MATHEMATICAL MODEL FOR DETERMINING OF HOURLY AVERAGE TOTAL SOLAR RADIATION ON TILTED SURFACE OF TWO DIFFERENT CITIES (MANSOURA AND RIYADH)

NASSER M. EL ASHMAWY

Agricultural Engineering Research Institute (AEnRI) , Giza, EGYPT.

(Manuscript received 13 June 2016)

Abstract

The main drawback of solar energy utilization in any application based on calculated hourly average solar radiation flux incident on a horizontal plane is the clearness index of the specific location. A mathematical model using MATLAB program was functioned to compute the hourly average solar radiation flux incident on a horizontal surface of Mansoura University (latitude and longitude angles, and altitude above the sea level, respectively, are 31.045ºN, 31.365ºE, and 6.0 m) and King Saud University (24.725°N, 46.617°E, and 611 m). The hourly average solar radiation measured on a horizontal surface at the same locations and times was used with that calculated for the average day of each month throughout a whole year in order to determine the clearness index (K_T). The split of total solar radiation measured on a horizontal surface into its beam and diffuse components is of interest in two contexts. Firstly, methods for calculating total solar radiation on surfaces of other orientation from data on a horizontal surface require separate treatments of beam and diffuse solar radiation. Secondly, estimates of the long-time thermal performance of most concentrating solar collectors must be based on estimates of availability of beam solar radiation. The measured data of hourly average solar radiation on tilted surface was validated against that computed by Duffie and Beckman model using coefficient of determination (R^2), correlation coefficient (r), and root mean square error (RMSE). The obtained results revealed that, the validation between the measure and calculated data was highly agreement as the (R^2) and (r) were high and the (RMSE) was low.

NOMENCLATURE

Φ	Latitude angle	Degree
δ	Solar declination angle	Degree
ω	Solar hour angle	Degree
β	Tilt angle	Degree
τ_b	The atmospheric transmittance for beam solar radiation	Decimal
τ_d	The atmospheric transmittance for diffuse solar radiation	Decimal
β_o	Optimum tilt angle at monthly average daily on a tilted surface at noon	Degree
ET	Equation of time, decimal minutes	Decimal
I_c	Hourly average total solar radiation flux incident on a horizontal surface.	W/m^2
I_{cb}	The clear sky beam solar radiation flux incident on a horizontal surface	W/m^2
I_{cd}	The diffuse Irradiance on the horizontal plane	W/m^2
I_d/I	the fraction of the hourly average solar radiation on a horizontal surface which is diffuse	Decimal
$\mathbf{I_{on}}$	The extraterrestrial solar radiation	W/m^2
I_T	Total solar energy on tilted surface	W/m^2
K_T	An hour clearness index	Decimal
LAT	Local Apparent Time	Number
LON	Local longitude, decimal degree	Decimal
LSM	Local standard time meridian, decimal degree	Decimal
LST	Local solar time, decimal hours	Number
n	Number of day	Number
R_b	The ratio of beam solar radiation on a tilted surface to that on a horizontal surface.	Decimal
S	The altitude of the observer	km
z	Solar Zenith angle	Degree

INTRODUCTION

The solar energy is one of the most important energy sources in the world. One of the most prominent factors in the prediction, the study and design of solar power systems at different sites is to get information and statistics minute on solar radiation degree on each site, to the extent that it is necessary to estimate the amount of solar energy in each area before measuring and scheduling to be used (Raeiszadeh and Behbahanizadeh, 2012). Solar radiation emitted per unit area of the sun is about 6.33 x 10^7 W/ha (6.33 x 10^3 W/m^2). If it is possible to come from just 10 hectares of the sun's surface energy harvesting, it will be sufficient to provide enough energy for the world. But this is not possible because the amount of radiation leaving the unit area of the surface of the sun is not equally accessible to the unit equal space on the Earth's surface. It is due to some factors that could predict such as the displacement of the earth from the sun, the atmospheric conditions of the Earth and the reason for this decline.

As a result of these factors reductive, has found by engineers and designers, it is important to know the estimate of radiation that reaches the earth's surface based on the location of its usefulness in the proper analysis of the solar energy collection systems. The hourly and also instantaneous distribution of solar radiation is needed in various applications in the field of solar energy. The most reliable predictions of solar system performance are based on pyranometer data taken over a period of year at the place of interest. In many instances, however, available solar radiation data that have been collected are presented as a sum of integrated daily values (Vieira et al., 2002; Bakirci, 2008). Besides, it can also be affected by the density of radiant energy in the atmosphere that reaches the earth's surface, according to the extent of cloud cover and dust aerosol particles as through the location. Radiation that reaches the earth's surface lower by 30% on a clear day, and by 90% in the hazy days (cloudy) belonged to the beam out of the atmosphere. Therefore, it is appropriate to say that solar power systems are designed with better performance on a clear day because there is more radiation. Therefore, the need to make sure estimate radiation (directly or beam and the dissemination of the total radiation) on the surface (vertical, horizontal and diagonal) on a clear day in a specific location (s) using the analytical method (models) or experimental measurements become very important and very necessary. The analytical methods, whether simple or complex, were developed by different authors for several locations to estimate solar radiation.

The daily global solar radiation data obtained from three different Libyan locations (Sabha-desert region, Ghdames-middle region and Tripoli-Mediterranean region) were used to establish a relationship between daily diffuse fraction and daily clearness index K_T. Solar radiation and sunshine duration are intimately related phenomena, which was used to study the equation related the daily average radiation with the extraterrestrial radiation for location and average fraction of possible sunshine hours. Moreover the daily clearness index was calculated and was used to estimate the frequency of occurrence of days with different values of K_T and the cumulative frequency of occurrence of those days. Finally, the relationships for estimating the beam and diffuse components of daily global radiation were obtained using models of many researchers (ASHRAE, 2005; Duffie and Beckman, 2013; Ahwide, et al., 2013).

Hourly and daily measurements of total and diffuse solar radiation and sunshine duration are analyzed. Three measurements of the age of meteorological data available in Mosul city, Iraq (latitude 36.32°N, Longitude 43°E and altitude 223 m above the sea level) were used in study carried out by Hassan (2014). His current work involves two parts; the first one, monthly average based on daily and hourly of all dissemination and analysis of solar radiation. The results showed that the annual rate of total daily and diffuse solar radiation is 5.11 and 1.6 kWh/ m^2, respectively. About 57% of clear days a year, while only 11.5% of cloudy days. Many of mathematical equations to estimate the monthly average global solar radiation and disarmament daily diffuse have been developed and compared with other models available. The second part; was the implementation of time-series model using the procedure of Jenkins Fund Index daily and clarity. The results of this study indicated that, the maximum values of daily average monthly total solar radiation and dissemination of solar radiation in Mosul is 7.99 and 2.39 kWh/m^2, respectively, while the minimum values were 2.13 and 0.93 kWh/m^2, respectively. Hourly average of total solar radiation and the dissemination of solar radiation, respectively, were 958 and 269 W/m^2 which reaches a maximum values between 13: 00 -14: 00 hours local time. It must be known incident solar radiation on the surfaces of buildings and collectors in order to perform thermal analysis. In general, measurements of the daily average total solar radiation flux incident on a horizontal surface are only available. As most inclined surfaces of interest, it is necessary to determine the hourly average solar radiation on the inclined surface. Usually it requires appreciation packages and diffuse components of the hourly average solar radiation procedures. The beam and diffuse radiation components must be estimated daily during the applications.

