT: longitude 139 deg 46 min is f(location)
%  LGTstd:  meridian 139 longitude is f(location)
LAT=LATD*conv; % latitude in radian unit
DEC=-8.316;EQT=0.2338; % data for October 15 from Table 5.1
DEG=DEC*conv;
%  DEC: declination -8 deg 19 min is  f(Julian day)
%  EQT: Equation of time 14 min 2 sec is f(Julian day)
%  DEG: declination
JW=1360;   % JW:  solar constant (W/m2)
J0=JW*3.6; % J0:  solar constant (kJ/m2/hr)
pp=0.7;    % pp:  atmospheric transmittance
FN=1.526;FK=0.0441;
% FN: Index of reflection
% FK: extinction coefficient (1/mm)
CST=clk-12;
HAG=(CST+((LGT-LGTstd)/15)+EQT)*15;  HAG=HAG*conv;
SALT=asin(sin(LAT)*sin(DEG)+cos(LAT)*cos(DEG)*cos(HAG));
if SALT<=0
   TRAN=0;REFL=1;ABSO=0;RAD=0;RADS=0;
```

```
else
   [RAD, RADS]=RADcal(J0,SALT,pp);    % Calling function RADcal()
   THET=pi/2-SALT;
   [RF, CTHETP]=RFcal(THET,FN);       % Calling function RFcal()
   AB=exp(-FK*FL/CTHETP);
   TRAN=(1-RF)*(1-RF)*AB/(1-RF*RF*AB*AB);
   REFL=RF+RF*(1-RF)*(1-RF)*AB*AB/(1-RF*RF*AB*AB);
   ABSO=1-RF-(1-RF)*(1-RF)*AB/(1-RF*AB);
end
return
```

Figure 6.4a. Subprogram to calculate transmissivity and absorptivity of clear film **(FRSNL.m)**.

The one-dimensional interpolation function **Interp1** is a very convenient tool for generating a non-linear relationship based on observed values in the following way:

$$\mathbf{YI} = \mathbf{INTERP1}(\mathbf{X}, \mathbf{Y}, \mathbf{XI}, \text{'method'}) \qquad (6.1)$$

Available methods are:

'nearest'	- nearest neighbor interpolation
'linear'	- linear interpolation
'spline'	- cubic spline interpolation
'cubic'	- cubic interpolation

The default method is linear interpolation. **X** and **Y** are vectors containing x and y values, respectively. **XI** is the value of **X** of interests and **YI** is the derived **Y** value corresponding to **XI**. All the interpolation methods require that **X** be monotonic. **X** can be non-uniformly spaced. For faster interpolation when **X** is equally spaced and monotonic, use the methods '*linear', '*cubic' or '*nearest'.

```
% Functions for Black and White PE Mulch in CUC20 model       FRSNLa.m
% Also involved function(s): RADcal.m, RFcal.m
%
function [TRAN, ABSO, RAD, RADS]=FRSNLa(clk)
global FL pp GSI;
global colr;
conv=pi/180;
JW=1360;   J0=JW*3.6;     pp=0.7;
LATD=35.68;LAT=LATD*conv; LGT=139.77;    LGTstd=135;
DEC=-8.32; DEG=DEC*conv;  EQT=0.234;
FN=1.526;  FK=0.0441;
CST=clk-12;
HAG=(CST+((LGT-LGTstd)/15)+EQT)*15;      HAG=HAG*conv;
SALT=asin(sin(LAT)*sin(DEG)+cos(LAT)*cos(DEG)*cos(HAG));
if SALT<=0
   TRAN=0;REFL=1;ABSO=0;RAD=0;RADS=0;
else
   [RAD, RADS]=RADcal(J0,SALT,pp);% Calling function RADcal()
   THET=pi/2-SALT;
   ang=THET/conv;
   [Xtran, Ytran, Xabso, Yabso]=mulching(colr);
   %colr='black'  or  colr='white';  colr is a global variable
```

```
   TRAN=interp1(Xtran,Ytran,ang,'nearest');
   ABSO=interp1(Xabso,Yabso,ang,'nearest');  % Interpolation method 1
   %TRAN=interp1(Xtran,Ytran,ang,'linear');
   %ABSO=interp1(Xabso,Yabso,ang,'linear');  % Interpolation method 2
   % method 3 is ‘spline’ and method 4 is ‘cubic’
   % # of pts is not enough in this example for methods 3 & 4.
end
return
%----------------------------------------------------------------------
function [Xtran, Ytran, Xabso, Yabso]= mulching(colr)
switch colr
   case 'black'        % Black PE Mulch
      Xtran=[0 10 60 65 80 90];   Ytran=[0.05 0.05 0.05 0.045 0.03 0.0];
      Xabso=[0 10 88 90];         Yabso=[0.9 0.9 0.9 0.0];
   case 'white'        % white PE Mulch
      Xtran=[0 10 60 65 80 90];   Ytran=[0.58 0.58 0.58 0.5 0.4 0.0];
      Xabso=[0 10 88 90];         Yabso=[0.05 0.05 0.05 0.0];
end
return
```

Figure 6.4b. Subprogram to calculate transmissivity and absorptivity of black and white opaque films **(FRSNLa.m)**.

6.2.4. Results of CUC20 model

In Fig. 6.5, the temperature patterns of each component are shown. In general, soil temperatures with mulching (model **CUC20**) are much higher than those of soil without mulching (model **CUC03**), mostly because mulching prevents cooling of the soil surface due to evaporation. In Fig. 6.5, Comparison of maximum values also shows that the temperature of the soil surface (**TF**) is the highest because of the transmissivity of the covering film. It is assumed that the clear film is just 1 mm thick and that its transmissivity is very high. The soil surface is therefore heated by the large amount of transmitted solar radiation. Because of their limited heat capacities, the temperatures of these components drop when they are not heated. Among the components in the model, the film (**TC**) has the lowest minimum temperature. The components are cooled by way of radiative cooling.

Under which mulching is the soil temperature highest: clear, black, or white? Let us compare the simulation results in Figs. 6.5, 6.6, and 6.7. First of all, the film temperature is the highest for black mulch mainly because of its radiation absorptivity. There is some variation in the minimum temperatures of films, but the difference is small and can be considered negligible.

Maximum soil surface temperature is the highest for clear mulch, followed by white and black, in that order. It is clear that the main factor for this is transmissivity. In the present calculations, it is assumed that transmissivity is 0.85 for clear, 0.58 for white, and 0.05 for black film at 0^o incident angle. The difference between black and white films is caused by the difference in their absorptivity, which is assumed to be 0.05 for white film and 0.9 for black film. White mulching reflects more radiation back to the air, while black mulching absorbs it. Both reflected and absorbed radiation are used to heat the film and to some extent warm the soil. This tendency governs all soil layers. Minimum temperatures or night time temperatures are almost the same for these mulchings but are highest by a small margin for clear film, followed by white and black, in the same order as the maximum temperatures in the daytime.

It should be noted that these soil temperature regimes under mulching are governed by film properties such as absorptivity, transmissivity and reflectivity. Typical values for each film are used here, but measured values for your own use are highly recommended if you need exact comparisons. Outside input conditions such as solar radiation and dew point temperature are also adjustable for various experimental conditions.

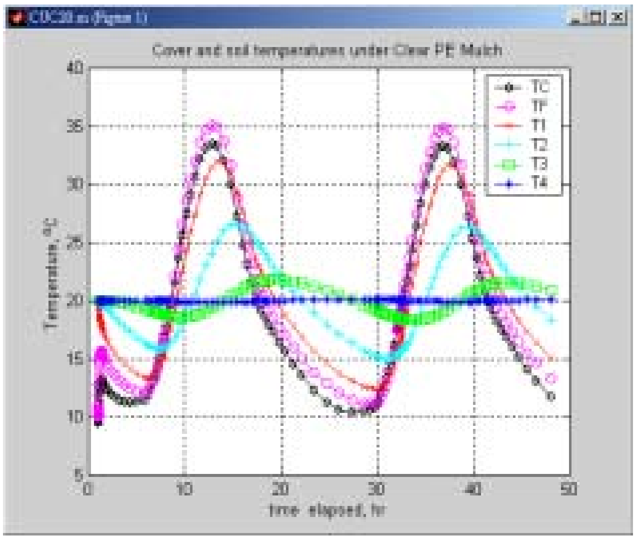

Figure 6.5. Cover and soil temperatures under clear PE mulch, result of cuc20(1).

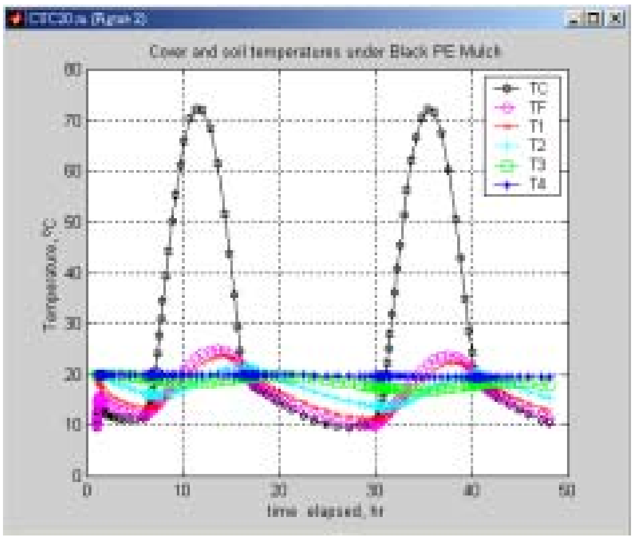

Figure 6.6. Cover and soil temperatures under black PE mulch, result of cuc20(2)

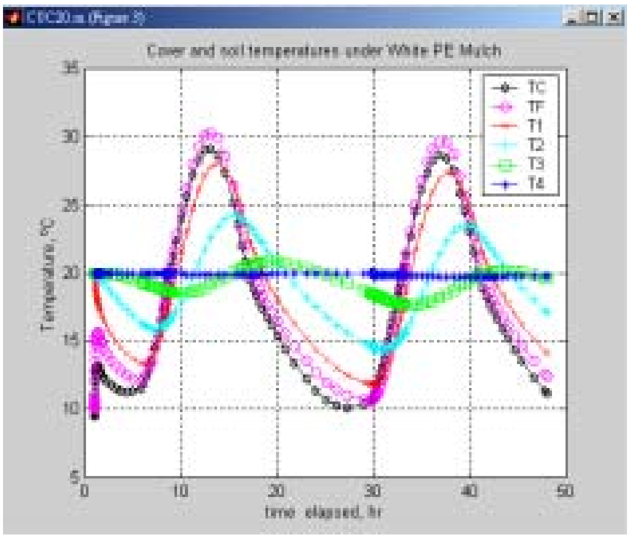

Figure 6.7. Cover and soil temperatures under white PE mulch, result of cuc20(3).

6.3. TEMPERATURE ENVIRONMENT UNDER ROW COVERS (**CUC30**)

Inflating the air gap between the cover and the soil surface in mulching can recreate the environment of row covers. Row covers are not flat; therefore, irradiation is different from mulching in its details. But the overall nature could be simulated using a simple model neglecting this difference. The only difference is that in the air layer, between the cover and the soil surface, air is replaced by ventilation. The heat balance of the inside air is depicted in Fig. 6.8.

In mulching it is assumed that the air between the cover and the soil surface is saturated with water vapor and that the air temperature is the arithmetic average of the soil and cover surface temperatures. In the present model, the air temperature between these two surfaces is one of the unknown variables and must be defined in an integral form. The heat balance of inside air is rather easy to calculate because of the lack of thermal radiation terms. Energy comes through the cover, soil, and ventilation (see Fig. 6.8). Latent heat transfer also occurs at the soil surface and is caused by ventilation.

The whole model is shown in Figs. 6.9a and 6.9b, and the computed result is given in Figs. 6.10a, b and c. Closely look at the **% Inside air layer** part of the program in Fig. 6.9b. **ITI** is net energy gain and **TI** is inside air temperature. **IWI** is net mass gain and **WI** is inside humidity ratio. All components in the equation of **ITI** and **IWI** are shown in Fig. 6.8: energy gain from the cover, **HI*(TC-TI)**, from ventilation, **CA*QH*(TO-TI)** where **QH** is the airflow rate ($m^3/hr/m^2$), and from the soil surface, **HI*(TF-TI)**. Also, mass gain due to ventilation, **RHO*QH*(WO-WI)** and that from the soil surface, **KM*(GSI*WSTF-WI)**.

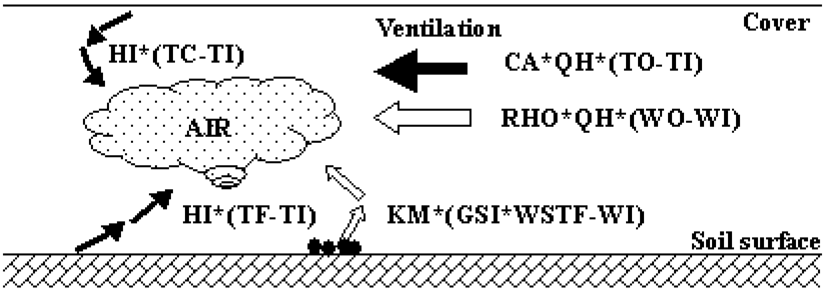

Figure 6.8. Energy balance of inside air.

