Daily Utilizability at Two Tropical Locations

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ABSTRACT

Flat plate solar collectors are being increasingly used in India for water heating. Prediction of their long term performance is necessary for optimum system design. This could be done by using either simulation techniques such as the f-chart method or more conveniently by the utilizability methods of Klein (1978) and Collares-Pereira and Rabl (1979).

Utilizability correlations have been developed on the basis of data pertaining to US locations, which lie in the temperate region. Their applicability to tropical regions has not been studied in detail. It is important to consider this aspect as the generalised $\bar{K}$ curves that have been developed by Liu and Jordan (1960) have been found to be unsuitable for the tropics (Saunier et al., 1987). Since the utilizability correlations are based on long term radiation data, it is necessary to study their performance for tropical locations.

Long term data (5 years) for two locations in India have been used for analysis and the utilizability based on this data has been compared with the correlation proposed by Klein. The results of the study indicate that the relative standard deviation between the data and Klein's utilizability correlation is 10% on average. Therefore, if data based utilizability correlations are not available, Klein's utilizability correlation can be used to estimate the daily utilizability and the useful energy collected by a flat plate solar thermal collector.

INTRODUCTION

One of the design methods available in the sizing of hot water systems using solar radiation is utilizability. This concept, originally introduced by Hottel and Whillier, was developed by Liu and Jordan [1] and then by Klein [2] and Collares-Pereira and Rabl [3, 4].

The utilizability ($\bar{\phi}$) is the fraction of the long term average radiation which is above the specified critical radiation level that can be collected by an idealised collector for which $F_R(\tau\alpha) = 1$. Among the utilizability methods used, the daily utilizability concept of Klein [2] and Collares-Pereira and Rabl [3, 4] is simple and easy to apply and is the subject of the present study. Major applications of the method include: domestic hot water and space heating [5], industrial process heat [6], and photovoltaic systems [7].

The correlation for the daily utilizability given by Klein [2] and Collares-Pereira and Rabl [3, 4] has been obtained by using data from temperate locations (mostly US) only. However, recent studies on the cumulative frequency and probability density of radiation data in tropical locations have clearly indicated that there is an appreciable difference between the classical Liu and Jordan [8] given by Bendt et al. [9] model as compared to the data from tropical locations [10]. As utilizability is defined using the cumulative frequency curve, the applicability of correlations obtained from data based on temperate locations for use in tropical locations is suspect.

The main objective, therefore, of the present work is to confirm whether the proposed utilizability correlations based on data of US locations can be used (with little error) for tropical locations. This has been attempted by drawing the utilizability curves for tropical locations using long term radiation data and comparing them with the values obtained using correlations. Two tropical locations (Madras and Kodaikanal) for which data of the hourly global radiation on a horizontal surface for a period of 5 years were available have been used. The calculation procedure adopted to calculate utilizability and the comparison made with respect to the Klein method has been described. It should be noted that the comparison has been made only with the Klein method as the differences between Klein [2] and Collares-Pereira and Rabl [3, 4] are very minor.

DATA USED

The data of hourly solar radiation for the years 1983 to 1987 pertaining to Madras [Latitude 13° N and Longitude 80°18' E] and Kodaikanal [Latitude 10°23' N and Longitude 77°47' E] were obtained from the Indian Meteorological Department. The data for Madras includes both global and diffuse radiation data, whereas the data for Kodaikanal consisted only of global radiation data. For Madras, 17076 hours of data were used for the analysis for both global and diffuse radiation (each), while for Kodaikanal, 17280 (global only) hours were used.

CALCULATION PROCEDURE

The daily utilizability fractions were calculated for each month of the year for different critical radiation (I_c) values for both horizontal and tilt = latitude for Madras and for a horizontal surface for Kodaikanal using the data from the Indian Meteorological Department. The utilizability values were also determined by using the correlation proposed by Klein [2]. The procedure used is described below:

(a) Utilizability from Data

The values of the utilizability fraction were obtained by the numerical integration of long term weather data. The fraction $\bar{\phi}_d$, was calculated assuming a critical radiation I_c, ranging from 0 to 3.660 MJ/m² hour in steps of 0.180 MJ/m² hour by using the following expression (for a horizontal surface):

$$\bar{\phi}_d = \frac{\sum^{N}\sum^{n}[I - I_c]^+}{\sum^{N}\sum^{n} I} \qquad (1)$$

where the "+" sign indicates that the summation is extended over all hours in which $(I - I_c)$ is positive.

