Slope Angle for Seasonal Applications of Solar Collectors in Thailand

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ABSTRACT

Flat plate collectors are usually fixed at a certain slope angle and oriented towards the equator. For year-round operation, many authors have suggested that a collector's slope equal to the latitude angle is the best. However, for seasonal applications where the collectors are used for part of the year, the slope angles need to be different from those for year-round operation in order to get maximum solar radiation. This paper describes a method to determine the slope and orientation angles of flat plate collectors, for any period of operation. Equations and constants applicable to the average atmospheric conditions and latitude angles of Thailand are given in the paper. The method takes into account the direct and the diffuse components of solar radiation. For simplicity, the reflected component is neglected. It is shown that for seasonal applications, an optimally oriented collector can get as high as 13% more energy than a collector with its slope equal to the latitude angle.

1. INTRODUCTION

Most flat-plate collectors are mounted in a stationary position with the orientation tilted towards the equator, whereas their slope angles vary with the latitude (ϕ). Many authors [1-4] suggested that the latitude angle is the optimum tilt angle for year-round operation. However, for better winter performance a few authors mentioned that the tilt angle should be 10° more than the latitude angle [3, 5] for countries of higher latitudes ($\phi > 40°$). It is obvious that for better performance of solar collectors, they should be tilted in such a way to get the maximum solar radiation over the period of usage. Applications like crop-drying, water-pumping, heating or even air-conditioning are seasonal, i.e. these types of applications need the use of the solar collector for only part of the year. While the slope angle for year-round operation at different latitudes is at hand in literature, the slope angle for operation periods of less than a year is not readily available. Bairi [6] described a method to determine the optimum slope angle and the orientation of solar collectors for different periods of operation in Algeria. The method is based on extraterrestrial solar radiation. Also, the period of operation is confined to starting on the 1st or 15th of any month, and lasts for at least 15 days. This paper describes a method to determine the optimum slope angle and orientation of collectors for any period of operation. The average atmospheric conditions and latitude angles of Thailand are used to find the constants needed in the equations. The method utilizes both direct and diffuse components of solar radiation.

2. SLOPE ANGLE AND ORIENTATION

Figure 1 shows some important angular parameters of a solar collector. The slope angle (β) is the angle between the horizontal and the plane of the collector. The azimuth angle (γ) is the displacement

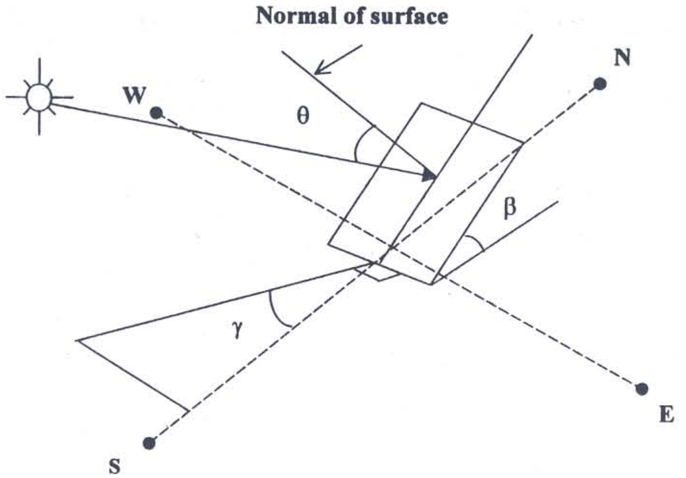

Fig. 1. Inclined solar collector showing the slope angle, β, the azimuth angle, γ, and the angle of incidence, θ.

angle between the due south and the projection on a horizontal plane of the normal to the collector surface. The angle of incidence (θ) is the angle between the direct radiation on a surface and the normal to that surface. Duffie and Beckman [1] provided a detailed description of these parameters and their sign conventions.

