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Utilizability for Chennai, Trivandrum and Visakhapatnam

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Abstract— an attempt has been made to find the monthly mean daily utilizability at Chennai, Trivandrum and Visakhapatnam by using long-term (15 years) measured data of solar radiation on horizontal surface. Utilizability has also been found by using Klein's correlation and found its suitability on the three locations. Comparisons have been done by finding standard and relative standard deviation between utilizability fraction based on measured data and Klein's correlation. Results have shown the best fit of Klein's correlation for the locations with least error and recommended that Klein's correlation can be used to find utilizability fraction in the respective locations in the absence of measured data of solar radiation on horizontal surface.

***Index Terms*—Klein's correlation, Solar radiation, Utilizability fraction**

I. INTRODUCTION

Long term performance of any solar thermal device is indispensable for optimum system design and installations. There are many techniques to find the long term performance of such system without much problem. Among the techniques, utilizability is one of the most viable methods for predicting the performance by using solar radiation on horizontal surface. Utilizability is the fraction of long-term average radiation which is above the specified critical radiation level that can be collected by an idealized solar thermal system [1]. Correlations have been proposed for utilizability by many researchers by using the measured data of solar radiation on various locations and presented. Utilizability correlations proposed by Klein [3] and Collares-Pereira and Rabl [2] have been based on data pertaining to US locations which are temperate regions. An analytical expression has been derived to evaluate the time average of physical quantities non-linearly dependant on collected solar radiation based on utilizability method by Fraidenraich and Vilela [6] and applied for photovoltaic pumping systems. Results have shown the applicability of the expression to calculate long-term averages, maximum water volume propelled by various types of pumps and design procedures of photovoltaic pumping equipment. Tawanda Hove [7] has proposed a method to predict long-term average conventional energy displaced by a photovoltaic system and designed a chart relating annual solar fraction with photovoltaic array and storage battery size for a given location basis for design and economic optimization of the system. By using utilizability method, long term estimation of the water volume pumped by PV systems driven by tracking collectors has been done by Vilela *et al.* [8]. It has been confirmed that the increased in pumped water volume, annual average, varies between 1.29 and 1.53 for critical irradiance within the interval from 275 to 575 W/m^2. A multi step optimization procedure has been adopted to develop a algorithm for optional PV array slope, solar radiation interval and number of PV panels with optimal electrical configuration by Abidin Firatoglu and Bulent Yasilata [9]. It has been inferred that the performance of the system is better with less PV array area by accurate selection of the array configuration. Karatasou *et al*. [10] have developed a simple method for the evaluation of monthly average hourly and daily flat plate collector utilizability and confirmed that the method reduced the calculations required to determine utilizability compared to long-term hourly simulations as well as hourly and daily utilizability calculation methods. Oliveira [11] has proposed a method to evaluate long-term performance of solar thermal systems quantified through monthly of seasonal solar fraction. Results have shown the applicability for solar cooling and solar cogeneration systems by considering two different temperature levels corresponding to minimum and maximum operating temperatures. Further three diffuse hourly irradiance models have been proposed by using data of hourly global and diffuse radiation on a horizontal surface, global solar radiation on a tilted surface at Cordoba University, Spain by Posadillo and Lopez Luque [12]. It has been found that the anisotrophic model gave the best results. Simulation of a solar-assisted ejector cooling system has been done to compute solar fraction and results have been compared with the results obtained by utilizability concept by Colle *et al*. [13]. Results have shown good agreement with the results obtained by utilizability method. Morteza Khalaji Assadi *et al*. [14] have designed and tested a new solar system to reduce energy usage in rural residential buildings and food drying industry. The system has shown better performance which include energy supply and storage equipment, solar dryer, water collectors and rectangular, trapezoidal, triangular and double pass with longitudinal fins air heaters. Xi Chen and Hongxing Yang [15] have done a numerical simulation of a solar assisted ground coupled heat pump system for space heating and domestic hot water supply. The optimization process has done on the TRNSYS based platform and confirmed the optimized design with a minor difference of 0.75%. A numerical study of solar/thermal gas single effect lithium bromide absorption chiller has been carried out by Rabah Gomri [16] and inferred that the system reduced the cost for electricity and operates in regions where there are abundant solar energy. Kicsincy *et al*. [17] have proposed ordinary differential equation models for solar

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heating systems with a solar collector, a heat exchanger, storage and pipes. Comparison between the measured and simulated results of a real solar heating system has confirmed the validity of the model. Followed by the researchers, in the present study an attempt has been made to find the utilizability based on measured data at Chennai, Trivandrum and Visakapatnam and by utilizability correlation based on US data proposed by Klein. Also, to find the suitability of Klein's correlation in the three locations with least error so that it can be used for the locations where measured data are not available.

