INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 6, Issue 4, 2015 pp.367-376
Journal homepage: www.IJEE.IEEFoundation.org

A comprehensive solar angles simulation and calculation using matlab

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Abstract
During the experimental or theoretical work in the field of solar energy it is found that there is many parameters need to be estimated or calculated, the calculation procedure of these parameters is long and dull for students, researchers and designers. This paper introduces the most important parameters such as solar angles and provides a MATLAB code to calculate these angles at any time and location. Specific case has been studied to analyze the pattern of solar angles and the solar path. The simulation results could be a fast reference for orientation of solar energy application, design and sun tracking. Baghdad city (and any place on 33° latitude) chosen for the simulation. different angles and times have been concluded to determine whether the bests and worsts for solar energy exploitation.

Keywords: MATLAB simulation; Solar angles; Solar energy; Solar path; Sun tracking.

1. Introduction

Recently, interest in alternative energy has been increasing due to rise of oil price by limit of fossil fuels and environment pollution caused by indiscriminate use of fossil fuels. Compare to traditional energy sources, the solar energy is limitless and does not generate any pollution emission [1]. The amount of solar energy that reaches the Earth is well over 1000 times higher than all of the energy we actually use [2], therefore solar energy is the most promising means to maintain the intensive need for energy.

Primary estimation of solar radiation incident on collector plane is very important to engineers designing solar energy collecting application, to architects designing buildings, and shadow calculation for the solar power plants. To meet all these requirements, one should know the amount of radiation falling upon the collecting surface and its variation over a period of one day and one year.

The amount of the solar radiation incident on a surface is inversely proportional to the value of incidence angle which is defined as the angle between the solar rays and the normal line on the surface. The incidence angle can be calculated by a long equation which depends on several angles.

In addition to the importance of determination of the incident solar radiation, the placement of the solar collector (thermal, electrical) is critical to avoid shading. Especially solar power plants need very large area, so to minimize the occupied area the spaces between the arrays of the collectors should be kept as small as possible. The designer must have an idea about the sun path along the year that's how he will stay away from array-to-array shading. Shading calculation is important for passive buildings design.

The third thing is enhancing the capturing of the solar radiation by sun tracking system which depends basically on the sun position prediction.

2. Solar angles and sun position

The solar angle used in the literatures can be classified to two groups.

2.1 sun position in the sky

For most solar energy applications, one needs reasonably accurate predictions of where the sun will be in the sky at a given time of day and year.

The sun position with respect to an observer on earth can be fully described by means of two astronomical angles, the solar altitude (α) and the solar azimuth (z). The following is a description of each angle, together with the associated formulation. Before giving the equations of solar altitude and azimuth angles, the solar declination and hour angle need to be defined. These are required in all other solar angle formulations.

1- Declination angle, δ: The angle between the Sun's direction and the equatorial plane (is the plane of orbit of the earth around the sun.). δvaries smoothly from +23.45 ° at midsummer in the northern hemisphere, to -23.45 ° at northern midwinter, see Figure 1.

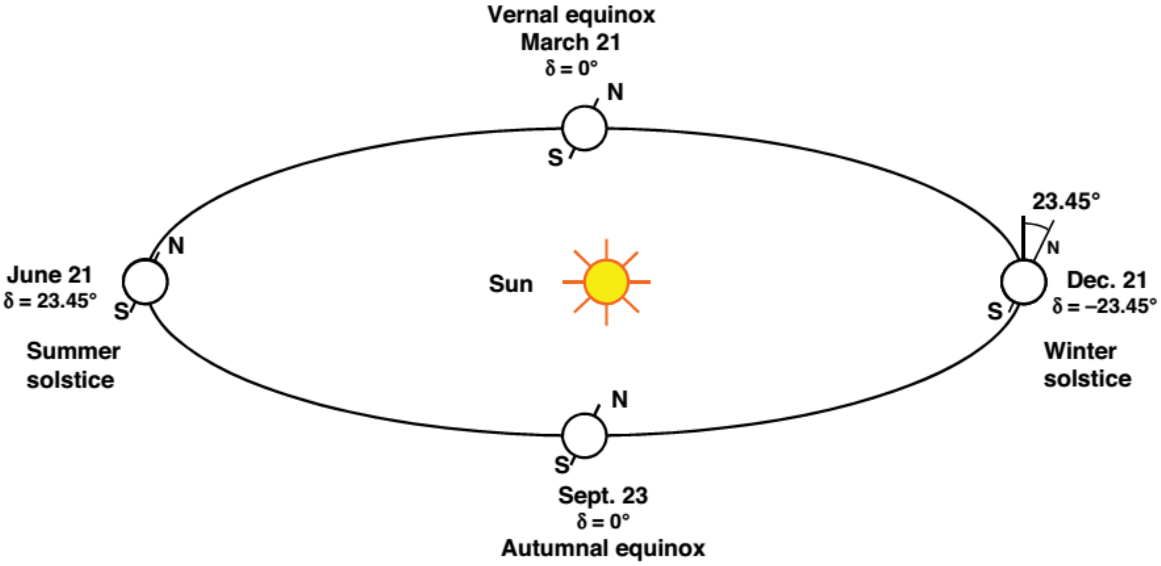


Figure 1. Annual orbital motion of the earth about the sun [2]

Declination angle can be determined by [3]

$$\delta = 23.45° \ sin\left[\frac{360}{365}(n + 284)\right] \qquad (1)$$

where *n* is the day in the year (*n* = 1 on 1 January).