Theoretical Approach

The quantities of solar radiation flux incident on a tilted surface are considered to be very important particularly for solar collectors which tracking the sun's rays from sunrise to sunset. To estimate the hourly average solar radiation on a tilted surface, the following steps should be taken into consideration (Duffie and Beckman, 2013):

1- Hourly average total solar radiation flux incident on a horizontal surface

The horizontal plane of the ground surface continually receives two components of solar radiation; beam solar radiation, and diffuse solar radiation. Sum of these two components is the hourly average total solar radiation on a horizontal surface (I_c)

$$I_c = I_{cb} + I_{cd}, \quad W/m^2 \quad \ldots\ldots\ldots\ldots\ldots (1)$$

Where, I_{cb}, is the clear sky beam solar radiation flux incident on a horizontal surface. It can be estimated from the following equation:

$$I_{cb} = I_{on}\ \tau_b\ \cos z, \quad W/m^2 \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where, $\mathbf{I_{on}}$, is the extraterrestrial solar radiation and is given by

$$I_{on} = 1353\,[1 + 0.033 \cos(\frac{360\,n}{365})], \quad W/m^2 \quad .... (3)$$

τ_b **,** is the atmospheric transmittance for beam solar radiation and is given by

$$\tau_b = a_o + a_1\ exp\left(-\frac{k}{\cos(z)}\right), \quad decimal \quad .... (4)$$

The constants**,** a_o , a_1 , and k for the standard atmosphere with 23 km visibility are found from a_o^* , a_1^* and k^* **,** which are given for altitude less than 2.5 km.

$$a_o^* = 0.4237 - 0.00821\,(6 - S)^2, \quad decimal \quad .... (5)$$

$$a_1^* = 0.5055 + 0.00595\,(6.5 - S)^2, \quad decimal \quad .... (6)$$

$$k^* = 0.2711 + 0.01858(2.5 - S)^2, \quad decimal \quad .... (7)$$

Where, S, is the altitude of the observer in km. Correction factors are applied to a_o^*, a_1^* and k^* to allow for changes in climate types. The correction factors $r_o \equiv a_o / a_o^*$ ($a_o = r_o\ x\ a_o^*$), $a_1 \equiv r_1\ x\ a_1$, and $k \equiv r_k\ x\ k^*$ are given in Table (1).

Table 1. Correction factors for different climate types (Duffie and Beckman, 2013)

Climate type	r_o	r_1	r_k
Tropical	0.95	0.98	1.02
Mid-latitude summer	0.97	0.99	1.02
Sub-arctic summer	0.99	0.99	1.01
Mid-latitude winter	1.03	1.01	1.00

For a horizontal surface, the solar zenith angle (z) is obtained from the following equation:

$$\cos z = \cos\Phi \cos\delta \cos\omega + \sin\Phi \sin\delta, \quad decimal \quad .... (8)$$

The declination angle (δ) which accounts for the seasonal changes of the sun's path through the sky throughout the months of the year is given in degrees, by the following equation:

$$\delta = 23.45 \sin[0.9863\,(n + 284)] \quad .... (9)$$

The solar hour angle can be determined from the following equation:

$$\omega = (LAT - 12) \times 15, \quad degree \quad .... (10)$$

Equation (11) relates apparent solar time (LAT) to local standard time (LST) as follows **(ASHRAE, 2005)**:

$$LAT = LST + (ET/60) + (LSM - LON)/15 \quad .... (11)$$

The equation of time (ET) in minutes can be calculated from the following Equation:

$$ET = 9.87 \sin 2x - 7.53 \cos x - 1.5 \sin x \quad .... (12)$$

$$x = (n - 81)\,\frac{360}{365} \quad .... (13)$$

It is also necessary to estimate the atmospheric transmittance for diffuse solar radiation (**τ_d**) to get the total solar radiation flux incident on a horizontal plane. An empirical relationship between the transmission coefficients for beam and diffuse solar radiation for clear days has been developed as follows:

$$\tau_d = 0.2710 - 0.2939 \ \tau_b, \quad \text{decimal} \quad \ldots\ldots\ldots\ldots\ldots (14)$$

I_{cd} **,** is the diffuse Irradiance on the horizontal plane and is given by

$$I_{cd} = I_{on} \ \tau_d \ \cos(z), \quad W/m^2 \quad \ldots\ldots\ldots\ldots (15)$$

2- An hour clearness index (K_T)

An hour clearness index **(**K_T**)** can also define as the ratio of hourly average measured solar radiation on a horizontal surface (I) to the hourly average estimated solar radiation on a horizontal surface (I_c)

$$K_T = \frac{I}{I_c} \quad \ldots\ldots\ldots\ldots (16)$$

For values of (K_T) greater than 0.8 there are very few data. Some of the data that are available show increasing diffuse fraction as (K_T) increases above 0.8. This apparent rise in the diffuse fraction is probably due to reflection of solar radiation from clouds during times when the sun is un-obscured but when there are clouds near path from the sun to observer.

(3) Beam and diffuse components of solar radiation

Erbs et al. (1982), Reindl et al. (1990a) and Duffie and Beckman (2013) linked between**,** I_d/I, (the fraction of the hourly average solar radiation on a horizontal surface which is diffuse) and**,** I/I_c **,** (the ratio of an hour's solar radiation to the standard clear sky radiation for that hour). An equation representing this correlation is:

$$\frac{I_d}{I} = \begin{cases} 1.00 - 0.1 \ K_T & \text{for } 0 \le K_T < 0.48 \\ 1.11 + 0.0396 \ K_T - 0.789 \ K_T^{\ 2} & \text{for } 0.48 \le K_T < 1.10 \\ 0.20 & \text{for } K_T \le 1.10 \end{cases} \quad \ldots (17)$$

(4) Hourly average total solar radiation on a tilted surface

Horizontal flat-plate solar collector receives both beam and diffuse components of solar radiation. Whilst, the tilted solar collectors received three components; beam radiation, diffuse solar radiation, and solar radiation diffusely reflected from the ground. A surface tilted at slope, β, from the horizontal has a view factor to the sky (the angle factor between the surface and the sky) given by $(1 + \cos\beta)/2$. The surface also has a view factor to the ground (the angle factor between the surface and the ground) given by $(1 - \cos\beta)/2$, and if those surroundings have reflectance of, ρ, for the total solar radiation, the reflected radiation from the surroundings on the surface is [(I_d + I_b) ρ (1 - cos β)/2]. The total solar radiation on the tilted surface for an hour is then the sum of three terms (Foster et al., 2010; Duffie and Beckman, 2013):

$$I_T = I_b\ R_b + I_d\ R_d + I\ \rho\ R_r, \quad W/m^2 \ \ldots\ldots\ldots\ldots (18)$$

Where, R_b, is the ratio of beam solar radiation on a tilted surface to that on a horizontal surface. For stationary non-tracking solar collector it is given by

$$R_b = \frac{\cos(\theta)}{\cos(z)}, \quad \text{decimal} \ \ldots\ldots\ldots\ldots (19)$$

$$R_b = \frac{\cos(\phi-\beta)\cos(\delta)\cos(\omega)+\sin(\phi-\beta)\sin(\delta)}{\cos(\phi)\cos(\delta)\cos(\omega)+\sin(\phi)\sin(\delta)}, \quad \text{decimal} \ \ldots (20)$$

For tracking solar collector to track the sun's rays from sunrise to sunset it is given by (Reindle et al., 1990b)

$$R_b = \frac{1}{\cos(z)}, \quad \text{decimal} \ \ldots\ldots\ldots\ldots (21)$$

The angle factor between the tilted surface and the sky (R_d) for diffuse radiation can be computed as follows:

$$R_d = \cos^2\frac{\beta}{2} \ \ldots\ldots\ldots\ldots\ldots\ldots (22)$$

The angle factor between the tilted surface and the ground surface (R_r) for reflected radiation can be estimated as follows:

$$R_r = \sin^2\frac{\beta}{2} \ \ldots\ldots\ldots\ldots\ldots\ldots (23)$$

A computer model has been developed and used for computing the hourly average total solar radiation flux incident on tilted surface. The model has implemented as a stand-alone program running on IBM compatible microcomputer. The developed mathematical model has solved with the help of computer program based on MATLAB. The program requires two input files: one contains the simulation parameters and the other contains the input data. Table (2) lists all inputs required to run the program together with the parameter values used for the simulations runs. The program outputs data listed in Table (2). The simplified flowchart for MATLAB program showed in Fig. (1).