II. DATA

Measured data of daily average global and diffuse solar radiation of three South Indian locations viz., Chennai, Trivandrum and Visakapatnam for the period of 15 years are collected from Indian meteorological Department, Pune. For the three locations, 15 year data of daily average global and diffuse radiation has been averaged to find the daily average global and diffuse radiation for all the days in the year. Followed by the calculation of daily average global and diffuse solar radiation, monthly average global and diffuse solar radiation has been found and used.

The latitude and longitude of the locations have been presented in Table. 1.

Location	Latitude	Longitude
Chennai	13°N	80°E
Trivandrum	8°28'N	76°57'E
Visakapatnam	17°N	83°E

III. METHODOLOGY

Using the data of monthly global and diffuse radiation the monthly mean daily utilizability fractions were calculated for each month for different critical radiation (I_c) values for horizontal surface utilizing the Klein's [3] concept of daily utilizability. Data based correlation has been found by utilizing the monthly mean global and diffuse radiation. The procedure used is described below.

(a) Utilizability from Klein method

The correlation is of the form [4]

$$\bar{\phi}_k = \exp [(A + B (R_n / \bar{R}) (X_c + C X_c^2)] \quad (1)$$

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

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

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

The constants A, B and C used have been taken from Theilacker and Klein [4]. The monthly average daily utilizability can be determined from equation (2) as follows.

1. Using the monthly average hourly global radiation, $\bar{k}$ is found for each month, calculate A, B and C.
2. $\bar{R}$ is calculated using the equation A.1.2 of [4]. $\bar{R}$ is a function of $\bar{R}_b$ and $\bar{H}_d/\bar{H}$. $\bar{R}_b$ is calculated using expression A.1.4 of [3] $\bar{H}_d/\bar{H}$ can be estimated from the correlation given in [3].
3. R_n is a function of $\bar{H}_d/\bar{H}$, $r_{d,n}$ and $R_{b,n}$, $r_{t,n}$, $r_{d,n}$ and $\bar{R}_{b,n}$ can be evaluated using the equation A.2.2, A.2.3 and A.2.4 respectively of [3]. Hence R_n is evaluated.
4. Evaluate X_c from

$$X_c = \frac{I_c}{r_{t,n}\, R_n\, \bar{H}} \quad (2)$$

Using equation (1) and substituting the values for a given I_c (i.e., for a given X_c), $\bar{\phi}_k$ can be calculated.

(b) Utilizability from data

The numerical integration of long term weather data gives the utilizability fraction $\bar{\phi}_d$. The utilizability fraction $\bar{\phi}_d$ was calculated for different critical radiation I_c, ranging from 0 to 3.6 MJ/m^2 hour in steps of 0.45 MJ/m^2 hour by using the following expression.

$$\bar{\phi}_d = \frac{\sum^{N}\sum^{n} [I_T - I]^+}{\sum^{N}\sum^{n} I} \quad (3)$$

I_T was calculated using the following expression given by Liu and Jordan [5] as,

$$I_T = [I - I_d] R_b + I_d [(1+\cos\beta)/2] + I \rho [(1-\cos\beta)/2] \quad (4)$$

Utilizability can then be calculated by putting [I_T = I] in equation (3).

The values obtained from both the equations (1) and (3) were compared by evaluating the standard deviation (SD) given by

$$SD = [(1/n_o) \sum^{n_o} (\bar{\phi}_d - \bar{\phi}_k)^2]^{1/2} \quad (5)$$

In absolute units and relative standard deviation (RSD) given by

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

In relative units.