2- Hour angle, h: is the angle through which the Earth has rotated since solar noon. Since the Earth rotates at 360°/24 hour = 15°/ h. The hour angle is positive in the evening and negative in the morning, the hour angle is given by [3]:

$$h = (local\ time - 12)15° \qquad (2)$$

3- Solar altitude angle, α: The angle between the solar beam and the horizontal.

4- Solar zenith angle, ϕ: The angle between the solar beam and the normal on the horizon (Figure 2).

Solar altitude and solar zenith angles are complementing each other $(\alpha + \phi = 90°)$ and calculated by [3]:

$$\sin\alpha = \cos\phi = \sin L \ sin\,\delta + cosL\ cos\delta\ cosh \qquad (3)$$

where, L is the local latitude, values north of the equator are positive and those south are negative, -90< L <90.

5- Solar azimuth angle, z: the angle between the solar beam and the longitude meridian. In northern hemisphere, z equals 0º for a surface facing due south, 180º due north, 0º to 180º for a surface facing westwards and, 0º to −180º eastward.

$$\sin z = \cos\delta \;\; sinh \,/\, cos\alpha \tag{4}$$

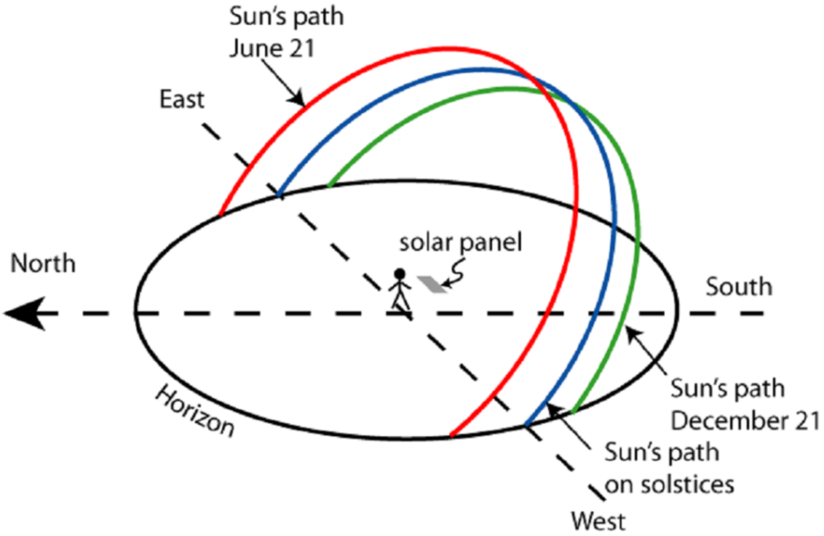


Figure 2. Annual changes in the sun's position in the sky [4]

2.2 Surafce-sun angles

These angles calculated based on a specified mounting and orientation of the solar collector; Figure 3.

1- Tilt angle, β: is the angle between the plane surface and the horizontal (with 0< β <90 for a surface facing towards the equator; 90 < β < -90 for a surface facing away from the equator).

2- Surface azimuth angle, Zs : is the angle between the normal to the surface and the local longitude meridian. Sign convention is as for z. For a horizontal surface, Zs is 0º always.

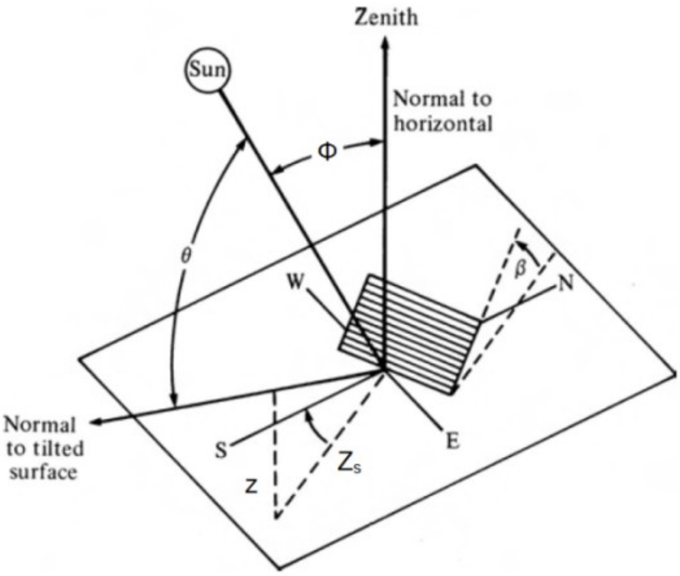


Figure 3. Zenith angle, angle of incidence, Tilt angle, solar azimuth angle and Surface azimuth angle for a tilted surface [3]

