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Analysis of swimming pool solar heating using the utilizability method

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Abstract

A study was carried out to predict the long-term energy performance of swimming pool solar heating systems for four Brazilian cities using the utilizability method. The chosen cities were Brasília, Fortaleza, Porto Alegre and São Luís. The pool area was kept constant and both glazed and unglazed solar thermal collectors were considered for the different locations, with a slope equal to the latitude of each city. The meteorological data used in the analysis such as wind speed, ambient temperature, radiation on a horizontal surface and clearness index were specific for each city and obtained from Meteonorm. The geometric parameters of the collectors were constant for all simulations and the results were carried out with a specially developed computational code. In addition, statistical analyses of the data using ANOVA (Analysis of Variance) and Tukey's test were made.

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Keywords: Solar fraction; Swimming pool heating; Utilizability

1. Introduction

Preliminary designs for active solar systems require inexpensive methods for predicting their long-term performance. Utilizability is defined as the fraction of the total incident solar radiation that is received at an intensity higher than the critical radiation level [1]. This critical level is the value that is just enough so that the absorbed radiation equals the collector energy losses. Using solar thermal collectors, the utilizability can be defined as the fraction of the incident solar radiation that can be converted into useful heat. After the utilizability, the solar fraction (amount of energy provided by the solar system divided by the total energy required) is easily calculated, as can be seen in the next section. The utilizability method requires knowledge of the collector inlet fluid temperature, which has to be known, either fixed or estimated. The time to perform the manual simulations can be significant, but the procedure can be easily implemented with computational means. This work shows predicted results of the

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Nomenclature

A_c	Collector area
f_{annual}	Annual solar fraction
f_i	Monthly solar fraction for i month
f_{inv}	Inverse function of Fischer's distribution
$F_R \tau \bar{\alpha}$	Optical efficiency of the collector
$F_R U_{col}$	Loss coefficient of the solar collector
G_{SC}	Solar constant
\bar{H}	Monthly average daily radiation on a horizontal surface
\bar{H}_d	Average diffuse radiation component
H_o	Daily solar extraterrestrial radiation
\bar{H}_o	Monthly mean daily extraterrestrial radiation
\bar{H}_β	Monthly average daily radiation on a tilted surface
\bar{K}_T	Monthly average clearness index
MSE	Error mean square
MSR	Regression mean square
n	Day of the year
N_i	Number of the days in each month
$Q_{conv,i}$	Heat losses by convection and evaporation for i month
$Q_{evap,i}$	Heat losses by evaporation for i month
$Q_{load,i}$	Overall thermal load of a swimming pool for i month
$Q_{rad,i}$	Heat losses by radiation for i month
$Q_{useful,i}$	Monthly useful energy
R_b	Ratio of total radiation on the tilted surface to that on the horizontal surface
α	Significance level
β	Tilt angle
δ	Declination
ϕ	Latitude
Φ_i	Utilizability for i month
ρ_g	Diffuse ground reflectance
w_s	Sunset hour angle

long-term energy performance of solar heated swimming pools, using the utilizability method, obtained through a code created by the authors, named Softsun software, and developed within Matlab. A review of the methodologies used in softwares for solar heating systems [2,3] has shown that none of them uses the utilizability method.

In this work, the utilizability method was applied to four Brazilian cities with very different climatic conditions. From the countries in Latin America, Brazil is one where a renewable energy tendering process is ongoing, and has received significant investments in renewable energy [4]. Until now, outdoor swimming pool are commonly used in different regions of the country without utilization of renewable systems in several cases. The Brazilian cities chosen, with specification of latitude and longitude, are: Brasília (15.78°S, 47.93°W), Fortaleza (3.76°S, 38.60°W), Porto Alegre (30.02°S, 51.22°W) and São Luís (2.53°S, 44.28°W). In addition, statistical analyses of the data using ANOVA and Tukey test [5] were developed.

2. Theoretical analysis

To predict the long-term energy performance of solar heated swimming pools, using the utilizability method, it is necessary to calculate different solar angles and solar radiation components. The equations for calculating the angles and components are explained below.

