CHAPTER 5

SOLAR RADIATION ENVIRONMENT

5.1. INTRODUCTION

Solar radiation is one of the most important environmental factors for plant growth. In general it is known that radiation is generated from a material close to a blackbody. Solar radiation received at the earth's surface varies with the season because of the planetary relation between the sun and the earth. Therefore, for cultivation in controlled environments, it is very important to calculate how much of the solar radiation we can utilize at a given place on the earth at a given time of the year.

Coverings can improve the temperature environment by increasing inside temperature, but they cannot enhance the solar radiation level. Shading to reduce solar radiation level is sometimes important, but in most cases, the most important problem is minimizing the reduction of solar radiation due to coverings.

Three properties of coverings are related to the solar radiation environment: transmissivity, reflectivity and absorptivity. It is hard to see with the human eye, but solar radiation is decreased by reflectivity and absorptivity as it travels through transparent films. In a normal situation, the amount of solar radiation transmitted into the covered area is less than that outside.

These three properties are dependent on wavelength. PVC film in the early years created serious problems for eggplant production under PVC cover, because the stabilizer in the film absorbed solar radiation in the ultraviolet region (290 - 360 nm) that triggers the violet coloring of eggplants. Another problem is that the eyes of honeybees are sensitive in the ultraviolet region (< 400 nm), and the bees cannot fly well if the covering does not transmit solar radiation in this region. Therefore, it is essential to be careful about the spectral distribution of transmitted solar radiation if you are growing plants with color generated by anthocyanin (a pigment for red to violet color) or plants with flowers pollinated by bees.

5.2. UNITS OF RADIATION AND LIGHT

The radiation in the range from 400 to 700 nm is called photosynthetically active radiation (PAR) for plants. The photoreactive part of photosynthesis is considered directly proportional to the amount of photons in the light which have been absorbed by the plant in accordance with the chlorophyll absorptance curve when CO_2 concentration is not limiting. This curve shows the relationship of photons absorbed as a function of wavelength and has two peaks, in the blue and red regions. A mole of photons is 6.02×10^{23} photons, with each photon having energy proportional to its frequency. The photon energy of green light whose wavelength is 500 nm is approximately 2.35 x 10^5 J/mol photon (*e.g.*, Takakura, 1991). For the range of PAR (400-700 nm), a conversion factor of 4.6 µmol photon /J can be used (Ting and Giacomelli, 1987).

Light, the visible part of radiation perceived by the human eye, is commonly measured by a lux meter, an instrument which has a filter of the range from 400 to 700 nm and a sharp peak in the green region. The amount of illumination is expressed in a unit called lux (lx). Plants have different absorption characteristics than the human eye, and lux cannot be correctly used as a measure of the light for a plant. Light measured by lux meters will exaggerate the green light available. Radiometers which have a linear filter with transmissivity slightly greater in red than blue wavelengths, are also used to measure PAR (µmol photon/m^2/s or W/m^2). If radiation is measured beyond the visible region, an energy unit such as W/m^2 is used. If an instrument has a particular filter, such as a lux meter, its readings are restricted to be used for a special purpose. If universal comparison among different radiation sources, such as radiation from the sun and from various artificial light sources, is necessary, and photosynthesis is not a consideration, then an energy unit such as W/m^2 would be better, even for the visible region. The results should clearly indicate the wavelength measured.

The annual average of the irradiance measured outside of the earth's atmospheric layer on a surface held perpendicular to the solar beam is called the solar constant. Its value is 1367$\pm$7 W/m^2 (see eq. 5.10). The solar constant varies slightly according to the sun’s activity as well as the distance between the sun and the earth. The solar energy flux density measured at sea level cannot exceed this value due to attenuation by the atmosphere. A maximum of approximately 75% of the solar constant or 1000 W/m^2 can be measured at the Earth’s surface (Monteith and Unsworth, 1990).

Near noon on a clear day the average photon flux density on the ground in PAR can be calculated; assuming a measured total solar flux density of 500 W/m^2, then multiplying by 4.6 µmol photon/J will result in 2300 µmol photon/m^2/s. Due to the reason that PAR range (400-700 nm) only occupies 38.15 % of the total solar energy (Ting and Giacomelli, 1987), 877 µmol photon/m^2/s of PAR can be derived. PAR flux density from artificial light sources such as high pressure sodium lamps and fluorescent lamps, commonly used in practice, varies from 200 to 1000 µmol photon/m^2/s.

5.3. SOLAR RADIATION PROPERTIES OF COVERING MATERIALS

The spectral distributions of transmissivity for three types of films are shown in Fig. 5.1. Spectral distribution of transmissivity is important, but reflectivity and absorptivity should also be noted. All three properties are expressed in either decimal fractions or percentages; their total is 1, or 100%. If expressed in decimal fractions,

$$\mathbf{TRAN} + \mathbf{REFL} + \mathbf{ABSO} = 1 \tag{5.1}$$

where **TRAN** is transmissivity, **REFL** is reflectivity and **ABSO** is absorptivity, all in decimal fractions. This equation holds for both monochromatic and broad spectrum of wavelength.

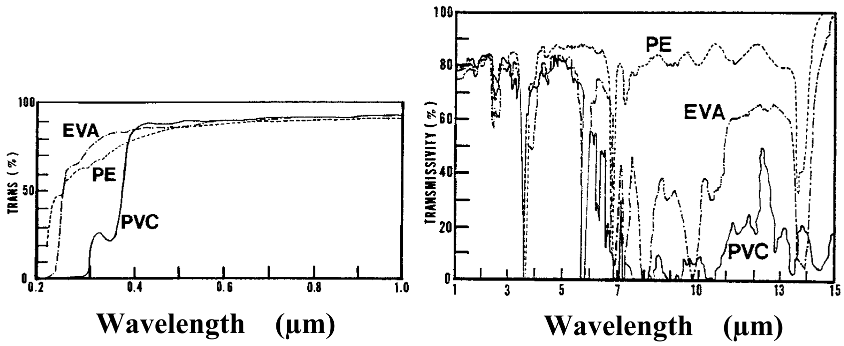

Figure 5.1. Spectral distribution of transmissivity of films (after Takahashi, 1975).