Data Base

Data measurements, including hourly average daily solar radiation and sunshine duration of the global radiation on horizontal surface for a period of 3 years from 2012 to 2014 using meteorological station in the field of experiments and researches at Mansoura University in Egypt (latitude 31° 2.7' N, longitude 31° 21.9' E and altitude 6 m) , and meteorological station at King Saud University in Riyadh (latitude 24° 43.5' N, longitude 46° 37' E and altitude 611 m) and the data for the 3 years from 2012 to 2014. The direct and diffuse radiation per day was computed. In general, solar energy abundance in Mansoura and King Saud Universities, and clear from the annual average global solar radiation, daily average on horizontal surfaces was ranged between 2.935 and 7.236 kWh/m^2, and between 3.992 and 7.601 kWh/m^2, respectively. This corresponds to a total annual value of 1.071 – 2.641 and 1.457 – 2.774 MWh/m^2, respectively. The maximum values of the diurnal average solar radiation at selected meteorological stations were achieved on June and July and the lowest value occurred on December.

Table 2. Parameters and variables required as input and variables output by MATLAB program.

Configuration file inputs	Value
Latitude angle (Φ), ºN (Mansoura)	31.045
Latitude angle (Φ), ºN (Riyadh)	24.725
Altitude above the sea level (S), km (Mansoura)	0.006
Altitude above the sea level (S), km (Riyadh)	0.611
Correction factors for mid-latitude winter, r_o, r_1, and r_k	1.03, 1.01, and 1.00
Correction factors for mid-latitude summer, r_o, r_1, and r_k	0.97, 0.99, and 1.02
Data file inputs	
Measured solar radiation flux incident on horizontal surface (I), W m^{-2} (Mansoura)	
Measured solar radiation flux incident on horizontal surface (I), W m^{-2} (Riyadh)	
Reflectance of surroundings (ρ), decimal	
Data outputs	
Extraterrestrial solar radiation (I_{on}), W m^{-2}	
Hourly average total on horizontal surface (I_C), W m^{-2}	
Hour clearness index (K_T), dimensionless	
Fraction of hourly average radiation on horizontal surface which is diffuse (I_d/I), dimensionless	
Ratio of beam solar radiation on tilted surface to that on	
Beam solar radiation on tilted surface (R_b I_b), W m^{-2}	
Diffuse solar radiation on tilted surface (I_d), W m^{-2}	
Reflected solar radiation on tilted surface, (I_r), W m^{-2}	

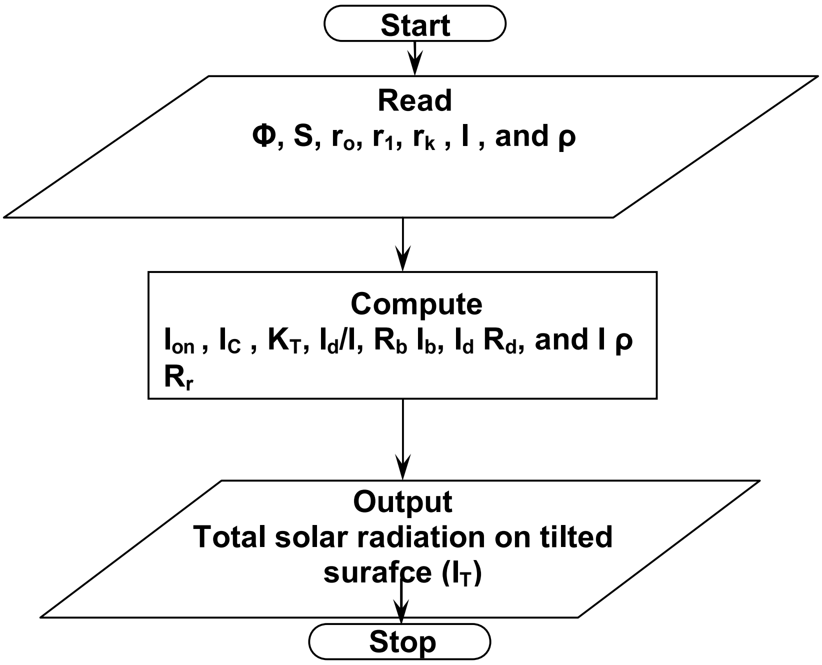


Fig. 1. Simplified flowchart for MATLAB program.

MATERIALS AND METHODS

Terrestrial solar radiation

The total solar radiation incident on either a horizontal or tilted plane consists of three components; beam, diffuse and reflected radiation. As sunlight passes through the atmosphere, some of it is absorbed, scattered, and reflected by water vapour, molecules of dry air, clouds, dust, and pollutants. The diffuse solar radiation is the portion scattering downward from the atmosphere that arrives at the earth's surface and the energy reflected on the surface from the surroundings. The solar radiation that reaches the earth' surface without being modified in the atmosphere is the beam solar radiation. Atmospheric conditions can reduce beam solar radiation by 10% on clear and dry days, and by nearly 100% during dark and cloudy days (Foster et al., 2010). Moreover, records on the Earth's surface include uncertainty due to measurement errors. Since solar radiation is associated with the sun's rays, tried by many researchers based on their estimations on the development of measurement records for the brightness of the sun are more easily and economically. The integration of instantaneous values of global solar radiation to obtain an hourly and daily averages solar radiation for each day from 2012 to 2014 (in Egypt), and from 2013 to 2015 in Riyadh were executed. These values of global radiation, the number of days, time of the day, latitude angle, elevation, and the form of the equations were presented in and used a clear radiation sky in the model.

Measurements of daily average total solar radiation

Experimental measurements of the hourly average total solar radiation flux incidence on a horizontal surface which is the sum of tow components (beam and diffuse radiation) were functioned using disk solarimeter device located on horizontal plane throughout the daylight-time (duration from 9 to 13 hours) according to the day-length and intensity of solar radiation. The maximum possible number of bright sunshine hours of Mansoura University is 4385.0 hrs of which 3587.8 hrs is the actual number of bright sunshine hours. While, the maximum possible number of bright sunshine hours of Riyadh city is 4380.9 hrs of which 3845.7 hrs is the actual number of bright sunshine hours.

Analytical methods for beam radiation estimation using Duffie and Beckman model (2013).

Analytical data generation employed in equation 4 with a_0, a_1 and k being determined using correction factor as described by equations 5 through 7. The declination angle, δ, which accounted for the seasonal changes of the sun's path through the sky throughout the months of the year, was used and given by equation 9. For the horizontal surface, the zenith angle, z, was calculated by equation 8 and the hour angle, ω, was determined using equation 10; where LAT is the solar time in hours and it is in reference to a particular location. It is given by equation 11. The output data from the MATLABP program terrestrial solar radiation and measured data for Egypt and Saudi Arabia to determine the value of K_T by equation 16, and determine the proportion of I_d/I by using the equation 17, as well as the expense of the total solar radiation on the tilted surface for an hour by Eq. 18.