3. ENERGY RECEIVED BY A SURFACE

The total solar energy flux, I_{tot}, received by any surface consists of direct radiation from the sun, I_D, diffuse-scattered radiation from the sky, I_{DS}, and reflected radiation from the surroundings, I_R:

$$I_{tot} = I_D + I_{DS} + I_R \tag{1}$$

The direct solar intensity depends on the atmospheric thickness, which is the distance a solar ray travels through the atmosphere before reaching a collector. It is also governed by the atmospheric levels of water vapor and other pollutants, which have been investigated by many authors [7-10]. The intensity of the direct component of solar radiation can be estimated using the following equation [11]:

$$I_{DN} = A_S \exp\left(\frac{-B_S}{\cos\theta_Z}\right) \tag{2}$$

where A_S is the apparent extraterrestrial solar radiation received by a surface normal to the direction of propagation of the radiation, and B_S is the atmospheric extinction coefficient. The values of B_S depend on the water vapor level in the atmosphere and the time of year. The values of A_S and B_S for average atmosphere are sourced from Ref. 11.

Iqbal [8] investigated the effect of air mass on the spectral distribution of direct irradiation, and found that the available solar energy decreases as the air mass increases. The air mass can be closely represented by ($1/\cos\theta_Z$), which is part of Eqn. (2).

On the other hand, the amount of direct solar energy received by any surface is equal to the product of the direct radiation collected by a surface normal to the sun's ray, I_{DN}, and $\cos\theta$:

$$I_D = I_{DN}\cos\theta \tag{3}$$

Diffuse-scattered radiation, which comes from the entire sky dome, is the distributed component of solar radiation. It is governed by the ever-changing conditions of cloudiness and atmospheric clarity. The isotropic diffusion model [1, 11, 12] is selected because it has a reasonably safe lower bound to the available energy. This diffuse-scattered solar insolation can be estimated from:

$$I_{DS} = I_{DN} C_S F_{SS} \tag{4}$$

where C_S is the ratio of the diffuse-scattered radiation to the direct solar radiation received by a horizontal surface, and F_{SS} is the radiation shape factor for radiation leaving the surface that reaches the sky. The value of C_S is about 10% to 20% on a clear day [3, 13]. This value depends also on the time of year. The values of C_S are taken from Ref. 11, and fluctuate between 5% to 14% during the year. The shape factor can be estimated by:

$$F_{SS} = \left(\frac{1 + \cos\beta}{2}\right) \tag{5}$$

The reflected radiation, conversely, is usually only a minor component in most solar energy calculations. Except for extraordinary cases where reflected radiation is a major component, such as in "solar power tower" and solar heaters with reflectors, its contribution to the total solar insolation collected by a surface is not important. Moreover, reflected components should be handled individually - evaluating reflections from the ground, buildings, roofs, streets etc. Hence, the reflected component is neglected to simplify the calculations.

Using the method described above, a computer program was written to determine the optimum orientation of solar collectors at different latitudes in Thailand (5° to 20° North). Calculations involve the time-based integration [1] of instantaneous solar energy flux from sunrise to sunset for a particular day, which gives the daily total energy. The program first comes up with the daily total solar energy flux receivable by a surface and then compares this total by subjecting the surface to different orientations. The angle that gives the maximum energy received is the optimum angle. The day length and other different parameters required to solve Eqns. (2) and (3) are given in many solar energy books [1, 11, 14].

Solar radiation data is the best source of information for estimating average incident radiation on a particular surface. Consequently, the models employed in the computer program for this study will definitely overestimate the total solar radiation. Nevertheless, this paper mainly focuses on the orientation of solar collectors rather than the available energy. The direction of direct solar radiation is determined by the position of the sun in the sky. Likewise, the amount of surface exposed to the sky determines how much diffuse-scattered radiation exists. So, for actual sky conditions, the total available energy is less than that predicted by using average atmosphere conditions, but the angle to get that maximum radiation is the same. The diffuse-scattered component can be roughly 10% to 20% of the total radiation on a clear day, but can rise to 100% of a much lower total radiation on an overcast day [3]. Solar collectors are primarily designed for sunny days and not for overcast days; thus, the collector should be oriented to get the most direct radiation while considering the diffuse-scattered component for clear days. For that reason, the model utilized in this study estimates the correct orientation of solar collectors, which is valid for actual atmospheric conditions that range from not cloudy to partially cloudy.