IV. RESULTS AND DISCUSSION

Utilizability fraction for different critical radiation (I_c) level ranging from 0 to 3.6 MJ/m^2 has been evaluated by using long-term measured data of solar radiation on horizontal surface and Klein's correlation equation for all the months of the year for Chennai, Trivandrum and Visakapatnam. Graphs have been drawn for utilizability based on data and Klein's utilizability with respect to different critical radiation level in order to compare the results obtained from both the correlations. Figs. (1-3) represents the utilizability fraction for Chennai in the month of January, May and August respectively. From the graphs, it is clear that the data based and Klein's monthly mean daily utilizability have same trend for different critical radiation level. It has also been found that the utilizability is maximum for minimum critical radiation and vice-versa. Thus in Chennai, utilizability fraction led to identify the long-term performance of solar thermal devices with lower to higher critical solar radiation level. The performance of the solar

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thermal devices can be found by finding the product of utilizability fraction, solar radiation and collector area to optimize the design parameters for large scale installations. In order to find the suitability of Klein's correlation in Chennai for evaluating the utilizability fraction, standard and relative standard deviation between data based utilizability and Klein's utilizability are found.

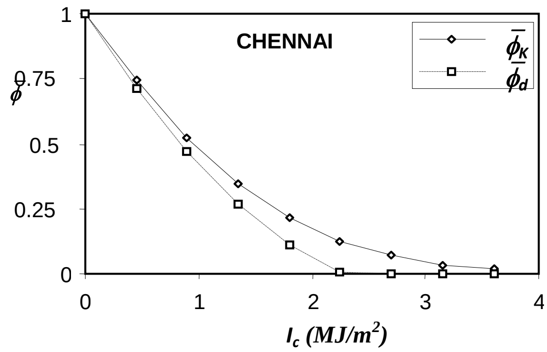

Fig. 1 Monthly mean daily utilizability Values in January in Chennai (both Klein and Data)

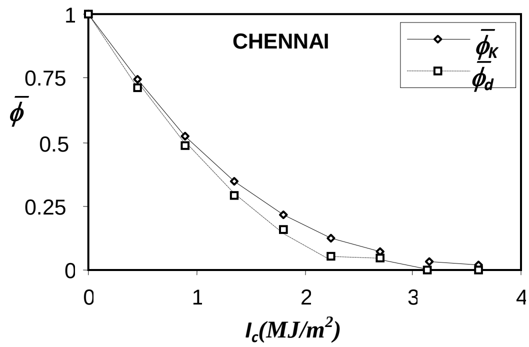

Fig. 2 Monthly mean daily utilizability Values in May in Chennai (both Klein and Data)

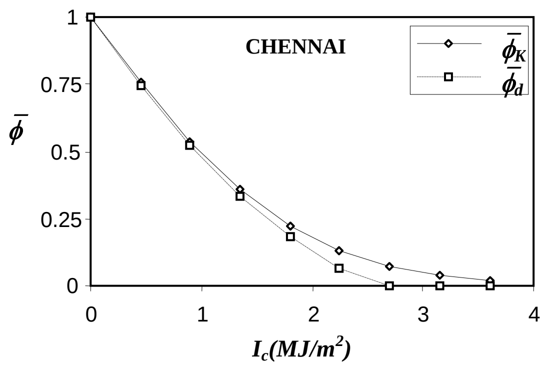

Fig. 3 Monthly mean daily utilizability Values in August in Chennai (both Klein and Data)

Similarly in Trivandrum and Visakapatnam, Klein's and data based utilizability fraction has been found for all the months of the year and standard and relative standard deviation between the two fractions has been found. Figs. (4-9) represents the utilizability fraction for different critical solar radiation level based on Klein's correlation and measured data in the month of January, May and August for Trivandrum and Visakapatnam. In both the locations, it has been found that, the results based on data and Klein's correlation is in mere agreement for different critical solar radiation level. To quantify the results obtained, for all the months the standard deviation and relative standard deviation has been found. It is also confirmed that the performance of the solar thermal system in the respective locations will be good for lower critical solar radiation level with maximum utilizability fraction. In order to signify the closeness of the utilizability fraction based on data and Klein's correlation, the standard and relative standard deviation for each month for the three locations are presented in Table. 2

