Review of Solar Radiation Analysis Techniques for Predicting Long-Term Thermal Collector Performance – Applicability to Bangkok Data

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ABSTRACT

Depending on the ultimate objective, studies of measured solar irradiation data at specific locations can be classified as either primary or secondary. A primary analysis focuses predominantly on obtaining or verifying interactions of the various radiation components over different time scales. A secondary analysis aims at studying irradiation patterns specially suited for long-term solar collector performance predictions. Techniques and methodologies for performing the above, as well as corresponding generalized correlations, have been proposed in the literature reviewed in the first half of this article. Since these correlations for computing the long-term collector performance have been developed from data of relatively few temperate locations, their validity to tropical locations is still unproven. The second part of this article, which addresses itself to reassessing the above with raw irradiation data at Bangkok, have revealed the following important features:

a) *The cumulative frequency curves of daily global irradiation on a horizontal surface in Bangkok differ appreciably from the Liu & Jordan generalized curves. However the present study also revealed that the same functional form for the underlying probability distribution could still be retained provided certain modifications are made.*

b) *The cumulative frequency curves of daily and hourly global irradiation could be said to be similar for the six months covering the dry period in Bangkok (November – April), while during the remaining rainy period of six months, distinct differences were noticed.*

c) *The monthly cumulative frequency curves of global irradiation on a horizontal surface for all the hours of the month (from which the daily utilizability fractions are obtained) can be considered to be linear and close enough to allow the curves for all the 12 months to be represented by a single linear curve.*

It is urged that an analysis of this type be performed for additional locations in the tropical belt so as to enable solar scientists to acquire a better understanding of the long-term irradiation fluctuation patterns and to propose more accurate and tested correlations of long-term collector performance.

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INTRODUCTION

Solar energy as a renewable energy resource is basically an applied field. It is hoped that by collecting it suitably and converting it into the required energy form (thermal or otherwise) and at the required temperature level (low or high), solar energy will be able to supply part of the energy requirements of mankind – either by replacing conventional energy resources or by satisfying needs which have not yet been fulfilled. Though theoretical studies are imperative since they lead to fundamental knowledge and insight into the various interacting factors and parameters, thereby enabling a rational and economical use of the solar resource, the final objective should always be that of application.

The principal input-forcing parameter of a solar apparatus or system is of course the level of solar irradiation. Since solar irradiation is subject to diurnal and seasonal variations over the year, special attention is required for simulating this particular aspect of its behaviour. This simulation could be done in two ways – either by using an irradiation model or by using generalized empirical correlations (with the concept of *generalized* indicating independence of the location and the month).

Developing a model to simulate the radiation climate of a location entails having at one's disposal actual measured irradiation data (both hourly and daily) over several years from which basic probability functions can be constructed for the various radiation components over different time scales. Minor modifications in the model subsequently enable it to be applied to neighbouring locations having similar climatic fluctuations. One such model has been developed by Exell (1976, 1980, 1981) which, though originally meant for Thailand, could equally well be used for Southeast Asia. The model is based on observed atmospheric transmission patterns with respect to clear day irradiation values, these having been computed from atmospheric conditions prevalent in Southeast Asia.

Another widely used approach is the empirical correlation approach, wherein from a wide irradiation data base covering several locations, correlations between the various irradiation components over different time scales are developed as a function of key climatic and astronomical parameters. The original work of Liu & Jordan (1960), followed by numerous workers as outlined in Duffie & Beckman (1980) or Iqbal (1983), has led to the widespread use of this approach. In fact, among many solar scientists and engineers the concept of radiation analysis or reassessment has come to mean verifying or proposing new empirical correlations.

Both the above methods enable the prediction of solar irradiation and its components over individual hourly periods of specific days. In this sense, both these approaches provide fundamental irradiation data. The performance of solar systems can of course be predicted using such data but since such predictions involve observations made over a relatively long time scale (a season or a year), computations become lengthy. Consequently in order to overcome this, techniques are described in the literature whereby the long-term performance of solar collectors (which are obviously the single most influential component) can be directly predicted. These techniques are in no way dependent on the collector type and configuration as such, but are based on long-term statistics of solar irradiation fluctuations. However, since these correlations have been obtained from data obtained from relatively few temperate locations, it is necessary not only to verify their validity to tropical locations but also to suggest suitable modifications if deviations do occur. The aim of this article is therefore to briefly review these techniques, to discuss the relevant observations and correlations proposed in the literature regarding solar irradiation fluctuations, and to present an analysis of actual solar irradiation data in Bangkok which has been performed with the specific objective of substantiating the above observations and correlations.