The declination (δ) is given by Eq. (1) [6], where n is the day of the year:

$$\delta = 23.45 * \sin \left(360 * \frac{24 + n}{365} \right) \quad (1)$$

The sunset hour angle (w_s) is determined by Eq. (2), where ϕ is the latitude (north positive and south negative)

$$w_s = \cos^{-1} (\tan (\phi) * \tan (\delta)) \quad (2)$$

The daily solar extraterrestrial radiation (H_o) over the period from sunrise to sunset is given by Eq. (3), where G_{SC} is the solar constant (in watts per square meter):

$$H_o = \frac{24 * 3600 * G_{SC}}{\pi} \left(1 + 0.33 \cos \frac{360n}{365} \right) * \left(\cos (\phi) \cos (\delta) \cos (w_s) + \frac{\pi w_s}{180} \right) \sin (\phi) \sin (\delta) \quad (3)$$

The monthly mean daily extraterrestrial radiation (\overline{H}_o) for latitudes in the range $+60^\circ$ to -60° , can be calculated using n and δ for the mean day of the month according to Klein [7]. For simplification, even though all components are referred to each month, the subscript (i) will only be used for the solar fraction and utilizability.

The monthly average clearness index (\overline{K}_T) is the ratio of the monthly average daily radiation on a horizontal surface (\overline{H}) to the monthly average daily extraterrestrial radiation (\overline{H}_o):

$$\overline{K}_T = \frac{\overline{H}}{\overline{H}_o} \quad (4)$$

The correlations for the average diffuse radiation component (\overline{H}_d), using the average clearness index, adapted from Erbs et al. [8]:

$$w_s \leq 81.4^\circ \text{ and } 0.3 \leq \overline{K}_T \leq 0.8, \quad \frac{\overline{H}_d}{\overline{H}} = 1.33 - 3.560\overline{K}_T + 4.189\overline{K}_T^2 - 2.13\overline{K}_T^3 \quad (5)$$

$$w_s > 81.4^\circ \text{ and } 0.3 < \overline{K}_T \leq 0.8, \quad \frac{\overline{H}_d}{\overline{H}} = 1.33 - 3.022\overline{K}_T + 3.427\overline{K}_T^2 - 1.821\overline{K}_T^3 \quad (6)$$

The monthly average daily radiation on a tilted surface (\overline{H}_β) is a sum of beam or direct radiation, diffuse and earth reflected radiation. Considering that the diffuse radiation is isotropic, according to Liu and Jordan [9], \overline{H}_β can be written as:

$$\overline{H}_\beta = \overline{H} \left(1 - \frac{\overline{H}_d}{\overline{H}} \right) R_b + \overline{H} \frac{\overline{H}_d}{\overline{H}} \frac{(1 + \cos (\beta))}{2} + \overline{H} \rho_g \frac{(1 - \cos (\beta))}{2} \quad (7)$$

where β is the tilt angle, \overline{H}_d is the diffuse radiation, ρ_g is the diffuse ground reflectance and R_b is the ratio of total radiation on the tilted surface to that on the horizontal surface, given by Eq. (8) (for latitudes in the South Hemisphere):

$$R_b = \frac{\cos (\phi + \beta) \cos (\delta) \sin (w_s) + \frac{\pi}{180} w_s \sin (\phi + \beta) \sin (\delta)}{\cos (\phi) \cos (\delta) \sin (w_s) + \frac{\pi}{180} w_s \sin (\phi) \sin (\delta)} \quad (8)$$

with w_s given by Erbs et al. [8] correlation:

$$w_s = \min \left[\cos^{-1} (-\tan (\phi) \tan (\delta)); \cos^{-1} (-\tan (\phi + \beta) \tan (\delta)) \right] \quad (9)$$

The monthly solar fraction (f_i , Eq. (10)) is defined as the amount of useful energy provided by the solar system divided by the total energy required, where each month is represented by i . The monthly useful energy ($Q_{useful,i}$, Eq. (11)) depends on the collector area (A_c), optical efficiency of the collector ($F_R \overline{\tau \alpha}$), monthly average daily radiation on the tilted surface ($\overline{H}_{\beta,i}$), number of the days in each month (N_i) and utilizability (Φ_i). The overall thermal load of a swimming pool ($Q_{load,i}$) is an algebraic sum of four components: heat losses by radiation ($Q_{rad,i}$), convection ($Q_{conv,i}$) and evaporation ($Q_{evap,i}$); and solar gains ($Q_{solgains,i}$), as shown in Eq. (12). The annual solar fraction (f_{annual}) is given by Eq. (13).