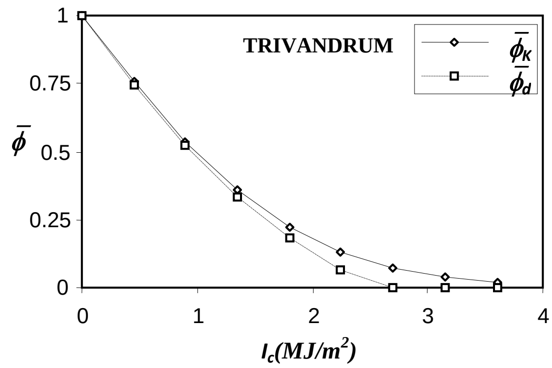

Fig. 4 Monthly mean daily utilizability Values in January in Trivandrum (both Klein and Data)

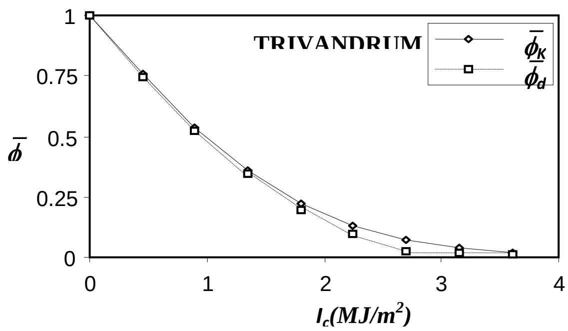

Fig. 5 Monthly mean daily utilizability Values in May in Trivandrum (both Klein and Data)

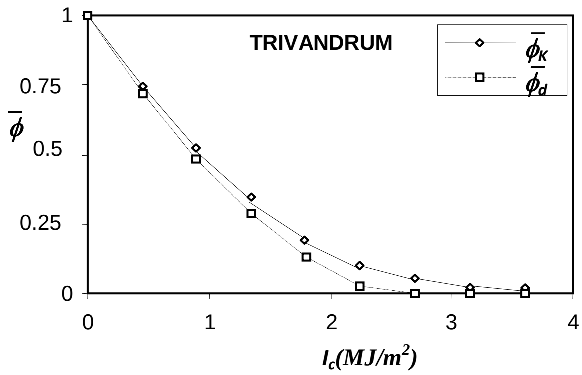

Fig. 6 Monthly mean daily utilizability Values in August in Trivandrum (both Klein and Data)

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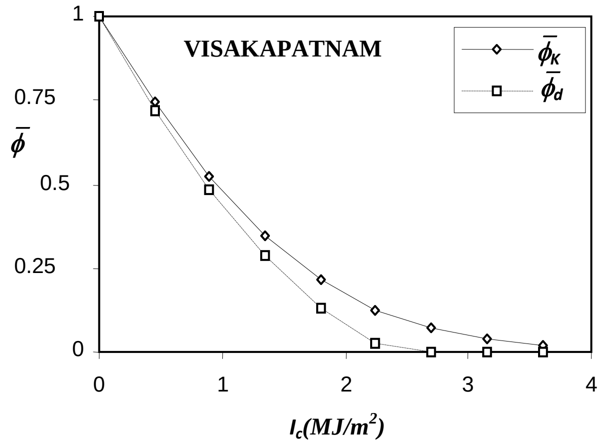

Fig. 7 Monthly mean daily utilizability Values in January in Visakapatnam (both Klein and Data)

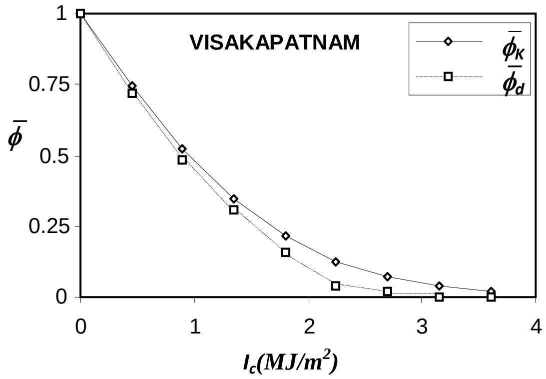

Fig. 8 Monthly mean daily utilizability Values in May in Visakapatnam (both Klein and Data)

