CHAPTER 6

IMPLEMENTATION OF KLEIN’S UTILIZABILITY FUNCTION
FOR CHENNAI, TRIVANDRUM AND VISAKHAPATNAM

6.1 INTRODUCTION

The optimum system design and application of any solar thermal device depends on long term performance. Long term performance of solar thermal devices can be found by various methods, the easiest of which is utilizability function. This is found by using solar radiation on horizontal surface (Klein & Beckman 1979). 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 is known as utilizability. Researchers all over the world have proposed correlations for utilizability function using the measured data of solar radiation in various locations.

Solar radiation data of US locations were used by Klein (1978) and Collares-Pereira & Rabl (1979) to propose Klein’s correlation. Fraidenraich & Vilela (2000) have derived an analytical expression to evaluate the time average of physical quantities non-linearly dependant on the solar radiation collected based on utilizability method and applied for photovoltaic pumping systems. The results obtained proved the applicability of the expression for long-term average performance and maximum water volume pumped by different types of pumps and also for the procedure to design photovoltaic pumping equipment. Long-term average conventional energy replaced by photovoltaic system was done by Hove (2000). A designed a chart relating annual solar fraction of the photovoltaic array and storage battery for given location for the optimization of economy and design of the system was also designed.
Long term estimation of the water volume pumped by PV systems driven by tracking collectors by utilizability method was done by Vilela et al. (2003), who confirmed that the increased in pumped water volume, annual average, varies between 1.29 and 1.53 for a critical irradiance within the interval from 275 to 575 W/m².

Developed an algorithm by a multi step optimization procedure for optional PV array slope, solar radiation interval and number of PV panels with optimal electrical configuration by Firatoglu & Yesilata (2004). The performance was found to be better with a lesser PV array area by accurate selection of the array configuration. Karatasou et al. (2006) developed a simple method for the evaluation of monthly average hourly and daily flat plate collector utilizability. They confirmed that the method reduced the calculations required to determine utilizability when compared to long-term hourly simulations as well as hourly and daily utilizability calculation methods. Oliveira (2007) proposed a method to evaluate long-term performance of solar thermal systems quantified through monthly of seasonal solar fraction. Results showed the applicability of radiation 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 & Lopez Luque (2009). It was found that the anisotrophic model proved the best results.

A solar-assisted ejector cooling system was simulated to compute solar fraction and the results were compared with those obtained by utilizability concept by Colle et al. (2009). Their results showed a good agreement with the results obtained by utilizability method. Assadi et al.
(2011) designed and tested a new solar system to reduce energy usage in rural residential buildings and food drying industry. The system seemed to show a better level of performance which includes energy supply, storage equipment, solar dryer, water collectors and rectangular, trapezoidal, triangular and double pass with longitudinal fins air heaters.

Chen & Yang (2012) did a numerical simulation of a solar assisted ground coupled heat pump system for space heating and domestic hot water supply. The optimization process was 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 was carried out by Gomri (2013). It was inferred that the system reduced the cost for electricity and operates in regions where there is abundant solar energy. Kicsiny et al. (2014) proposed ordinary differential equation models for solar heating systems with a solar collector, a heat exchanger, a storage and pipes. A Comparison between the measured and simulated results of a real solar heating system confirmed the validity of the model.

In the present study, an attempt has been made to find the utilizability based on measured data at Chennai, Trivandrum and Visakhapatnam and correlation based on US data proposed by Klein. The suitability of Klein’s correlation for utilizability in the three locations has been found by comparing the results obtained using measured data and Klein’s correlation equation.

6.2 DATA USED

Three important coastal areas Chennai, Trivandrum and Visakhapatnam have been selected to find the applicability of Klein’s correlation based on US data to predict the long-term performance of solar thermal collectors. Fifteen years of measured data of daily average global and
diffuse solar radiation for the three locations have been used for the study. These data have been collected from Indian Meteorological Department, Pune, India. The hourly data have been used to find the daily average global and diffuse solar radiation for the select locations and the monthly average global and diffuse solar radiation has also been determined.