```
% Model for Rrow Cover                                         CUC30.m
% function involves: soil30.m
%
clear all;clc
global FL pp GSI QH
fprintf('\nPlease wait.\n');
t0=1;        tfinal=48;
y0=[10; 10; 0.01; 10; 20; 20; 20; 20];
%  TC, TI, WI,   TF, T1, T2, T3, T4  (initial condition)
%
[t,y]=ode23t('soil30',[t0 tfinal],y0);
%
h1=findobj('tag','cuc30_part1');      close(h1);
figure('tag','cuc30_part1','Resize','on','MenuBar','none',...
   'Name','CUC30.m (Figure 1)',...
```

```
   'NumberTitle','off','Position',[120,120,520,420]);
plot (t,y(:,1),'r:',t,y(:,2),'b-.',t,y(:,4),'k-',t,y(:,5),'m--');
grid on;
axis([-inf, inf, 5, 40]);
titcont=['Temperatures changes under Row tunnel, given pp='...
     num2str(pp,3),', GSI=' num2str(GSI,3),', QH=' num2str(QH,4)];
title(titcont);
xlabel('time  elapsed, hr'); ylabel('Temperature, ^oC');
legend('T_c_o_v_e_r','T_i_n_s_i_d_e_ _a_i_r','T_f_l_o_o_r','T_1');
h1=findobj('tag','cuc30_part2'); close(h1);
figure('tag','cuc30_part2','Resize','on','MenuBar','none',...
   'Name','CUC30.m (Figure 2)',...
   'NumberTitle','off','Position',[160,80,520,420]);
plot (t,y(:,3)); grid on;
axis([-inf, inf, 0, inf]);
xlabel('time  elapsed, hr');
ylabel('Humidity Ratio, kg vapor/kg dry air');
titcont=['HR changes inside air layer of Row tunnel, given pp='...
     num2str(pp,3),', GSI=' num2str(GSI,3),', ...
     QH=' num2str(QH,4)];
title(titcont);
clc
  disp('Thank you for using CUC30');
  disp('');
  disp('You can enter ''close all'' to close figure windows.');
  disp(' ');
```

Figure 6.9a. Main program to calculate temperatures in a small tunnel **(CUC30.m)**.

```
%  Subprogram to be used with CUC30.m                        soil30.m
%  Also requires function(s) FRSNL.m, FWS.m, TABS.m
%
%  Try various pp  values  in‘FRSNL.m’ to see the effects of radiation.
%  Try various GSI values  in‘soil30.m’ to see the effects of wetness.
%  Try various QH  values  in ‘soil30.m’ to see the effects of airflow rate.
%
function dy = soil30(t,y)
global FL pp GSI QH
Tavg=15.0; TU=5.0; TBL=20.0; TD=8; % Temp (C)
%TD: outside dew point temperature, in degree C
KS = 5.5; CS= 2.0E+3; CA=1.164; CC=50.0;
% KS (kJ/m/C/hr) and KS/3.6 (W/m/C) also CS (kJ/m^3/C)
% CA: Volumetric heat capacity of air (kJ/m^3/C)
% CC: Heat capacity of cover (kJ/m^3/C)
RHO=1.164;GSI=1.0;SIG = 20.4;
% RHO: Density of air (kg/m^3)
% GSI: Greenhouse Soil's Wetness Index (1.0 is totally wet)
% SIG:Stefan-Boltzmann constant (kJ/m^2/K^4/hr) = 5.67(W/m^2/K^4)
HI=7.2; HO= 25.2;AH=0.5; QH=300;
%  HI: Heat transfer coeff at soil surface (kJ/m^2/hr/C)
%  HO: Heat transfer coeff at cover surface
%  AH: Average air space height (m)
%  QH: Air flow rate (m^3/m^2/hr)
Z0=0.01; Z1=0.05; Z2=0.1; Z3=0.2; Z4=0.5; %Z0-Z4: Depths of soil layers
(m)
ALC=0.1;ALF=0.7; RMC=0.1;RMSC=0.05;
EPSC=0.15; EPSF=0.95;
EPSA = 0.711+(TD/100)*(0.56+0.73*(TD/100));
TDS=1-ALC-RMSC;  TLV=1-EPSC-RMC;
HLG=2501.0;LE=0.9; KM=3.6*HI/LE/CA*RHO;
```