RESULTS AND DISCUSSION

The total solar radiation flux incident on the tilted tracking surfaces using an optimum tilt angles and orientation for Mansoura and Riyadh cities were measured and computed. Two solar collectors each having a surface area of 2.0 m^2 were mounted individually on movable frames at Mansoura and King Saud Universities. The movable frames were adjusted manually to change the orientation and tilt angle once each half hour so that at that time the angle of incidence of the solar collector surface and the sun's rays was set at zero. The optimum tilt angle used in this research work was computed using equation (8). Comparison between the measured and calculated total solar radiation incoming into a tilted surface was examined and the root mean square error was determined.

For the duration of winter months start from October till March, the daily average extraterrestrial solar radiation (I_{on}), terrestrial solar radiation on horizontal surface includes beam component (I_{cb}) and diffuse component (I_{cd}), total terrestrial radiation incoming into a horizontal surface (I_c), measured solar radiation flux incident on a horizontal surface (I), clearness index (K_T), and total solar radiation incoming into a tilted surface (I_T) for Mansoura and Riyadh cities are listed in Tables (3 and 4).

Table 3. Solar radiation data obtained for Mansoura University during the winter months.

Month	I_{on}, W m^{-2}	I_{cb}, W m^{-2}	I_{cd}, W m^{-2}	I_c, W m^{-2}	I, W m^{-2}	K_T, decimal	I_{TC}, W m^{-2}	I_{TM}, W m^{-2}
Oct. (11 hrs)	1363.9	3837.8	894.3	4732.1	4638.9	-	6854.2	6707.5
		348.9	81.3	430.2	421.7	0.9427	623.1	609.8
		218.6	22.7	239.9	260.4	0.0838	265.1	259.4
Nov. (9 hrs)	1383.8	2825.3	757.6	3582.9	3522.9	-	5785.7	5579.1
		313.9	84.2	398.1	391.4	0.9646	642.9	619.9
		145.1	13.0	157.4	175.0	0.0504	187.8	176.0
Dec. (9 hrs)	1394.8	2391.5	721.9	3113.4	2934.9	-	4894.6	4649.8
		265.7	80.2	345.9	326.1	0.9118	543.8	516.6
		142.9	16.0	158.5	168.3	0.0799	218.3	207.4
Jan. (9 hrs)	1395.7	2626.6	744.8	3371.4	3321.1	-	5573.1	5294.4
		291.8	82.8	374.6	368.0	0.9542	619.2	588.3
		149.6	14.9	164.1	179.8	0.0742	222.3	211.2
Feb. (11 hrs)	1383.8	3510.9	867.8	4378.7	4311.6	-	6681.3	6397.3
		319.2	78.9	398.1	392.0	0.9399	607.4	581.6
		210.1	25.6	234.0	245.9	0.0863	275.6	263.9
March (11 hrs)	1365.3	4614.3	961.9	5576.2	5520.9	-	7577.9	7308.2
		419.5	87.5	506.9	501.9	0.9562	688.9	664.4
		236.5	18.1	253.9	272.0	0.0769	262.0	252.7
Total (60 hrs)	8287.3	19805.6	4948.6	24754.2	24241.3	-	37366.8	35936.3
Mean	1381.2	330.1	82.5	412.6	404.0	0.9450	622.8	598.9
SD	13.9	183.8	18.4	201.3	216.9	0.0753	238.5	228.4
RMSE							184.7	

Cyclic changes in terrestrial solar radiation included beam and diffuse radiation with time of the day during winter months were observed. The terrestrial solar radiation (I_C) for Mansoura and King Saud Universities was ranged between 52.1 and 842.1 W m^{-2}, and between 83.6 and 935.5 W m^{-2}, respectively. These differences between minimum and maximum values can be attributed to the variation of solar altitude angle and accordingly to the solar zenith angle. The daily average total terrestrial solar radiation flux incident on horizontal surface during winter months for Mansoura and King Saud Universities, respectively, are 4.126 and 5.126 kWh m^{-2}, while, the daily average total solar radiation measured on horizontal surface during the same period for the two universities was 4.040 and 4.889 kWh m^{-2}, respectively. Therefore, changes in an hour clearness index (K_T) with time of the day throughout the winter months for Mansoura and King Saud Universities were also observed and plotted in Figs. (2 and 3).

Table 4. Solar radiation data obtained for King Saud University, Riyadh during the winter months.

Month	I_{on}, W m^{-2}	I_{cb}, W m^{-2}	I_{cd}, W m^{-2}	I_c, W m^{-2}	I, W m^{-2}	K_T, decimal	I_{TC}, W m^{-2}	I_{TM}, W m^{-2}
Oct. (11 hrs)	1363.9	4939.2	779.4	5718.6	5361.1	-	7103.6	6951.9
		449.0	70.9	519.9	487.4	0.8957	645.8	632.0
		258.6	15.7	273.4	282.3	0.0892	283.3	277.3
Nov. (9 hrs)	1383.8	3928.5	669.4	4597.9	4402.9	-	6352.2	6120.4
		436.5	74.4	510.9	489.2	0.9350	705.8	680.0
		182.7	8.8	191.3	207.3	0.0705	218.1	210.1
Dec. (9 hrs)	1394.8	3499.7	652.7	4152.4	3992.4	-	6147.9	5882.0
		388.9	72.5	461.4	443.6	0.9390	683.1	653.6
		174.8	9.9	184.5	198.1	0.0639	215.7	206.4
Jan. (9 hrs)	1395.7	3739.8	664.9	4404.7	3960.4	-	6198.3	5971.4
		415.5	73.9	489.4	440.0	0.9324	731.4	663.5
		179.9	9.4	189.1	193.6	0.0619	211.7	197.1
Feb. (11 hrs)	1383.8	4644.0	768.3	5412.3	5147.7	-	7347.9	7013.6
		422.2	69.8	492.0	468.0	0.9275	668.0	637.6
		253.5	17.8	270.0	268.3	0.0651	249.5	240.2
March (11 hrs)	1365.3	5654.8	817.5	6472.3	6257.7	-	8189.7	7903.0
		514.1	74.5	588.4	568.9	0.9443	744.5	718.5
		271.5	13.0	283.9	291.1	0.0543	246.1	237.5
Total (60 hrs)	8287.3	26406.0	4352.2	30758.2	29335.2	-	41339.6	39842.3
Mean	1381.2	440.1	72.5	512.6	488.9	0.9290	689.0	664.0
SD	13.9	220.2	12.4	232.0	240.1	0.0675	237.4	228.1
RMSE							193.3	

The ratio of hourly average measured solar radiation on a horizontal surface (I) to the hourly average terrestrial solar radiation (calculated) on a horizontal surface (I_c) for Mansoura and King Saud Universities was ranged between 0.7907 and 1.0632, and between 0.7316 and 1.0202, respectively. These variations in clearness index can be attributed to the changes in atmospheric conductions (molecules of dry air, water vapour, carbon dioxide, and air mass). Therefore, the minimum values of clearness index during winter month mainly occurred just after sunrise and prior to sunset for both different locations. While, the maximum values of clearness index were achieved at and around noon time. The diurnal average total solar radiation flux incident on tilted surfaces during winter months using Duffie and Beckman model for Mansoura and King Saud Universities, respectively, were 6.228 and 6.890 kWh m^{-2}. Whilst, the daily average measured total solar radiation flux incident on tilted surface for the two Universities (different locations), respectively, was 5.989 and 6.640 kWh m^{-2}. Accordingly, movable surface with an optimal orientation and tilt angle realized increasing in daily average total solar radiation by 48.24% and 35.82%, respectively, as compared with that measured on horizontal surfaces. Therefore, using Duffie and Beckman model achieved a highly agreement with the data measured on movable tilted surface as the root mean square error (RMSE) for the two different locations was 184.7 and 193.3 W m^{-2}, respectively.

