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MATHEMATICAL MODEL DEVELOPMENT FOR OPTIMUM ORIENTATION OF A FLAT PLATE COLLECTOR

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ABSTRACT

Depletion of fossil fuels, increase in energy demand, escalation of cost of fuels and environmental pollution has enforced all the countries to give thought on using the renewable energy sources. Among all the possible renewable energy sources solar energy may be a better substitute. The main objective of solar energy application is its collection by collecting device of suitable shape and proper orientation. In this paper, an attempt has been made to develop a mathematical model for optimum orientation of a south facing flat plate collector. The model is studied in connection with the prediction of month wise optimum slope for a flat plate collector for two Indian locations, Kolkata and New Delhi. The study reveals that the present model for optimum slope of a south facing collector can safely be used for locations with latitudes from 0^o to 40^o. The present investigation also includes a comparative performance analysis of the present method and the methods available in the literature. The comparative study reveals that our formulation provides better results.

Key Words : Latitude, Optimum slope, Tilt factor, Monthly average daily diffuse fraction, Monthly mean daily global radiation on tilted surface.

1. INTRODUCTION

The depletion of fossil fuels, increase in energy demand, escalation of cost of fuels and environmental pollution have forced all the countries to give thought on using the renewable energy sources for human beings. Among all the renewable energy sources, importance of solar energy is enhancing gradually, because it is an abundant and pollution-free source of energy. The main objective of solar energy application is collection of solar radiation by collection device, storing and utilizing it for domestic or industrial applications.

Utilization of solar radiation incident on a fixed flat surface depends on a large number of factors, namely, its latitude of location, solar declination, surface tilt, azimuth angles, time of year, meteorological information such as global and diffuse radiation data on a horizontal surface, and all the inherent factors like cloudiness, total precipitable water, atmospheric turbidity and surface reflectivity, that attenuate solar radiation from its extraterrestrial value while reaching the surface receiving in terrestrial conditions. As the solar energy is a dilute form of low temperature energy, its collection and utilization is directly proportional to the area of the aperture of the collection device and hence the area must be carefully sized along with a proper orientation so that the energy collected would be maximum and cost minimum. Since the slope of the surface can determine the extent of solar radiation that may be received by the surface, therefore, precise optimization of this slope can be considered very important in installing collection devices, for utilizing maximum solar insolation throughout the year.

A number of researchers have carried out their research activity in assessing the optimum slope for a fixed flat plate solar collector to receive the

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maximum solar insolation. Among them Heywood [1] has proposed some simple rules for the collector tilt angle, relating it only to the latitude. As per his recommendation, the tilt angle can be determined by subtracting 10^o from the latitude. According to the research activity done by Chinnery [2] the tilt angle can be determined by adding 10^o to the latitude for South Africa. Yellott [3] has suggested a wide range of tilt angle within latitude ± 20^o. Manes and Ianetz [4] have proposed a simple computational procedure, suitable for the calculation of optimum tilt angles of a south facing solar collector with respect to the maximum amount of incident solar energy in various time scales, and for given values of direct, diffuse and global radiation and surface reflectivity. Chiou and El-Nagger [5] have presented an analytical method to determine the optimum tilt angle of a flat plate collector facing the equator only in the hot season. Their final conclusion is that the optimum tilt angle for the heating season is about latitude + (10^o to 30^o). Reddy [6] , based on calculations under extra-terrestrial conditions, has proposed a simple mathematical formulation to assess the optimum tilt angle for south facing surfaces for each month as,

$$\beta_{opt} = \emptyset + \tan^{-1}(-1.319 \tan \delta)$$

Evans et. al. [7] have recommended the optimum tilt angles for different months as given in table 1.

Table 1:Collector Tilt Angle Minus Latitude for Optimum Monthly Incident Solar Energy

Month	$(\beta_{opt} - \phi)$, deg	Month	$(\beta_{opt} - \phi)$, deg
January	29	July	– 24
February	18	August	– 10
March	3	September	– 2
April	– 10	October	10
May	– 22	November	23
June	– 25	December	30

Elsayed [8] has developed an analytical model based on long term averaging of solar data for determination of the optimum tilt angle of the absorber plate at any orientation for a given period of time. The given correlation is as,

$$\beta_{opt} = (6 - 4.8\overline{K} + 0.86\,\overline{K}^{0.27}\,\phi + 0.0021\phi^2) + (31\,\overline{K}^{0.37} + 0.094\,\overline{K}^{0.46}\,\phi + 0.000634\,\overline{K}^{-1.7}\,\phi^2)\cos\left[\frac{360}{365}(n+11.5)\right]$$

where, $\overline{K}$ is the monthly average clearness index and n is the number of days.