$$f_i = Q_{useful,i} / Q_{load,i} \quad (10)$$

$$Q_{useful,i} = A_c \cdot F_R \overline{\tau \alpha} \cdot \overline{H}_{\beta,i} \cdot N_i \cdot \Phi_i \quad (11)$$

$$Q_{load,i} = Q_{rad,i} + Q_{conv,i} + Q_{evap,i} - Q_{sol\ gains,i} \quad (12)$$

$$f_{annual} = \sum_i^n (f_i * Q_{load,i}) / \sum_i^n Q_{load,i} \quad (13)$$

Utilizability (Φ_i , Eq. (14)) can be defined as the fraction of the incident solar radiation that can be converted to useful heat. It depends on the time distribution of solar radiation and there are several methods of calculation, some more accurate than others, as the method of Evans et al. [10] or Klein [11]. Utilizability may also be calculated after the statistical treatment of solar radiation time distribution, using the Euftrat method. In this work, utilizability was evaluated with the approach of Evans et al. [10], where $\bar{K}_{T,i}$, A and B are components defined by Eqs. (15)–(17), respectively.

$$\Phi_i = 1 + A \frac{(T_{in} - \bar{T}_{ext,i})}{\bar{K}_{T,i}} + B \left(\frac{(T_{in} - \bar{T}_{ext,i})}{\bar{K}_{T,i}} \right)^2, \quad \frac{(T_{in} - \bar{T}_{ext,i})}{\bar{K}_{T,i}} \leq -\frac{A}{2B} \quad (14)$$

$$\bar{K}_{T,i} = K_{T,i} * \cos(0.8|\beta_{optim,i} - \beta|) \quad (15)$$

$$A = -3.26 * 10^{-4} * 1.08 * 10^{-4} * (F_R U_{col} / F_R \bar{\tau} \bar{\alpha}) + 6.49 * 10^{-6} * (F_R U_{col} / F_R \bar{\tau} \bar{\alpha})^2 \quad (16)$$

$$B = 3.55 * 10^{-8} * 6.778 * 10^{-7} * (F_R U_{col} / F_R \bar{\tau} \bar{\alpha}) + 2.12 * 10^{-7} * (F_R U_{col} / F_R \bar{\tau} \bar{\alpha})^2 \quad (17)$$

where $F_R U_{col}$ and $F_R \bar{\tau} \bar{\alpha}$ are obtained through the efficiency parameters of the solar collector.

3. Statistical treatment

Statistical analyses of the data using ANOVA and Tukey test [5] were developed. The ANOVA, variance analyses, is performed by $F_o = f_{inv}(\alpha, a - 1, N - a)$ which is the inverse function of Fischer's distribution, F-test. F_o is calculated for a confidence interval of $(1 - \alpha) = 0.95$, with “ $a - 1$ ” degrees of freedom to regression (MSR) and “ $N - a$ ” degrees of freedom to error (MSE); being that “ a ” is the numbers of groups, “ N ” is total number of observations, and “ $N - 1$ ” the total of degrees of freedom. Under null hypothesis, $(MSR/MSF) > F_o$, meaning that the F -test reject, i.e. the populations are different. Tukey test, also known as TSD — Tukey Significant Difference, defines the smallest significant difference:

$$TSD = q_{(\alpha,a,N-a)} \sqrt{MSE/n} \quad (18)$$

in which “ n ” is the number of replicas of the level, “ $a - 1$ ” degrees of freedom to group and “ $N - a$ ” degrees of freedom to error (MSE); where “ a ” is the numbers of groups and “ N ” is the total number of observations.

4. Results and discussion

The simulations and results, for an outdoor swimming pool, were carried out with a specially developed computational code created by the authors, named Softsun software, according to the equations described in the previous section. The Brazilian cities analyzed were: Brasília (15.78°S, 47.93°W), Fortaleza (3.76°S, 38.60°W), Porto Alegre (30.02°S, 51.22°W) and São Luís (2.53°S, 44.28°W). The outdoor swimming pool is uncovered, no storage tank is considered and a heat exchanger between the solar collectors and the swimming pool is used. The fixed parameters used in the simulation are shown in Table 1. Several simulations were analyzed, using glazed and unglazed solar collectors, and considering a variable collector area.