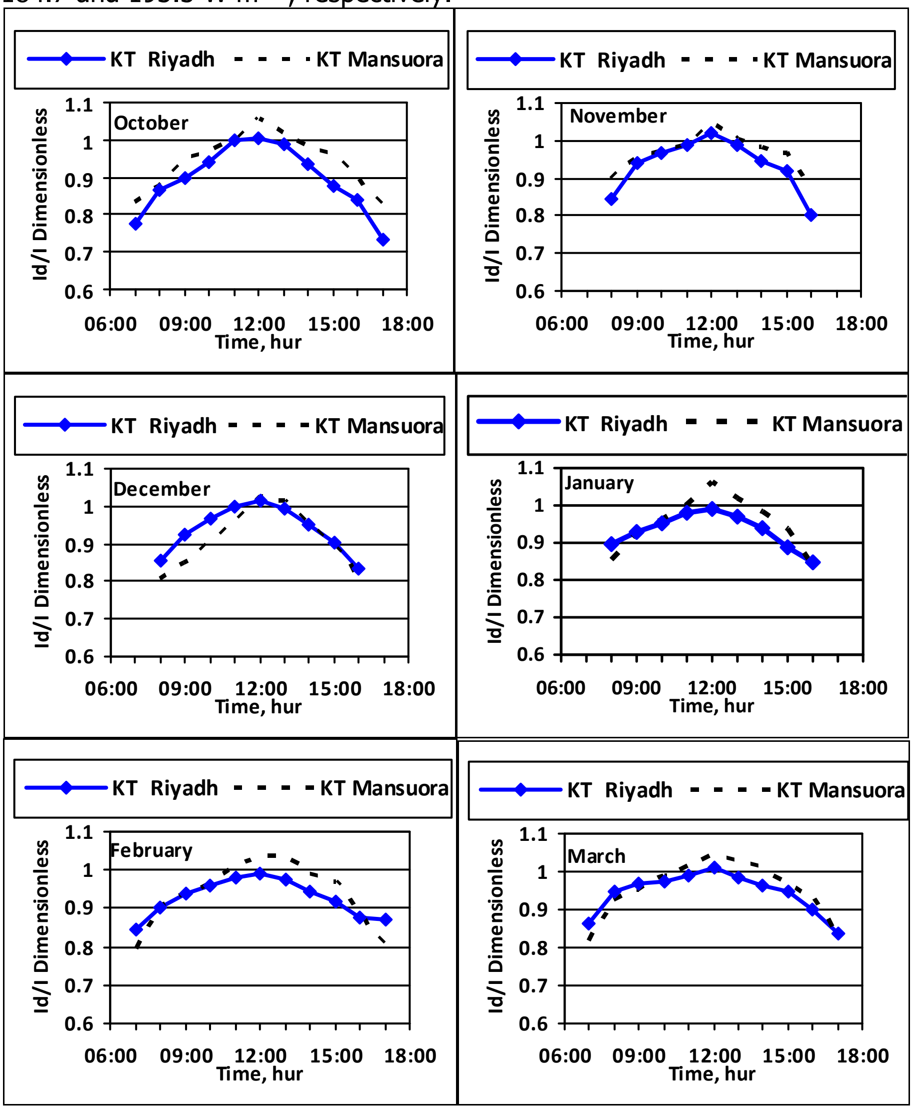


Fig. 2. Frequency distributions of an hour clearness index (K_T) for the two cities of Mansoura and Riyadh during winter months.

For the duration of summer months which start from April to September, the daily average extraterrestrial solar radiation (I_{on}), terrestrial solar radiation on horizontal surface includes beam component (I_{cb}) and diffuse component (I_{cd}), total terrestrial radiation incoming into a horizontal surface (I_c), measured solar radiation flux incident on a horizontal surface (I), clearness index (K_T), and total solar radiation incoming into a tilted surface (I_T) for Mansoura and Riyadh Universities are listed in

Tables (5 and **6)**. Cyclic changes in terrestrial solar radiation included beam and diffuse radiation with time of the day during summer months were observed.

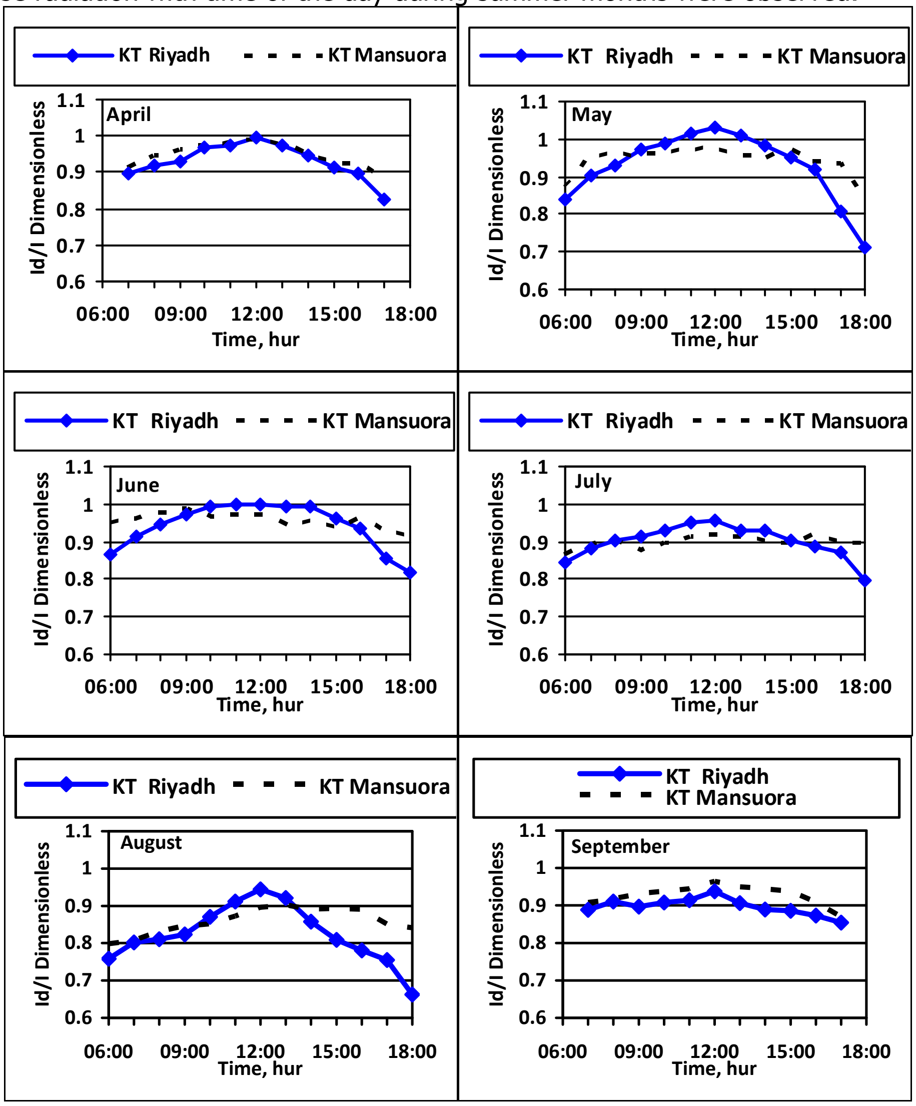


Fig. 3. Frequency distributions of an hour clearness index (K_T) for the two cities of Mansoura and Riyadh during summer months.