H. Gunerhan and A. Hepbasli [9] have proposed the scheme of determination of optimum tilt angle of solar collector for building applications. In their study, they have determined the optimum values of tilt angles for solar collectors in Izmir, Turkey using the meteorological data.

From this review of literature, it is revealed that a simple, compact, analytical expression for optimum orientation of collector plate for individual months applicable for any location and any climatic conditions has not been developed so far. Therefore, in the present work, an attempt has been made to develop a simple compact analytical expression for optimum orientation of flat plate collector that can be used universally.

2. MATHEMATICAL MODEL DEVELOPMENT

In this section, a comprehensive mathematical formulation in assessing long term average beam radiation component, angle of incidence for beam radiation, monthly average daily tilt factor for beam radiation under terrestrial conditions, optimum tilt factor for global radiation, optimum slope, and monthly mean daily global radiation on the tilted surface have been presented.

2.1 Long Term Average Beam Radiation Component $\overline{I_b}$

The correlation due to Collares-Pereira and Rab1 [10] for r_t (I / H) and the correlation due to Liu and Jordan [11] for r_d (I_d / H_d) have been employed to express the hourly component of beam radiation. The long term average beam radiation component, $\overline{I_b}$ is given by

$$\overline{I_b} = r_t\overline{H} - r_d\overline{H_d} \tag{1}$$

Where

$$r_d = K_1(\cos\omega - \cos\omega_s) \tag{2}$$

$$r_t = K_1(a + b\cos\omega)(\cos\omega - \cos\omega_s) \tag{3}$$

With

$$a = 0.409 + 0.5016\sin(\omega_s - 60^o) \quad (4)$$

$$b = 0.6609 - 0.4767\sin(\omega_s - 60^o) \quad (5)$$

$$K_1 = \pi/[24(\sin\omega_s - \omega_s\cos\omega_s)] \quad (6)$$

Simplifying Eq.1 with Eq. 2, Eq. 3 and Eq. 6 we have

$$\bar{I_b} = K_1\bar{H}(\cos\omega - \cos\omega_s)(a' + b\cos\omega) \quad (7)$$

Where

$$a' = a - \overline{D_f} \quad (8)$$

Now $\overline{D_f}$ can be calculated by $\overline{D}_f = \overline{H}_d / \overline{H}$

Where $\overline{H}$ and $\overline{H}_d$ are the mean daily global and diffuse solar radiation (MJ/m^2-day) respectively on a horizontal surface. The magnitudes of $\overline{H}$ and $\overline{H}_d$ for typical Indian stations are available in [12] and is highlighted in table2.

Table 2: Mean daily global ($\overline{H}$) and diffuse ($\overline{H}_d$) solar radiation (MJ/m^2-day) on a horizontal surface for typical Indian stations

Station		Jan	Feb	Mar	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec
New Delhi Φ=28°35'N L= 77°12'E	$\overline{H}$	14.33	18.00	22.07	24.95	26.21	23.54	19.19	18.18	20.16	19.26	16.27	13.82
	$\overline{H}_d$	4.46	5.29	6.70	8.89	10.51	12.74	11.27	9.83	7.74	5.26	4.10	4.03
Kolkata Φ=22°39'N L= 88°27'E	$\overline{H}$	14.96	17.46	20.09	22.10	22.68	17.28	16.49	16.42	15.37	15.95	16.16	14.65
	$\overline{H}_d$	5.08	5.69	7.56	8.68	10.40	4.80	10.76	10.04	8.60	6.66	4.90	4.59

Angle of Incidence for Beam Radiation for a fixed flat surface with a slope β, at a location of latitude ϕ, on a day with declination δ, the angle of incidence θ_i, corresponding to an hour angle ω is given by,

$$\cos\theta_i = A_1 + B_1\cos\omega \quad (9)$$

where

$$A_1 = \sin\delta\ \sin(\phi - \beta) \quad (10)$$
$$B_1 = \cos\delta\ \cos(\phi - \beta) \quad (11)$$