LITERATURE REVIEW ON LONG-TERM COLLECTOR PERFORMANCE DETERMINATION

Basic model for long-term collector performance

Though the basic principles are equally valid for different collector types and configurations, we shall limit ourselves to simple flat plate solar thermal collectors for ease in comprehension. The instantaneous (or hourly) performance equation of such collectors is given by the Hottel-Whiller-Bliss (HWB) equation (Duffie & Beckman, (1980)):

$$q_{i,j} = F_R\,[I_{T,i,j}\,\eta_{o,i,j} - U_L\,(T_{Ci} - T_a)], \tag{2.1}$$

where
- $q_{i,j}$ – collected energy per unit collector area during hour i of day j
- F_R – heat removal factor
- $I_{T,i,j}$ – instantaneous or hourly incident global irradiation during hour i of day j
- $\eta_{o,i,j}$ – collector optical efficiency during hour i of day j.
- U_L – overall heat loss coefficient
- T_{Ci} – fluid temperature inlet to the collector
- T_a – ambient air temperature (taken as constant during the sunshine hours of the month).

If the collector output over a period of one month is required, the following summations have to be performed:

over n hours of each day:
$$Q_j = \sum_{i=1}^{n} q_{i,j}, \tag{2.2}$$

and over N days of the month:
$$Q_M = \sum_{j=1}^{N} Q_j \tag{2.3a}$$

$$= \sum_{j=1}^{N} \sum_{i=1}^{n} q_{i,j}. \tag{2.3b}$$

Whillier (1953) and later Liu & Jordan (1963) proposed a much simpler method called the 'hourly utilizability method', by which an estimate of Q_M could be obtained. They suggested that the summations of eq. 2.3b be interchanged such that

$$Q_M = \sum_{i=1}^{n} \sum_{j=1}^{N} q_{i,j}. \tag{2.4}$$

The hourly utilizability method then proposes that the value of

$$q_{M,i} = [\sum_{j=1}^{N} q_{i,j}],$$

be determined by a single computation. Thus the long-term monthly output of a solar collector for a specified hourly interval is first determined and a subsequent summation over the n hours of the day would yield an estimate of Q_M.

Liu & Jordan suggested the use of a minimum threshold radiation I_C (also called critical radiation), which is defined as the level only above which the collector will be able to deliver useful energy. I_C can be calculated from equation 2.1 by putting $q_{i,j} = 0$. Thus

$$I_C = \frac{U_L (T_{Ci} - T_a)}{\bar{\eta}_{o,i}}, \tag{2.5}$$

where $\bar{\eta}_{o,i}$ is the monthly mean collector optical efficiency during the particular hour i.

Substituting this value back into the original collector model (given by equation 2.1) we have

$$q_{M,i} = F_R \, \bar{\eta}_{o,i} \bar{I}_{T,i} \sum_{j=1}^{N} [X_{i,j} - X_{C,i}]^+, \tag{2.6}$$

where $X_{i,j}$ = radiation ratio = $I_{T,i,j}/\bar{I}_{T,i}$

$X_{C,i}$ = critical radiation ratio = $I_C/\bar{I}_{T,i}$,

and the + sign indicates that only positive sums are added.

Defining the hourly utilizability function ϕ_i as

$$\phi_i (X_{C,i}) = \frac{1}{N} \sum_{j=1}^{N} [X_{i,j} - X_{C,i}]^+, \tag{2.7}$$

we have

$$q_{M,i} = F_R \, \bar{\eta}_{o,i} \bar{I}_{T,i} N \phi_i (X_{C,i}). \tag{2.8}$$

For a specific location and for a given month, ϕ_i can be determined very simply by drawing the cumulative radiation curve for the hour in question (say 10-11 a.m.) using several years' data (at least 5 years) and the shaded area above a given value of $X_{C,i}$ represents ϕ_i (Fig. 1).

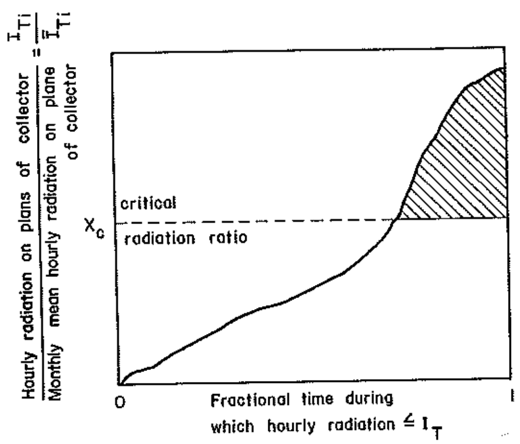

Fig. 1 Graphical significance of the hourly utilizability factor (The shaded area represents the monthly total solar energy collected during the hour in question).