The terrestrial solar radiation (I_C) for Mansoura and King Saud Universities was ranged between 60.4 and 927.5 W m^{-2}, and between 53.3 and 986.5 W m^{-2}, respectively. These differences between minimum and maximum values can be attributed to the variation of solar altitude angle, solar zenith angle and times of sunrise and sunset. The daily average total terrestrial solar radiation flux incident on horizontal surface (calculated) during summer months for Mansoura and King Saud Universities, respectively, are 6.888 and 7.409 kWh m^{-2}, while, the daily average total solar radiation measured on horizontal surface during the same period for the two different locations was 6.427 and 6.894 kWh m^{-2}, respectively. Thus, changes in an hour clearness index (K_T) with time of the day throughout the summer months for Mansoura and King Saud Universities were also observed.

Table 5. Solar radiation data obtained for Mansoura University during the summer months.

Month	I_{on}, W m^{-2}	I_{cb}, W m^{-2}	I_{cd}, W m^{-2}	I_c, W m^{-2}	I, W m^{-2}	K_T, decimal	I_{TC}, W m^{-2}	I_{TM}, W m^{-2}
April (11 hrs)	1324.5	5427.8	1077.9	6505.7	6062.0	-	7815.6	7603.8
		493.4	98.0	591.4	551.1	0.9481	710.5	691.3
		235.9	15.4	251.0	235.5	0.0331	190.5	189.3
May (13 hrs)	1322.5	6075.2	1196.9	7272.1	6973.7	-	8746.1	8434.1
		467.3	92.1	559.4	536.4	0.9432	672.8	648.8
		281.2	23.2	303.3	235.5	0.0631	236.2	224.3
June (13 hrs)	1311.1	6284.4	1214.6	7499.0	7236.1	-	9093.4	8653.1
		483.4	93.4	576.8	556.6	0.9599	699.6	665.3
		222.6	20.6	295.8	287.4	0.0249	202.7	191.6
July (13 hrs)	1309.9	6168.0	1201.8	7369.8	6671.3	-	8147.0	7845.5
		474.5	92.8	566.9	513.2	0.9015	626.7	603.5
		277.3	21.6	298.0	265.5	0.0473	203.5	193.7
August (13 hrs)	1321.4	5695.2	1152.9	6848.1	5980.8	-	7274.0	6947.4
		438.1	88.7	526.8	460.1	0.8596	559.5	534.4
		280.1	26.7	305.1	373.5	0.1097	228.7	218.4
Sept. (11 hrs)	1341.0	4800.8	1031.6	5832.4	5477.1	-	7151.0	6812.1
		436.4	93.8	530.2	497.9	0.9288	650.1	619.3
		231.3	17.9	248.7	241.2	0.0260	191.5	182.4
Total (74 hrs)	7948.4	34451.3	6875.7	41327.0	38562.9	-	48189.0	46292.2
Mean	1324.7	465.6	92.9	558.5	521.1	0.9223	651.2	625.6
SD	14.2	254.8	20.9	283.7	273.1	0.0507	209.9	200.0
RMSE							224.4	

The hourly average clearness index for Mansoura and King Saud Universities was ranged between 0.7985 and 0.9890, and between 0.6625 and 1.0313, respectively. These variations in clearness index can also be attributed to the changes in atmospheric conductions (molecules of dry air, water vapour, carbon dioxide, and air mass). Therefore, the minimum values of clearness index during summer month mainly occurred just after sunrise and prior to sunset for both different locations. Whilst, the maximum values of clearness index were achieved at and around noon time. The diurnal average total solar radiation flux incident on tilted surface during summer months using Duffie and Beckman model for Mansoura and King Saud Universities, respectively, were 8.032 and 8.322 kWh m^{-2}. While, the daily average measured total solar radiation flux incident on tilted surface for the two Universities (different locations), respectively, was 7.715 and 8.002 kWh m^{-2}. Accordingly, movable surfaces achieved increasing in daily average total solar radiation by 20.04% and 16.07%, respectively, as compared with that measured on horizontal surface.

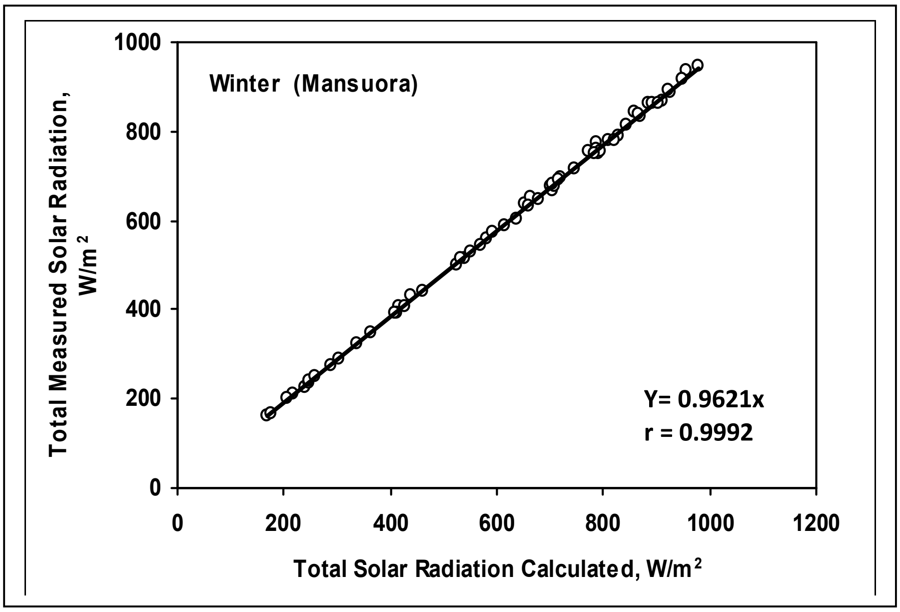
These percentages are lower than that during winter months due to the solar altitude angles are very high during summer months and accordingly, the optimum tilt angles are lower (closest to horizontal plane particularly at and around noon). Therefore, using Duffie and Beckman model realized an excellent agreement with the data measured on tilted surface as the root mean square error (RMSE) for the two different locations was 224.4 and 223.7 W m^{-2}.

Table 6. Solar radiation data obtained for King Saud University, Riyadh during the summer months.

Month	I_{on}, W m^{-2}	I_{cb}, W m^{-2}	I_{cd}, W m^{-2}	I_c, W m^{-2}	I, W m^{-2}	K_T, decimal	I_{TC}, W m^{-2}	I_{TM}, W m^{-2}
April (11 hrs)	1324.5	6243.2	915.1	7158.3	6785.1	-	8201.0	7979.2
		567.6	83.2	650.8	616.8	0.9310	745.5	725.4
		263.6	12.3	275.7	281.1	0.0479	216.1	209.3
May (13 hrs)	1322.5	6710.0	996.9	7706.9	7495.0	-	9068.1	8746.2
		516.2	76.7	592.8	576.5	0.9282	697.5	672.8
		312.3	20.4	313.6	346.9	0.0926	300.2	289.6
June (13 hrs)	1311.1	6825.5	1007.0	7832.5	7600.7	-	9277.5	8886.9
		525.0	77.5	602.5	584.7	0.9414	713.7	683.6
		304.8	18.3	322.2	330.3	0.0616	266.6	255.4
July (13 hrs)	1309.9	6748.1	998.3	7746.4	7129.6	-	8591.1	8272.3
		519.1	76.8	595.9	546.4	0.8998	660.9	636.3
		307.0	19.1	325.1	312.4	0.0474	248.6	239.4
August (13 hrs)	1321.4	6431.1	967.1	7398.1	6380.6	-	7372.3	7046.5
		494.7	74.4	569.1	490.8	0.8236	567.1	542.0
		314.0	23.3	335.5	313.3	0.0779	280.5	268.1
Sept. (11 hrs)	1341.0	5724.5	887.4	6611.9	5973.9	-	7424.4	7079.1
		520.4	80.7	601.1	543.1	0.8967	674.9	643.6
		262.0	14.0	275.6	255.9	0.0225	190.8	181.9
Total (74 hrs)	7948.4	38682.4	5771.8	44454.2	41364.9	-	49934.4	48010.2
Mean	1324.7	522.7	78.0	600.7	559.0	0.9029	674.8	648.8
SD	14.2	294.0	17.9	308.0	306.7	0.0583	250.5	240.6
RMSE							223.7	

