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Evaluation of Flat Plate Solar Collector to Optimizing the Tilt Angle, Case Study: Tabriz, Iran

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ABSTRACT

It is a well-known fact that solar resource or solar radiation varies spatially as well as temporally across the face of the earth. Hence, resource assessment is a preliminary step for all solar applications. In this study, a flat plate surface solar collector of dimension 2 m^2, hinged on a horizontal support for quick adjustment of inclination from 0^o to 80^o was fabricated and marked out at 0.5^o intervals on a telescopic leg graduated in degrees. Measurement of the solar radiation, varying degrees of inclination were taken between 11:00 a.m. and 4:00 p.m. for 7 days of each month at clear sky hours. The measurements were made for five months of the year in Tabriz, East-Azerbaijan Province, Iran. These months selected because they have maximum average solar radiation energy in Iran. At each 0.5 degree of inclination, the solar radiation intensity was replicated three times at each hour and the average value was taken. The flat plate was set truly facing south with an engineering prismatic compass. The result showed that the optimum tilt angle of a flat plate for maximum collection of solar radiation intensities in each month. This work also revealed that the average angle of inclination at which a flat plate surface solar collector will be mounted at fixed position in Tabriz is 31^o approximately in studied months. The analysis indicated that when a flat surface was located at the forecasted optimum tilt angle for each of five months, solar radiation intensity was increased, when compared with solar radiation intensity harnessed by the same flat plate collector on other angles and under the same condition. Moreover this improvement impose no extra-cost. Comparison of the measured and calculated optimum values of tilt angle of a flat plate surface for trapping maximum solar radiation intensity for each of five months indicated a high correlation with R^2 of 0.98 approximately.

Introduction

Solar energy is an alternative to fossil fuels for more sustainable and reliable energy options, with a huge potential to meet many times the present world energy demand. Solar radiation is the principal energy source for physical, biological and chemical processes, such as, snow melt, plant photosynthesis, evapotranspiration, crop growth and is also a variable needed for biophysical models to evaluate risk of forest fires, hydrological simulation models and mathematical models of natural processes (Meza and Varas, 2000). Solar radiation that floods the earth's surface on daily basis is renewable energy, which can be harnessed into three primary technical uses by helio-chemical, helio-electrical and helio-thermal processes.

An accurate knowledge of the solar radiation data at a particular geographical location is of vital importance because the design and simulation of solar energy projects requires knowledge of solar data (El-Sebaii and Trabea, 2003). The data should be reliable and readily available for design, optimization and performance evaluation of solar technologies for any particular location (El-Sebaii *et al.*, 2010). On the earth, surface solar radiation is only effectively available in hours of clear sky weather. Nielsen (2005) gave an expression for determination of the global horizontal solar radiation intensity in different hours of the day. Bena and Fuller (2002) and Sharma *et al.* (2009) indicated that solar energy trapped by solar dryers is now commonly used globally in drying and preservation of agricultural products. The uses of helio-electrical devices, which trap solar radiation on horizontal plane, are increasing worldwide. Thanailakis (1985) and Beaupré *et al.* (2010) reported various works done on solar energy-electrical devices. Since solar radiation is not always available at the desired quantity and time, the challenge is how to maximize available solar energy. It is an established fact that the solar radiation intensity falling on a horizontal flat surface, at a given time and location, increases with the increase in surface tilt angle at a solar hemispherical inclination (Hartley *et al.*, 1999). Solar collectors need to be inclined at the optimum angle to maximize the receiving energy. This is due to the fact that the variation of tilt angle changes the top loss coefficient and the amount of solar radiation reaching the absorber plate. In Manes and Ianetz (1983) a computational algorithm is proposed suitable for the calculation of optimum tilt angles of a solar collector, receiving the maximum insolation for given values of direct or beam, global and diffuse radiation, and given surface reflectivity. Shariah *et al.* (2002) showed that the yearly optimum angle in Jordan is less than the latitude by about $5\sim8^o$. In another

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research, Chen *et al.* (2005) had estimated the monthly optimal installation angle for solar cell in Chiayi, Taiwan, according to the climatology data from 1995 through 1998, by means of genetic algorithm and simulated annealing methods. In the past, many researchers have devoted to studying the optimal installation angle for maximum solar energy collection of the given locations in the world (Chau, 1982; El-Kassaby, 1988; Morcos, 1994; Yakup and Malik, 2001; Chow and Chan, 2004; Koray, 2006; Gunerhan and Hepbasli, 2007; Moghadam *et al.*, 2011; Benghanem, 2011).