The Fig. 1 shows the climatic data for all cities during one year: (a) the monthly average daily radiation on a tilted surface (\bar{H}_β) and (b) the ambient temperature.

The cities with lower latitudes (Fortaleza and São Luís) maintain \bar{H}_β practically constant during the year, contrarily to Porto Alegre with a variation of almost 5 kWh/m² between Winter and Summer. The ambient temperature follows similar trends, with about 27 °C during the year in Fortaleza and São Luís, in contrast with Porto Alegre with a variation of almost 13 °C between Winter and Summer.

Fig. 2 shows the annual solar fraction depending on the collector area, for all cities and for unglazed solar collectors.

As can be seen, a higher collector area implies a higher annual solar fraction. The monthly solar fraction was higher than 1 for collector areas higher than 150 m² in several months in Fortaleza and São Luís. Therefore, a

Table 1. Input parameters for simulations.

Parameter	Value
A_p -swimming pool area	250 [m ²]
T_p -swimming pool temperature	30 [°C] ^a
η_{ex} - heat exchanger efficiency	0.7
β - collector tilt	Equal to the latitude of each city
$F_R U_{col}$ glazed	8 [W/m ² /°C]
$F_R(\tau\alpha)_n$ glazed	0.75
$F_R U_{col}$ unglazed	21 [W/m ² /°C]
$F_R(\tau\alpha)_n$ unglazed	0.9
ρ_g - diffuse reflectance	0.2
Water absorptance and emissivity	0.9

^aDifferent swimming pool temperatures will be later analyzed for cities with lower ambient temperatures.

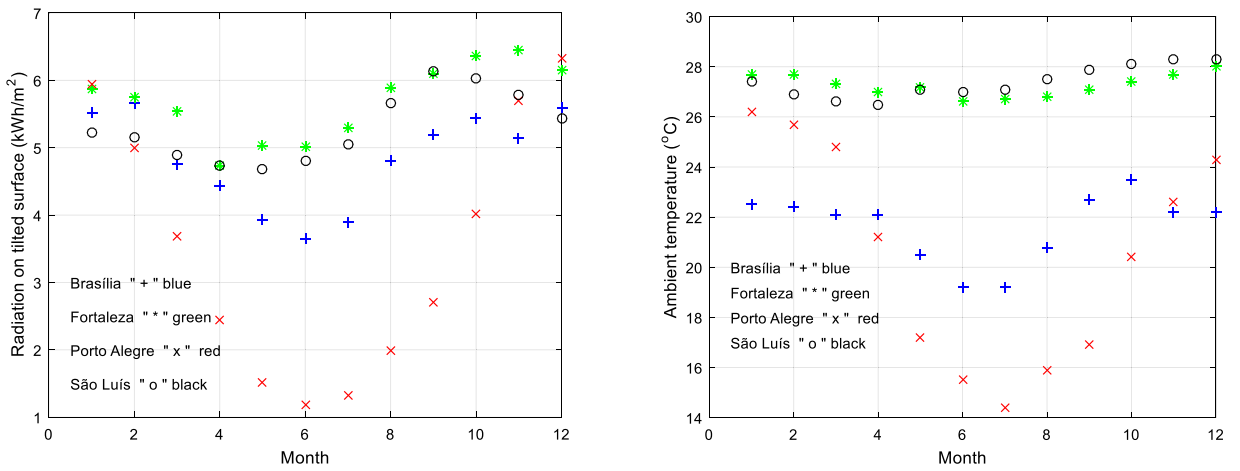


Fig. 1. Climatic data for all cities: (a) monthly average daily radiation (\bar{H}_β) and (b) ambient temperature.

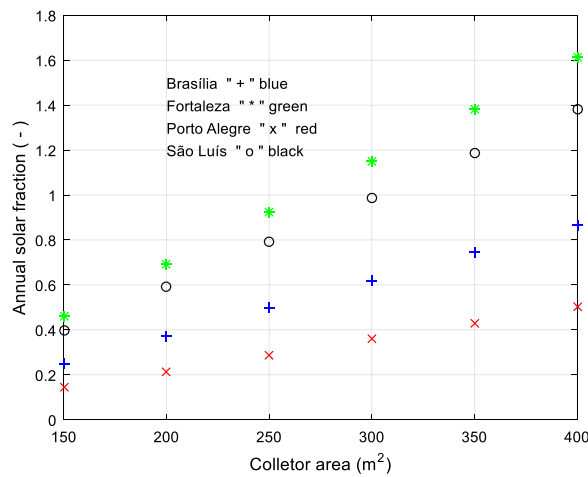


Fig. 2. Annual solar fraction varying with the collector area (unglazed collectors).