The hourly average total solar radiation data calculated using Duffie and Beckman model during winter months for Mansoura and King Saud Universities was compared with that measured using disk solarimeter. The relationship between the measured and calculated solar radiation was higly agreement by 96.21% (RMSE = 184.7 W m^{-2}) and 96.37% (RMSE = 193.3 W m^{-2}) during winter months with highly coefficient of determination (R^2 = 0.9992 and R^2 = 0.9994), respectively, as plotted in Fig. (4). The corresponding obtained data during summer months, respectively, were 96.08% (RMSE = 224.4 W m^{-2}) and 96.17% (RMSE = 223.7 W m^{-2}) with highly coefficient of determination (R^2 = 0.9994 and R^2 = 0.9996) as plotted in Fig. (5). The slight variation between the measured and calculated solar radiation on tilted surfaces due to the model of Duffie and Beckman is based on data measured on a horizontal surface. Therefore, the model only changed the measured data on horizontal surface into tilted surface. Solar energy represents an inexhaustible clean energy source that allows for local energy independence. In designing, sizing, and utilizing solar energy systems, the quantification of the amount of solar energy incoming to solar collectors or solar panels can be represented as irradiance and insolation. Irradiance is the instantaneous radiant power incident on a surface per unit area (Watts per square meter). The integration of the irradiance over a specified period of time corresponds to the insolation. Nowadays, solar energy has been utilized as thermal energy and photovoltaic (PV) for generating electricity.

Solar thermal energy has widely been used for heating space, drying different agricultural products, and many other thermal applications (Kalogirou, 2003). Photovoltaic is the one technology that makes electric power available to anyone virtually anywhere on the planet. Solar energy is indeed the energy force that sustains life on Earth for all plants, animals, and people. From the obtained data, the total measured solar radiation available on movable solar collector (thermal energy) or solar panel (photovoltaic) has a surface area of one square meter during winter months for Mansoura and King Saud Universities, respectively, is 2.180 and 2.418 MW. When using solar collector (solar thermal energy) with an overall thermal efficiency of 70%, these solar energy available can be converted into 1.526 and 1.693 MW useful heat energy gain to storage, respectively. When using ordinary photovoltaic with conversion factor of 17%, these amounts can be generated electric power of 370.600 and 411.606 kWh, but when using high photovoltaic concentration with conversion factor of 39%, they can be generated 850.200 and 943.020 kWh, respectively. Whilst, during summer months, the total measured solar radiation available for the two different locations is 2.824 and 2.929 MW, respectively, of which 1.977 and 2.050 MW useful heat energy gain to storage, and 480.080 kWh and 497.930 kWh electric power when using (PV), and 1.101 and 1.142 MW when using (HPVC).



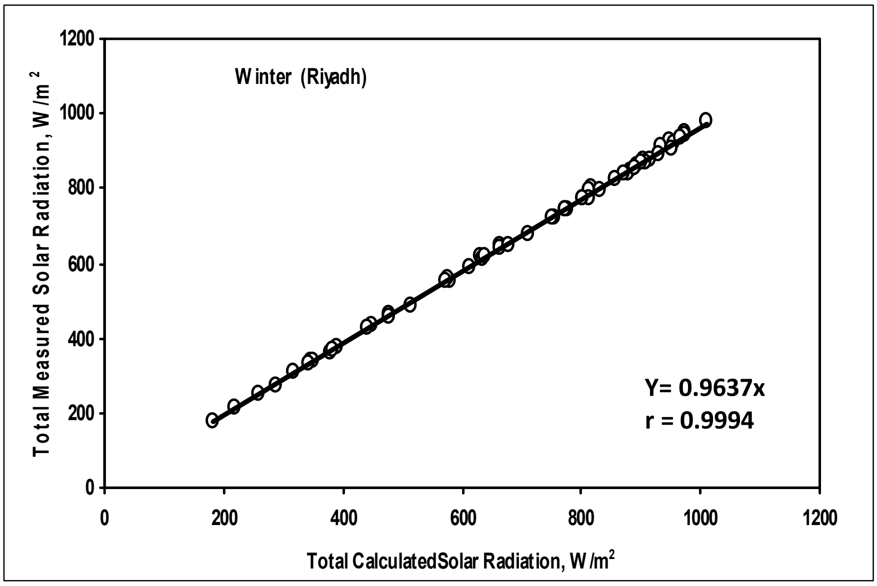
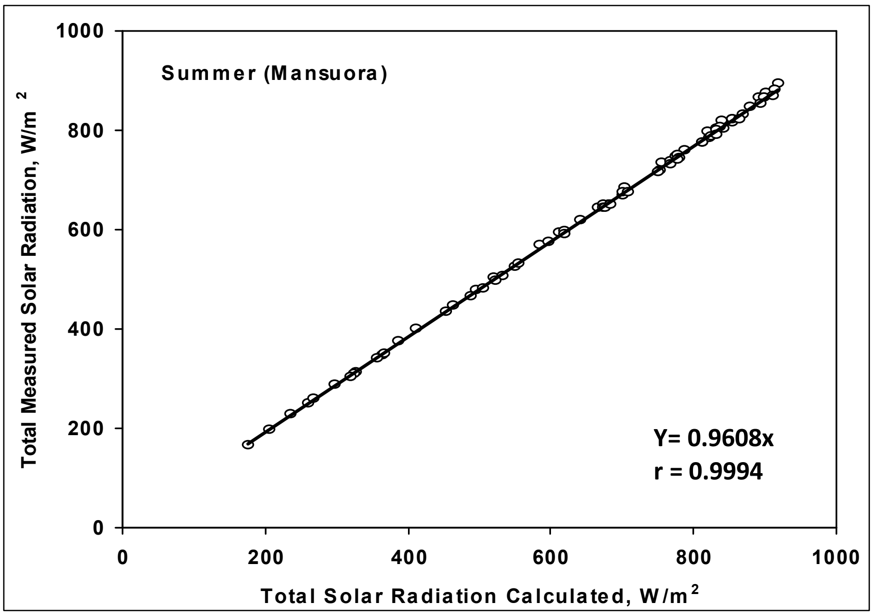


Fig. 4. Measured solar radiation on tilted surface as a function of calculated solar radiation for Mansoura and King Saud Universities during winter months.