The global radiation falling on a tilted surface (I_T) can be calculated using the isotropic sky model of Liu and Jordan [8] as,

$$I_T = [I - I_d]R_b + I_d\left[\frac{1+\cos\beta}{2}\right] + I\rho\left[\frac{1-\cos\beta}{2}\right] \quad (2)$$

Utilizability can then be estimated by putting $[I_T = I]$ in equation (1).

(b) Utilizability from the Klein Method

The correlation is of the following form [2]

$$\bar{\phi}_k = \exp[(A + B(R_n/\bar{R}))(X_c + CX_c^2)] \quad (3)$$

where, $A = 7.476 - 20\bar{K} + 11.188\bar{K}^2$

$B = -8.562 + 18.679\bar{K} - 9.948\bar{K}^2$

$C = -0.722 + 2.426\bar{K} + 0.439\bar{K}^2$

For the present study, the constants A, B and C used have been taken from Theilacker and Klein [11]. The monthly average daily utilizability can be determined from equation (3) as follows:

1. Using $\bar{K}$ for the chosen month, calculate the A, B and C.
2. Calculate $\bar{R}$ from equation A 1.2 of [2]. $\bar{R}$ is a function of $\bar{R}_b$ and $\bar{H}_d/\bar{H}_g$.

   $\bar{R}_b$ is calculated from equation A 1.4 of [2] and $\bar{H}_d/\bar{H}_g$ *from* the equation [12] for Madras.

$$\bar{H}_d/\bar{H}_g = 1.238 - 1.456\bar{K} \quad (4)$$

3. Estimate $\bar{H}_T$ from $\bar{H}_T = \bar{R}\,\bar{H}_g$.
4. Evaluate R_n from equation A 2.1 of [2]. R_n is a function of H_d/H_g, $r_{d,n}$ and $R_{b,n}$. H_d/H_g can be estimated from the correlation given in [13]. $r_{d,n}$, $r_{T,n}$ and $R_{b,n}$ can be calculated from equation A 2.2, A 2.3 and A 2.4, respectively of [2].
5. Calculate X_c from

$$X_c = \frac{I_c}{r_{T,n}R_n\bar{H}_g} \quad (5)$$

6. Using equation (3) and substituting the values for a given I_c [i.e., for a given X_c], $\bar{\phi}_k$ can be calculated.

The values of $\bar{\phi}_d$ and $\bar{\phi}_k$ were compared by calculating the standard deviation (SD) given by

$$SD = \left[\frac{1}{n_o}\sum^{n_o}\left(\bar{\phi}_d - \bar{\phi}_k\right)^2\right]^{1/2} \quad (6)$$

in absolute units and the relative standard deviation (RSD) given by

$$RSD = \left[\frac{1}{n_o}\sum^{n_o}\left(\frac{\bar{\phi}_d - \bar{\phi}_k}{\bar{\phi}_k}\right)^2\right]^{1/2} \quad (7)$$

in relative units.

DISCUSSION

The values of $\bar{\phi}$ for different critical radiation ratios (I_c) have been plotted for Madras for two tilt positions (tilt = 0 (i.e. horizontal) and tilt = latitude) for the months of April and October (Figs. 1 and 2). For Kodaikanal, $\bar{\phi}$ values for one tilt position (tilt = 0) for the months of April and October are shown in Figs. 3 and 4. It can be seen that the two curves (data and correlation) have a similar trend and are close to each other.

In order to quantify the closeness of the two curves, standard deviation and relative standard deviation have been calculated for each month for the two cities and the results are presented in Table 1. The *SD* for horizontal surfaces at Madras varies from 0.009 to 0.050, the average being 0.0237, while the *RSD* values vary from a minimum of 4.9% to a maximum of 17.9%, the average being 9.5%. Similarly, for tilt = latitude for Madras, the average *SD* is 0.020 and the average *RSD* is 8.3%, while for Kodaikanal, the average *SD* is 0.027 and the average *RSD* is 9.13%.

It is, therefore, clear that the difference between the data based utilizability and the correlation proposed by Klein for tropical locations is about 10%. Thus, for locations where long term insolation data on an hourly basis are not available, the utilizability correlation proposed by Klein [2] or Collares-Pereira and Rabl [3, 4] can be used with little error. On the other hand, if such data are available, it is easy to propose daily utilizability correlations which have much less error. For example, Agami Reddy [14] has suggested a procedure to calculate utilizability from long term hourly data.