4. OPTIMUM SLOPE ANGLE AND ORIENTATION

Thailand has latitudes (ϕ) ranging from 5°N to 20° N. Figure 2 shows the variation of optimum slope angle for different days for ϕ = 6°N and 20°N, respectively. A positive slope angle means that the surface is tilted towards the equator, whereas, a negative one means that the surface is tilted towards the pole (for Thailand it is towards the North Pole). The slope angle changes mainly due to the sun's position relative to the earth (declination, δ). A polynomial fit to either curves of Fig. 2 is:

$$\beta_n = a_0 + a_1 n + a_2 n^2 + a_3 n^3 + a_4 n^4 + a_5 n^5 + a_6 n^6 \qquad (6)$$

where n = day of the year and Jan 1 (n = 1) $\leq n \leq$ Dec 31 (n = 365).

The values of n can be conveniently found from column 2 (Jan – Dec) of Table 1. The values of coefficient a_1, a_2... are given in Table 2 for different latitudes, at an interval of 2°. The optimum slope angle and orientation for any day can be found by applying Eqn. (1). Interpolation for other latitudes (4° N $\leq \phi \leq$ 20° N) is allowed. The accuracy is ±1°. This accuracy is good enough because a variation of ±5° from optimum slope angle reduces the total radiation by only 0.5%, as shown in Fig. 3.

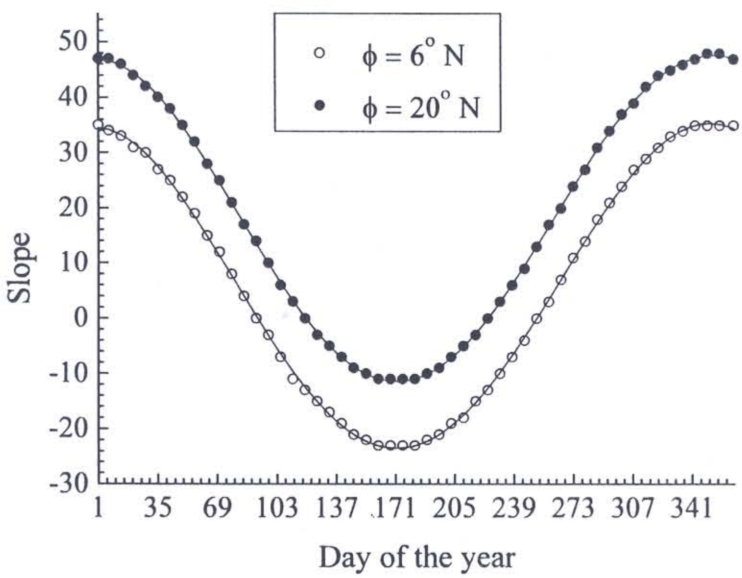

Fig. 2. Variation of slope angle as a function of day of the year for ϕ = 6° N and ϕ = 20° N, respectively.