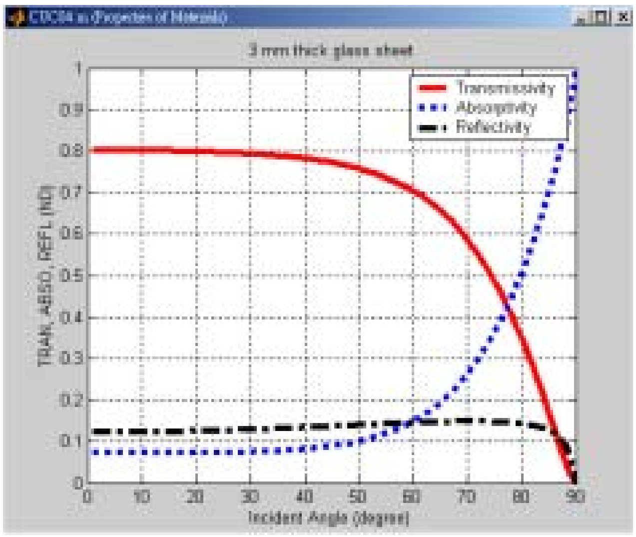

Figure 5.2. Transmissivity, reflectivity and absorptivity of a 3 mm glass sheet with an index of refraction of 1.526.

As we discussed, transmissivity is the most important of the three properties. It depends on the incident angle of solar radiation to the film, as does reflectivity. Reflectivity increases while transmissivity decreases with an increase in the incident angle, as shown in Fig. 5.2. Absorptivity is fairly constant through all incident angles from 0 to 90 degrees.

5.4. CALCULATION OF TRANSMISSIVITY (**CUC04**)

Although the following relationships all hold monochromatically -- that is, based on unit wavelength -- all representations here will be of total energy for the sake of simplicity.

As light hits a transparent material such as PVC film, direct solar radiation is partly transmitted and partly reflected and absorbed. The detailed mechanism is shown in Fig. 5.3. An incoming light ray **J** (incident angle **THET**) is partly reflected at the surface and is refracted (refracted angle **THETP**). We have the relation

$$\mathbf{FN} = \mathbf{sin}(\mathbf{THET}) \,/\, \mathbf{sin}(\mathbf{THETP}) \qquad (5.2)$$

where FN is the index of refraction of a film. The index of refraction of the air is unity.

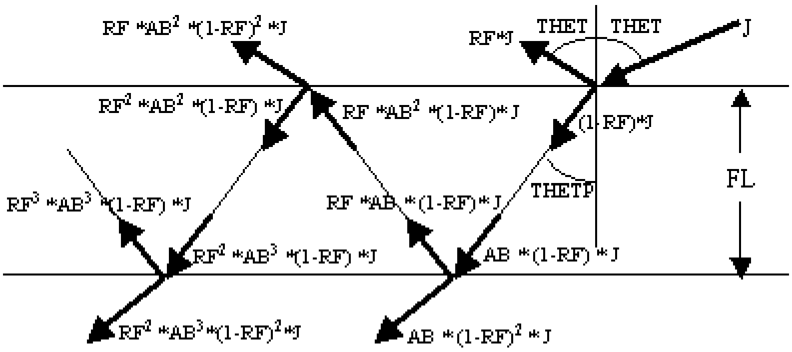

Figure 5.3. Multiple reflections of direct solar radiation by a sheet of film (after Threlkeld, 1962).

The ray in the material penetrates according to the law of Lambert-Beer: that is, absorption coefficient **AB** is the fraction of the radiation component available after absorption, also termed single pass transmittance, and is expressed as

$$\mathbf{AB} = \mathbf{exp}(\, -\mathbf{FK} * \mathbf{FL} \,/\, \mathbf{cos}(\mathbf{THETP})\,) \qquad (5.3)$$

where **FK** is the extinction coefficient (1/mm) and **FL** is the thickness of the film (mm). This equation is the expression of Lambert-Beer’s law and the term **FL**/**cos**(**THETP**) is the actual path length for the radiation beam. As shown in Fig. 5.3, because of successive internal reflections, the equations for reflected, absorbed and transmitted light are given by the sums of infinite series. Let **RF** be the fraction of each component reflected, termed specular reflectance or single pass reflectance. The total transmissivity **TRAN** is given by

$$\mathbf{TRAN} = (1 - \mathbf{RF})^2 * \mathbf{AB} / (1 - \mathbf{RF}^2 * \mathbf{AB}^2) \tag{5.4}$$

In a similar way, we obtain the total reflectivity **REFL** as

$$\mathbf{REFL}=\mathbf{RF}+\mathbf{RF}*(1-\mathbf{RF})^2*\mathbf{AB}^2/(1-\mathbf{RF}^2*\mathbf{AB}^2) =\mathbf{RF} *(1+\mathbf{TRAN}*\mathbf{AB}) \tag{5.5}$$

and absorptivity **ABSO** as

$$\mathbf{ABSO} = 1 - \mathbf{RF} - (1 - \mathbf{RF})^2 * \mathbf{AB} / (1 - \mathbf{RF} * \mathbf{AB}) = 1 - \mathbf{TRAN} - \mathbf{REFL} \tag{5.6}$$

The reflectivity component **RF** may be derived from the Fresnel relations. Light is a kind of electromagnetic wave, and natural or unpolarized light may be assumed to consist of two vibrating components, one vibrating in a plane normal to the sheet and the other vibrating in a plane parallel to the sheet. A light ray entering a flat material reflects at the first surface and again at the second surface. The reflectivity component, which is the ratio of the reflected part to the entering light is

$$\mathbf{RP} = \mathbf{tan}^2 (\mathbf{THET} - \mathbf{THETP}) / \mathbf{tan}^2 (\mathbf{THET} + \mathbf{THETP}) \tag{5.7}$$

in the plane parallel to the sheet and

$$\mathbf{RN} = \mathbf{sin}^2 (\mathbf{THET} - \mathbf{THETP}) / \mathbf{sin}^2 (\mathbf{THET} + \mathbf{THETP}) \tag{5.8}$$

in the plane normal to the sheet. If the reflected components are of equal intensity in the parallel and normal planes,

$$\mathbf{RF} = (\mathbf{RN} + \mathbf{RP}) / 2 \tag{5.9a}$$

If **THET** equals 0, **RF** is calculated using the follow equation:

$$\mathbf{RF = (1 - 1 / FN)^2 / (1 + 1 / FN)^2 = (FN - 1)^2 / (FN + 1)^2} \tag{5.9b}$$

The program to obtain the result shown in Fig. 5.2 is given in Fig. 5.4. In eq. 5.9a, incident angle **THET** is given, but **THETP** is an unknown variable. Therefore, eq. 5.9 is broken down into its components: that is, the trigonometric functions for **THET** and **THETP** are separated, and then the trigonometric function for **THETP** is found from eq. 5.2 because the value of **FN** is also given. **Cos**(**THETP**) is also calculated from eq. 5.2. **AB** is calculated by eq. 5.3, as **FK** is given. Finally **TRAN** is calculated by eq. 5.4, and **REFL** and **ABSO** from eqs. 5.5 and 5.6, respectively. In the program given in Fig. 5.4b, several intermediate variables for trigonometric functions used for convenience such as **STHET, CTHET, STHETP, CTHETP, STHENG, CTHENG, STHEPS, CTHEPS, TANPS, TNANNG, STHEN2, TANPS2** and **TANNG2** might make the program difficult to follow, but the explanation given here will help us to understand the program.