3- Angle of incidence, θ: the angle between solar beam and surface normal. θ is Given by [3]:

$$\cos\theta = \sin L \sin\delta \cos\beta - \cos L \sin\delta \sin B \cos Zs + \cos L \cos\delta \,\mathrm{cosh}\, \cos\beta \ldots.$$
$$\ldots + \cos h \sin\beta \cos Zs + \cos\delta \sin h \sin\beta \sin Zs \tag{5}$$

3. Amount incident solar radiation on the collector surface

Usually, solar energy applications (panels, collectors…) are not installed horizontally but at an angle to increase the amount of radiation intercepted and reduce reflection and cosine losses. Therefore, system designers need data about solar radiation on such titled surfaces; measured or estimated radiation data from the Meteorological Stations, however, are mostly available either for normal incidence or for horizontal surfaces [5]. Therefore, there is a need to convert these data to radiation on tilted surfaces. Figure 4 shows the ratio of beam radiation on the tilted surface to that on a horizontal surface at any time R_b,[6].

$$R_b = \frac{G_{Bt}}{G_{Bn}} = \frac{\cos\phi}{\cos\theta} \tag{6}$$

$$G_{Bt} = R_b \; G_{Bn} \tag{7}$$

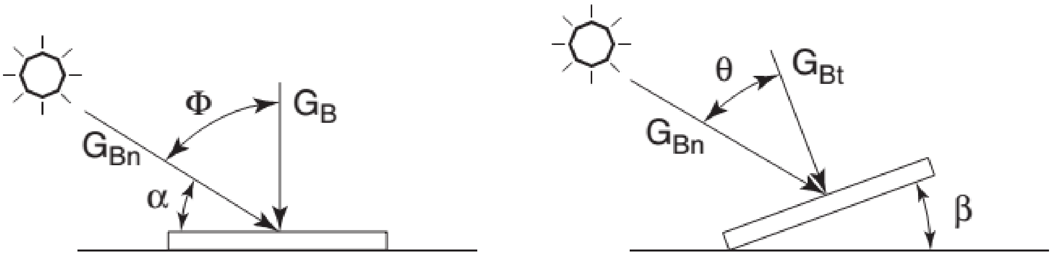


Figure 4. Beam radiation on horizontal and tilted surfaces [6]

4. Matlab code

The MATLAB R2014a platform used to calculate all the aforementioned solar angles and the incident solar radiation on any tilted surface anywhere and anytime.

```
day=input('Day=');%insert the sequence of the day in the month, from 1 to 31
x=input('Month=');%insert the corresponding number of the month, from 1 to 12

m=[0 31 59 90 120 151 181 212 243 273 304 334];
n=m(x)+day %this step evaluate the day sequence number in the year

declination_angle=23.45*sin(360*(284+n)/365*pi/180) %see equ(1)
d=declination_angle*pi/180;

hour=input('Hour =');%insert the hour in the 24 hour system (e.g. 13 for 1 p.m.)
min=input('Minute=');%insert the minute, from 0 to 59

hour_angle=((hour+min/60)-12)*15 %see equ(2)
h=hour_angle*pi/180;

B=input('Slope(tilt angle)in deg=')*pi/180;
L=input('Local latitude in deg=')*pi/180;
Z=input('Surface azimuth angle in deg=')*pi/180;
%the values above is local and independent.

Daily_optimum_tilt_angle=(L-d)*180/pi
Altitude_angle= asin(sin(L)*sin(d)+cos(L)*cos(d)*cos(h))*180/pi %see equ(3)
a=Altitude_angle*pi/180;
```