```
FL=1;         %Thickness of cover FL in mm
DEX=0.001*FL; %Thickness of cover DEX in m
%
WO=FWS(TD);                          % calling function FWS()
clk = mod(t,24);
OMEGA=2*pi/24;                       % Time (hr)
TO= Tavg+TU*sin(OMEGA*(clk-8));
[TRAN,ABSO,RAD,RADS]=FRSNL(clk);     % calling function FRSNL()
%---------------------------------------------------------------------
TC=y(1);TI=y(2);WI=y(3);TF=y(4);
T1=y(5);T2=y(6);T3=y(7);T4=y(8);
%---------------------------------------------------------------------
% cover
TO4=TABS(TO);  TC4=TABS(TC);  TF4=TABS(TF);  % calling function TABS()
%  Beginning of HWT calculation
HWT=0;
WSS=FWS(TC);                                 % Calling function FWS()
if WSS < WI
  TW=WI-WSS;WI=WSS;
  HWT=TW*HLG*KM;          % Energy required to condense TW amount of water
End
% End of HWT calculation
ITC=(RAD*ABSO+RADS*ALC+(1-ALF)*(RADS*TDS+RAD*TRAN)*ALC...
  +SIG*EPSC*(EPSF*TF4 + EPSA*TO4+((1-EPSF)-2)*TC4)...
  -HO*(TC-TO)-HI*(TC-TI)+HWT)/DEX/CC;
%---------------------------------------------------------------------
% Inside Air Layer
ITI=(HI*(TC-TI)+CA*QH*(TO-TI)+HI*(TF-TI))/CA/AH;
% ITI: net energy gain
% TI: Inside air temperature (C)
% WI: Inside humidity ratio (kg/kg)
WSTF=FWS(TF);
IWI=(RHO*QH*(WO-WI)+KM*(GSI*WSTF-WI))/RHO/AH;
% IWI: net mass gain
%---------------------------------------------------------------------
%   At soil surface
ITF=(ALF*(RADS*TDS+RAD*TRAN)-KS*(TF-T1)*2/(Z0+Z1) ...
  -HI*(TF-TI)+HLG*KM*(WI-GSI*WSTF)...
  -SIG*EPSF*((1-RMC)*TF4-EPSA*TLV*TO4-EPSC*TC4))/CS/Z0;
%---------------------------------------------------------------------
% In soil layer
IT1 = (KS*(TF - T1)*2.0/(Z0+Z1)+KS*(T2 - T1)*2.0/(Z1+Z2))/CS/Z1;
IT2 = (KS*(T1 - T2)*2.0/(Z1+Z2)+KS*(T3 - T2)*2.0/(Z2+Z3))/CS/Z2;
IT3 = (KS*(T2 - T3)*2.0/(Z2+Z3)+KS*(T4 - T3)*2.0/(Z3+Z4))/CS/Z3;
IT4 = (KS*(T3 - T4)*2.0/(Z3+Z4)+KS*(TBL - T4)*2.0/Z4)/CS/Z4;
dy=[ITC; ITI; IWI; ITF; IT1; IT2; IT3; IT4]; % a column matrix
return
```

Figure 6.9b. Subprogram to calculate temperatures in a small tunnel **(soil30.m)**.

If we change some constants that represent film properties, we can discuss the difference between covering materials such as PVC and PE using this model. Furthermore, this model can be used to simulate the environment in a greenhouse with a single layer cover if the average height (**AH**) of the air gap is increased. The first dynamic model of a greenhouse was reported by the author (Takakura et al., 1971), and its scheme is shown in Fig. 6.11. Two programs of this model, one in **FORTRAN** and the other in **MIMIC**, have been compared and are discussed from the viewpoint of simulation techniques (Takakura and Jordan, 1970). This model was later translated into **CSMP** and compared with other models (van Bavel et al., 1987). The main difference between the original model and the present model **CUC30** is that the heat flow in the soil was two-dimensional in the original model, as shown in Fig. 6.11. Simulation study is quite advanced for the analysis of the greenhouse system; Takakura (1988 and 1989) gives literature reviews on this topic.

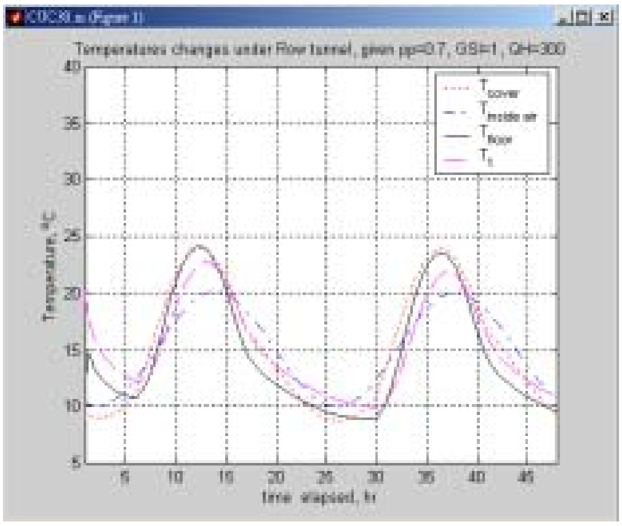

Figure 6.10a. Temperatures changes in a row tunnel

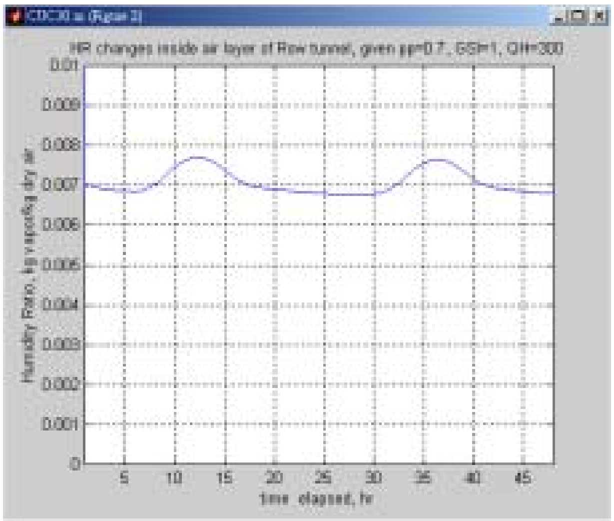

Figure 6.10b. Humidity ratio changes in a row tunnel.

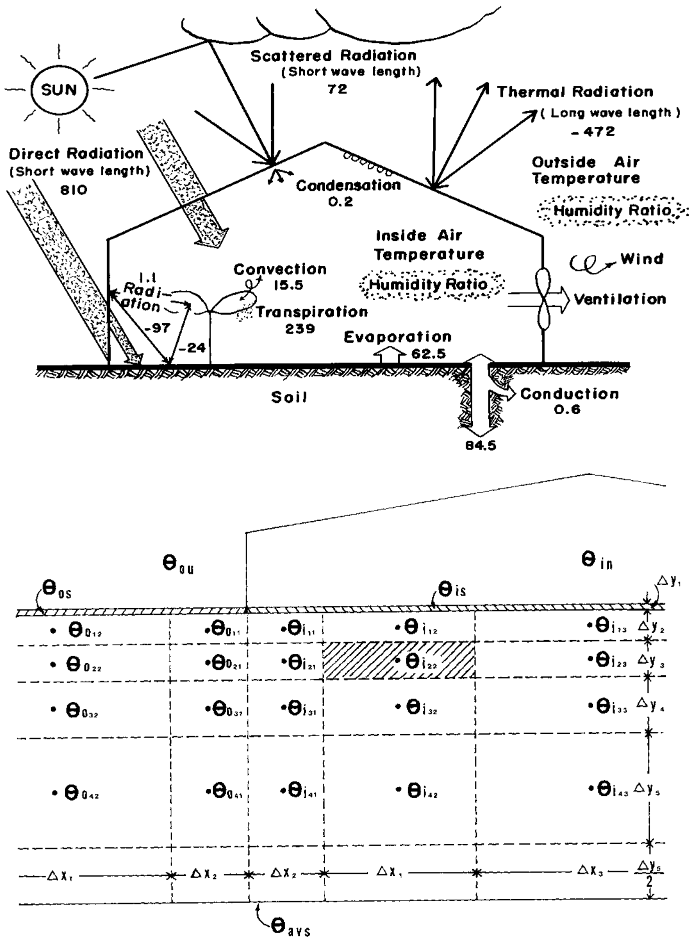

Figure 6.11. Heat flow components considered and their typical values in the dynamic model developed by Takakura et al. (1971).

6.4. DOUBLE LAYER GREENHOUSE MODEL (**CUC50**)

In this section we will discuss a greenhouse with two layers of cover. Radiation exchanges around two layers of cover are rather complicated because three phases -- transmissivity, absorptivity, and reflectivity -- are involved.

The radiation exchange is shown in the diagram in Fig. 6.12. From left to right in the figure, thermal radiation balance at the outer cover, at the inner cover, at the soil surface, and two types of short-wave radiation incoming to the soil surface, direct (**RAD**) and diffuse (**RADS**) radiation, are indicated. The coefficients **TLV** and **TLVS** are the thermal radiation transmissivity of the outer cover and the inner screen, respectively. **TDS** and **TDSS** are the absorptivity of the outer cover and the inner cover, respectively, for diffuse solar radiation, and the corresponding terms are **TRAN** and **TRANS** for direct solar radiation. Radiation rays are indicated using arrows. First order reflectance at the cover and screen is taken into consideration and shown by dotted arrows. The temperature of the outer cover (**TC**), inner cover (**TS**) and floor (**TF**) are also indicated.

Combining these elements in radiation exchange form makes it possible to understand the energy balance equations in Fig. 6.13, which gives the whole program for an unheated greenhouse with a double layer cover. For example, let us consider long wave radiation exchange at the outside cover, which is the left-most part of Fig. 6.12. There are four incoming components: one is from the sky (**SIG * EPSA * TO4**), and three are from below the cover and directed upward -- Long wave radiation from the soil surface transmitted through the inside screen (**SIG * EPSF * TF4 * TLVS**), Long wave radiation emitted from the inside screen (**SIG * EPSS * TS4**), and radiation from the outside cover which is reflected back from the inside screen (**RMS * SIG * EPSC * TC4**).

There are two outgoing radiation components from the outside cover itself: one component is directed toward the sky, and the other component is directed downward **(2.0 * SIG * EPSC * TC4)**. These relationships are programmed in Fig. 6.13. A close look at the **% Outer cover** part of the program shows that the incoming and outgoing long wave radiation components are combined, and this is expressed as **SIG * EPSC * (EPSF * TF4 * TLVS + EPSA * TO4 + EPSS * TS4 + (RMS * EPSC - 2.0) * TC4)** in the equation for **ITC** in the **% Outer cover** part. All energy gains are shown with plus signs and losses with minus signs, and the absorptivity of the cover (**EPSC**) is multiplied to get net energy gain in the cover. You will be able to understand the rest of the radiation balance in the same way. Two lists of symbols, attached at the end of this chapter, were compiled to help the readers in understanding the program. First is the list of symbols for all optical properties and second is a list of all symbols with descriptions.

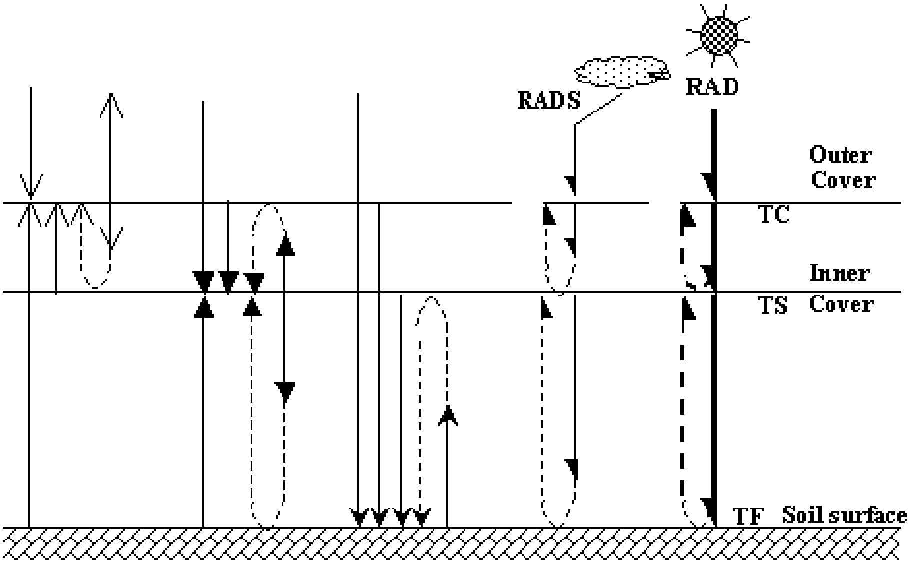

Figure 6.12. Thermal radiation exchange around a double layer of covering (radiation balance of leaves is omitted).