The fraction ϕ_i can be considered as the fraction of the hourly incident solar radiation that is above a critical radiation value. It is thus a radiation statistic which is not directly dependent on the thermal behaviour of the solar collector. Only after the statistic has been obtained do we assign a collector-dependent significance to $X_{C,i}$. Its value is obviously always less than or equal to unity.

The utilizability curve is thus obtained by integration from the corresponding cumulative frequency curve, which in turn is an integral of the underlying probability density curve of the radiation ratio $X_{i,j}$. This is illustrated in Fig. 2.

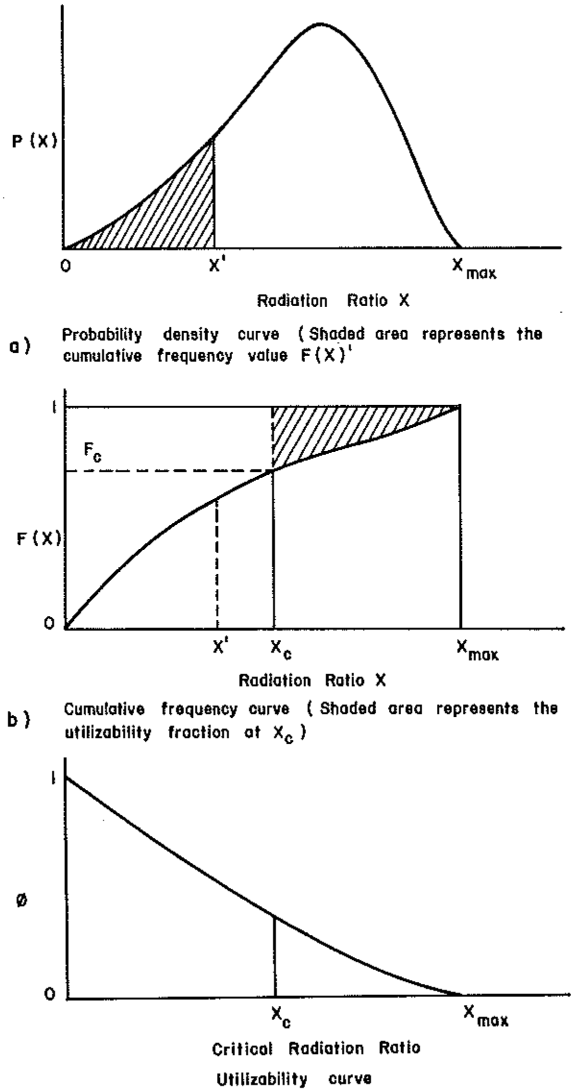

Fig. 2 Interaction of the probability density, cumulative frequency and the utilizability curves.
a) Probability density curve (shaded area represents the cumulative frequency value ($F(X')$).
b) Cumulative frequency curve (shaded area represents the utilizability fraction at X_C.
c) Utilizability curve.

Generalized utilizability

Equation 2.8 is the basis of the hourly utilizability technique. However, as such it is of limited use since determination of ϕ_i $(X_{C,i})$ entails knowledge of the following cumulative frequency curves:

a) for the specific location

b) for the specific month

c) for the specific hour

d) for the specific collector tilt and orientation

Fortunately, Liu & Jordan (1963) also did work on generalizing the hourly utilizability method. They noticed that irrespective of the location and the month of the year, the cumulative frequency curves of the daily total atmospheric transmission values K_j defined as:

$$K_j = \frac{H_j}{H_{o,j}} = \frac{\text{Daily total radiation on a horizontal surface for day } j}{\text{Daily extraterrestrial radiation on a horizontal surface for day } j}, \tag{2.9}$$

exhibited marked similarity for particular mean values of atmospheric transmission K. (Due to the importance of the parameter K, a special term, namely the clearness index, has been assigned to it). Thus from relatively limited data, Liu & Jordan were able to present their so-called 'generalized' K curves (Fig. 3), which were meant to be independent of the location and the month.

Subsequent workers, for example Bendt et al. (1981) and Hollands & Huget (1983), proposed functional forms for the underlying probability distribution which can be expressed in a general form as:

$$P(K) = C\,[\frac{K_{max} - K_{min}}{K_{max}}]^n \exp(\gamma K) \tag{2.10}$$

where K_{max} and K_{min} are the monthly maximum and minimum values of K,
C and γ are constants, solely dependent on $\bar{K}$,

and n is an exponent to be taken as equal to 0 in order to obtain the Bendt et al. function and equal to 1 for the Hollands & Huget function.