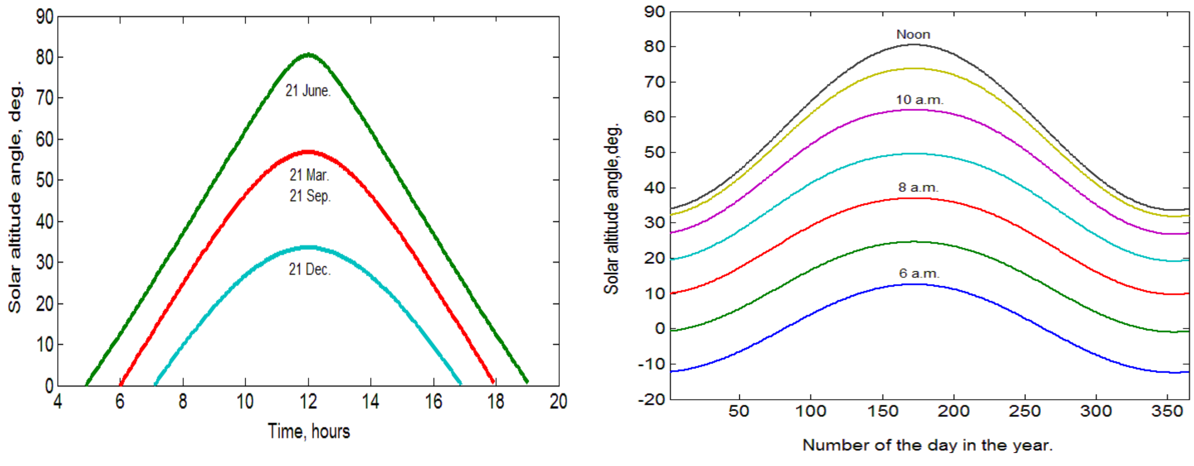
```
Solar_zenith_angle=90-Altitude_angle
phi=Solar_zenith_angle*pi/180;

Solar_azimuth_angle=asin(cos(d)*sin(h)/cos(a))*180/pi %see equ(4)
z=Solar_azimuth_angle*pi/180;

Incidence_angle=acos(sin(L)*sin(d)*cos(B)-
cos(L)*sin(d)*sin(B)*cos(Z)+cos(L)*cos(d)*cos(h)*cos(B)+sin(L)*cos(d)*cos(h)*sin(B)*cos(Z)+cos(d)
*sin(h)*sin(B)*sin(Z))*180/pi %see equ(5)
theta=Incidence_angle*pi/180;

Gbn=input('Solar radiation on horizontal plane =');
RB=cos(theta)/cos(phi) %see equ(6)
Solar_radiation_on_the_surface=RB*Gbn%see equ(7)
```

5. Simulation

A MATLAB simulation had been done for Baghdad city and any place all over the world that share the same latitude (30°). the simulation will provide the sun path (Annual and daily solar altitude angle, Annual and daily solar azimuth angle), also the annual and daily pattern of the solar incidence angle to obtain the optimum tilt angle and the optimum surface azimuth angle for any day during the year and for any time during the day.

6. Results and discussion

1- Daily and Annual pattern of the solar altitude angle:
Figure 5a shows how the solar altitude angle changes for four different dates summer solstice (21 June), winter solstice (21 Dec.), spring equinox (21 Mar.) autumn equinox (21 Sep.), found that in summer the sun sunrise is the earlier than the others (~5am) and suns elevation is higher for about 60° in solar noon than winter and about 25° for the equinoxes (see Figure 2). For 21 December the sunrise happens nearly at 7:00 am.
The solar altitude angle along the year (Figure 5b), six different times in morning to the noon had been chosen to simulate, found that at the noon the sun elevates higher for about 30° than 9 am in summer. But in winter the overall sun elevation for all the times is low about 35° at 1 January. See for 6am; the negative values means that before sunrise and the sun is under the horizon.
Solar altitude angle determine how the collector surface has to be tilting of the horizon.

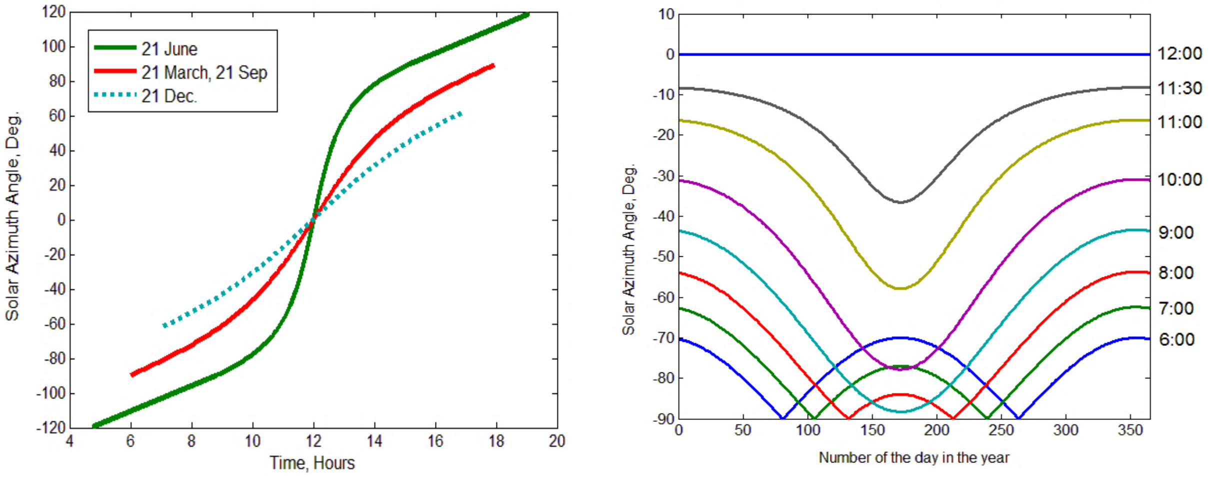


(a) (b)

Figure 5. The pattern of solar altitude angle; (a) daily, (b) annual

2- Daily and Annual pattern of the solar azimuth angle:
In Figure 6a, the solar azimuth angle changes for four different dates (21 March, 21 June, 21 Sep and 21 Dec), it was found that in summer, the longest day and a sun tracking system is preferred than winter to track the sun from the east to the west to capture solar radiation as much as possible (see Figure 2).