```
%  Double layer greenhouse model                                CUC50.m
%  function(s): soil50.m
function cuc50(action)
if nargin==0, action='init';end
switch action
case 'init'
clc
global FL pp ARTO QH
tic
tini=0;tfinal=48;
y0=[10; 10; 0.01; 10; 15; 20; 20; 20; 20; 20]; % a column matrix
%  TC, TS,  WI,  TI, TP, TF, T1, T2, T3, T4
[t,y]=ode23t('soil50',[tini tfinal],y0);
toc
%-----------------------------------------------------------------------
h1=findobj('tag','cuc50_part1');close(h1);
figName='CUC50.m (Figure 1: Temperature changes ';
figName=[figName 'in a double-layer plastic house)'];
figure('tag','cuc50_part1','Resize','on','MenuBar','none',...
   'Name',figName,'NumberTitle','off','Position',[120,120,520,420]);
plot (t,y(:,1),'x-',t,y(:,2),'*-',t,y(:,4),'o-',t,y(:,5),'^-', ...
     t,y(:,6),'v-');
grid on;  axis([-inf, inf, 5, inf]);
titcont=['Given pp=' num2str(pp,3) ', ARTO=' num2str(ARTO,4) ...
     ', QH=' num2str(QH,4)];
title(titcont); xlabel('time  elapsed, hr');  ylabel('Temperature, ^oC');
legend('T_C','T_S','T_I','T_P','T_F',-1);
%-----------------------------------------------------------------------
h1=findobj('tag','cuc50_part2');close(h1);
figName='CUC50.m (Figure 2: (Under)ground soil temperature ';
figName=[figName 'changes in a double-layer plastic house]'];
```

```
figure('tag','cuc50_part2','Resize','on','MenuBar','none', ...
   'Name',figName,'NumberTitle','off','Position',[160,80,520,420]);
plot (t,y(:,6),'x-',t,y(:,7),'*-',t,y(:,8),'o-',t,y(:,9),'^-',t, ...
    y(:,10),'v-');
grid on;  axis([-inf, inf, 5, inf]);
titcont=['Given pp=' num2str(pp,3) ', ARTO=' num2str(ARTO,4)...
     ', QH=' num2str(QH,4)];
title(titcont);
xlabel('time  elapsed, hr');  ylabel('Temperature, ^oC');
legend('T_F','T1','T2','T3','T4',3);
%-------------------------------------------------------------------
h1=findobj('tag','cuc50_part3');close(h1);
figName='CUC50.m (Figure 3: HR and Temperature ';
figName=[figName ' of air in a double-layer plastic house)'];
figure('tag','cuc50_part3','Resize','on','MenuBar','none','Name',...
   figName,'NumberTitle','off','Position',[200,40,520,420]);
subplot(2,1,1);    plot(t,y(:,3));  ylabel('Humidity Ratio, kg/kg DA');
grid on;
titcont=['Given pp=' num2str(pp,3) ', ARTO=' num2str(ARTO,4)...
     ', QH=' num2str(QH,4)];
title(titcont);
subplot(2,1,2); plot(t,y(:,4));
ylabel('Air Temperature, ^oC');   xlabel('time  elapsed, hr');
grid on;
%
disp('Thank you for using CUC50.');  disp(' ');
disp('You can enter ''close all'...
     ' in the command window to close figure windows.');
disp(' ');
end % switch
```

Figure 6.13a. Main program to calculate temperatures in a plastic house with double layer covering **(CUC50.m)**.

```
%  Subprogram to be used with CUC50.m                        soil50.m
%  Also require other functions: FRSNL.m, FWS.m, TABS.m
%  by varying pp value in FRSNL.m,
%    the effect of radiation on T can be revealed.
%
function dy = soil50(t,y)
%
global FL pp QH ARTO
Tavg=15.0; TU=5.0; TBL=20.0; % in degree C
TD=8;              % outside dew point temperature, in degree C
KS = 5.5;          % KS is in kJ/m/C/hr and KS/3.6 is in W/m/C
CS= 2.0E+3;        % CS is in kJ/m^3/C
CA=1.164;          % Volumetric heat capacity of air (kJ/m^3/C)
CC=50.0;           % Heat capacity of cover (kJ/m^3/C)
RHO=1.164;         % Density of air (kg/m^3)
GSI=1;             % Greenhouse Soil's Wetness Index (1.0 is totally wet)
SIG = 20.4;        % Stefan-Boltzmann cst.(kJ/m^2/K^4/hr)=5.67W/m^2/K^4
QH=10.8;           % Air flow rate (m^3/m^2/hr), 8 cfm/ft^2 = 146 m^3/m^2/hr
                   % Case 1: QH=146; case 2: QH=10.8;
% Convective heat transfer coefficients (h): HO, HS and HI
HO= 25.2;          % h for outer cover facing upward
HS=10.8;           % h for outer cover facing downward
                   %   for inner cover facing upward.
                   %   for TB(inside covers' air T) facing up and down.
HI=7.2;            % h for inner cover facing downward (kJ/m^2/hr/C)
                   %   for plant surface (and floor) to inside air
```

```
                   %    for TI(air T in GH) facing up, down & facing plant
Z0=0.01; Z1=0.05; Z2=0.1; Z3=0.2; Z4=0.5;    % Depths of soil layer (m)
ALC=0.1;           % Absorptivity of cover for diffused solar radiation
ALF=0.7;           % Absorptivity of solar radiation at soil surface
ALS=0.1;           % Absorptivity of screen for diffused solar radiation
ALP=0.8;           % Absorptivity of plant for solar radiation
RMSC=0.05;         % Reflectivity, outer cover, diffused
RMSS=0.005;        % Reflectivity, inner cover, diffused
RMS=0.1;           % Reflectivity, outer cover, long wave
RMC=0.1;           % Reflectivity, inner cover, long wave
EPSA = 0.711+(TD/100)*(0.56+0.73*(TD/100));
                   % Emissivity, outside air,    long wave
EPSC=0.15;         % Emissivity, outer cover,    long wave
EPSS=0.15;         % Emissivity, inner cover,    long wave
EPSP=0.95;         % Emissivity, plant surface,  long wave
EPSF=0.95;         % Emissivity, soil surface,   long wave
TDS=1-ALC-RMSC;    % Transmissivity, outer cover, diffused
TDSS=1-ALS-RMSS;   % Transmissivity, inner cover, diffused
TLV=1-EPSC-RMC;    % Transmissivity, outer cover, long wave
TLVS=1-EPSS-RMS;   % Transmissivity, inner cover, long wave
HLG=2501.0; LE=0.9;
KM=3.6*HI/LE/CA*RHO;
AF=1000;           % AF:   Floor area, m^2
AH=2;              % AH:   Average air space height (house height, m)
AP=1;              % AP:   Projected plant area (m^2) per plant
NP=1;              % NP:   number of plants (NP*AP should not > AF)
                   % Case 1: NP=600; case 2: NP=1;
VP=1;              % VP:   Volume of crop per plant
LAI=1;             % LAI:  Leaf area index per plant
CP=4180;           % CP:   heat capacity of plant, (kJ/m3/C)
GAM=0.132;         % GAM:  water vapor diffusion resistance (hr/m)
FL=1;              % Thickness of cover in mm
DEX=0.001*FL;      % Thickness of cover in m
WofTD=FWS(TD);     % calling function FWS()
ARTO=NP*AP/AF;     % Ratio of total plant area to floor area
ARTO1=1-ARTO;      % Ratio of non-plant area to floor area
%---------------------------------------------------------------------
clk = mod(t,24);  OMEGA=2*pi/24;      TO= Tavg+TU*sin(OMEGA*(clk-8));
[TRAN,ABSO,RAD,RADS]=FRSNL(clk);         % calling function FRSNL()
%---------------------------------------------------------------------
%  Outer Cover
TC=y(1);TS=y(2);WI=y(3);TI=y(4);TP=y(5);
TF=y(6);T1=y(7);T2=y(8);T3=y(9);T4=y(10);
TO4=TABS(TO);      % calling function TABS()
TC4=TABS(TC);      % TC is T of outside cover
TS4=TABS(TS);      % TS is T of inside screen
TP4=TABS(TP);      % TP is T of plant surface
TF4=TABS(TF);      % TF is T of floor (soil surface)
TB=(TC+TS)/2;      % TB is average T of TC and TS
TRANS=TRAN;  ABSOS=ABSO;
ITC=(RAD*ABSO+RADS*ALC+((1-TRANS-ABSOS)*RAD...
   *TRAN+RMSS*RADS*TDS)*ALC+SIG*EPSC*(EPSF...
   *TF4*TLVS+EPSA*TO4+EPSS*TS4+(RMS-2)*TC4)...
   +HO*(TO-TC)+HS*(TB-TC))/DEX/CC;
%---------------------------------------------------------------------
% Inner Cover
HWT=0;
ITS=(RAD*ABSOS*TRAN+RADS*TDS*ALS+(1-ALF)*(RADS...
   *TDS*TDSS+RAD*TRAN*TRANS)*ALS+HS*(TB-TS)+HI...
   *(TI-TS)+SIG*EPSS*(EPSF*TF4+EPSA*TLV*TO4...
   +EPSC*TC4-(2-RMC-(1-EPSF))*TS4)+HWT)/DEX/CC;
```