An illustrative example for calculating ϕ using Klein's correlation is given below.

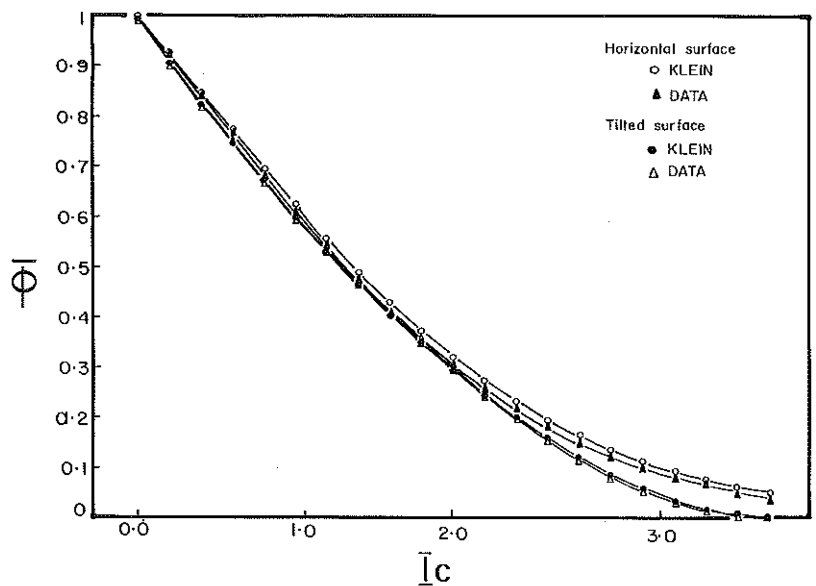

Fig. 1. Monthly average daily utilizability values of Klein and data at Madras in April.

Table 1. Standard deviation and relative standard deviation between data and Klein's expression for Madras and Kodaikanal.

Month	Madras				Kodaikanal	
	Horizontal		Tilt (Tilt = Latitude)		Horizontal	
	SD	RSD(%)	SD	RSD(%)	SD	RSD(%)
Jan	0.009	5.9	0.021	8.1	0.043	18.1
Feb	0.010	4.9	0.016	5.5	0.037	13.5
Mar	0.017	5.7	0.017	5.2	0.022	6.3
Apr	0.022	5.9	0.012	3.3	0.017	5.1
May	0.028	8.1	0.019	7.5	0.012	2.0
Jun	0.038	12.7	0.013	6.7	0.035	10.4
Jul	0.050	17.9	0.026	12.9	0.029	7.9
Aug	0.044	16.0	0.028	12.6	0.028	7.4
Sep	0.031	12.7	0.026	11.0	0.017	2.9
Oct	0.016	8.1	0.020	8.2	0.012	2.1
Nov	0.010	7.4	0.021	8.9	0.032	15.3
Dec	0.010	9.1	0.023	10.8	0.038	18.6

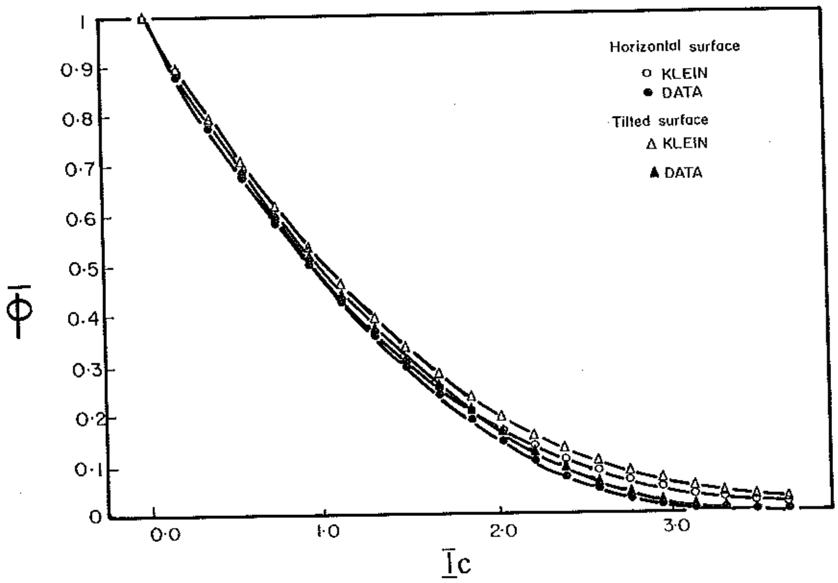

Fig. 2. Monthly average daily utilizability values of Klein and data at Madras in October.