The solar azimuth angle along the year (Figure 6b), eight different times in morning to the noon had been chosen to simulate, found that at the noon the sun is at the south all the year. In summer the incremental change in the sun position with the time is greater than winter which prove the need for the tracking system, from 11:30 to 12:00 the sun moves about 30°, while in winter just 9°.



(a) (b)

Figure 6. The pattern of solar azimuth angle; (a) daily, (b)annual

3- Daily pattern of the solar incidence angle with different tilt angles:

First of all, it is important to remember that the smaller incidence angle, the better radiation capturing. Seven different tilt angles as shown in Figure 7, Each of them plotted separately for four dominant dates and the surface considered to be due to south, to get an idea for how the incidence angle change along the day. Between the chosen tilt angles 30° is the best. Results showed that the Daily optimum tilt angle, $\beta_{\text{opt}} = \text{L} - \delta$ as [3, 7].

4- Annual pattern of the solar incidence angle different tilt angles:

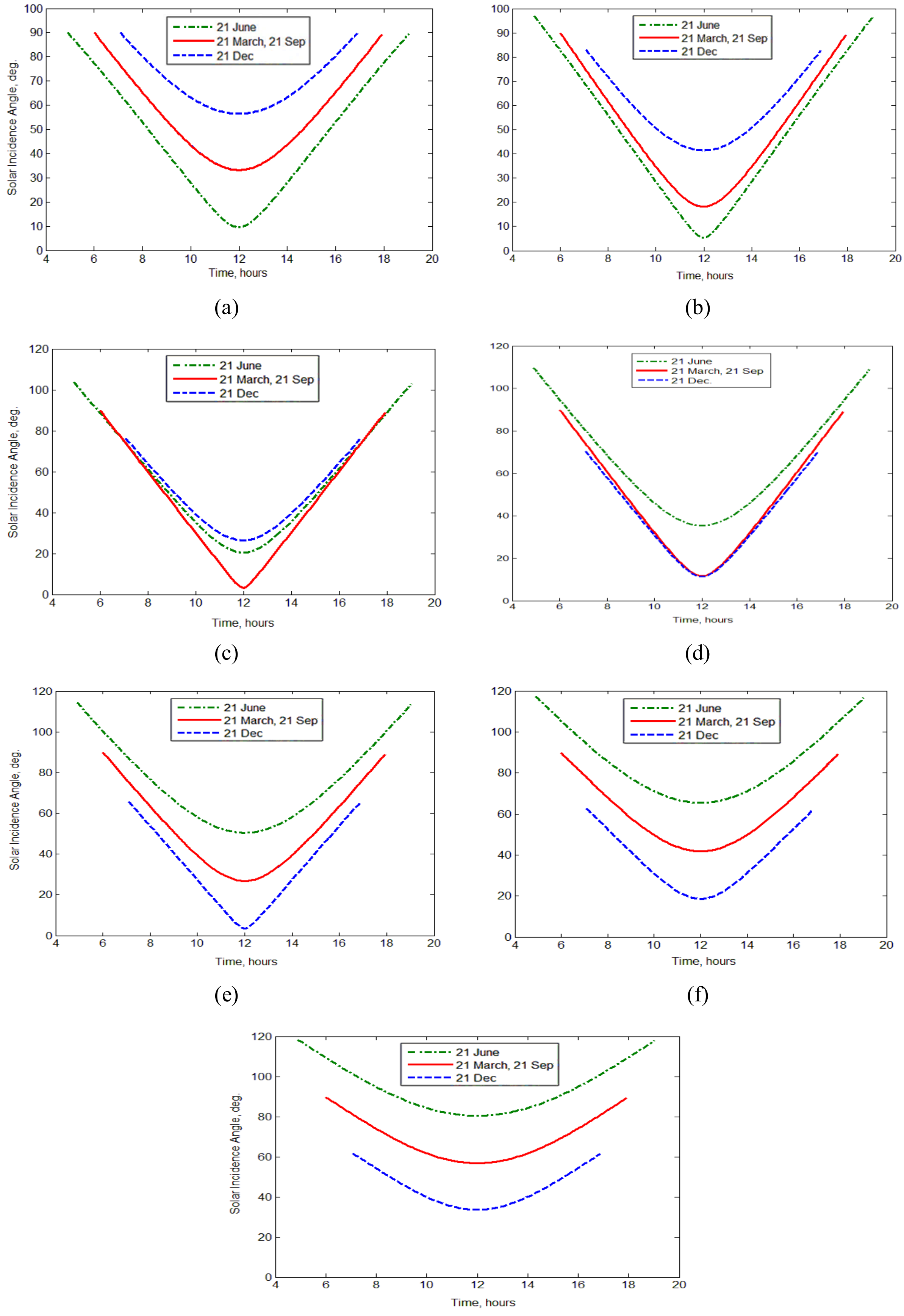
A surface oriented to the south and at three times of the day. Four cases of different dates, the pattern of the solar incidence angles with tilt angles, Figure 8. At 8:00 on the morning, sun tracking system is not needed for 21 March and 21September because the incidence angle varies $\pm 5^{\circ}$ along the year. In contrary for noon time, the incidence angle varies linearly with the tilt angle. In Figure 9, the incidence angle pattern along the year for five tilt angles. At 8:00, in winter no tracking is needed. The plots prove that 30° tilt angle is the best among the chosen tilt angles, which is close to 33o the value of local latitude as [7, 8].