```
%
WSS=FWS(TC);           % Calling function FWS()
if WSS < WI
   TW=WI-WSS;          % amount of water condensed
   WI=WSS;
   HWT=TW*HLG*KM;      % Energy required to condense TW amount of water
end
%-------------------------------------------------------------------
% Inside Air Layer
ITI=(HI*(TS-TI)+CA*QH*(TO-TI)+HI*(TP-TI)*ARTO*LAI...
   *2+HI*(TF-TI))/CA/AH;
%-------------------------------------------------------------------
WSTP=FWS(TP);  WSTF=FWS(TF);
IWI=(RHO*QH*(WofTD-WI)+KM*(GSI*WSTF-WI)+2*LAI*...
   ARTO*RHO/GAM*(WSTP-WI))/RHO/AH;
%-------------------------------------------------------------------
%  At plant surface
ITP=(2*LAI*HI*(TI-TP)+ALP*(RADS*TDS*TDSS+RAD*...
   TRAN*TRANS)+SIG*EPSP*(EPSA*TLV*TLVS*TO4+...
   EPSS*TS4-(1-RMS)*TP4+EPSC*TLVS*TC4)...
   -RHO*HLG/GAM*(WSTP-WI)*2*LAI)/CP/VP*ARTO;
%-------------------------------------------------------------------
%  At soil surface
ITF=(ALF*(RADS*TDS*TDSS+RAD*TRAN*TRANS)*ARTO1...
   -KS*(TF-T1)*2/(Z0+Z1) ...
   -HI*(TF-TI)+HLG*KM*(WI-GSI*WSTF)...
   -SIG*EPSF*((1-RMS)*TF4-EPSA*TLV*TLVS*TO4...
   -EPSS*TS4-EPSC*TLVS*TC4))/CS/Z0;
%-------------------------------------------------------------------
% In Soil layer
IT1 = (KS*(TF - T1)*2/(Z0+Z1)+ KS*(T2 - T1) *2/(Z1+Z2))/CS/Z1;
IT2 = (KS*(T1 - T2)*2/(Z1+Z2)+ KS*(T3 - T2) *2/(Z2+Z3))/CS/Z2;
IT3 = (KS*(T2- T3) *2/(Z2+Z3)+ KS*(T4 - T3) *2/(Z3+Z4))/CS/Z3;
IT4 = (KS*(T3 - T4)*2/(Z3+Z4)+ KS*(TBL - T4)*2/Z4)/CS/Z4;
dy=[ITC; ITS; IWI; ITI;ITP; ITF; IT1; IT2; IT3; IT4];
return
```

Figure 6.13b. Subprogram to calculate temperatures in a plastic house with double layer covering **(soil50.m)**.

Two separate simulation results are given in Figs. 6.14a, b and c. The left figures of Figs. 6.14a, b and c are results using **ARTO**=0.6 and **QH**=146 m^3/m^2/hr, representing 60% coverage of plants in the greenhouse and moderate ventilation, and the right figures are results using **ARTO**=0.001 and **QH**=10.8 m^3/m^2/hr, representing almost no plants in the greenhouse and limited air exchange. **ARTO** represents the degree of coverage of the projected area of plants in the greenhouse and is calculated by **NP * AP / AF**. **QH** is the airflow rate in metric units.

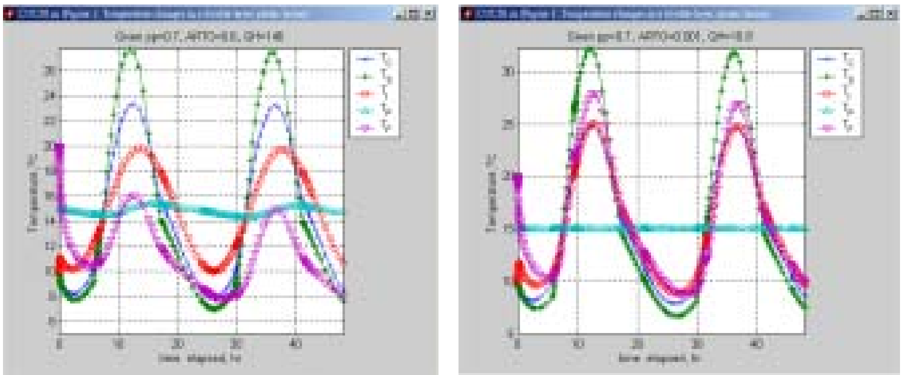

Figure 6.14a. Temperature changes of outer and inner cover, inside air, plant surface and floor in a plastic house with double layer s at various ARTO and QH when PP equals 0.7.

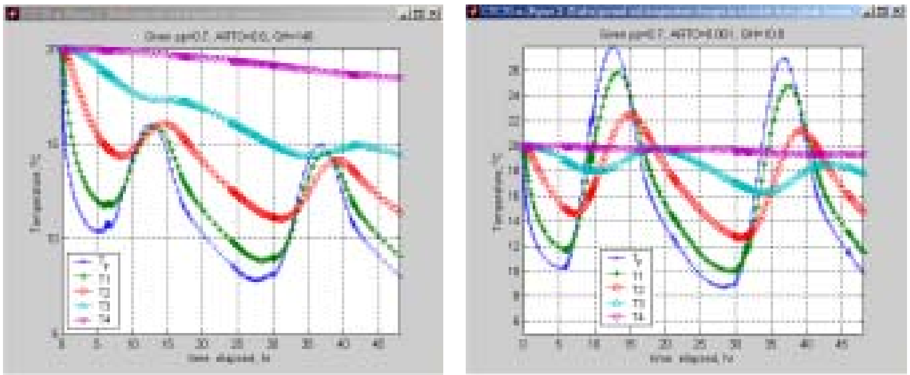

Figure 6.14b. Temperature changes of floor and soil layers in a plastic house with double layers at various ARTO and QH when PP equals 0.7.

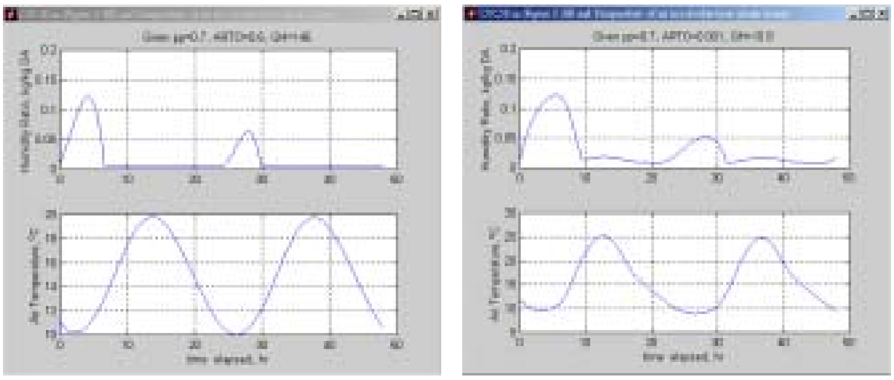

Figure 6.14c. Humidity ratio and temperature changes of air in a plastic house with double layers at various ARTO and QH when PP equals 0.7.

Fig. 6.14a shows temperature changes of the outer cover, inner cover, inside air, plant surface and soil surface. Fig. 6.14b shows temperature changes the of floor and soil layers, and Fig. 6.14c shows Humidity ratio and temperature changes of air in a plastic house with double layers. For ease of comparison, some data were shown more than once among the three figures.

As shown in Fig. 6.14a, Temperatures of the inner cover have greatest variation throughout the day. The maximum and minimum temperatures of the cover are due to solar radiation in the daytime and radiative cooling at night. It might be strange to have inside air temperature lower than outside; the phenomenon may be a bit exaggerated in the simulation results, but it is what often happens on cold nights. The main heat source for unheated greenhouses is solar radiation absorbed into the soil layer during the daytime. A double layer cover reduces incoming daytime energy at the soil surface more than does a single layer. The better insulation that a double layer provides at night cannot compensate. However, higher wind speed, higher dew point air temperature, and more cloudiness will increase the inside air temperature. Wind speed changes the heat transfer coefficient at the outside surface as a result of convection. Long wave radiation from the sky varies with dew point temperature and cloudiness, and these factors can easily be incorporated into the model.

6.5. A PAD AND FAN GREENHOUSE MODEL (**CUC35**)

There are several types of evaporative cooling systems being used in practical greenhouses. The pad and fan system is one type of evaporative cooling system that is very common in area with hot and dry weather conditions. On the psychrometric chart (in Fig. 4.8), the process can be shown by following along the contour line of wet bulb temperature of the air. When water is sprayed into the air, it is vaporized and the amount of water used is not large. The whole process is considered as adiabatic and the process ends in an ideal condition at the saturation point (relative humidity is 100%), which is when the dry-bulb temperature is equal to the wet-bulb temperature. Normally 70-80% of the total process can be reached.

In a pad and fan greenhouse, for example, a pad is installed on one end of a greenhouse wall. Water is sprayed from the top of the pad and the air is sucked in through the pad by fans that are installed at the other end of the greenhouse wall. The air flows horizontally from one side of the greenhouse to the other. Air temperature and humidity gradients exist along the greenhouse. One pair of air temperature and humidity measurements cannot represent the inside condition well. A model simulate this type of situation can be built by modifying the model of a single greenhouse or a row tunnel (**CUC30**). The model in program **CUC35** includes two-dimensional heat flow. The basic parts are shown in Fig. 6.15.

The greenhouse is divided into three equal parts. Normally air is sucked in through the pad, flows through the greenhouse, and is exhausted through the fan. Air temperature is expressed by **TI1**, **TI2** and **TI3**, and humidity is expressed by humidity ratios **WI1**, **WI2**, and **WI3**. In this example, the temperature of the glass covering (**TC**) is uniform, and is the same as the surface temperature of the soil (**TF**).

Temperature and humidity conditions immediately after the air passes through the pad are **TOI** and **WOI**, respectively. These are determined by the psychrometric properties of the air and the efficiency of the pad and fan system.

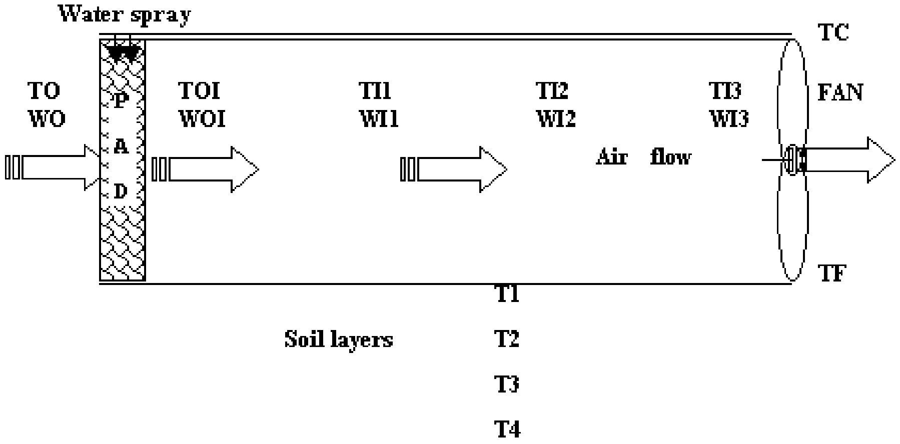

Figure 6.15. Diagram of a pad and fan greenhouse

The model solves 12 unknown variables simultaneously as shown in eq. 6.2 and listed in Fig. 6.16b. The initial conditions of these variables are shown in eq. 6.3 and listed in Fig. 6.16a. The dimension of **dy** and **y0** arrays/matrices must be identical. As shown in eqs. 6.2 and 6.3, the ' sign after the right bracket of matrices **dy** and **y0** is the command to take the transpose of a matrix.

dy = [**ITC ITF ITI1 ITI2 ITI3 IWI1 IWI2 IWI3 IT1 IT2 IT3 IT4**]' (6.2)

y0 = [10 10 10 10 10 0.01 0.01 0.01 20 20 20 20]' (6.3)

To solve **TC**, **TF,** and **T1** to **T4**, there are no differences between this model and **CUC30**. However, for the temperatures and humidity ratios within the greenhouse, some modifications are required. First, define **TI1**, **TI2**, **TI3**, **WI1**, **WI2**, and **WI3** using eq. 6.4 as an example (see corresponding equation in Fig. 6.16B). Eq. 6.4 is used to solve for **TI1**, which is the air temperature of the first 1/3 part of the greenhouse. Note that the integral of **ITI1** is in fact **TI1**.

ITI1 = (**HI** * (**TC** - **TI1**) + **CA** * **QH** * ((**TOI** - **TI1**) –
(**TI1** – **TI2**)) + **HI** * (**TF** - **TI1**)) / **CA** / **AH** (6.4)

where **QH** is the air flow rate ($m^3/hr/m^2$) on a unit floor area basis and can be a function of time.

Second, change the boundary conditions **TC** and **TF**. To generate the equation for the **ITC** term, the **–HI** * (**TC - TI**) term is replaced by -**HI** * (**TC –TIaverage**), where **TIaverage** equals (**TI1** + **TI2** + **TI3**) / 3. Also +**HWT** is replaced by (+ **HWT1** + **HWT2** + **HWT3**).

Third, change the condensation term. For each of the three regions, comparisons should be made between the humidity ratio of the covering temperature (**TC**) and that of the air temperature (**TI**). Create a separate function **conds** (listed in Fig. 6.16b) to facilitate comparison of humidity ratios.

Fourth, remove the **HWT** calculation section (from **% Beginning of HWT calculation** to **% End of HWT calculation** in the '**soil30.m'** program listed in Fig. 6.9b) and include the following:

HWT1 = CONDS(TC, WI1)

HWT2 = CONDS(TC, WI2)

HWT3 = CONDS(TC, WI3)

In this model, outside dew point temperature is one of the inputs. The physical properties of outside air then can be determined by dry bulb and dew point temperatures. One of the reasons for using dew point is that it is fairly constant throughout the day, and during initial testing, we can assume it is constant. Secondly, in this model the emissivity of the air is expressed as a function of dew point temperature. When at least two properties of the air are given, the remaining properties can be determined. In this case, first, humidity ratio (**WO**) is calculated. Using the **wbcal** function, a regression equation solving wet-bulb temperature (**TOW**) as functions of dry-bulb and dew point temperature, the wet-bulb temperature is calculated. Dry-bulb temperature is always greater than or equal to wet bulb temperature, which is again always greater than or equal to dew point temperature. The three temperatures are the same when the relative humidity equals 100%.

Intermediate inputs **TOI** and **WOI** are given as the functions of **TO** and **WO** using the psychrometric relationships and the efficiency of the pad (**PEFF**). **TOI** and **WOI** can be obtained using the following relations:

TOI = TO – PEFF * (TO - TOW)

WOI = WO + PEFF * (WWS - WO)

In evaporative cooling systems such as pad and fan systems, incoming air is cooled along the wet-bulb contour line on the psychrometric chart. If the efficiency is 100% (1 in decimal notation), **TOI** equals **TOW** and **WOI** equals **WWS**, which means the incoming air temperature drops to the wet bulb temperature and the humidity is 100%. This is the maximum efficiency situation.