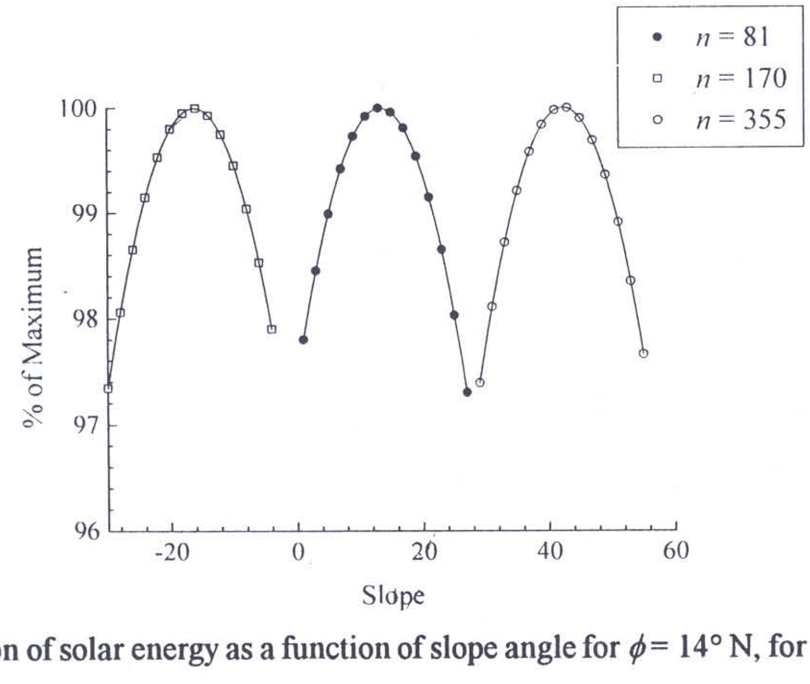

Fig. 3. Variation of solar energy as a function of slope angle for ϕ = 14° N, for different days.

Table 1 Value of n by Month

Month	n for i^{th} Day of Month	
	Jan-Dec	Jul-Jun
January	i	184 + i
February	31 + i	215 + i
March	59 + i	243 + i
April	90 + i	274 + i
May	120 + i	304 + i
June	151 + i	335 + i
July	181 + i	i
August	212 + i	31 + i
September	243 + i	62 + i
October	273 + i	92 + i
November	304 + i	123 + i
December	334 + i	153+ i

Table 2 Values of Coefficients for January to December

Latitude °N	a_0	a_1 $\times 10^3$	a_2 $\times 10^3$	a_3 $\times 10^5$	a_4 $\times 10^8$	a_5 $\times 10^{10}$	a_6 $\times 10^{13}$
4	32.594476	8.3103295	-6.8461363	2.595986	6.680662	-3.818319	3.953185
6	34.505679	-4.3112815	-6.4848525	2.165456	9.019478	-4.393123	4.472939
8	36.628871	-35.179625	-5.614046	1.196697	14.0407	-5.611624	5.591772
10	38.131919	-14.046041	-5.9173448	1.355318	13.75302	-5.623887	5.655031
12	40.110005	-46.261753	-4.9732294	.3284376	18.84232	-6.794297	6.669735
14	41.71824	-27.192194	-5.3024919	.5689059	17.97585	-6.637929	6.552741
16	43.629829	-42.489781	-4.7904305	-.08848106	21.66767	-7.570405	7.424208
18	45.131112	-33.569592	-4.6785222	-.4465124	24.26167	-8.309209	8.16273
20	47.0618	-18.060321	-5.2963093	.2792282	20.56008	-7.443239	7.39828

5. SEASONAL APPLICATIONS

Applications such as crop or fruit drying, salt distillation, or even air-conditioning are seasonal and need to use the collector only for part of the year. For such intermittent applications, the slope angle and orientation will be quite different from those for year-round applications. The following equation can be used to find the optimum angle and orientation for seasonal applications:

$$\beta_{n_1-n_2} = \frac{\int_{n_1}^{n_2} \beta_n \quad dn}{\int_{n_1}^{n_2} dn} \tag{7}$$

Substituting Eqn. (1) into Eqn. (2) and integrating, the following equation is obtained:

$$\beta_{n_1-n_2} = \left[a_0(n_2-n_1)+\frac{a_1}{2}\left(n_2^2-n_1^2\right)+\frac{a_2}{3}\left(n_2^3-n_1^3\right)+\frac{a_3}{4}\left(n_2^4-n_1^4\right)+\frac{a_4}{5}\left(n_2^5-n_1^5\right) + \frac{a_5}{6}\left(n_2^6-n_1^6\right)+\frac{a_6}{7}\left(n_2^7-n_1^7\right)\right] \div (n_2-n_1) \tag{8}$$

where n_1 is the starting day and n_2 is the finishing day of the year, and Jan 1 ($n = 1$) $\leq n_1 < n_2 \leq$ Dec 31 ($n=365$).