The tilt angle under 15° may not be appropriate when the location is under dusty environment, the accumulation of dust is faster than tilt angles above 15° [4, 9-12].

Duffie and Beckman [3] calculated this angle as $\beta_{opt\,(y)} = (\phi + 15) \pm 15$. Lund [13] achieved this angle as $\beta_{opt\,(y)} = \phi \pm 15$. Heywood [14] obtained the yearly optimum angle as $\beta_{opt\,(y)} = \phi - 10$, Qiu and Riffat [15] found the yearly optimum tilt angle of solar collectors as $\beta_{opt\,(y)} = \phi \pm 10$ at a location with latitude of and the solar energy gain calculated based on the above angles had a relative error below 1.5%. In the above equations, the plus sign is for the northern hemisphere and the minus sign is for the southern hemisphere.

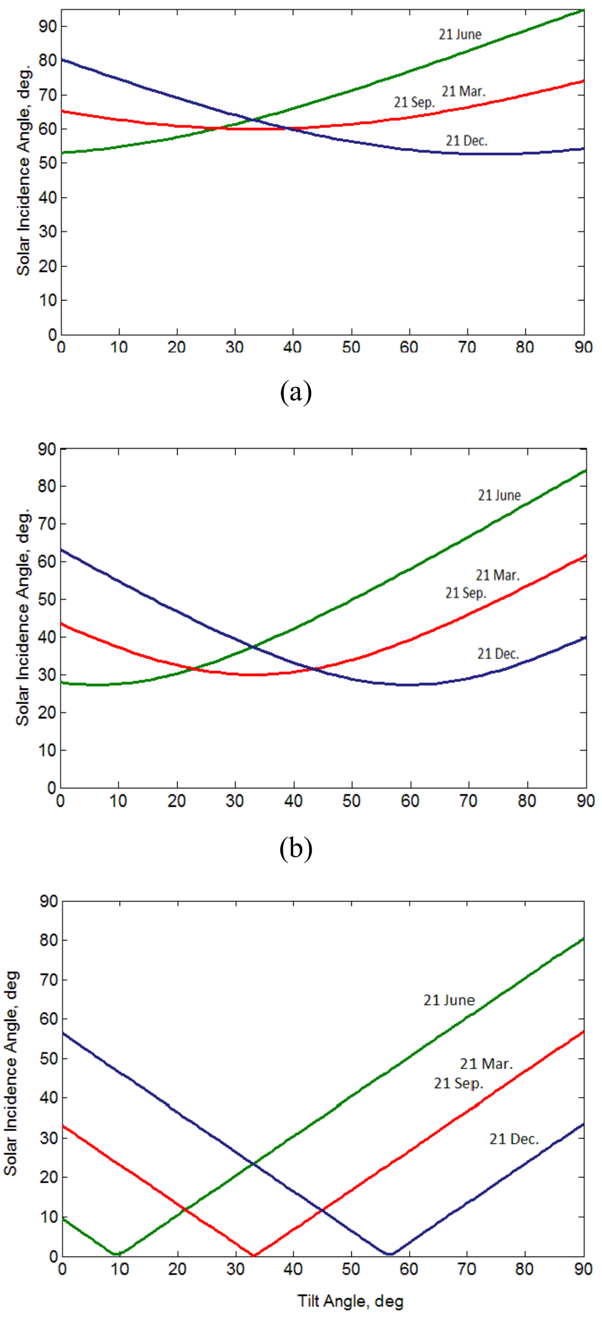
Figure 10 shows the annual pattern of the change of solar incidence angle with surface azimuth angles 0°, 30°,45°, 60° and 90°at the noon for several tilt angles. In summer the figure shows that sun tracking system is not needed at all for the tilt angle except $90^{\circ,}$ incidence angle varies just about 5° that was for summer, while for winter the effect of azimuth is stronger. (Same result in Figure 11, 21 June).

Four dates and at the noon with different tilt angles $\beta=0^{\circ}$, 30°, 45°, 60° and 90° in Figure 11.The change of solar incidence angle with surface azimuth angle, the plot shows that in June sun tracking is not needed for the change of the surface azimuth angle. In winter (21 Dec.), if the collector oriented to -30° to -60° then any tilt angle tracking is not needed (similar for the south west).