Hence, the main objective of the present study is to investigate and forecast the optimum angles of inclination for maximum collection of solar energy for five month of the years, which have maximum average solar radiation energy, in Tabriz, East-Azerbaijan Province, Iran. This study provides important and useful information to improve the collection of solar energy radiation intensity of south-facing surfaces flat plate solar collectors.

Materials and methods

To carry out the experimental analysis, an active collector was used with the size of 2×1×0.15 m. The wall of the collector is made from iron profile insulated by glass wool with the thickness of 5 cm. The absorber plate is made from steel with the thickness of 0.5 mm painting the black and the sleek glass with a thickness of 4 mm used as a screen transparent collector cover. In addition, a horizontal support was hinged on the collector. The hinges gave the flat plate surface a freedom of adjustment of angle of inclination from 0^o to 80^o, marked at the intervals of 0.5^o. The adjustment for varying the angle of inclination was done manually.

For time saving and decrease computational processes, studied angle ranges limited to forecasted smaller range which can harness more collection of solar energy radiation intensity. So 38^o was chosen as the upper limit of inclination and 24^o the lower one for this work. Provision for fixing solar radiation intensity measuring equipment was made on the surface of the flat plate in such a way that the total solar energy falling on the flat plate at the varying angle of inclination was captured. The system was mounted to slope toward south.

The experiments were conducted on days, which the atmospheric conditions were almost uniform and data was collected from the collector. Study was performed in a time period in which the weather was clear where the case study was carried out. Measurements were taken between 11:00 a.m. and 4:00 p.m. for 7 days of each month, at clear sky hours for five months of the year (May, June, July, August and September), because in these months we have maximum average solar radiation energy in Iran. At each 0.5 degree of inclination, the solar radiation intensity was replicated three times at each hour. Then the data were averaged to obtain the mean values at each angle degree. The experiment was conducted in an open area of the building No.2 of Agricultural Faculty, University of Tabriz, Iran. The flat plate surface solar collector is presented in Figure 1.

There are a number of aspects important in the understanding and use of solar data: geographic information of the site; whether the measurements are instantaneous (irradiance) or cumulative values (irradiation) over a period of time (usually hour or day); the time stamp and period of measurement; the parameters (*e.g.* global, diffuse or direct) being measured; the instruments used; the receiving surface orientation (usually horizontal, sometimes inclined at a fixed slope, or normal to the beam radiation); and if averaged, the period over which they are averaged (like, monthly averages of daily radiation) (Duffie and Beckman, 1980). Calculation of radiation received by tilted surfaces, the most common manifestation of a solar application, needs both diffuse and direct (beam) components.

Figure 1. Flat plate surface solar collector

Generally, the spatial variability of solar radiation is determined by the interplay of chronological, geographical, atmospheric and surface conditions (Breitkreuz *et al.*, 2007). However, there are simple geometric formulas that allow a relatively reliable estimation, so the spatial modeling of this variable is crucial to quantify the availability of energy per area unit for its potential use. The measured values were verified with the calculated values. Liu and Jordan (1960) developed the most common isotropic expression for calculation of incident solar radiation on a tilted flat collector surface truly facing south. The expression is shown in Equation (1) and was used in this work.

$$I_{Ts} = I_{Dh}R_a + [I_{dh}(1+\cos b)/2] + [I_{Th}G_d(1+\cos b)/2] \quad (1)$$

According to the Equation (1), the global solar energy radiation (l_{Ts}) incident on a south-facing collector tilted at an angle b to the horizontal surface can be calculated. G_d is the ground reflection coefficient which was given as 0.2 by (Liu and Jordan, 1960). The clear sky radiation on horizontal surface, l_{Th}, is the sum of l_{Dh} and l_{dh} and can be expressed as Equation (2).

$$I_{Th} = I_{Dh} + I_{dh} \quad (2)$$

Where l_{Dh} is the clear sky beam radiation on horizontal surface and l_{dh} is diffusion component of clear sky radiation on horizontal surface. l_{Dh} can be calculated by the Equation (3) of Hottel (1976).

$$I_{Dh} = I_o \tau_b \cos d \quad (3)$$

Where, d is declination angle of sun and τ_b is the atmosphere transmittance for beam radiation, which is equal to the ratio of the beam radiation on horizontal surface to the air mass zero (AM0) extraterrestrial radiation, and can be approached by the empirical Equation (4).

$$\tau_b = a_o + a_1 \exp(-k/\cos d) \quad (4)$$

The constants $a_o=r_oa_o^*$, $a_1=r_1a_1^*$ and $k=r_kk^*$ for the standard atmosphere with 23 km visibility are calculated from the following relationship (Equation 5) assuming that the observation altitude is less than 2.5 *km*.

$$\begin{aligned} a_o^* &= 0.4237 - 0.00821(6.0-H)^2 \\ a_1^* &= 0.5055 - 0.00595(6.5-H)^2 \\ k^* &= 0.2711 - 0.01858(2.5-H)^2 \end{aligned} \quad (5)$$

Where, H is the altitude of observer in kilometers. The correction parameters r_o, r_1 and r_k are related to climate conditions as summarized in Table 1.