As clearly shown in Fig. 5.2, transmissivity drops rather rapidly after the incident angle exceeds 60 degrees. On the other hand, absorptivity is fairly constant throughout the range, and it is around 5% in this case. Therefore, the decrease in transmissivity occurs along with the increase in reflectivity. The values of **FL**, **FN** and **FK** are material dependent. Table 5.1 shows these properties of some popular glazing materials. In Table 5.1, information of **FL** and **FN** of selected glazing were compiled from the commercial catalogue. Extinction coefficients **FK** were calculated based on the equation, derived from eqs. 5.3 and 5.4, listed below (Fang, 1992).

$$\mathbf{FK} = -\,\mathbf{log}\,((\mathbf{X}^{0.5} - \mathbf{B}) / (2 * \boldsymbol{\tau} * \mathbf{RF}^2)) / \mathbf{FL} \qquad (5.9c)$$

where **X** equals ($\mathbf{B}^2 + 4 * \boldsymbol{\tau}^2 * \mathbf{RF}^2$), **B** equals $(\mathbf{RF} - 1)^2$, **RF** equals $[(\mathbf{FN}\text{-}1)/(\mathbf{FN}+1)]^2$, $\boldsymbol{\tau}$ is the direct transmissivity when incident angle (**THET**) equals zero and **FL** is the thickness of glazing (in mm).

```
% Program to calculate optical properties of glazing          CUC04.m
% Function required: RFcal.m
clear all;clc
tit='3 mm thick glass sheet';
FL=3;       % Thickness (mm)
FN=1.526;   % FN: Index of refraction
FK=0.0441;  % FK: extinction coefficient (1/mm)
% Above 3 values are subject to change for different glazing.
TRAN=zeros(1,90);REFL=zeros(1,90);ABSO=zeros(1,90);
for angle=1:90                    % ANGLE: Incident angle in degree
   THET=angle*pi/180;             % THET: Incident angle in radian
   [RF, CTHETP]=RFcal(THET,FN);   % Calling function RFcal()
   AB=exp(-FK*FL/CTHETP);
   TRAN(angle)=(1-RF)*(1-RF)*AB/(1-RF*RF*AB*AB);
   REFL(angle)=RF+RF*(1-RF)*(1-RF)*AB*AB/(1-RF*RF*AB*AB);
   ABSO(angle)=1-RF-(1-RF)*(1-RF)*AB/(1-RF*AB);
end
% TRAN: Transmissivity, REFL: Reflectivity and ABSO: Absorptivity
h1=findobj('tag','Coefficients'); close(h1);
figure('tag','Coefficients','Resize','on','MenuBar','none',...
  'Name','CUC04.m (Properties of Materials)','NumberTitle','off',...
  'Position',[200,40,520,420]);
x=1:1:90;
plot(x,TRAN(:),'r-',x,REFL(:),'b:',x,ABSO(:),'k-.','linewidth',4);
axis([0,inf,0,1]);grid on; title(tit);
xlabel('Incident Angle (degree)'); ylabel('TRAN, ABSO, REFL (ND)');
legend('Transmissivity','Absorptivity','Reflectivity');
disp('You can enter ''close'' to close figure window.');
%END
```

Figure 5.4a. Main program to calculate light properties of a film (**CUC04.m**).

Table 5.1. Properties of some popular glazing (after Fang, 1994).

Glazing	*FL Thickness*	*FN, Index of refraction*	*FK, Extinction coefficient (1/mm)*
Acrylic,(Acrysteel*,1/8 inch)	3.175 mm	1.56	0.0065
EVA	0.15 mm	1.515	0.0699
FRP	25 mil**	1.54	0.2482
Glass (ordinary float)	3.175 mm	1.526	0.0473
Glass (double strength)	3.175 mm	1.526	0.0094
Glass (sheet lime)	3.175 mm	1.51	0.0178
PC (Lexan*)	3.175 mm	1.59	0.0662
PC (Lexan dripguard*)	6 mm	1.586	0.0042
PE (UV resistant)	4 mils	1.515	0.0752
PE (IR barrier, Monsanto 602*)	4 mils	1.515	0.432
PE	4 mils	1.515	0.165
Polyester (Mylar*)	5 mils	1.54	0.205
PVC (Bioriented*)	0.9 mm	1.46	0.17
PVC (clear)	0.15 mm	1.46	0.09
PVC (haze)	0.15 mm	1.46	0.3106
PVF (Tedlar*)	2 mils	1.46	0.4806

* Trade names ** 1 mil is 1/1000 inch

```
% Function to calculate fraction of each component reflected         RFcal.m
function [RF, CTHETP]=RFcal(THET,FN)
%
STHET=sin(THET);  CTHET=cos(THET);
if (THET-0.0)<=0.000001
          RF=(1-1/FN)*(1-1/FN)/((1+1/FN)*(1+1/FN));
          CTHETP = 1;
else
           STHETP=STHET/FN;   CTHETP=sqrt(1.0-STHETP*STHETP);
           STHENG=STHET*CTHETP-CTHET*STHETP;
           STHEPS=STHET*CTHETP+CTHET*STHETP;
           CTHEPS=CTHET*CTHETP-STHET*STHETP;
           CTHENG=CTHET*CTHETP+STHET*STHETP;
           TANPS=STHEPS/CTHEPS;       TANNG=STHENG/CTHENG;
           STHEN2=STHENG*STHENG;      STHEP2=STHEPS*STHEPS;
           TANPS2=TANPS*TANPS;        TANNG2=TANNG*TANNG;
           RF=0.5*(STHEN2/STHEP2+TANNG2/TANPS2);
end
```

Figure 5.4b. Function used in **CUC04** *model* **(RFcal.m)**.