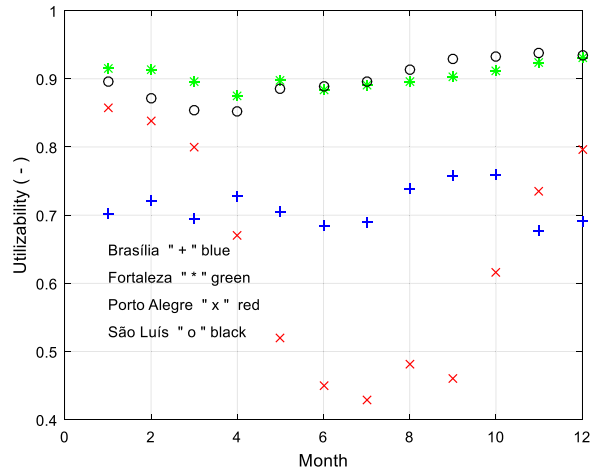


Fig. 3. Utilizability during the year for all cities.

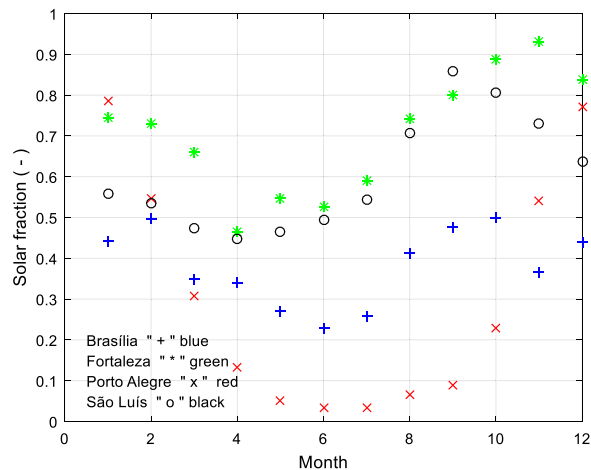


Fig. 4. Monthly solar fraction for all cities.

collector area of 150 m^2 was selected for the following calculations. Fig. 3 shows the utilizability during the year and the monthly solar fraction is in Fig. 4, for all cities and with unglazed collectors.

The monthly solar fraction presents a similar variation to \overline{H}_β . Note that the solar fraction curves have a minimum for all the cities in June (Winter time) with values of 52% in Fortaleza, 49% in São Luis, 23% in Brasilia and less than 10% in Porto Alegre, indicating that in this city a 150 m^2 collector area will not be enough to maintain the swimming pool at $30 \text{ }^\circ\text{C}$ during the year. The annual solar fraction has values of 37% in Brasilia, 69% in Fortaleza, 21% in Porto Alegre and 59% in São Luis, with unglazed collectors. When the glazed solar collectors are used, the annual solar fraction is lower just for two cities (60% Fortaleza and 52% São Luis), maintaining constant values in the others. When the swimming pool temperature is modified to $26 \text{ }^\circ\text{C}$ and the unglazed collector area is increased to 200 m^2 , the annual solar fraction in Brasilia and Porto Alegre increased to 79% and 44%, respectively.

4.1. Statistical analyses

Regarding the statistical analyses, monthly average daily radiation on a horizontal surface and clearness index presented the same behavior, i.e., at 5% significance level the populations are not significantly different for radiation, according to ANOVA, as can be seen in Table 2.

Table 2. ANOVA table for radiation.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_o	Prob > F_o
Radiation	5023.22	3	1674.40	2.1207	0.1112
Error	34 740.75	44	789.56		
TOTAL	39 763.97	47			

Table 3. ANOVA table for wind speed.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_o	Prob > F_o
Wind speed	30.957	3	10.319	17.181	1.57E–7
Error	26.427	44	0.6006		
TOTAL	57.384	47			

Table 4. ANOVA table for temperature.