Table 1. Atmospheric parameters for different climate types

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

The accumulated extraterrestrial beam radiation at AM0 for a period of time can be obtained by the integration of Equation (6).

$$I_o = \int S_c (1 + 0.033\cos(2\pi dn/365.25))dt \quad (6)$$

Here, S_c is solar constant (1367 W/m^2). The diffusion component of clear sky radiation on horizontal surface, I_{dh}, can be estimated using the Equation (7) of Liu and Jordan (1960).

$$I_{dh} = I_o \tau_d \cos d \quad (7)$$

$$\tau_d = 0.2710 - 0.2939\tau_b \quad (8)$$

Where, τ_d is the atmosphere transmittance of diffusion radiation, and the accumulated extraterrestrial radiation on a tilt panel, I_{ext}, is given by Equation (9).

$$I_{ext} = I_o \cos\theta \quad (9)$$

Where, θ is the instantaneous angle between direct beam and the normal of collector. Additionally, the geometric dimensionless factor or radiation tilt factor, R_a, is the ratio of beam radiation on the tilted surface to that on a horizontal surface as given by Equation (10):

$$R_a = \frac{\cos(L-b)\cos d + \sin(L-b)\sin d}{\cos L \cos d + \sin L \sin d} \quad (10)$$

Where L is geographic latitude of the location.

The measurements of the amount of total solar radiation intensity falling on the surface of the flat plate at varying degrees have been carried out using TES 1333 solar meter. Engineering prismatic compass was employed to determine the cardinal position of the flat plate and to ensure it was truly facing south. The solar radiation data measured by the authors, during the May, June, July, August and September 2011, were used in this study.

Results and Discussion

The evaluation was carried out and results from directly measured solar energy radiation intensity on tilted surfaces, for five months of the year are shown in Figure 2. For more clarity, three months (May, June and July) are represented in one figure and two months (August and September) are represented in another one. It is clear from the figures that a unique optimum tilt angle exists for each month of the year that corresponds to the maximum point of each curve.

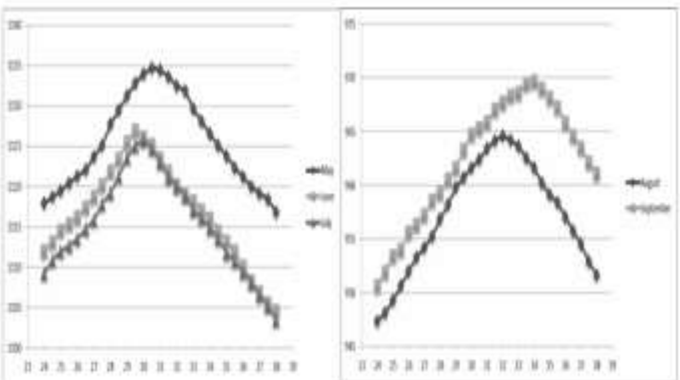

Figure 2. Measured solar radiation intensity on flat plate surface at varying angle of inclination

Furthermore, to find the optimum tilt angle of the sloped surface, numerical calculations have been performed for different tilt angles. The results from the calculated values using the given formulas are summarized in Figure 3. For more clarity, three months (May, June and July) are represented in one figure and two months (August and September) are represented in another one.

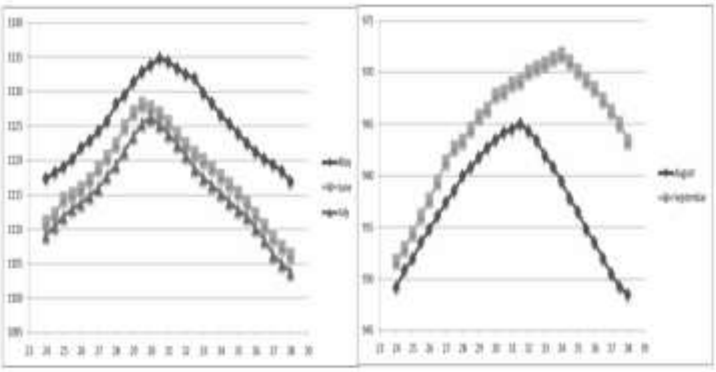

Figure 3. Calculated solar radiation intensity on flat plate surface at varying angle of inclination

According to Figures 2 and 3, it was observed that the measured and the calculated solar energy radiation intensities incident on the flat surface increased to a certain angle of inclination, after which, further increase in angle of inclination of the flat surface resulted to decrease of the solar energy radiation intensity trapped. From the above results, it can be concluded that the optimum angle for catching maximum solar energy radiation on a flat plate surface varies with the months of the year.