<table>
<thead>
<tr>
<th>Location</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chennai</td>
<td>13°N</td>
<td>80°E</td>
</tr>
<tr>
<td>Trivandrum</td>
<td>8°28’N</td>
<td>76°57’E</td>
</tr>
<tr>
<td>Visakhapatnam</td>
<td>17°N</td>
<td>83°E</td>
</tr>
</tbody>
</table>

6.3 METHODOLOGY

In order to validate the Klein’s utilizability fraction in the three locations, the results of data based correlation has been found and the results of both Klein and Data based correlation have been compared by finding the standard and the relative standard deviation between them. Monthly mean daily utilizability for all the months in the year for the locations have been found using Klein’s correlation equation and data based correlation equation. Calculations have been done for different critical radiation (Ic) values. Klein’s method and data based method for determining of utilizability fraction are given as follows

6.3.1 Klein’s utilizability method

The correlation is of the form by Theilacker and Klein (1980)

$$\bar{\phi}_k = \exp \left[ (A + B \left( \frac{R_n}{\bar{R}} \right) (X_c + C X_c^2) \right]$$

(6.1)

where, $$A = 7.476 - 20 \ k + 11.188 \ k^2$$
The constants A, B and C used have been taken from Theilacker and Klein (1980). The monthly average daily utilizability can be determined from equation (6.2) 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 Theilacker and Klein (1980). $\bar{R}$ is a function of $\bar{R}_b$ and $\bar{H}_d/\bar{H}$. $\bar{R}_b$ is calculated using expression A.1.4 of Klein (1978) $\bar{H}_d/\bar{H}$ can be estimated from the correlation given by Klein (1978).
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 $R_{b,n}$ can be evaluated using the equation A.2.2, A.2.3 and A.2.4 respectively of Klein (1978). Hence $R_n$ is evaluated.
4. Evaluate $X_c$ from

$$X_c = \frac{I_c}{r_{t,n} \cdot R_n \cdot \bar{H}} \quad (6.2)$$

Using equation (6.1) and by substituting the values for a given $I_c$ (i.e., for a given $X_c$), $\bar{\phi}_k$ can be calculated.

6.3.2 Data based utilisability

The numerical integration of long term weather data gives the utilisability fraction $\bar{\phi}_d$. The utilisability fraction $\bar{\phi}_d$ has been 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 using the following expression.

$$\bar{\phi}_d = \frac{N \sum \sum [I_T - I]^+}{\sum \sum I}$$

(6.3)

$I_T$ has been calculated using the following expression given by Liu and Jordan (1963) as,

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

(6.4)

Utilizability can then be calculated by putting $[I_T = I]$ in equation (6.3).

The values obtained from both the equations (6.1) and (6.3) has been compared by evaluating the standard deviation (SD) and relative standard deviation (RSD) is given as follows

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

(6.5)

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

(6.6)

6.4 RESULTS AND DISCUSSION

6.4.1 Utilizability for Chennai

In order to find the suitability of Klein’s correlation for utilizability fraction, it is indispensable to find the fraction for different critical radiation levels. Radiation levels have varied from 0 to 3.6 MJ/m$^2$ and the fraction has been found using Klein’s equation and data based equation for all the months.
for the three locations. The three locations with the same climatic conditions i.e., warm and humid and utilizability fraction based on both data and Klein’s correlation is calculated more precisely as the measured values of monthly mean global and diffuse solar radiation is available for all the months. For all the three locations, both Klein’s and data based correlation for utilizability fraction for different critical radiation levels and for the months of March, May and September have been presented graphically.