5.5. SOLAR RADIATION

The sun is the largest energy source in our system; we get an equivalent temperature of 5,700 K if we calculate its temperature from its radiation, as shown in Fig. 5.5. The solar constant **J0W** (defined in section 5.2) varies, as it is a kind of indicator of the energy that reaches the earth, based on observations over many years. It is reported that the value of the solar constant throughout the year can be calculated using the following equation:

J0W = **Jsc** * (1 + 0.033 * **cos**(2 * **pi** * **n** / 365)) (5.10)

where **n** is the Julian day, **Jsc** was equal to 1353 W/m^2, which is the average of **J0W** throughout the year. The value was updated to 1367$\pm$7 W/m^2 in 1981.

When solar radiation passes through the atmosphere around the earth, some parts of the radiation are absorbed, and others reflected (see Fig. 4.2). The solar radiation received on the earth's surface, therefore, consists of directional and non-directional radiation -- that is, direct and diffuse radiation. Direct radiation is that which comes from the sun directly, and diffuse is that which is reflected in the atmosphere and comes from all directions of the sky. Hemispherical radiation on a horizontal surface is given as the sum of two components, **RAD** and **RADS**, where **RAD** is direct radiation (W/m^2) and **RADS** is diffuse radiation (W/m^2) (see Fig. 5.6).

Sometimes it is convenient to use semi-empirical mathematical expressions to calculate these two radiation components. The equation for **RAD** is

RAD = **J0W** * **sin**(**SALT**) * **PP**^(1 / **sin**(**SALT**)) (5.11)

where, **J0W** is the solar constant (W/m^2), **SALT** is the sun's altitude and **PP** (ND) is atmospheric transmittance. Extinction of **J0W** due to the air layer is counted. The direct radiation is directional; therefore, the so-called cosine law rules:

J0W * **sin**(**SALT**) = **J0W** * **cos**(**THET**) (5.12)

where **J0W** is solar radiation irradiated to a surface normal to sun ray outside the atmosphere (W/m^2), and **THET** is the incident angle of the radiation to the horizontal surface on earth. The diffusion of solar radiation due to the air layer is calculated as follows:

RADS=**J0W***sin**(**SALT**)*(1-**PP**^(1/**sin**(**SALT**)))/(1-1.4***log**(**PP**))/2 (5.13)

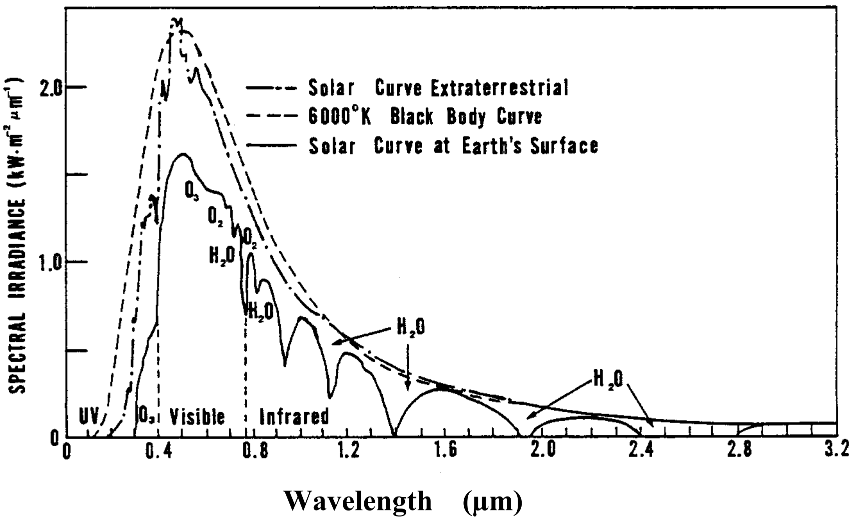

Figure 5.5. Solar radiation (after Gates, 1962).

An example of the calculated direct and diffuse solar radiation using eqs. 5.11 and 5.13 is shown in Fig. 5.6. The parameter **PP** is atmospheric transmittance (also termed clearness index), which gives the degree of sky clearness: the larger **PP**, the clearer the sky. Therefore, when the value of **PP** is large, the portion of direct solar radiation is large and the diffuse portion is small and vice versa as shown in Fig. 5.6b. The program, **CUC04a.m**, to generate Fig. 5.6b is listed in Fig. 5.6a.

```
% Program to calculate solar radiation on the earth              CUC04a.m
%
clear all;clc
h1=findobj('tag','cuc04a');  close(h1);
prgtitle=’CUC04a.m (Direct and diffuse ‘
prgtitle= prgtitle+’solar radiation under various atmospheric transmittance)';
figure('tag','cuc04a','Resize','on','MenuBar','none','Name', ...
   prgtitle, 'NumberTitle','off','Position',[200,80,520,420]);
%
J0W=1367; % Solar Constant in W/m2
conv=pi/180; RAD=zeros(3,90); RADS=zeros(3,90);
for j=1:3
   pp=0.5+0.2*(j-1);  % pp=0.5,0.7,0.9
   for xx=1:90
     salt=xx*conv;  ALTS = sin(salt); ALTC = 1/ALTS;
     ppp=pp^ALTC;   RAD(j,xx)=J0W*ALTS*ppp;           % eq.5.11, in W/m2
     RADS(j,xx)=J0W*ALTS*(1-ppp)/(1-1.4*log(pp))/2;  % eq.5.13, in W/m2
   end
end
x=1:1:90;
plot(x,RAD(1,:),'r-',x,RAD(2,:),'b:',x,RAD(3,:),'k-.',x,RADS(1,:),...
```

```
   'r-',x,RADS(2,:),'b:',x,RADS(3,:),'k-.','linewidth',2);
axis([0,90,0,1400]);
xlabel('Solar Altitude, degree');  ylabel('Solar Radiation, W/m^2');
legend('Direct,  PP=0.5','Direct,  PP=0.7','Direct,  PP=0.9',...
   'Diffuse, PP=0.5','Diffuse, PP=0.7','Diffuse, PP=0.9',2);
title('Direct and Diffuse Solar Radiation');
text(61,900,'Direct'); text(61,220,'Diffuse');
grid on;
disp('You can enter ''close'' to close figure window.');
```

*Figure 5.6a. Program to calculate solar radiation on the earth (***CUC04a.m***).*

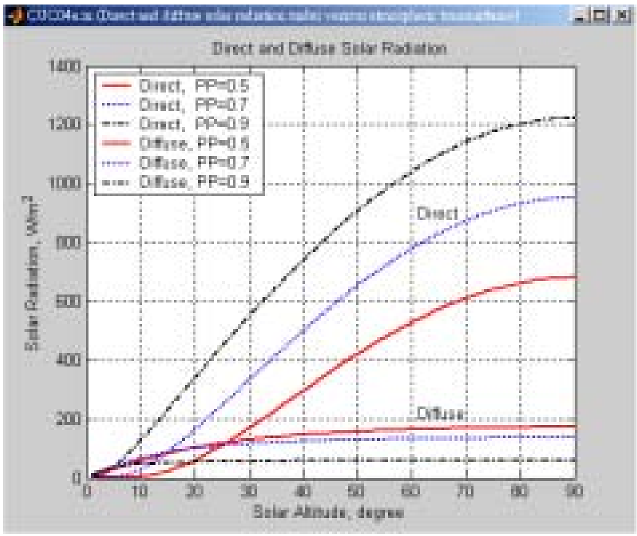

Figure 5.6b. Solar radiation on the earth calculated using eqs. 5.11 and 5.13.