(a) (b) (c) (d) (e) (f) (g)

Figure 7. The daily pattern of the change of solar incidence angle for four different dates and the surface oriented to the south and tilted with: (a) β=0° (b) β=15° (c) β=30°(d) β=45°(e) β=60°(f) β=75°(g) β=90°

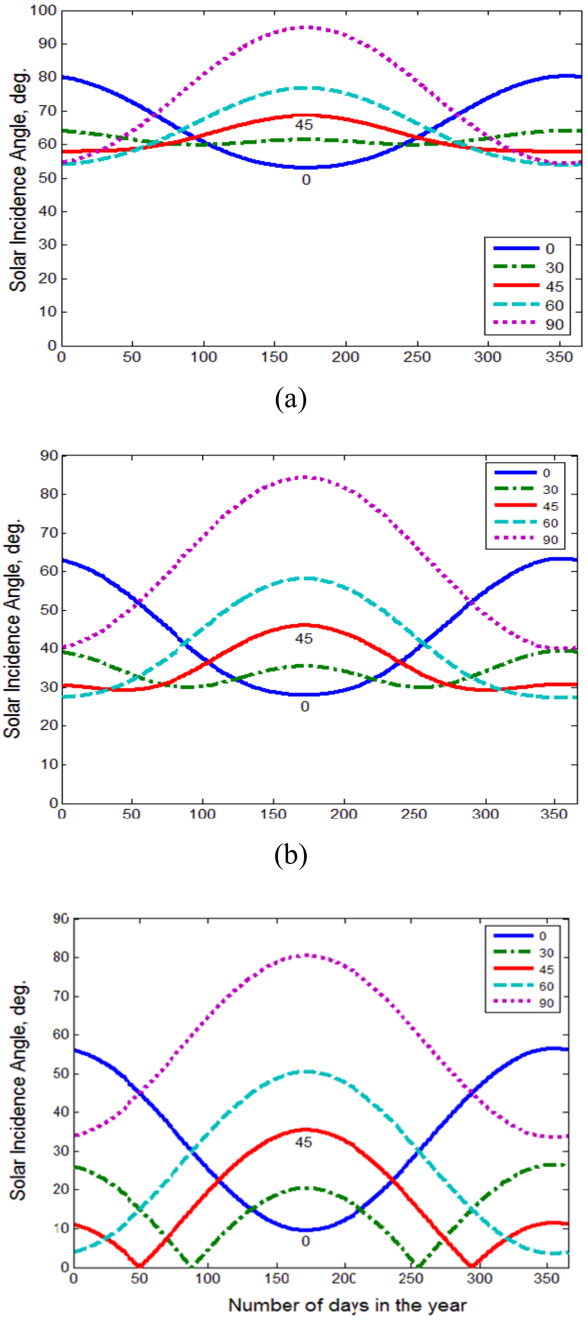


(a)

(b)

(c)

Figure 8. The pattern of the change of solar incidence angle with tilt angle from 0° to 90° cases of four different dates and the surface oriented to the south at (a) 8:00 am, (b)10:00 am, (c) 12:00 noon



(a)

(b)

(c)

Figure 9. The annual pattern of the change of solar incidence angle with five tilted angles and the surface oriented to the south at (a) 8:00 am, (b) 10:00 am, (c) 12:00 noon