For Chennai, Figures (6.1-6.3) represents the Klein’s and data based utilizability fraction for critical radiation level ranging from 0 to 3.6 MJ/m$^2$. From the graphs for the month of March and September, utilizability fraction of both Klein and data based correlation have the same trend and signifies with each other. In May, there is small deviation in utilizability fraction for a higher critical radiation levels, because in May, Chennai is very humid and due to higher level of humidity cloudy days may be expected. It can also be observed that the maximum utilizability i.e 1 for solar thermal systems with minimum critical radiation level. In Chennai, the maximum utilizability fraction clearly reflects the maximum absorption of solar energy by the thermal systems throughout the year leading to the complete conversion of solar energy into useful energy. In order to find the closeness of the two utilizability curves i.e., Klein’s and data based, both standard and relative standard deviation have been found between them.

Further, the utilizability fraction can be used to find the thermal performance of the solar thermal systems by finding the product of utilizability fraction and collector absorption area. It is also possible to optimize the design and climatic parameters that influence the performance of the solar thermal systems for large scale installations. In locations like Chennai, solar thermal systems can deliver useful energy with minimum absorption of radiation.
Figure 6.1 Utilizability values of Klein and Data based correlation equation in the month of March in Chennai

Figure 6.2 Utilizability values of Klein and Data based correlation equation in the month of May in Chennai
6.4.2 Utilizability for Trivandrum

Klein’s equation and data based equations have been used to find the utilizability fraction for different critical radiation levels ranging from 0 to 3.6 MJ/m\(^2\) in Trivandrum. The results of the fraction for all the months seem to be favourable as the location receives large amount of solar radiation throughout the year. The coastal area is so warm and humid that low levels of radiation are enough for solar thermal system to deliver useful energy. The latitude of the location reflects the position in the lower equatorial belt and the intensity of solar radiation is higher, as expected. The Utilizability curves based on both Klein’s and data have been found and figures (6.4-6.6) represent the curves for the months March, May and September. Results of these three months in a year clearly reflect the performance of the solar thermal systems for the entire year. From the three graphs, it is clear that the both Klein’s and data based correlation equation the utilizability fraction attains a maximum value of 1 for a minimum critical radiation. To quantify the results obtained,
the trends of the two curves have been examined and it can be seen that, both the 
curves exhibit a similar trend for all the critical radiation levels from 0 to 3.6 
MJ/m$^2$. The results of both the curves have slight variations as expected due to 
the intermittent nature of solar radiation in the coastal area. The standard and 
relative standard deviation between utilizable fractions based on Klein’s and 
measured data have been found to compare the suitability of the Klein’s 
equation in the location considered. In the month of September in Trivandrum, 
the weather is hazy and humid due to the presence of passing clouds. This 
results in a minute variation between data based and Klein’s based results for 
utilizable fraction and though it does not affect the suitability of Klein’s 
correlation.

![Graph](image-url)

**Figure 6.4 Utilizability values of Klein and Data based correlation equation in the month of March in Trivandrum**
Figure 6.5 Utilizability values of Klein and Data based correlation equation in the month of May in Trivandrum

Figure 6.6 Utilizability values of Klein and Data based correlation equation in the month of September in Trivandrum
6.4.3 Utilizability for Visakhapatnam

Figures (6.7-6.9) represents the monthly mean utilizability fraction based on Klein’s and data based method for different critical radiation levels in the months of March, May and September. From the graphs, it can be understood that, the curves of Klein and data based have a similar trend i.e., they decreases with increasing critical radiation levels. The useful energy delivered by the solar thermal systems in the location is found to be good and optimization of the design parameters of the system will be useful for the large scale installations. The combined trend of both Klein’s and data based utilizability fraction is found to be successful implementation of Klein’s utilizability in the location. In certain parts of the curve, slight deviation is due to the intermittent nature of solar radiation caused by the clouds due to high humidity. The results based on both the correlation for all the months in the year for utilizability fraction is similar to that of Chennai and Trivandrum as the location is also coastal.