```
% Pad-and-fan greenhouse model                                      CUC35.m
% Also requires function:  soil35.m
%
function cuc35(action)
if nargin==0, action='init';end
clc
fprintf('\n\nPress Enter to continue\n\n');
h1=findobj('tag','wait');close(h1);
figure('tag','wait','Resize','off','MenuBar','none','Name', ...
   'Please wait.','NumberTitle','off','Position',[300,300,160,80], ...
   'color',[0.8 0.8 0.8]);
h2a=uicontrol('style','text','string', ...
    'This program will take a while to run.  Please switch to '...
    'Command Window'', then press <Enter> to start.',...
    'position',[10,5,140,70],'backgroundcolor',[0.8 0.8 0.8]);
pause
%
switch action
case 'init'
clc
%
t0=0;tfinal=48;
y0=[10  10  10  10  10  0.01  0.01  0.01  20  20  20  20]';
%   TC  TF  TI1 TI2 TI3 WI1   WI2   WI3   T1  T2  T3  T4
%   List of initial conditions
%
[t,y]=ode15s('soil35',[t0 tfinal],y0);
%
h1=findobj('tag','wait');close(h1);
h1=findobj('tag','cuc35_part1');close(h1);
figure('tag','cuc35_part1','Resize','on','MenuBar','none', 'Name',...
   'CUC35.m (Fig1: Temp. changes in a single layer pad & fan plastic house)',...
   'NumberTitle','off','Position',[120,120,520,420]);
%-[Fig.1]-------------------------------------------------------------
% regenerate TO data for Figure 1
t1=0:1:48;
OMEGA=2*pi/24;  % Time (hr)
Toutdoor= 30+5*sin(OMEGA.*(mod(t1,24)-8));
plot (t1,Toutdoor,'r-',t,y(:,3),'b-.',t,y(:,4),'k--',t,y(:,5),'m:');
grid on;
axis([-inf, inf, 10, 40]);
xlabel('time  elapsed, hr');
ylabel('Temperature, ^oC');
legend('TO','TI1', 'TI2', 'TI3',4);
%-[Fig.2]-------------------------------------------------------------
h1=findobj('tag','cuc35_part2');close(h1);
figure('tag','cuc35_part2','Resize','on','MenuBar','none', 'Name',...
   'CUC35.m (Fig2: Soil T changes in a single layer pad & fan plastic house)',...
   'NumberTitle','off','Position',[160,80,520,420]);
plot (t,y(:,1),t,y(:,2),t,y(:,9),t,y(:,10),t,y(:,11),t,y(:,12));
grid on;
axis([-inf, inf, 5, inf]);
xlabel('time  elapsed, hr');
ylabel('Temperature, ^oC');
legend('T_c_o_v_e_r','T_f_l_o_o_r','T_1','T_2','T_3','T_4',4);
%-[Fig.3]-------------------------------------------------------------
h1=findobj('tag','cuc35_part3');close(h1);
figure('tag','cuc35_part3','Resize','on','MenuBar','none', 'Name',...
   'CUC35.m (Fig3: Humidity Ratio in a single layer pad & fan plastic
```

```
house)',...
   'NumberTitle','off','Position',[200,40,520,420]);
plot (t,y(:,6),'r-',t,y(:,7),'b:',t,y(:,8),'k-.');
grid on;
legend('WI1','WI2','WI3',4);
xlabel('time  elapsed, hr');
ylabel('Humidity Ratio, kg vapor/kg dry air');
%
fprintf('\n\n');
%
  disp('Thank you for using CUC35');
  disp('You can enter ''close all'…
       ' in the command window to close figure windows.');
  disp(' ');
end    % switch
```

Figure 6.16a. Main program of the pad and fan greenhouse model **(CUC35.m)**