5.6. THE SUN'S ALTITUDE AND AZIMUTH

5.6.1. On a horizontal surface

It is clear that the sun's position is relative to the place and time at which it is observed. The sun's position is expressed in terms of the sun's altitude (**SALT**) and azimuth (**SAZM**) as shown in Fig. 5.7. They are expressed as angles (degrees). For altitude, the angle is taken from the horizontal plane upward toward the sun with the upward direction as positive -- that is, -90 < **SALT** < 90, and **SALT** = 0 at the horizontal surface. The angle for the azimuth is taken from the south when angles toward the west are positive -- that is, -180 < **SAZM** < 180 and **SAZM** = 0 at solar noon (when the sun is located to the exact south).

The observation location is expressed in terms of geographical latitude (**LAT**) and longitude (**LGT**), both in degrees.

It should be noted that time, which is so familiar to us in our daily lives, is expressed in different ways. The time by which we conduct our daily lives is called Central Standard Time (**CST**) or Greenwich time. **CST** for the United Kingdom is based on the meridian that passes through Greenwich, which is 0 degree longitude. The time for each particular place is calculated by its distance from this prime meridian. The earth is divided roughly into 24 time zones, by meridians 15 degrees apart (24x15=360). Japan is all in one time zone, and the **CST** for Japan is based on the longitude at Akashi city, 135 degrees. There is a difference between **CST** and solar time based on the position of the sun in the sky, except at the place where the longitude is adopted for **CST**; in Japan this place is Akashi. Even in places such as Akashi, there is some time difference between **CST** and the true solar time (**TST**) because the above calculation is based on the assumption that one rotation of the earth takes exactly 24 hours. This difference is called the equation of time (**EQT**). If we calculate mean solar time (**MST**) from **CST** and the difference in longitude, we have

$$\mathbf{TST} = \mathbf{MST} + \mathbf{EQT} \tag{5.14}$$

Using the relationship that one hour is equal to 15 degrees, it is convenient to express time in degrees and to call it the hour angle (**HAG**). The hour angle can be calculated as follows:

$$\mathbf{HAG = (CST + ((\ LGT - LGTstd\ )/15\ ) + EQT) * 15} \tag{5.15}$$

where **HAG** at solar time noon is zero and **LGTstd** is the longitude of **CST** for a particular region and for Japan is 135. **EQT** (in minutes) can be calculated using the following equation:

$$\mathbf{EQT} = 9.87 * \mathbf{sin}(2*\mathbf{B}) - 7.53 * \mathbf{cos}(\mathbf{B}) - 1.5 * \mathbf{sin}(\mathbf{B}) \tag{5.16}$$

where, **B** equals 2***pi*** (**n**-81) / 364 and **n** is Julian day.

The sun's declination (**DEC**) is the angle between a line connecting the centers of the sun and the earth and the projection of this line on the earth‘s equatorial plane. **DEC** (in degrees) can be calculated using the following equation:

$$\mathbf{DEC} = 23.45 * \mathbf{sin}\ (((284+\mathbf{n}) / 365)*(2*\mathbf{pi})) \tag{5.17}$$

On the vernal equinox (March 21, n=81) and autumnal equinox (September 21, **n**=264), **DEC** equals 0; on the summer solstice (June 21, **n**=172), **DEC** equals 23.45^o; and on the winter solstice (December 21, **n**=355), **DEC** equals -23.45^o.

Equations to calculate the sun's altitude and azimuth from the south for a horizontal surface are as follows:

$$\mathbf{sin}(\mathbf{SALT}) = \mathbf{sin}(\mathbf{LAT})*\mathbf{sin}(\mathbf{DEC}) + \mathbf{cos}(\mathbf{LAT})*\mathbf{cos}(\mathbf{DEC})*\mathbf{cos}(\mathbf{HAG}) \tag{5.18}$$

cos(SAZM)=(sin(SALT)*sin(LAT)-sin(DEC))/cos(SALT)/cos(LAT) (5.19)

The sun's declination and the equation of time for the year 1986 are given in Table 5.2; they do not change much from one year to another. If more exact values are needed, they can be obtained from an almanac or other reference.

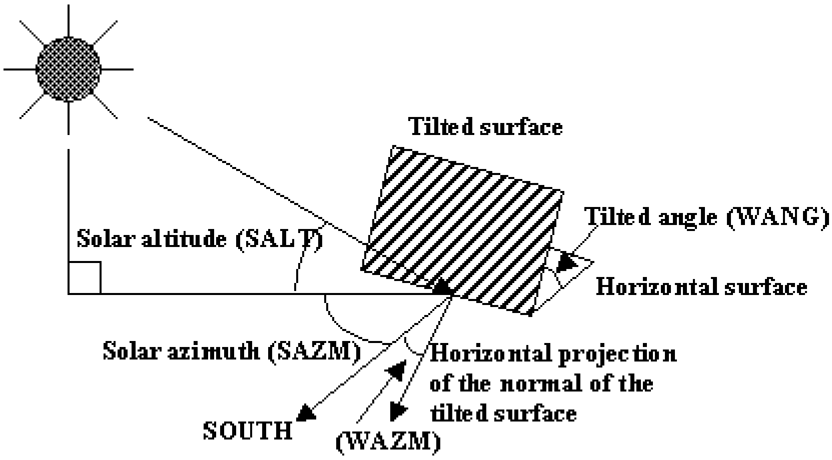

Figure 5.7. Solar angles for horizontal and tilted surfaces.

Table 5. 2. The sun's declination and the equation of time for the year 1986.