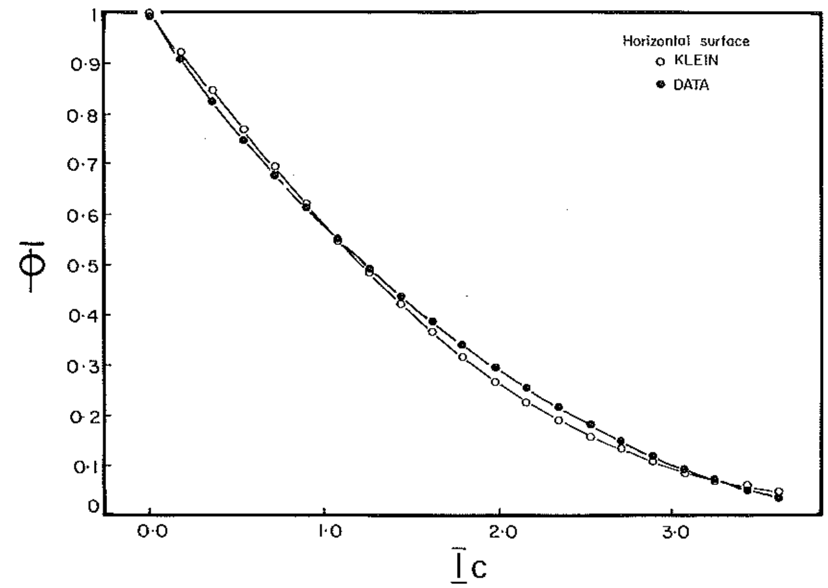

Fig. 3. Monthly average daily utilizability values of Klein and data at Kodaikanal in April.

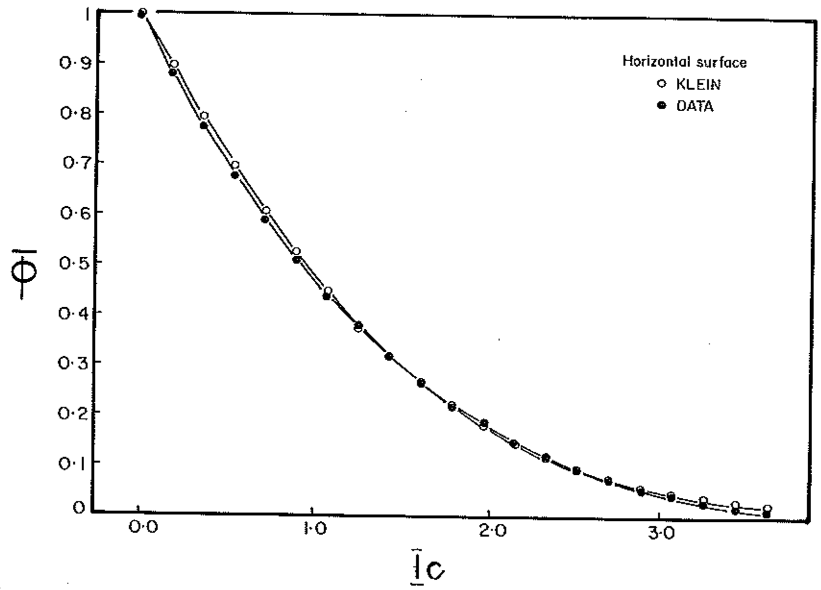

Fig. 4. Monthly average daily utilizability values of Klein and data at Kodaikanal in October.

ILLUSTRATIVE EXAMPLE

Calculate the value of $\bar{\phi}$ for two critical levels of 50 and 550 W/m² in October for a tilted surface at Madras ($\bar{K}$ = 0.492 and ρ = 0.2) having a slope equal to the latitude (13°N).

First, calculate the monthly average daily total radiation on the collector surface ($\bar{H}_T$). For October at Madras, the declination is -9.6° and sunset hour angle on a horizontal surface (ω_s) and on a tilted surface (ω_s') are (from equation 1.6.7 and 2.16.3b of [15]) 87.76° and 89.99°, respectively.