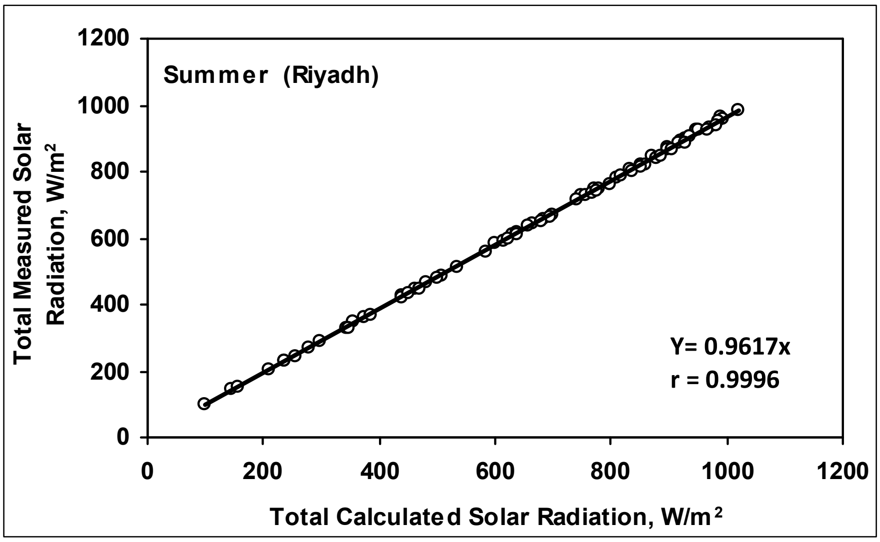


Fig. 5. Measured solar radiation on tilted surface as a function of calculated solar radiation for Mansoura and King Saud Universities during summer months.

CONCLUSION

The diurnal average total solar radiation flux incident on tilted surface during winter months using Duffie and Beckman model for the two different studied locations were 6.228 and 6.890 kWh m^{-2}, respectively. Whilst, the daily average measured total solar radiation flux incident on movable tilted surface for the two Universities (different locations), respectively, was 5.989 and 6.640 kWh m^{-2}. Therefore, movable surface with an optimal orientation and tilt angle realized increasing in daily average total solar radiation by 48.24% and 35.82%, respectively, as compared with that measured on horizontal surface. Therefore, using Duffie and Beckman model achieved an excellent agreement with the data measured on movable tilted surface as the root mean square error (RMSE) for the two different locations was 184.7 and 193.3 W m^{-2}, respectively. The daily average total solar radiation flux incident on tilted surface during summer months using Duffie and Beckman model for the two different locations , respectively, were 8.032 and 8.322 kWh m^{-2}, respectively. While, the daily average measured total solar radiation flux incident on tilted surface for the two Universities (different locations), respectively, was 7.715 and 8.002 kWh m^{-2}. Accordingly, movable surface with an optimal orientation and tilt angle achieved increasing in daily average total solar radiation by 20.04% and 16.07%, respectively, as compared with that measured on horizontal surface. Therefore, using Duffie and Beckman model realized an excellent agreement with the data measured on tilted surface as the root mean square error (RMSE) for the two different locations was 224.4 and 223.7 W m^{-2}.

REFERENCES

1. Ahwide, F.; A. Spena,; and A. El-Kafrawy. 2013. "Correlation for the Average Daily Diffuse Fraction with Clearness Index and Estimation of Beam Solar Radiation and Possible Sunshine Hours Fraction in Sabha, Ghdames and Tripoli–Libya" APCBEE Proceeded, 5: 208–220
2. ASHRAE. 2005. "Handbook of Fundamentals" American Society of Heating, Refrigerating and Air Conditioning Engineers, New York, USA
3. Bakirci, K. 2008. "Correlations for Estimation of Solar Radiation on Horizontal Surfaces", J. Energy Eng., 134(4),: 130–134.
4. Duffie, J. A.; and W. A. Beckman. 2013. "Solar engineering of thermal processes" Fourth Edition, John Wiley & Sons, Inc., Hoboken, New Jersey, USA.

5. Erbs. D. G.; S. A. Klein ; and J. A. Duffie. 1982. "Estimation of the diffuse radiation fraction for hourly, daily and monthly average global radiation" Solar Energy, 28: 293–302
6. Foster, R.; M. Ghassemi; and A. Cota. 2010. "Solar Energy: Renewable Energy and the Environment" 1[s] ed., by Taylor and Francis Group, LLC, New York, USA.
7. Hassan, J. 2014."ARIMA and regression models for prediction of daily and monthly clearness index" Renewable Energy 68: 421 - 427 journal homepage: www.elsevier.com/locate/renene
8. Kalogirou, S. A. 2003. "The potential of solar industrial process heat application" Applied Energy, 76: 337– 361.
9. Raeiszadeh, F.; and M. S. Behbahanizadeh. 2012. "The Application of Empirical Models to Compute the Solar Radiation in Shahrekord" J. Basic., Appl. Sci. Res., 2(11), : 10832-10842
10. Reindl, D. T.; W. A. Beckman ; and J. A. duffie. 1990a. "Diffuse Fraction Correlations" Solar Energy, 45: 1 – 12
11. Reindl, D. T.; W. A. Beckman ; and J. A. duffie. 1990b. "Evaluation of Hourly Tilted Surface Radiation Models" Solar Energy, 45: 9 – 19
12. Vieira, M. E.; A. de-Silva ; A. Sandro ; and M. R. Q. Medeiros. 2002. "Adjustment of the Clear Sky Coefficients for the Transmission of Solar Radiation under the Ambient Conditions in Fortaleza" World Climate & Energy Event, RIO 02: 85 – 88.

نموذج رياضي لتحديد متوسط الأشعة الشمسيه الكلية فى الساعة على سطح مائل لمدينتين مختلفتين (المنصورة والرياض)

ناصر مصطفى العشماوى

معهد بحوث الهندسة الزراعية – الدقى – جيزة

يعتبر تحديد كمية الأشعة الشمسية الكلية الساقطة على سطح مائل (الأشعة الشمسية المباشرة – الأشعة الشمسية المشتتة من السماء – الأشعة الشمسية المنعكسة من سطح الأرض) بزاوية ميل مثلى وتوجيه أمثل أحد أهم البيانات التى يمكن للباحثين الإعتماد عليها فى جميع تطبيقات نظم الطاقة الشمسية (النظم الحرارية ونظم الخلايا الكهروضوئية). ونظراً لإرتفاع الأسعار السوقية لأجهزة قياس الأشعة الشمسية على سطح مائل وبالتالى صعوبة توفرها لدى جميع الباحثين فى نفس الوقت الذى تتوفر فيه محطات الأرصاد الجوية فى جميع المناطق سواء فى مصر أو فى المملكة العربية السعودية والتى تقوم بقياس الأشعة الشمسية الكلية الساقطة على سطح أفقى (الأشعة المباشرة والأشعة المشتتة من السماء)، فإن هذا البحث يهدف إلى مقارنة أحد النماذج الرياضية التى تقوم بتحويل الأشعة الشمسية الكلية الساقطة على سطح أفقى إلى سطح مائل فى منطقتين مختلفتين من حيث زاوية خط العرض (جامعة المنصورة خط عرض 31.045ºN وجامعة الملك سعود خط عرض 24.725ºN) ومقارنة النتائج والبيانات المتحصل عليها بتلك الى يتم قياسها بأحدث الأجهزة على سطح مائل.

أوضحت النتائج المتحصل عليها تطابق النموذج الرياضى الذى تم إستخدامه فى هذه الدراسة مع تلك البيانات التى تم قياسها بنسبة تطابق عاليه سواء فى أشهر الشتاء (96.21% and 96.37%, respectively) أو فى أشهر الصيف (96.08% and 96.17%, respectively) وبالتالى يمكن إستخدام النموذج الرياضى للعالمين Duffie and Beckman فى تحويل كمية الأشعة الشمسية الساقطة على سطح أفقى إلى سطح مائل فى أية منطقة من مناطق البحث والتطبيق لنظم الطاقة الشمسية المختلفة وبمعنوية عالية.