Day	*1*		*8*		*15*		*22*	
Month	*DEC Deg:Min*	*Eq.of.Time min:s*	*DEC Deg:Min*	*Eq.of.Time min:s*	*DEC Deg:Min*	*Eq.of.Time min:s*	*DEC Deg:Min*	*Eq.of.Time min:s*
January	-23:03	-3:16	-22:19	-6:26	-21:13	-9:13	-19:48	-11:20
February	-17:17	-13:31	115:09	-14:10	-12:51	-14:12	-10:23	-13:37
March	- 7:47	-12:30	15:05	-10:59	-2:20	-9:19	0:25	-7:07
April	4:20	-4:05	7:01	-2:04	9:35	-0:13	12:01	1:21
May	14:55	2:50	16:57	3:30	18:45	3:41	20:17	3:26
June	21:59	2:20	22:48	1:09	23:17	-0:15	23:27	-1:46
July	23:09	-3:38	22:32	-4:54	21:37	-5:50	20:23	-6:22
August	18:09	-6:19	16:17	-5:42	14:13	-4:35	11:57	-3:02
September	8:28	-0:12	5:53	2:05	3:14	4:32	0:31	7:01
October	-2:59	10:06	-5:51	12:14	-8:19	14:02	-10:52	15:14
November	-14:15	16:22	-16:25	16:16	-18:21	15:30	-20:01	14:03
December	-21:43	11:13	-22:33	8:24	-23:14	5:11	-23:27	1:46

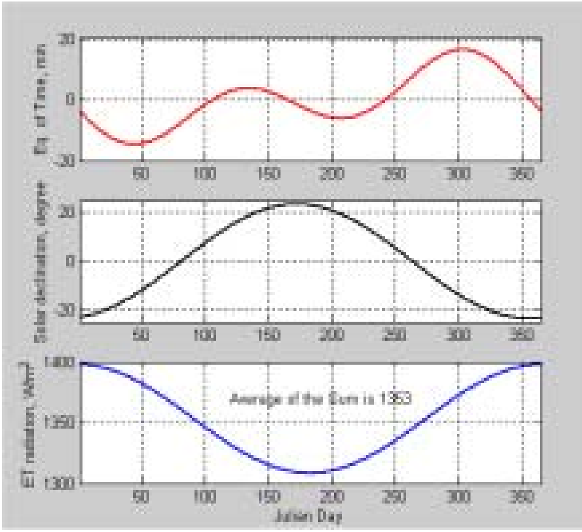

Figure 5.8. Output Figure Window of **cuc04b.m**.

The program, listed in Fig. 5.9, is provided to plot curves of equation of time (**EQT**, in min), solar declination (**DEC**, in degrees) and the daily solar constant as extraterrestrial (**ET**) radiation (W/m^2) throughout the year. The output is given as three output plots in one Figure Window as shown in Fig. 5.8.

```
% Program to plot equation of time, solar declination and          cuc04b.m
%       extraterrestrial radiation throughout the year.
h1=findobj('tag','cuc04b');close(h1);
figure('tag','cuc04b','Resize','on','MenuBar','none',...
   'Name','EQT','NumberTitle','off','Position',[120,60,520,480]);
x=1:1:365;              subplot(3,1,1);
B=2*pi*(x-81)/364;      EQT=9.87*sin(2*B)-7.53*cos(B)-1.5*sin(B);
plot(x,EQT,'r-','linewidth',2);
ylabel('Eq. of Time, min');axis([1 365 -20 20]);   grid on;
subplot(3,1,2);
dec=23.45*sin(2*pi*(284+x)/365);
plot(x,dec,'k-','linewidth',2);
ylabel('Solar declination, degree');axis([1 365 -25 25]);   grid on;
subplot(3,1,3);
Jsc=1353;      J0W=Jsc*(1+0.033*cos(2*pi*x/365));
plot(x,J0W,'b-','linewidth',2);      xlabel('Julian Day');
ylabel('ET radiation, W/m^2');  % ET is extraterrestrial
axis([1 365 1300 1400]);   grid on;
Solarconstant=sum(J0W)/365
tit=['Average of the Sum is ' num2str(Solarconstant)]
text(120,1370,tit);
```

*Fig. 5.9. Program to plot equation of time, solar declination and extraterrestrial radiation throughout the year (***cuc04b.m***).*

5.6.2. On a tilted surface

Suppose we have a tilted surface whose tilt angle is **WANG** (deg) and azimuth is **WAZM** (deg), as shown in Fig. 5.7; then the sun's altitude for the tilted surface (**SALTT**) is calculated by the following equation:

$$\mathbf{sin}(\mathbf{SALTT}) = \mathbf{sin}(\mathbf{SALT}) * \mathbf{cos}(\mathbf{WANG}) + \mathbf{cos}(\mathbf{SALT}) * \mathbf{sin}(\mathbf{WANG}) * \mathbf{cos}(\mathbf{SAZM} - \mathbf{WAZM}) \tag{5.20}$$

*5.6.3. Transmitted solar radiation (***CUC05***)*

Now consider a model to calculate transmitted direct solar radiation under a horizontal film when the time of the day is given. We already have a model to calculate transmitted solar radiation through a film, if the incident angle to the film (**THET**) is given (see Fig. 5.4). Use eq. 5.18 to find the sun's altitude. Then the incident angle of direct solar radiation at a given time of the day is 90 minus the sun's altitude. The whole program (**CUC05.m**) is given in Fig. 5.10a and two functions are listed in Fig. 5.10b (**RADcal.m**) and Fig. 5.4b (**RFcal.m**).

The program is dependent on time, but the relationships are entirely steady-state and are expressed sequentially. The material used in the simulation is a 1 mm thick glass sheet. The location is near Tokyo as defined by the latitude (**LATD**) and longitude (**LGT**). The value of **LGTstd** should be changed accordingly with the value of **LGT**. For example, **LGT** for New York City is around -121.5, so the **LGTstd** should be -120.

The same variable name can be placed on both sides of the equal sign in one equation, such as **SAZM**=**SAZM**/**CONV**, which gives the sun's azimuth in degrees converted from radian. The program consists of two parts. The first part is used to calculate the sun's altitude and then direct and diffuse radiation at given times; the second part is used to calculate transmissivity, absorptivity and reflectivity at the same times. The amounts of solar radiation transmitted through a film and absorbed by the film can be calculated using this program.