![Graph showing Utilizability values of Klein and Data based correlation equation in the month of March in Visakhapatnam](image)

Figure 6.7 Utilizability values of Klein and Data based correlation equation in the month of March in Visakhapatnam
Figure 6.8 Utilizability values of Klein and Data based correlation equation in the month of May in Visakhapatnam

Figure 6.9 Utilizability values of Klein and Data based correlation equation in the month of September in Visakhapatnam
In all the three coastal areas, there is a conjoint trend of the curves based on Klein’s and data based correlation. In order to validate Klein’s correlation in the locations, the results for both data based and Klein’s correlation for utilizability fraction have been compared by finding the standard and relative standard deviation for all the months and are presented in the Table 6.2.

In Chennai, the standard deviation between the data based and Klein’s correlation were found to vary between 0.026 to 0.162 and relative standard deviation, between 2 to 12. From the results it can be observed that, the average standard and relative standard deviation between data based and Klein’s correlation are 0.078 and 5.6. The results obtained led ascertain the suitability of Klein’s correlation equation in Chennai, with least error.

In Trivandrum, the average values of standard and relative standard deviation were found to be 0.0828 and 4.94 respectively. In Visakhapatnam, the values of standard and relative standard deviation between data based and Klein based correlation were found to be 0.059 and 3.88. Among these three locations, Visakhapatnam shows a significant impact of using Klein’s correlation for estimating of utilizability fraction. This is because among the three coastal areas, Visakhapatnam has the highest latitude towards North approaching the equator. Hence, a higher latitude in the equatorial belt shows the mere agreement of Klein’s correlation for utilizability fraction with least errors.
Table 6.2 Standard deviation and Relative standard deviation values for all the months between the data based and Klein’s correlation in Chennai, Trivandrum and Visakhapatnam

<table>
<thead>
<tr>
<th>Month</th>
<th>Chennai</th>
<th>Trivandrum</th>
<th>Visakhapatnam</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SD</td>
<td>RSD(%)</td>
<td>SD</td>
</tr>
<tr>
<td>January</td>
<td>0.094</td>
<td>10.25</td>
<td>0.088</td>
</tr>
<tr>
<td>February</td>
<td>0.026</td>
<td>2.04</td>
<td>0.029</td>
</tr>
<tr>
<td>March</td>
<td>0.056</td>
<td>2.07</td>
<td>0.046</td>
</tr>
<tr>
<td>April</td>
<td>0.027</td>
<td>2.00</td>
<td>0.028</td>
</tr>
<tr>
<td>May</td>
<td>0.029</td>
<td>2.25</td>
<td>0.030</td>
</tr>
<tr>
<td>June</td>
<td>0.120</td>
<td>7.18</td>
<td>0.101</td>
</tr>
<tr>
<td>July</td>
<td>0.117</td>
<td>7.89</td>
<td>0.127</td>
</tr>
<tr>
<td>August</td>
<td>0.035</td>
<td>2.59</td>
<td>0.066</td>
</tr>
<tr>
<td>September</td>
<td>0.120</td>
<td>7.83</td>
<td>0.199</td>
</tr>
<tr>
<td>October</td>
<td>0.084</td>
<td>5.94</td>
<td>0.046</td>
</tr>
<tr>
<td>November</td>
<td>0.073</td>
<td>5.20</td>
<td>0.123</td>
</tr>
<tr>
<td>December</td>
<td>0.162</td>
<td>12.00</td>
<td>0.111</td>
</tr>
</tbody>
</table>

6.5 CONCLUDING REMARKS

For all the three select locations, Klein’s correlation equation for utilizability fraction based on measured US data is found to be fit, with least error. Moreover, the average relative standard deviation between data based and Klein’s correlation was found to be less than 6% on an average. Thus, the implementation of Klein’s utilizability correlation equation for the tropical locations is validated further since it shows good results for the three important cities in India. Moreover, in Visakhapatnam Klein’s utilizability correlation holds good due to its proximity to the equator i.e., location with high latitude in the equatorial belt.