And the cosine of the zenith angle is given by,

$$\cos\theta_z = B'(\cos\omega - \cos\omega_s) \quad (12)$$

with

$$B' = \cos\phi\ \cos\delta \quad (13)$$

2.2 Formal Expressions for the Monthly Average Daily Tilt Factor for Beam Radiation under Terrestrial Conditions

The monthly average daily tilt factor for beam radiation, $\overline{R}_b$, can be formally written as

$$\overline{R}_b = \frac{\int_{-\omega_s'}^{\omega_s'} \overline{I}_b R_b\, d\omega}{\int_{-\omega_s}^{\omega_s} \overline{I}_b\, d\omega} \quad (14)$$

R_b in Eq. 14, the instantaneous tilt factor for beam radiation at the hour angle ω is given as

$$R_b = \cos\theta_i / \cos\theta_z \quad (15)$$

Inserting $\overline{I}_b$ (Eq. 7), cos θ_i (Eq. 9) and cos θ_z (Eq. 12) along with the limits ω_s and ω_s' ; in Eq. 14, a compact expression for $\overline{R}_b$ results in.

$$\overline{R}_b = \frac{C_1 I_1 + bC_1 I_2 / a'}{1 + bC_2 / a'} \quad (16)$$

where

$$C_1 = \frac{1}{2B'(\sin\omega_s - \omega_s\cos\omega_s)} \quad (17)$$

$$C_2 = \frac{\omega_s/2 - \sin 2\omega_s/4}{\sin\omega_s - \omega_s\cos\omega_s} \quad (18)$$

and the integrals I_1 and I_2 are expressed in terms of the primitives as

$$I_1 = 2J_1(\omega_s') \quad (19)$$

$$I_2 = 2J_2(\omega_s') \quad (20)$$

$$\omega_s' = \min\left[\omega_s, \cos^{-1}\left(-\tan(\phi-\beta)\tan\delta\right)\right] \quad (21)$$

$$J_1(\omega) = A_1\omega + B_1\sin\omega \quad (22)$$

$$J_2(\omega) = A_1\sin\omega + B_1(\omega/2 + \sin 2\omega/4) \quad (23)$$

The tilt factor for global radiation, $\overline{R}$, can finally be expressed as,

$$\overline{R} = \left(1-\overline{D}_f\right)\overline{R}_b + \left(\frac{1+\cos\beta}{2}\right)\overline{D}_f + \rho\left(\frac{1-\cos\beta}{2}\right) \quad (24)$$

2.3 Formulation for Optimum Tilt Factor, $\overline{R}$, for Global Radiation

The monthly average daily tilt factor for beam radiation $\overline{R}_b$ given by the Eq. 16 can be written in a more compact form as

$$\overline{R}_b = C_3 I_1 + C_4 I_2 \quad (25)$$

where

$$C_3 = \frac{C_1}{1 + bC_2/a'} \quad (26)$$

$$C_4 = \frac{(b/a')/C_1}{1 + bC_2/a'} \quad (27)$$

Putting I_1 and I_2 from Eq.19 and Eq. 20 we get,

$$\overline{R}_b = 2C_3 J_1\left(\omega_s'\right) + 2C_4 J_2\left(\omega_s'\right) \quad (28)$$

Eq. 28 is valid for any month of year, however, when $\delta < 0$, $\omega_s' = \omega_s$. Rewriting $\overline{R}_b$ for $\delta < 0$ i.e., for winter months only, we have

$$\overline{R}_b = 2\left[C_3 J_1(\omega_s) + C_4 J_2(\omega_s)\right] \quad (29)$$

Inserting the expressions for $J_1(\omega)$ (Eq. 22) and $J_2(\omega)$ (Eq. 23) in Eq. 29 and rearranging, we have,

$$\overline{R_b} = 2A_1(C_3\omega_s + C_4\sin\omega_s) + B_1(C_4\omega_s + 2C_3\sin\omega_s + 0.5C_4\sin 2\omega_s)$$

or

$$\overline{R}_b = C_5 A_1 + C_6 B_1 \quad (31)$$

where

$$C_5 = 2(C_3\omega_s + C_4\sin\omega_s) \quad (32)$$

$$C_6 = C_4\omega_s + 2C_3\sin\omega_s + 0.5C_4\sin 2\omega_s \quad (33)$$

Finally putting the expressions for A_1 (Eq. 10) and B_1 (Eq. 11) in Eq.31, we express $\overline{R}_b$ like

$$\overline{R}_b = C_7\sin(\phi-\beta) + C_8\cos(\phi-\beta) \quad (34)$$

where

$$C_7 = C_5\sin\delta \quad (35)$$

$$C_8 = C_6\cos\delta \quad (36)$$

$\overline{R}_b$, as given by Eq.34, can now be inserted in Eq. 24 for $\overline{R}$, the tilt factor for global radiation, for $\delta < 0$ and $\gamma = 0^0$, to have a modified form

$$\bar{R} = (1-\overline{D_f})[C_7\sin(\emptyset-\beta) + C_8\cos(\emptyset-\beta)] + \left(\frac{1+\cos\beta}{2}\right)\overline{D_f} + \rho\left(\frac{1-\cos\beta}{2}\right) \quad (37)$$