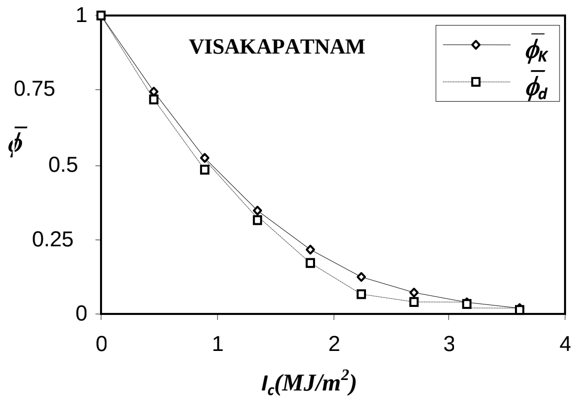

Fig. 9 Monthly mean daily utilizability Values in August in Visakapatnam (both Klein and Data)

Table 2 Standard deviation and Relative standard deviation between data based and Klein's correlation for Chennai, Trivandrum and Visakapatnam

Month	Chennai		Trivandrum		Visakapatnam	
	SD	RSD(%)	SD	RSD(%)	SD	RSD(%)
Jan	0.082	9.25	0.069	3.94	0.075	7.22
Feb	0.033	1.96	0.024	1.52	0.022	2.09
Mar	0.048	2.03	0.048	1.42	0.039	1.32
Apr	0.032	2.02	0.026	2.02	0.022	2.25
May	0.024	2.15	0.032	2.42	0.032	2.10
Jun	0.110	9.65	0.074	3.48	0.098	1.10
Jul	0.120	6.89	0.092	7.16	0.096	7.15
Aug	0.034	2.33	0.029	2.98	0.061	4.21
Sep	0.126	7.62	0.079	4.96	0.093	7.02
Oct	0.083	5.88	0.062	3.49	0.042	3.65
Nov	0.076	5.10	0.061	4.28	0.091	6.31
Dec	0.154	9.86	0.098	5.92	0.085	5.23

It is observed that in Chennai the SD varies from 0.024 to 0.154, the average being 0.07683, while the RSD values vary from a minimum of 1.96% to a maximum of 9.86%, the average being 5.395% and in Trivandrum it varies from 0.024 to 0.098, the average being 0.05783, while the RSD values vary from a minimum of 1.42% to a maximum of 7.16%, the average being 3.6325% and in Visakapatnam the SD varies from 0.022 to 0.098, the average being 0.063, while the RSD values vary from a minimum of 1.10% to a maximum of 7.22%, the average being 4.1375%. It is clear that the difference between data based correlation and Klein's correlation for Chennai, Trivandrum and Visakapatnam is less than 8% on average.

V. CONCLUSION

From this study, it is concluded that the utilizability fraction for Chennai, Trivandrum and Visakapatnam seems to be better for lower critical solar radiation level and the fraction found will be helpful in designing and optimizing solar thermal systems with an optimistic hope for large scale installations. Further Klein's correlation equation based on US data for utilizability fraction is found to be fit for the locations in India with least error. In the absence of the solar radiation, Klein's correlation equation can be used to find the utilizability fraction instead of data based correlation without much calculations and the method is simple and viable for the applications of utilization of solar radiation in the locations. Moreover Klein's correlation equation based on US data can also be recommended for the locations in South India with much less error.

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NOMENCLATURE

A, B and C: Coefficients in equation (1)

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)

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 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_n : Ratio of radiation on a tilted surface to that on a horizontal surface at noon (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)

$r_{t,n}$: Ratio of radiation at noon to the daily total radiation (dimensionless)

$r_{d,n}$: Ratio of diffuse radiation at noon to the daily diffuse radiation (dimensionless)

X_c : Monthly average critical radiation ratio given by Equation (3) (dimensionless)

Greek

$\bar{\phi}$: Monthly average daily utilizability (dimensionless)

$\bar{\phi}_d$: Monthly average daily utilizability using data expression (2) (dimensionless)

$\bar{\phi}_k$: Monthly average daily utilizability using Klein's expression (1) (dimensionless)

$\tau\alpha$: Monthly average transmittance-absorptance product (dimensionless)

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

$\omega s'$: Sunset hour angle on a tilted surface (degrees)

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ρ	:	Ground reflectance assumed to be 0.2
β	:	Slope of the collector plane with respect to the horizontal (degrees)