The calculated solar energy radiation intensity on an inclined surface and that of the directly measured were compared and the results presented in Figure 4.

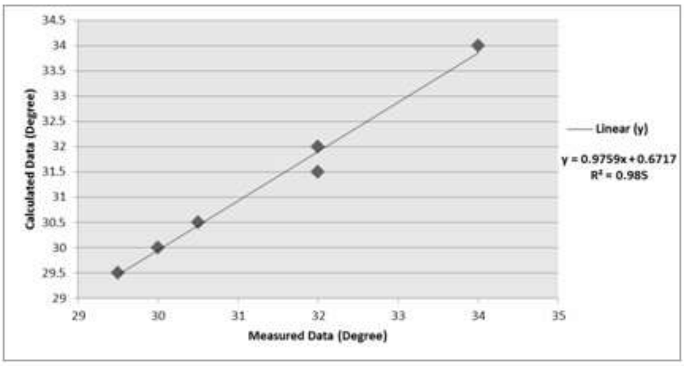

Figure 4. Comparison of the measured and calculated optimum values of angle of inclination of a flat plate surface

As it can be seen in Figure 4, comparison of the measured and calculated optimum values of angle of inclination of a flat plate surface for trapping maximum solar radiation intensity for each month of the year indicated a high correlation with R^2 equal to 0.98 approximately. It also showed that at 95% probability level, there was no statistical significant difference between the measured and calculated values. The highest optimum angle of inclination of a flat surface in Tabriz for trapping maximum solar radiation intensity was 34°. Month of September experienced high angle of inclination for trapping maximum solar radiation. On the other hand, the lowest optimum angle of inclination of a flat surface in Tabriz for harnessing maximum solar radiation intensity was 29.5° in the month of June. Besides, the earth's tilt angle, the sun's azimuth angle created by the revolution of the earth around the sun might have equally contributed to the varying optimum angle of inclination with time.

The statistical results of the average values of measured and calculated parameters, when a flat plate collector was located at optimum angle of inclination for collection of maximum solar energy, are summarized in Table 2.

Table 2. Value of measured and calculated optimum angle and solar radiation intensity

Month	Measured		Calculated	
	Optimum tilted angle (*degree*)	solar radiation intensity on optimum tilted angle (W/m^2)	Optimum tilted angle (*degree*)	solar radiation intensity on optimum tilted angle (W/m^2)
May	30.5	1134.7	30.5	1134.8
June	29.5	1126.1	29.5	1128.2
July	30	1125.8	30	1126.2
August	32	964.9	31.5	965
September	34	969.7	34	971.8

According to the analysis from all achieved data and Table 2 indicated that when a flat surface was located at the suggested optimum angle of inclination for each of mentioned month, solar radiation intensity was increased, when compared with solar radiation intensity harnessed by the same flat plate collector on other angles and under the same condition. In addition, this improvement impose no extra-cost. Moreover, for increasing the utilization efficiency of solar collectors, it is recommended that, if it is possible, the solar collector should be mounted at the monthly average tilt angle and the slope adjusted once a month. However, the average angle of inclination a solar flat surface collector should be mounted at fixed position is found to be 31^o approximately in above-mentioned months. It has been observed that the statistical results for the south-facing surface show reasonably good agreement between measured and calculated data. The obtained results are useful for solar engineering design calculations, such as solar collectors and PV modules sloped facing south at a fixed angle.

Conclusions

Solar energy is a sustainable, safe and abundant energy resource and solar collectors are the key component of active solar-heating systems. One of the important parameters that affect the performance of a flat plate solar collector is its angle of tilt with the horizontal. This research was performed to determine the optimum inclination angle of flat plate solar collector. According to the results, it is concluded that the optimum angle of inclination for maximum collection of solar energy radiation intensity varies with each month of the year. Optimum angles of tilt at which solar panels can be mounted to harness maximum collection of solar energy radiation intensity for five months of the year which have maximum average solar radiation energy in Iran, were identified for Tabriz. It was found that solar flat collector can be fixed permanently in Tabriz at 31^o approximately in above-mentioned months. Also when the solar energy radiation intensity obtained at the optimum angle of inclination was compared with that from other degree position, the increased value can be tracked.

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