For applications with periods crossing into the following year, Eqn. (3) can still be used, but the values of the coefficients should be read from Table 3 and it is valid for July 1 $\leq n_1 < n_2 \leq$ June 30. Also, the values of n should be read from the third column (Jul – Jun) of Table 1.

Like Eqn. (1), the accuracy of Eqn. (3) is also $\pm 1°$. Interpolation for other latitudes is also allowed. The following examples illustrate the use of Eqn. (1) and Eqn. (3) to find angles for different periods of operation. The examples also compare the results with the results produced by the computer program.

Examples

The following examples show how Eqn. (1) and Eqn. (3) are used to find slope angles for different periodic applications. The dates are chosen arbitrarily. An individual may want to conduct an experiment on 4 February. One example is shown to find the slope angle for that particular day so that the collector can receive the maximum solar radiation, which will improve the overall efficiency of the collector. For the other two examples, the periods are chosen as 10 March - 5 December and 14 July - 4 February, respectively. These may be the cases of applications for process heating, solar drying or solar distillation of water, respectively.

(a) $\phi = 4°$ N
Day = 4 February
Read from Table 1 (for Jan-Dec)
$n = 31 + 4 = 35$
From Eqn. (1) using values of coefficients from Table 2
$\beta = 26°$ (+ ve means tilting towards the equator)
By computer program, $\beta = 26°$.

(b) $\phi = 15.6°$ N
Period = 10 March to 5 December
Read from Table 1 (for Jan-Dec)
$n_1 = 59 + 10 = 69$
$n_2 = 334 + 5 = 339$
From Eqn. (3) using values of coefficients from Table 2
For $\phi = 14°$ N: $\beta = 5°$ and
For $\phi = 16°$ N: $\beta = 7°$
Then for $\phi = 15.6°$ N, by interpolation
$\beta = 6.6° \approx 7°$
By computer program, $\beta = 7°$.

Table 3 Values of Coefficients for July to June

Latitude °N	a_0	a_1 $\times 10^3$	a_2 $\times 10^3$	a_3 $\times 10^5$	a_4 $\times 10^8$	a_5 $\times 10^{10}$	a_6 $\times 10^{13}$
4	-24.255852	39.818802	4.3171981	.6305467	-23.62772	7.803151	-7.433224
6	-22.891278	65.979542	3.9096928	.9509931	-25.03991	8.127243	-7.73052
8	-20.87976	37.204659	4.772718	-.02638612	-19.94094	6.88826	-6.594666
10	-19.186082	48.048452	4.4414566	.3326045	-21.6868	7.286017	-6.943347
12	-17.854599	61.083985	4.4172586	.1830158	-20.46204	6.941111	-6.616082
14	-15.812215	40.803349	5.0613992	-.5973866	-16.21308	5.883557	-5.634796
16	-13.692514	1.6893345	6.0361233	-1.584803	-11.38404	4.750671	-4.615735
18	-12.934744	61.072019	5.0381452	-.790549	-14.69178	5.446716	-5.199684
20	-10.997144	70.569021	4.7872999	-.5912375	-15.32935	5.517817	-5.199032

(c) $\phi = 12°$ N
Period = 14 July to 4 February
Read from Table 1 (for Jul-Jun)
$n_1 = 14$
$n_2 = 215 + 4 = 219$
From Eqn. (3) using values of coefficients from Table 3
$\beta = 20°$
By computer program, $\beta = 21°$.