```
%  Subprogram to be used with CUC35.m                      soil35.m
%  Also requires functions FRSNL.m, FWS.m, TABS.m,
%             and functions conds() and wbcal() (in this file)
% Major inputs:
%      location (latitute and longitude)
%      Time of the year from Table 6.1
%      Extinction coefficient (pp) for solar radiation
%      outside dry-bulb temperature (TO) and dew point temperature (TD)
function dy = soil35(t,y)
global HLG KM FL pp ARTO
%
Tavg=30.0; TU=5.0; TBL=20.0; TD=15; % Temp (C)
%TD: outside dew point temperature, in degree C
KS = 5.5; CS= 2.0E+3; CA=1.164; CC=50.0;
% KS (kJ/m/C/hr) and KS/3.6 (W/m/C) also CS (kJ/m^3/C)
% CA: Volumetric heat capacity of air (kJ/m^3/C)
% CC: Heat capacity of cover (kJ/m^3/C)
RHO=1.164; % Density of air (kg/m^3)
GSI=1;     % Greenhouse Soil's Wetness Index (1.0 is completely saturated)
SIG = 20.4;
% SIG:Stefan-Boltzmann constant (kJ/m^2/K^4/hr) = 5.67(W/m^2/K^4)
QH=36;     % Ventilation air flow rate (m^3/m^2/hr), 8 cfm/ft^2 = 146 m/hr
AH=2;      % Average air space height (house height, m)
HO= 25.2;  % h at cover surface facing upward
HI=7.2;    % h at cover surface facing downward (kJ/m^2/hr/C)
Z0=0.01; Z1=0.05; Z2=0.1; Z3=0.2; Z4=0.5;    % Depths of soil layers (m)
ALC=0.1;   % Absorptivity of cover for diffused solar radiation (ND)
ALF=0.7;   % Absorptivity of solar radiation at soil surface
RMC=0.1;   % Reflectivity of screen for long wave radiation
RMSC=0.05; % Reflectivity of cover for diffuse solar radiation
EPSC=0.15; % Emissivity of cover
EPSF=0.95; % Emissivity of soil surface
HLG=2501.0;LE=0.9; KM=3.6*HI/LE/CA*RHO;
FL=3;  DEX=0.001*FL;  %Thickness of cover FL in mm and DEX in m
PEFF=0.8;  % Efficiency of pad and fan system
EPSA = 0.711+(TD/100)*(0.56+0.73*(TD/100));
% EPSA:Emissivity of air layer
WO=FWS(TD);% WO: humidity ratio of outdoor air=saturated V.P. at Tdp
TDS=1-ALC-RMSC;
% TDS: Transmissivity of cover for diffuse solar radiation
TLV=1-EPSC-RMC;    % Transmissivity of cover for long wave radiation
%----------------------------------------------------------------------
```

```
clk = mod(t,24);   OMEGA=2*pi/24;     % Time (hr)
TO= Tavg+TU*sin(OMEGA*(clk-8));       % TO is outdoor air temperature
[TRAN,ABSO,RAD,RADS]=FRSNL(clk);      % calling function FRSNL()
%--------------------------------------------------------------------
% Pad and fan system
TOW=wbcal(TO,TD);      % calling function wbcal to calculate Twb
WWS=FWS(TOW);          % calling function FWS()
TOI=TO-PEFF*(TO-TOW);  WOI=WO+PEFF*(WWS-WO);
% TOI: Dry bulb T right after pad (in oC)
% WOI: Humidity ratio right after pad (in kg vapor/kg dry air)
%--------------------------------------------------------------------
TC=y(1); TF=y(2); TI1=y(3);TI2=y(4); TI3=y(5);
WI1=y(6);WI2=y(7);WI3=y(8); T1=y(9);T2=y(10); T3=y(11);T4=y(12);
%--------------------------------------------------------------------
%  Cover
TO4=TABS(TO);  TC4=TABS(TC);  TF4=TABS(TF);   % calling function TABS()
WSS=FWS(TC);
%  calculating HWT [HWT WII]
[HWT1, WI1]=conds(WSS,WI1);   [HWT2, WI2]=conds(WSS,WI2);
[HWT3, WI3]=conds(WSS,WI3);
avgTCTIdif=(TC-(TI1+TI2+TI3)/3);
sumHWT=HWT1+HWT2+HWT3;
ITC=(RAD*ABSO+RADS*ALC+(1-ALF)*(RADS*TDS...
   +RAD*TRAN)*ALC+SIG*EPSC*(EPSF*TF4...
   +EPSA*TO4+((1-EPSF)-2)*TC4) ...
   -HO*(TC-TO)-HI*avgTCTIdif+sumHWT)/DEX/CC;
fprintf('t=%4.2f TO=%4.2f TOI=%4.2f WOI=%4.2f sumHWT=%4.2f\n',t,TO, ...
   TOI,WOI,sumHWT);
%--------------------------------------------------------------------
% Inside Air Layer
WSTF=FWS(TF);
ITI1=(HI*(TC-TI1)+CA*QH*((TOI-TI1)-(TI1-TI2))+HI*(TF-TI1))/CA/AH;
IWI1=(RHO*QH*((WOI-WI1)-(WI1-WI2)+KM*(GSI*WSTF-WI1)))/RHO/AH;
ITI2=(HI*(TC-TI2)+CA*QH*((TI1-TI2)-(TI2-TI3))+HI*(TF-TI2))/CA/AH;
IWI2=(RHO*QH*((WI1-WI2)-(WI2-WI3)+KM*(GSI*WSTF-WI2)))/RHO/AH;
ITI3=(HI*(TC-TI3)+CA*QH*((TI2-TI3)-(TI3-TO))+HI*(TF-TI3))/CA/AH;
IWI3=(RHO*QH*((WI2-WI3)-(WI3-WO)+KM*(GSI*WSTF-WI3)))/RHO/AH;
%--------------------------------------------------------------------
%   At soil surface
avgTITFdif=(TF-(TI1+TI2+TI3)/3);
avgWI=((WI1+WI2+WI3)/3);
ITF=(ALF*(RADS*TDS+RAD*TRAN)-KS*(TF-T1)*2/(Z0+Z1) ...
   -HI*avgTITFdif+HLG*KM*(avgWI-GSI*WSTF)...
   -SIG*EPSF*((1-RMC)*TF4-EPSA*TLV*TO4...
   -EPSC*TC4))/CS/Z0;
%--------------------------------------------------------------------
% In Soil layer
IT1 = (KS*(TF-T1)*2/(Z0+Z1)+KS*(T2-T1)*2/(Z1+Z2))/CS/Z1;
IT2 = (KS*(T1-T2)*2/(Z1+Z2)+KS*(T3-T2)*2/(Z2+Z3))/CS/Z2;
IT3 = (KS*(T2-T3)*2/(Z2+Z3)+KS*(T4-T3)*2/(Z3+Z4))/CS/Z3;
IT4 = (KS*(T3-T4)*2/(Z3+Z4)+KS*(TBL-T4)*2/Z4)/CS/Z4;
dy=[ITC ITF ITI1 ITI2 ITI3 IWI1 IWI2 IWI3 IT1 IT2 IT3 IT4]';
return
%--------------------------------------------------------------------
function [HWT, WII]=conds(WWS,WII)
global HLG KM
HWT=0;
if WWS < WII
   TW=WII-WWS;       % amount of water condensed
   WII=WWS;
   HWT=TW*HLG*KM/3;% Energy required to condense TW amount of water
```