2.4 Optimum Slope of Collector

Simplifying Equation 37 and differentiating $\overline{R}$ w.r.t β we get

$$\frac{\partial\bar{R}}{\partial\beta} = (1-\overline{D_f})[C_7\sin\emptyset(-\sin\beta) - C_7\cos\beta\cos\emptyset + C_8\cos\emptyset(-\sin\beta)$$

Equating $\frac{\partial\bar{R}}{\partial\beta}$ =0 for maxima we get

$$\cot\beta = \frac{C_7\sin\phi + C_8\cos\phi + C_9}{C_8\sin\phi - C_7\cos\phi}$$

Hence finally we get

$$\beta_{opt} = \cot^{-1}\left[\frac{C_7 \sin\phi + C_8 \cos\phi + C_9}{C_8 \sin\phi - C_7 \cos\phi}\right] \qquad (38)$$

where

$$C_9 = \frac{\overline{D}_f - \rho}{2(1-\overline{D}_f)} \qquad (39)$$

The closed form solution for β_{opt} given by Eq. 38 can be expected to be exact for any location having $\delta < 0$, and also applicable for $\delta > 0$ as well.

2.5 Estimation of Monthly mean daily global radiation

After knowing the optimum slope, β_{opt}, from the Eq. 38, the magnitude of this slope has been used in Eq. 37 to get the value of tilt factor for global radiation, $\overline{R}$, for different months. The monthly mean daily global radiation on tilted surface (MJ/m^2-day), $\overline{H}_T$ can now be estimated as

$$\overline{H}_T = \overline{R}\,.\,\overline{H} \qquad (40)$$

3. RESULTS AND DISCUSSION

The important results of the present study on the month wise prediction of optimum slope for south facing flat plate collectors, and recommendations for the correct seasonally or annually adjusted slope for south facing surfaces are reported in this section.

3.1 Prediction of Optimum Slope for a Month for a South Facing Flat Plate Collector

For equator facing fixed flat surfaces, solar radiation received in a month varies with the surface slope and reaches a maximum at a particular optimum slope. In the present work, the slope is varied arbitrarily from -90^o to $+90^o$ and the corresponding values of tilt factor and subsequently $\overline{H}_T$ are computed by using the Eq.37 and Eq.40 respectively, where the corresponding magnitudes of monthly average solar radiation on horizontal surface, $\overline{H}$, have been taken from Table 1. This exercise is performed by running a computer code, developed by us, repeatedly for individual month for the above mentioned slopes. From the outcome of the exercise, the slope corresponding to the maximum $\overline{H}_T$ is picked up and considered as an actual optimum slope, $\beta_{opt,act}$, for that particular month under consideration. Using this $\beta_{opt,act}$, along with the same set of values of latitude, declination and diffuse fraction, the tilt factor for global radiation, $\overline{R}$, is evaluated, which is the actual maximum tilt factor, $\overline{R}_{act}$. Then, β_{opt} is calculated with the help of mathematical formulation, i.e. Eq.38, derived in the present study and termed as $\beta_{opt,present}$. With the help of the value of $\beta_{opt,present}$, the corresponding tilt factor is evaluated and termed as $\overline{R}_{present}$. This exercise is carried out for latitudes ranging from 0^o to 60^o and monthly average daily diffuse fraction, $\overline{D}_f$, ranging from 0.2 to 0.8. For each latitude, twelve monthly calculations are performed and the maximum difference in β_{opt}, i.e., $(\beta_{opt,act} - \beta_{opt,present})$ and maximum percentage difference in $\overline{R}$, i.e., $(\frac{\overline{R}_{act} - \overline{R}_{present}}{\overline{R}_{act}} \times 100)$ have been identified. The outcome of the exercise is depicted in Table 3 and is represented graphically in Fig. 1 and Fig. 2.