Several expressions can be used to find **SAZM**. In the present case, eq. 5.19 is used. In summer the solar azimuth changes from northeast to northwest through east, south and west. If the solar azimuth is taken beginning at the south, it decreases from over 90 degrees to zero and then increases to over 90 degrees. Although the expression in eq. 5.19 for **cos**(**SAZM**) can give these angles for **SAZM** correctly, that in eq. 5.18 for **sin**(**SAMZ**) can give only the angle between 0 and 90 degrees because of restriction by **asin**.

```
% Program to calculate sun's position and transmitted          CUC05.m
% direct solar radiation through a horizontal film sheet
% Functions required: RFcal.m, RADcal.m
%
clear all; clc;
FL = 1;                             % FL: Thickness (mm)
FN = 1.526;                         % FN: Index of refraction
FK = 0.0441;                        % FK: extinction coefficient (1/mm)
```

```
CONV = pi/180;                     % CONV: Conversion factor
JW = 1360;                         % JW: Solar constant (W/m2)
J0 = JW*3.6;                       % JO: Solar constant (kJ/m2/hr)
pp = 0.7;                          % pp: atm. transmittance (ND)
%------ Data for Tokyo area ------------------------------------------
LATD = 35.68;                      % LATD: Latitude, 35 deg 41 min
LAT = LATD*CONV;                   % LAT:  in Radiant
LGT = 139.77;                      % LGT:  Longitude, 139 deg 46 min
LGTstd=135;                        % LGTstd: std. longitude of Japan
%------ Data for October 15 from Table 5.2 ---------------------------
DEC = -8.32;                       % DEC: Declination, -8 deg 19 min
DEG = DEC*CONV;                    % in Radiant
EQT = 0.234;                       % EQT: eq.of time,14 min 02 sec
%
t24=48;
TRAN=zeros(1,t24); REFL=zeros(1,t24); ABSO=zeros(1,t24);
RAD=zeros(1,t24); RADS=zeros(1,t24);
WRAD=zeros(1,t24); WRADS=zeros(1,t24);
IRAD=zeros(1,t24); IRADS=zeros(1,t24);
SALT=zeros(1,t24); SAZM=zeros(1,t24);
for t = 1:48                       % for 24 hr
  CST = t/2 - 12;
  % Central standard time is taken from noon and is positive in the afternoon
  HAG = (CST+((LGT-LGTstd)/15)+EQT)*15;     % Hour Angle, in degree
  HAG = HAG*CONV;                           % in Radiant
  SALT(t)= asin(sin(LAT)*sin(DEG)+cos(LAT)*cos(DEG)*cos(HAG));
  SAZM(t)=acos((sin(SALT(t))*sin(LAT)-sin(DEG))/cos(SALT(t))/cos(LAT));
  % SALT and SAZM both in Radiant
  if (SALT(t) <= 0)
    TRAN(t)=0; REFL(t)=1; ABSO(t)=0; RAD(t)=0; RADS(t)=0;
    SALT(t)=0; SAZM(t)=999;
  else
    % Calculation of solar radiation
    [RAD(t),RADS(t)]=RADcal(J0,SALT(t),pp); % Calling function RADcal()
    THET = pi/2-SALT(t);                    % in Radiant
    SALT(t)= SALT(t)/CONV;                  % in Degree
    SAZM(t)= SAZM(t)/CONV;                  % in Degree
    [RF, CTHETP]=RFcal(THET,FN);            % Calling function RFcal()
    AB=exp(-FK*FL/CTHETP);
    TRAN(t)=(1-RF)*(1-RF)*AB/(1-RF*RF*AB*AB);
    REFL(t) = RF+RF*(1-RF)*(1-RF)*AB*AB/(1-RF*RF*AB*AB);
    ABSO(t) = 1-RF-(1-RF)*(1-RF)*AB/(1-RF*AB);
  end
    WRAD(t) = RAD(t)/3.6; IRAD(t)=WRAD(t)*TRAN(t);
    WRADS(t) = RADS(t)/3.6;IRADS(t)=WRADS(t)*TRAN(t);
    % Assuming transmittance of direct and diffuse sunlight are the same
  end
  %[Figure 1]---------------------------------------------------------
  x=1:48;
  h1=findobj('tag','cuc05_part1');  close(h1);
  figure('tag','cuc05_part1','Resize','on','MenuBar','none',...
             'Name','CUC05.m (Figure 1: Solar Angles vs. Time)',...
             'NumberTitle','off','Position',[140,80,520,420]);
  plot(x/2, SALT,'r+-', x/2,SAZM,'b*-', 'linewidth',2);
  xlabel('Time, hour');  ylabel('Solar Angles, degree');
  legend('Solar altitude','Solar azimuth',0);
  axis([1,24,-inf,90]);  grid on;
  %[Figure 2]---------------------------------------------------------
  h1=findobj('tag','cuc05_part2');  close(h1);
  figure('tag','cuc05_part2','Resize','on','MenuBar','none',...
```

```
              'Name','CUC05.m (Figure 2: Solar Radiation vs. Time)',...
              'NumberTitle','off','Position',[180,60,520,420]);
plot(x/2,WRAD,'r+-', x/2, WRADS,'b*-', ...
   x/2, IRAD,'r^-.',x/2,IRADS,'bv-.','linewidth',2);
xlabel('Time, hour');  ylabel('Solar Radiation, W/m^2');
legend('Direct (Outdoor)','Diffuse (Outdoor)',...
   'Direct (under glazing)','Diffuse (under glazing)');
axis([1,24,-inf,inf]);  grid on;
%[Figur 3]-------------------------------------------------------
h1=findobj('tag','cuc05_part3');  close(h1);
figure('tag','cuc05_part3','Resize','on','MenuBar','none',...
              'Name','CUC05.m (Figure 3: Optical properties vs. time)',...
              'NumberTitle','off','Position',[220,40,520,420]);
subplot(1,1,1);
plot(x/2,TRAN,'r+-', x/2, REFL,'bo-', x/2, ABSO,'k*-','linewidth',2);
axis([1,24,0,1]);  xlabel('Time, hour');
ylabel('Tran., Refl. Abso. (ND)');
legend('Transmissivity','Reflectivity','Absorptivity',0); grid on;
clc;  disp('You can enter ''close all'' to close figure windows.');
```

*Figure 5.10a. Program to calculate time courses of solar angles, solar radiation and optical properties of glazing (***CUC05.m***).*

In the present program, calculation of azimuth is not included because it is not necessary. If azimuth is included, some consideration should be given to computer error because the time step in these calculations is small. If the calculation begins at exact solar noon -- that is, azimuth 0 -- acos(0) should be 1, but it can be slightly larger than 1. An error message told us this had happened in our early calculations. The discrepancy can be solved by filtering, such as we have in the program in Fig. 5.10b. We have an **if** statement that holds **ALTS** at not less than 0.01. If you look at the remaining several statements, it is not difficult to understand why it is necessary to have this filter. The value of **PP** is less than 1; therefore it is meaningless to calculate **PPP** with a large value of **ALTC**.

```
% RADcal.m
function [RAD,RADS]=RADcal(J0,SALT,pp)
ALTS=sin(SALT);
if ALTS < 0.01,ALTS=0.01;end  % filtering
ALTC=1/ALTS;  ppp=pp^ALTC;  RAD=J0*ALTS*ppp;
RADS=J0*ALTS*(1-ppp)/(1-1.4*log(pp))/2;
```

Figure 5.10b. Function required in program **CUC05.m** *(***RADcal.m***).*

The results of program '**CUC05.m**' are shown in Fig. 5.11. In total, three figures were drawn. Fig. 5.11a shows the time courses of solar angles. The times of sunrise and sunset are quite clear from this figure. The time for sunrise is the solar altitude changes from zero to a positive value, and the time for sunset is when the altitude returns to zero. Also, at solar noon, the solar azimuth is zero, and the solar altitude is at its peak.