```
                   % 3 is the number of evenly divided compartments.
end
%--------------------------------------------------------------------
function twb=wbcal(tdb,tdp)
if abs(tdb - tdp) < .001, twb = tdb;break;end
 X = tdb;
 a = .011569; b = .613423862;  c = -.00643928; D = 7.52158e-05;
 e = -4.5287e-07;
 ap1 = a + b * X + c * X ^ 2 + D * X ^ 3 + e * X ^ 4;
 a = .419636669; b = .027436851; c = .007711576; D = .001536155;
 e = .00023861;
 bp1 = (a + c * X + e * X ^ 2) / (1 + b * X + D * X ^ 2);
 a = .011146403;b = .027956528; c = .000255119;D = .002122386;
 e = 7.1215e-06;
 cp1 = (a + c * X + e * X ^ 2) / (1 + b * X + D * X ^ 2);
 a = 9.65426e-05;b = -.00292091; c = 7.15163e-07;D = .001201577;
 dp1 = (a + c * X) / (1 + b * X + D * X ^ 2);
 twb = ap1 + bp1 * tdp + cp1 * tdp * tdp + dp1 * tdp * tdp * tdp;
if twb > tdb,twb = tdb;end
if twb < tdp,twb = tdp;end
```

Figure 6.16b. Subprogram of CUC35 model **(soil35.m)**.

Fig. 6.17 shows results of the pad and fan (**CUC35**) model. In total, 3 figures were generated. Fig. 6.17a shows the outdoor and indoor air temperatures. In the first 1/3 of the greenhouse, **TI1** is lower than the outdoor temperature, which due to the evaporative cooling effect of the pad. Between 10 am to 3 pm, the air temperature at the last 1/3 (**TI3**) is higher than **TO.** Try to rerun the model with 50% shading by lowering transmissivity of the cover, or by doubling the air speed inside the greenhouse by ventilation..

Fig. 6.17b shows the cover temperature, the floor temperature and the 4 layers of soil temperatures. Due to the buffering effect of the air and the soil, the peak of each curves shifted to the right (time delay) can be clearly observed. In the legend of this figure, the subscript letters can be generated using a leading '_' before each character as shown in the '%-[Fig.2]-' portion of Fig. 6.16a. The curves in this figure in mono-color cannot be distinguwished well, but this problem could be solved by color output specification.

Fig. 6.17c shows the humidity ratio inside greenhouse. Only little differences among **WI1, WI2 and WI3** can be observed during peak hours. The increase of the humidity ratio inside the greenhouse is the result of the evapotranspiration of the plants. In the program listed in Fig. 6.16b, Greenhouse Soil's Wetness Index (**GSI**) equals 1 (saturation) is assumed. Try to run the program with small value to see the differences among **WI1**, **WI2**, and **WI3**.

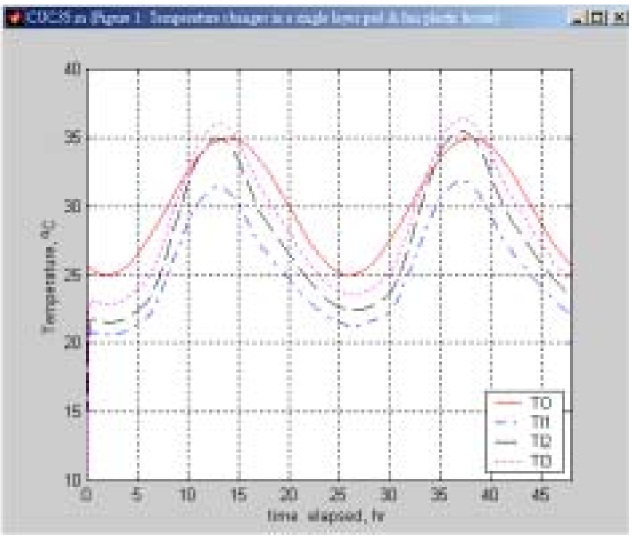

Figure 6.17a.The first output of the pad and fan model **(CUC35)**.

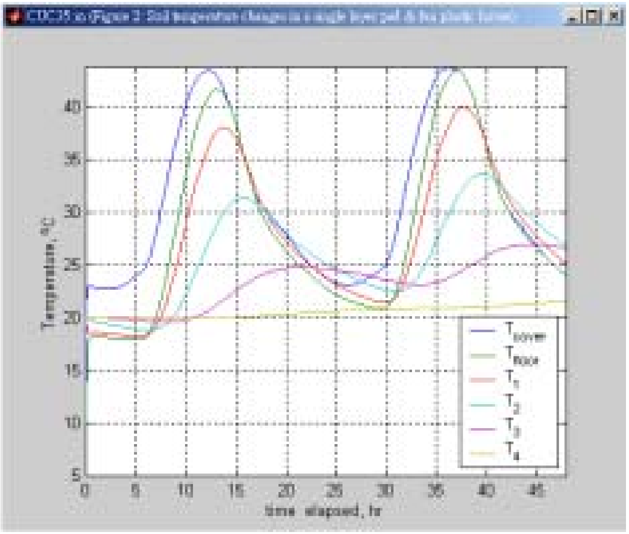

Figure 6.17b.The second output of the pad and fan model **(CUC35)**.

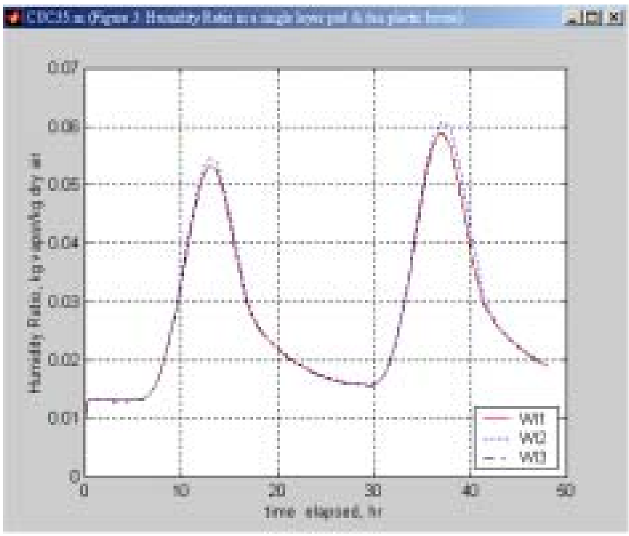

Figure 6.17c.The third output of the pad and fan model **(CUC35)**.

LIST OF SYMBOLS FOR OPTICAL PROPERTIES OF AIR, COVER, PLANT AND FLOOR FOR MODELS IN CHAPTER 6

	Absorptivity		*Emissivity*	*Reflectivity*		*Transmissivity*		
	direct	*diffuse*	*long wave*	*diffuse*	*long wave*	*direct*	*diffuse*	*long-wave*
Outside Air			**EPSA**					
Outer Cover	**ABSO**	**ALC**	**EPSC**	**RMSC**	**RMC**	**TRAN**	**TDS**	**TLV**
Inner Cover	**ABSOS**	**ALS**	**EPSS**	**RMSS**	**RMS**	**TRANS**	**TDSS**	**TLVS**
Plant	**ALP**	**ALP**	**EPSP**					
Floor	**ALF**	**ALF**	**EPSF**			**0**	**0**	**0**

LIST OF SYMBOLS WITH TYPICAL VALUES FOR MODELS IN CHAPTER 6

ABSO	Absorptivity of the outer cover for direct solar radiation, Calculated (ND)
AF	Floor area (Cover area), (m^2)
AH	Average height of a greenhouse, (m)
AP	Projected area of single plant, (m^2)
ALF	Absorptivity of the floor for solar radiation, 0.8 (ND)
ALP	Absorptivity of the plant for solar radiation, 0.8 (ND)
ALC	Absorptivity of the outer cover for diffuse solar radiation, 0.1 (ND)
ALS	Absorptivity of the inner cover for solar radiation, 0.1 (ND)
ARTO	Area ratio of total plant leaf area to floor area, 0 (ND)
ARTO1	1.0 – ARTO, 1.0 (ND)
CA	Volumetric heat capacity of air at constant pressure, 1.164 (kJ/m^3/^{o}C)
CC	Heat capacity of covers, 50.0 (kJ/m^3/^{o}C)
CLOCK	Hour of day, 0 - 24 (hr)
CS	Heat capacity of the floor, 2000.0 (kJ/m^3/^{o}C)
CP	Heat capacity of single plant, 4180.0 (kJ/m^3/^{o}C)
CWP	Heat capacity of water, 4180.0 (kJ/m^3/^{o}C)
DEC	Declination angle of the place, Input variable (deg)
DEX	Thickness of covers, 0.0001 (m)
EPSA	Effective emissivity of air, empirical equation after Brunt, (ND)
EPSC	Emissivity of outer cover, 0.15 (ND)
EPSF	Emissivity of the floor, 0.95 (ND)
EPSP	Emissivity of the plant, 0.95 (ND)
EPSS	Emissivity of inner cover, 0.15 (ND)
FK	Extinction coefficient, 0.0441 (1/mm)
FL	Thickness of the cover, 1 (mm)
FN	Index of refraction, 1.526 (ND)
GAM	Water vapor resistance, 0.132 (hr/m)
GSI	Greenhouse soil wetness index; 0 - 1.0 (ND)
HAG	Hour angle, Calculated (deg)
HF	Convective heat transfer coefficient at the floor, = HI (W/m^2/^{o}C)
HI	Convective heat transfer coefficient at the inner cover, 5.0 (W/m^2/^{o}C)
HLG	Latent heat for evaporation, 2501.0 (kJ/kg)
HO	Convective heat transfer coefficient at the outer cover, (W/m^2/^{o}C)
HS	Convective heat transfer coefficient between covers, (W/m^2/^{o}C)
HWT	Latent heat due to condensation on the inner surface of the cover, Calculated (kJ/m^2/hr)
J0W	Solar constant, 1360 (W/m^2)
K	Thermal conductivity of the floor, (W/m/^{o}C)
KM	Mass transfer coefficient, 3.6*HI/LE/CA*RHO (kg/m^2/hr)
KS	Soil thermal conductivity, 5.5 (kJ/m/^{o}C/hr)
LAI	Leaf area index, 1.0 (ND)
LATD	Latitude of the place, Input variable (deg)

LE	Lewis number, 3.6*HI/(KM*CA/RHO), (ND)
NP	Number of plants per unit area, 1 ($1/m^2$)
OMEGA	Frequency of time, 2x3.14/24 (1/hr)
PP	Extinction coefficient of the atmosphere, Input variable (ND)
RAD	Direct solar radiation, Calculated (W/m^2)
RADS	Scattered solar radiation, Calculated (W/m^2)
RHO	Density of air, 1.164 (kg/m^3)
RMC	Reflectivity of the outer cover for long wave radiation, 0.1 (ND)
RMS	Reflectivity of the inner cover for long wave radiation, 0.1 (ND)
RMSC	Reflectivity of the outer cover for diffuse solar radiation, 0.05 (ND)
RMSS	Reflectivity of the inner cover for diffuse solar radiation, 0.05 (ND)
SALT	Sun's altitude, Calculated (rad)
SO	Outside hemispherical solar radiation, Input variable (W/m^2)
SIG	Stefan-Boltzmann Constant, 5.67×10^{-8} ($W/m^2/K^4$)
TB	Air temperature between covers, Output variable (^oC)
TBL	Lower boundary of soil temperature, Input variable (^oC)
TC	Temperature of outer cover, Output variable (^oC)
TD	Dew point temperature of outside air, Input variable (^oC)
TDS	Transmissivity of cover for diffuse solar radiation, Input variable (ND)
TDSS	Transmissivity of screen for diffuse solar radiation, Input variable (ND)
TF	Temperature at the floor surface, Output variable (^oC)
TI	Inside air temperature, Output variable (^oC)
TLV	Transmissivity of cover for long wave radiation, Input variable (ND)
TLVS	Transmissivity of screen for long wave radiation, Input variable (ND)
TO	Outside air temperature, Input variable = **T0** + **TU** * **sin**(**OMEGA***clock**) (^oC)
TP	Plant temperature, Output variable (^oC)
TS	Temperature of inner cover, Output variable (^oC)
TRAN	Transmissivity of the covering material, calculated (ND)
TT	Temperature of feeding warm water, Input variable (^oC)
T1 - T4	Soil layer temperature, Calculated (^oC)
VG	Greenhouse volume, (m^3)
VP	Volume of single plant, (m^3)
WI	Humidity ratio in the greenhouse, Output variable (kg/kg dry air)
WO	Outside humidity ratio, Calculated from TD (kg/kg dry air)
Z0 - Z4	Depth of each soil layer, Input variable (m)

PROBLEMS

1. In Europe, a kind of glass with low emissivity is available. One side of the glass sheet is metal-coated and its emissivity is 0.25 instead of 0.95. Modify the program **CUC30** and find which side should be metal-coated.

2. From the simulation result shown in Fig. 6.14, explain why higher wind speed, higher dew point air temperature and more cloudiness will increase the inside air temperature.

3. Change the program **CUC20** for the condition that the input is the wet-bulb temperature instead of dew-point temperature.

4. Modify the **CUC35** model to have five equal regions of air space in the greenhouse along the direction of the airflow.

5. If the case 1 greenhouse is to be renovated to reduce the inside temperature in the summer, what would your selection for the new design among cases 2, 3 and 4. Case 2 represents shading 50%, case 3 represents doubling ventilation rate and case 4 represents doubling the greenhouse height. In the practical situation, the cost for renovation should be considered. Rerun **CUC35** model using the following values.

Case 1:	No shading,	QH=3.6,	AH=2
Case 2:	50% shading,	QH=3.6,	AH=2
Case 3:	No shading,	QH=7.2,	AH=2
Case 4:	No shading,	QH=3.6,	AH=4