Table 3: Maximum Difference in β_{opt} and Maximum % difference in $\bar{R}$ for Different Latitudes and Diffuse Fractions

ϕ	$\overline{D_f} = 0.2$		$\overline{D_f} = 0.5$		$\overline{D_f} = 0.8$	
	Max. Diff. in β_{opt}	Max % Diff in $\bar{R}$	Max. Diff. in β_{opt}	Max % Diff in $\bar{R}$	Max. Diff. in β_{opt}	Max % Diff in $\bar{R}$
0^0	0.485	2.957×10^{-3}	0.470	2.192×10^{-3}	0.468	1.678×10^{-3}
10^o	0.424	2.197×10^{-3}	0.495	2.478×10^{-3}	0.467	1.657×10^{-3}
20^o	0.496	3.006×10^{-3}	0.393	1.723×10^{-3}	0.501	1.822×10^{-3}
30^o	0.394	2.085×10^{-3}	0.550	2.160×10^{-3}	0.494	1.727×10^{-3}
40^o	0.856	7.354×10^{-3}	0.679	2.126×10^{-3}	0.515	1.750×10^{-3}
50^o	2.440	4.634×10^{-2}	1.730	0.0224	0.697	1.650×10^{-3}
60^o	4.500	0.27	5.650	0.220	2.320	2.600×10^{-3}

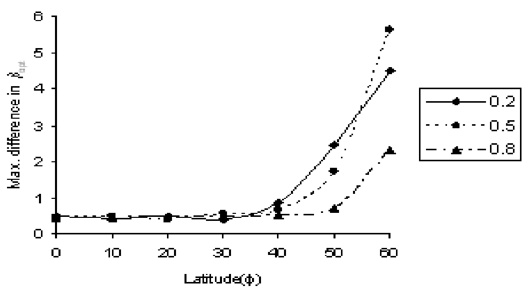

Fig. 1 Variation of max. difference in β_{opt} with ϕ for different $\overline{D}_f$

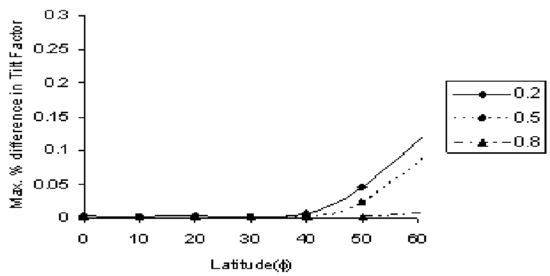

Fig. 2 Variation of Max. % difference in Tilt Factor ($\bar{R}$) with ϕ for different $\overline{D}_f$

From Table 3 and the respective graphs it is observed that up to latitude equal to 40^o, prediction of β_{opt} is almost exact, i.e., less than 1^o. When latitude exceeds 40^o and reaches 60^o, this difference increases and may be as large as 5.65^o for $\overline{D}_f = 0.5$. However, the monthly solar radiation is not very sensitive to this optimum value, even for a difference of 5.65^o in optimum slope, the monthly average daily tilt factor for global radiation makes only a difference of 0.22%, i.e., much less than 1%.

Strictly speaking, the present analytical formulation of the optimum slope is exact for winter months only. Differences in β_{opt} have appeared only in the summer months when the sunset hour angles for a horizontal and a tilted surface differ. For higher latitudes and higher slopes, this difference is more and that is why when $\phi > 40^o$, the present formulation produces greater differences in β_{opt} during summer months.

For Indian locations, the maximum latitude encountered is well within 40^o and hence, it is expected that the present formulation will perform its best for any Indian location. In the present study, we have chosen two Indian locations, Kolkata and New Delhi. For each month of the year and for each location, we have carried out our exercise and presented our results in Tables 4 and 5 respectively, wherein we have also presented the results using the methods stated by Reddy [6], Evans et al. [7] and Elsayed [8] for the respective locations to compare our model with the models established by the them.