6. APPLICATION

Seasonal applications such as crop drying may need to use a solar collector for only one month. A specific short-term project may need to utilize the collector for a single day. For these applications, the usual practice would be to tilt this collector to a latitude tilt angle. Figure 4 compares the variation of daily total radiation, when the collector slope is equal to the latitude tilt angle, with the maximum

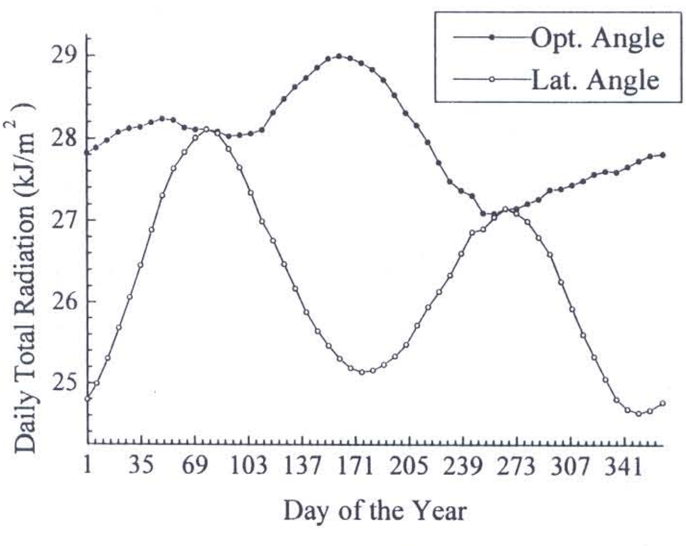

Fig. 4. Variation of daily total energy as a function of day of the year for ϕ= 18°N.

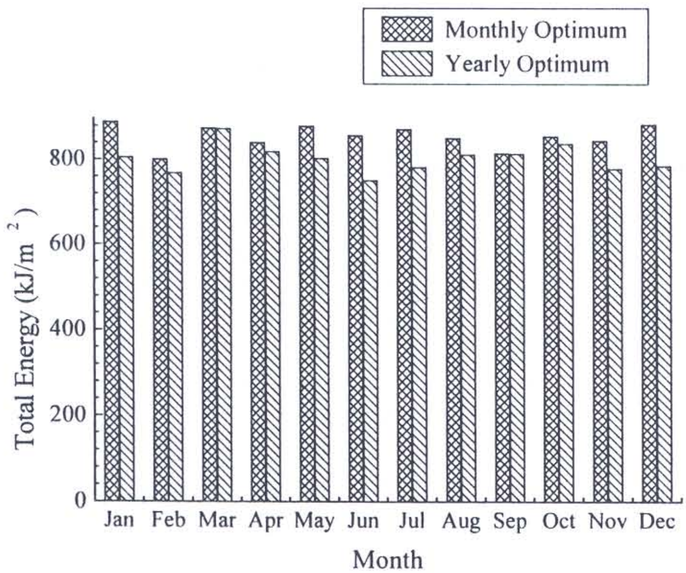

Fig. 5. Monthly total radiation for ϕ= 14°N.

radiation that would be received by an optimally oriented collector, for ϕ = 18°N. The optimally oriented collector receives a maximum of 13% more energy on June 17 (n = 168) than the collector with the slope of latitude tilt angle. On December 23 (n = 357), the difference is 11.2%. On March 25 (n = 70) and September 23 (n = 266), they get the same amount of energy. On other days, the optimally oriented collector always results in getting higher energy than the collector with latitude tilt angle.

Figure 5 compares the monthly total energy received by a collector using latitude tilt angle with that of a collector using a position that is optimized for each month, for ϕ= 14° N. Again, the optimally oriented collector gets the higher energy, with a maximum gain of 12.3% in June and a minimum gain of 0.1% in March. Similar gains can be expected for other combinations of months or days.

7. CONCLUSIONS

The analyses of fixed plate solar collectors show that for seasonal applications, where the collectors are used for a part of the year, the slope angles need to be different than those for year-round operation. However, slope angles for year-round operation for different latitudes are cited in the literature, but for seasonal applications, they are not readily available. In this paper, a method is proposed to find the slope angle and orientation for seasonal applications. Equations with constants, for the average atmospheric condition and latitude angles of Thailand, have been developed. However, similar equations can be developed for other countries.

It is found that the collector's slope and orientation optimized for seasonal applications can get as high as 13% more energy on a daily basis and 12.3% on a monthly basis than the collector with latitude tilt angle, as proposed for year-round operation by different authors. The angles for such seasonal applications can be found by the proposed method easily and accurately.

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