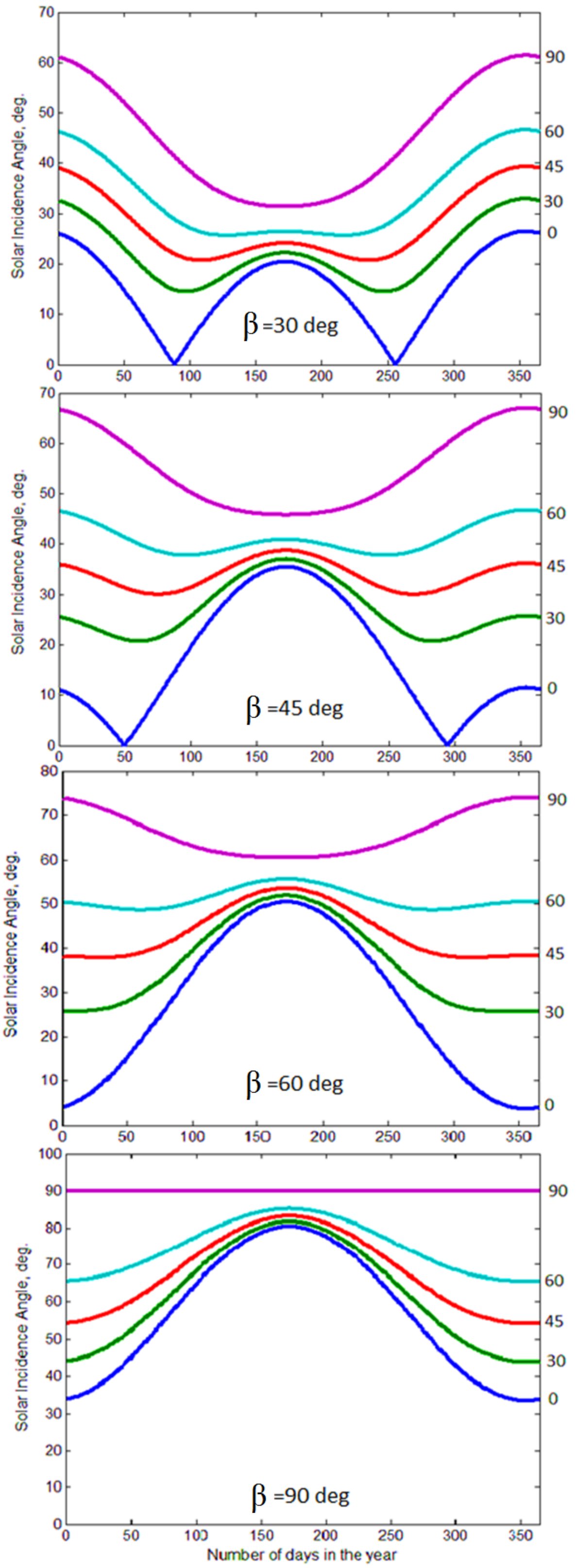


Figure 10. The annual pattern of the change of solar incidence angle with azimuth angles 30°,45°, 60° and 90°at the noon for tilt angles β=30°,45°, 60° and 90° from top to bottom respectively

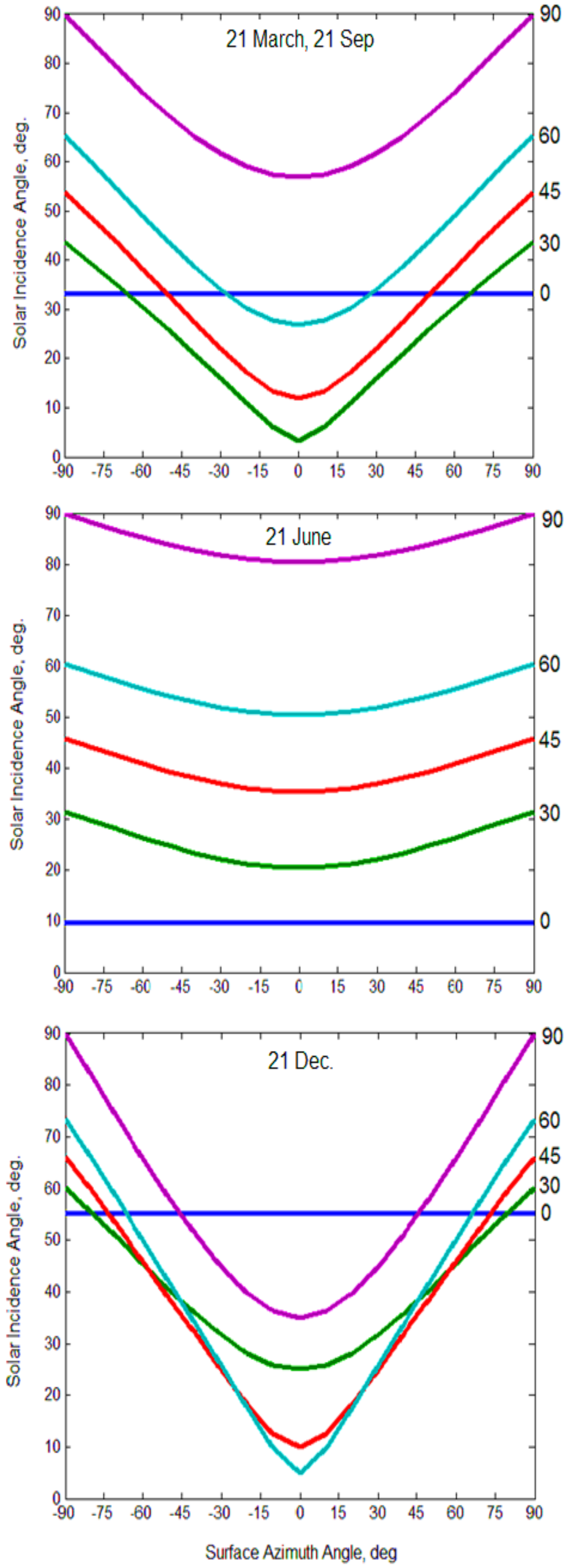


Figure 11. The change of solar incidence angle with azimuth angle for different tilt angles β=0°, 30°, 45°, 60° and 90° for four dates and at the noon

7. Conclusion

The priceless feature of solar energy applications, it consumes free fuel which is the solar radiation. Unfortunately, the sun is moving continuously. So, Sun Tracking systems are used to keep the sun rays perpendicular on the solar collector as possible. Trackers add cost and maintenance to the system depend on if they are simple, complicated and so on. Choosing the right tracker is made after studying the sun position and how much gain will be earned by installing the tracker.

A solar path and angles simulation was taken for 33°latitude (Baghdad city). The results showed that the annual optimum tilt angle is 33°,daily optimum tilt angle $\beta_{opt} = L - \delta$,annual and daily surface azimuth angle is due to the south for fixed solar collector. Additionally showed the dates and times that solar tracker is needed and when it is not needed. Also gave the sun position in the sky for shading calculation.

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