Fig. 5.11b shows the time courses of direct and diffuse solar radiations outside and under the glazing, assuming the transmittance of direct and diffuse sunlight are the same. In the early morning and late afternoon, of the components of total solar radiation, the diffuse sunlight contributes more than the direct sunlight.

Fig. 5.11c shows the time courses of optical properties of glazing. During the dark period (from 6 pm to 6 am), the reflectance shows a value of 1. This should not be interpreted as 100% reflection of sunlight for there is no sunlight at all during the dark period. It is simply the result of **TRAN** + **REFL** + **ABSO** =1. During the dark period, the **ABSO** and **TRAN** are zero, thus leading to **REFL** = 1.

It is possible that the legend can block part of the curves. In such situations, users can use the mouse to click on the legend and drag it to a better location as shown in Fig. 5.11c.

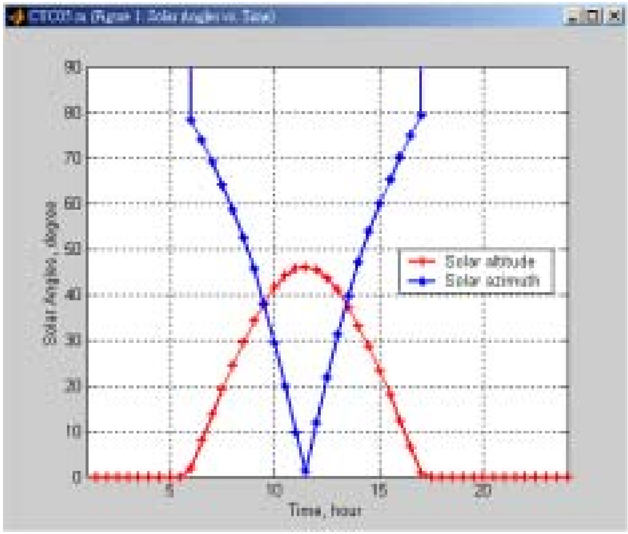

Figure 5.11a. Time courses of solar angles (Figure 1 generated by **CUC05.m***).*

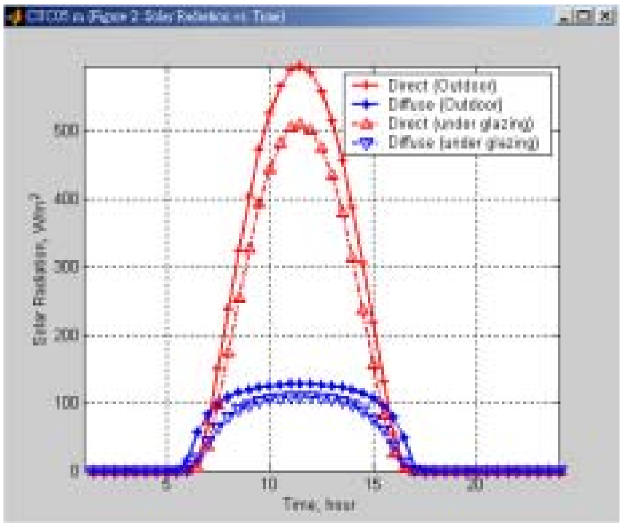

Figure 5.11b. Time courses of solar radiation above and under glazing (Figure 2 generated by **CUC05.m***).*

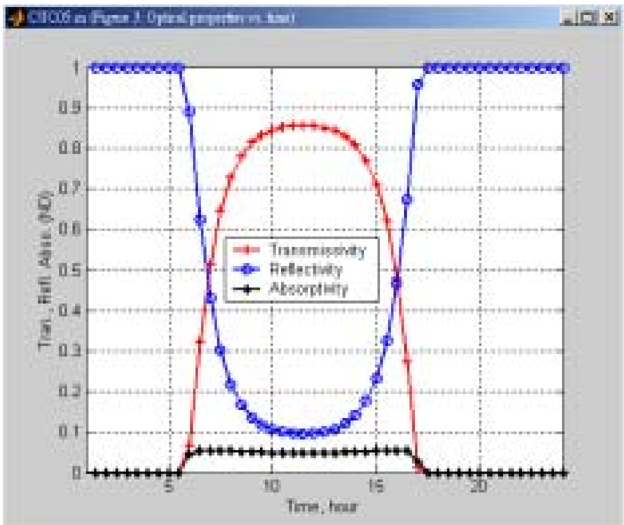

Figure 5.11c. Time courses of optical properties of a film (Figure 3 generated by CUC05.m*).*

PROBLEMS

1. Rerun the program **CUC04**, applying different values for **FN** and **FK** as shown in Table 5.1.

2. The thickness of the glass (**FL**) is assumed 3 mm in the model **CUC04**. Change it to 1 and 5 mm and generate the transmissivity curves.

3. Choose a day of the year other than Oct. 15 and use the data from Table 5.2 to rerun the program **CUC05**.

4. Calculate the hour angle at your location by using eq. 5.14 .

5. In the model **CUC05**, the longitude of the standard time location is fixed to 135 degrees. Change it to your standard time. For U.S.A., **EST** is -75, **CST** is -90, **MST** is -105, and **PST** is -120, respectively. Then input the latitude and longitude of your location as **LATD** and **LGT** and run the program. The date is set for October 15. You can also select other days using Table 5.2.

6. Write a program to derive the direct transmittance for materials listed in Table 5.1 when incident angle equals 0. Note: make use of '**RFcal.m**'.

7. In the model of **CUC05**, **DEC** and **EQT** are selected from Table 5.2. Use eqs. 5.16 and 5.17 to calculate **DEC** and **EQT** with given Julian day (n=288 for October 15) and rerun the model.