Table 4: Comparative Performance of the Present Method and Methods due to Reddy [6], Evans et al. [7] and Elsayed [8] for Kolkata

Months	β_{opt}(deg) Actual	β_{opt}(deg) Present	β_{opt}(deg) as per Reddy	β_{opt}(deg) as per Evans et al.	β_{opt}(deg) as per M. M. Elsayed
January	46.15	46.15	49.35	51.60	45.70
February	37.11	37.11	39.48	40.60	36.05
March	23.04	23.04	25.80	25.60	23.38
April	8.24	8.18	10.26	12.60	9.34
May	-2.96	-2.94	- 1.60	0.60	-1.51
June	-9.19	-9.16	- 6.80	-2.40	-4.71
July	-4.06	-4.04	- 4.50	-1.40	-2.17
August	2.64	2.64	5.10	12.60	6.32
September	14.17	14.18	19.70	20.60	18.64
October	30.83	30.83	35.20	32.60	32.39
November	44.71	44.71	47.00	45.60	44.33
December	49.19	49.19	52.00	52.60	48.92
Maximum difference in β_{opt} with actual	—	0.36	5.68	9.60	4.64

Table 5: Comparative Performance of the Present Method and Methods due to Reddy [6], Evans et al. [7] and Elsayed [8] for New Delhi

Months	β_{opt} (deg) Actual	β_{opt} (deg) Present	β_{opt} (deg) as per Reddy	β_{opt} (deg) as per Evans et al.	β_{opt} (deg) as per M. M. Elsayed
January	52.58	52.58	55.38	57.63	52.72
February	43.64	43.64	45.51	46.63	42.69
March	30.11	30.11	31.82	31.63	29.15
April	13.90	13.75	16.29	18.63	13.97
May	1.66	1.60	4.46	6.63	2.29
June	- 3.09	- 3.06	-0.72	3.63	- 2.17
July	- 0.99	- 0.98	1.56	4.63	1.18
August	7.20	7.10	11.12	18.63	10.40
September	22.61	22.60	25.71	26.63	24.16
October	39.95	39.95	41.21	38.63	39.60
November	51.57	51.57	52.95	51.63	51.69
December	55.39	55.39	57.93	58.63	56.14
Maximum difference in β_{opt} with actual	—	0.43	3.92	11.63	3.40

From the results presented in Tables 4 and 5 for the locations under study, it is very clear that the present value of β_{opt} is exact with that of the value of actual β_{opt} during winter months. Some minor difference between these two values is noted for summer months. This happens because, during summer months, the sunset hour angles for a horizontal and a tilted surface differ. The maximum difference in β_{opt} in a year with the present formulation is the lowest and much smaller than the corresponding differences produced by the other methods. However, the optimum slopes recommended by Evans et al. produces much larger differences than all the other methods. The results also establish that the predictions by our present model are almost exact and this model may be used for various locations and for various weather conditions without sacrificing much accuracy.

4. CONCLUSIONS

A simple, compact, and explicit analytical expression for β_{opt} has been developed for a south facing flat plate collector. It is seen that the present expression for β_{opt} can be safely used for a south facing collector for locations from 0^o to 40^o latitudes, where the prediction of β_{opt} is almost exact, i.e., less than 1^o. This range of latitude covers the whole of South Asia including India. The present investigation also includes a comparative performance analysis of the present method and the methods available in the literature. The comparative study reveals that our formulation provides better results.

NOMENCLATURE

$\overline{D}_f$	Monthly average daily diffuse fraction
H	Daily global radiation on a horizontal surface (MJ/m^2-day)
H_d	Daily diffuse radiation on a horizontal surface (MJ/m^2-day)
$\overline{H}_d$	Monthly average Daily diffuse radiation on a horizontal surface (MJ/m^2-day)
$\overline{H}$	Monthly average daily radiation on a horizontal surface (MJ/m^2-day)
I_b	Hourly beam radiation on a horizontal surface(MJ/m^2-hr)
I_d	Hourly diffuse radiation on a horizontal surface (MJ/m^2-hr)
I	Hourly global radiation on a horizontal surfac(MJ/m^2-hr)
$\overline{I}_b$	Long term average hourly beam radiation on a horizontal surface(MJ/m^2-hr)
r_d	Tilt factor for instantaneous beam radiation
r_t	Tilt factor for instantaneous reflected radiation
R_b	Tilt factor for daily beam radiation
$\overline{R}$	Monthly average daily tilt factor
$\overline{R}_b$	Monthly average daily tilt factor for beam radiation
β	Slope (degree)
β_{opt}	Optimum Slope(degree)
δ	Declination (degree)
θ_i	Incidence Angle (degree)
θ_z	Zenith Angle (degree)
ρ	Reflectivity
ϕ	Latitude (degree)
ω	Hour Angle (radian)
ω_s	Hour Angle Corresponding to Sunrise and Sunset on a Horizontal Surface(radian)
ω_s'	Hour Angle Corresponding to Sunrise and Sunset on a Tilted Surface(radian)

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