Source of variation	Sum of squares	Degrees of freedom	Mean square	F_o	Prob > F_o
Temperature	486.155	3	162.051	30.734	7.15E–11
Error	231.995	44	5.2726		
TOTAL	718.15	47			

Table 5. Tukey Test regarding temperature for all cities.

	Mean Diff	MSE	q value	Prob	α	Sig
FOR-BRZ	5.65	0.93734	8.5236	1.7768E–6	0.05	1
POA-BRZ	–1.19167	0.93734	1.79776	0.58578	0.05	0
POA-FOR	–6.84167	0.93734	10.32142	0	0.05	1
SLZ-BRZ	5.775	0.93734	8.71224	1.11986E–6	0.05	1
SLZ-FOR	0.125	0.93734	0.18858	0.99914	0.05	0
SLZ-POA	6.96667	0.93734	10.51	0	0.05	1

Sig 1 indicate that means difference is significant at 5% level.

Sig 0 indicate that means difference is not significant at 5% level.

In contrast are the monthly average wind speed and ambient temperature, for which at 5% significance level the populations are significantly different, according to ANOVA (see [Tables 3](#) and [4](#)).

Regarding the difference between populations, when the monthly average wind speed and ambient temperature are compared for all the cities, in [Table 5](#), the main differences were found out between Porto Alegre and São Luís, Porto Alegre and Fortaleza, as well as Brasília and São Luís, Brasília and Fortaleza, according to the Tukey Test for temperature.

5. Conclusion

The utilizability method to predict the long-term energy performance of swimming pool solar heating systems for four Brazilian cities was applied. Simulations for unglazed solar collectors showed a better performance than glazed solar collectors. Results for unglazed solar collectors with 150 m² of area and a swimming pool temperature (T_p) of 30 °C presented an annual solar fraction of 37% for Brasilia, 69% for Fortaleza, 21% for Porto Alegre and 59% for São Luis. When T_p is modified to 26 °C and the unglazed collector area is increased to 200 m², the annual solar fraction in Brasilia and Porto Alegre increased up to 79% and 44%, respectively.

Regarding the statistical analysis, monthly average daily radiation on a horizontal surface and clearness index presented the same behavior, i.e., at 5% significance level the populations are not significantly different. In contrast are the monthly average wind speed and ambient temperature, for which at 5% significance level the populations are significantly different. Regarding the difference between populations, when the monthly average wind speed and ambient temperature are compared for all the cities, the main differences between pairs of cities were found between Porto Alegre and São Luis, as well as Brasília and São Luis.

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References

- [1] Duffie JA, Beckman WA. Solar engineering of thermal processes. third ed.. Wiley; 2006.
- [2] Nogueira CEC, Vidotto ML, Toniazio F, Debastiane G. Software for designing solar water heating systems. *Renew Sustain Energy Rev* 2016;58:361–75.
- [3] Dongellinia M, Falcionia S, Martellia A, Morinia GL. Dynamic simulation of outdoor swimming pool solar heating. *Energy Procedia* 2015;81:1–10.
- [4] REN21 (Renewable Energy Policy Network for the 21st Century), (2017). http://www.ren21.net/lac-report_banner-suggestion-2/ (accessed 25 March 2019).
- [5] Montgomery DC. Design and analysis of experiments. New York: John Wiley & Sons, Inc; 2001.
- [6] Cooper PI. The absorption of solar radiation in solar stills. *Solar Energy* 1969;12(3):333–46.
- [7] Klein SA. Calculation of monthly averaged insolation on tilted surfaces. *Sol Energy* 1977;19:325.
- [8] Erbs DG, Klein SA, Duffie JA. Estimation of the diffuse radiation fraction for hourly, daily and monthly average global radiation. *Solar Energy* 1982;28(4):293–302.
- [9] Liu BYH, Jordan RC. The interrelationship and characteristic distribution of direct, diffuse and total solar radiation. *Sol Energy* 1960;4(3):1–19.
- [10] Evans DL, Rule TT, Wood BD. A new look at long term collector performance and utilizability. *Solar Energy* 1982;28(1):13–23.
- [11] Klein SA. Calculation of flat-plate collector utilizability. *Sol Energy* 1978;21:393.