The ratio of the monthly average beam radiation on the tilted surface to that on a horizontal surface $\bar{R}_b$ is 1.0916 using equation A1.4 of Klein [2].

From equation 4,

$\bar{H}_d / \bar{H}_g = 0.5216$

and from equation A1.2 of Klein [2], $\bar{R} = 1.0397$.

Therefore, $\bar{H}_T = \bar{R}\,\bar{H}_g = 17.3163$ MJ/m²

R_n can be calculated using

$r_{d,n}$	=	0.1339	equation A2.2 of Klein [2]
$r_{T,n}$	=	0.1448	equation A2.3 of Klein [2]
$R_{b,n}$	=	1.068	equation A2.4 of Klein [2]

and $H_d / H_g = 0.6167$ from Muneer and Hawas [13]

Thus, $R_n = 1.0245$ equation A2.1 of Klein [2]

$\bar{R}/R_n = 1.0149$

For $I_c = 50$ W/m², from equation (5)

$X_c = 0.073$

Therefore, $\bar{\phi}_k$ could be determined from equation (3) as 0.899. Similarly, for the critical radiation level of 550 W/m², $\bar{\phi}_k = 0.192$.

CONCLUSION

In this study, data for two tropical locations in India were used to calculate the daily utilizability value. This was compared to the utilizability value obtained by using the correlations proposed by Klein [2]. The results indicate that the average standard deviation values for both horizontal and tilted surfaces is about 0.025 while the relative standard deviation is less than 10%. Thus, for locations for which only $\bar{K}$ is available, daily utilizability can be estimated using the correlation of Klein [2].

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NOMENCLATURE

A	:	Coefficient in equation (3)
B	:	Coefficient in equation (3)
C	:	Coefficient in equation (3)
F_R	:	Collector overall heat removal efficiency factor (dimensionless)
H_d	:	Daily diffuse radiation on a horizontal surface (MJ/m^2)
$\bar{H}_d$	:	Monthly average daily diffuse radiation on a horizontal surface (MJ/m^2)
H_g	:	Daily global radiation on a horizontal surface (MJ/m^2)
$\bar{H}_g$	:	Monthly average daily global radiation on a horizontal surface (MJ/m^2)
$\bar{H}_T$	:	Monthly average daily global radiation on a tilted surface (MJ/m^2)
I	:	Hourly global solar radiation incident on a horizontal surface (MJ/m^2)
I_c	:	Critical radiation level (MJ/m^2 hour, W/m^2)
I_d	:	Hourly diffuse radiation incident on a horizontal surface (MJ/m^2)
I_T	:	Hourly total solar radiation incident on a tilted surface (MJ/m^2)
$\bar{K}$	:	Ratio of the monthly average daily global radiation on a horizontal surface to the monthly average daily extraterrestrial radiation on a horizontal surface (dimensionless)
N	:	Number of days
n	:	Number of hours
n_o	:	Number of data
$\bar{R}$	:	Ratio of monthly average daily global radiation on a tilted surface to that on a horizontal surface (dimensionless)
R_b	:	Ratio of daily beam radiation on a tilted surface to that on a horizontal surface (dimensionless)
$\bar{R}_b$	:	Ratio of monthly average daily beam radiation on a tilted surface to that on a horizontal surface (dimensionless)
$R_{b,n}$	:	Ratio of beam radiation on a tilted surface to that on a horizontal surface at noon (dimensionless)
R_n	:	Ratio of radiation on a tilted surface to that on a horizontal surface at noon (dimensionless)
$r_{d,n}$	:	Ratio of diffuse radiation at noon to the daily diffuse radiation (dimensionless)
$r_{T,n}$	:	Ratio of radiation at noon to the daily total radiation (dimensionless)
X_c	:	Monthly average critical radiation ratio given by Equation 5 (dimensionless)

Greek

$\bar{\phi}$	:	Monthly average daily utilizability (dimensionless)
$\bar{\phi}_d$	:	Monthly average daily utilizability using data given by equation (1) (dimensionless)
$\bar{\phi}_K$	:	Monthly average daily utilizability using Klein's expression given by equation (3) (dimensionless)
$\tau\alpha$	:	Monthly average transmittance absorptance product (dimensionless)

ρ : Ground reflectance assumed to be 0.2

β : Slope of the collector plane with respect to the horizontal (degrees)

ω_s : Sunset hour angle on a horizontal surface (degrees)

ω_s' : Sunset hour angle on a tilted surface (degrees)

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