Hollands & Huget suggest that K_{max} be taken as 0.864, while Bendt et al. advocate a value of 0.05 for K_{min}, and their value of K_{max} (as later suggested by Hollands and Huget) can be determined from the following best-fit equation:

$$K_{max} = 0.6313 + 0.267\bar{K} - 11.9\,(\bar{K} - 0.75)^8 \tag{2.11}$$

For the Bendt et al. function, the cumulative frequency distribution can be then written as

$$F(X) = \frac{\exp(\gamma X) - \exp(\gamma X_{min})}{\exp(\gamma X_{max}) - \exp(\gamma X_{min})} \tag{2.12}$$

where $X = K/\bar{K} = H/\bar{H}$

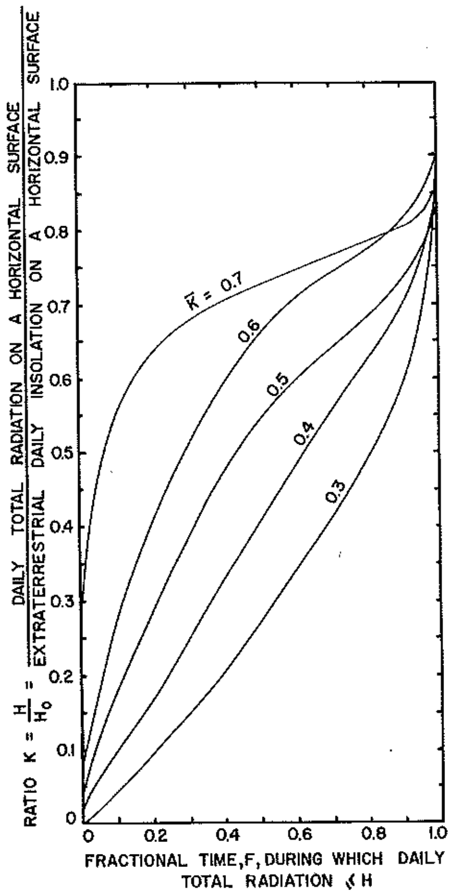

Fig. 3 Liu and Jordan's generalized K distribution curves (From Liu and Jordan (1960)).

and where γ is found by solving the transcendental equation

$$\gamma = \frac{(\gamma X_{max} - 1) \exp(\gamma X_{max}) - (\gamma X_{min} - 1) \exp(\gamma X_{min})}{\exp(\gamma X_{max}) - \exp(\gamma X_{min})}. \tag{2.13}$$

The corresponding function for utilizability assuming $X_{min} = 0$ is

$$\phi_i (X_{C,i}) = \frac{\gamma (1 - X_{C,i}) \exp(\gamma X_{max}) + \exp(\gamma X_{C,i}) - (\gamma + 1)}{\gamma [\exp(\gamma X_{max}) - 1]}. \tag{2.14}$$

It should be noted that the above equations are only applicable for horizontally placed flat plate collectors.

At this stage, a few comments concerning the Bendt et al. probability density function need to be made. The function is such that P(K) is equal to zero at $K = K_{min}$, increases monotonically with K, and abruptly drops to zero when $K = K_{max}$. Strictly speaking, no real climate will exhibit such a variation, and in this sense the Bendt et al. function is mathematically not representative of reality. (It must however be noted that as locations of increasingly clearer climate are considered the actual corresponding probability density functions will probably tend to approach that given by Bendt et al.) Though the theoretical approach which led to the Bendt et al. density function is based on very sound statistical concepts, the first approximation which was assumed is thus not accurate enough to be representative of reality. Saunier (1985) has suggested a second order approximation which seems to yield better results than the Bendt et al. function, and this is currently under investigation.

However, the objective of this secondary analysis is not so much to predict daily irradiation values as to arrive at long-term probability fluctuation patterns from which long-term collector performance can be directly evaluated. In this respect, the Bendt et al. function need not necessarily be discarded – and in fact, as later discussion shows, its relevance to a secondary type of analysis seems undisputable.

Liu & Jordan were also able to overcome the limitation (C) mentioned above, since they observed that the cumulative frequency curves of total irradiation for particular hours were equally close to those of the daily values (Fig. 4). Hence they suggested that the hourly utilizability fraction be computed from the frequency curves of the daily total values, and were able to present a series of hourly utilizability curves of different values of $\bar{K}$, and the critical radiation ratio $X_{C,i}$ for different equator-facing tilted surfaces. These were meant for generalized (i.e. independent of the location and the month) usage.

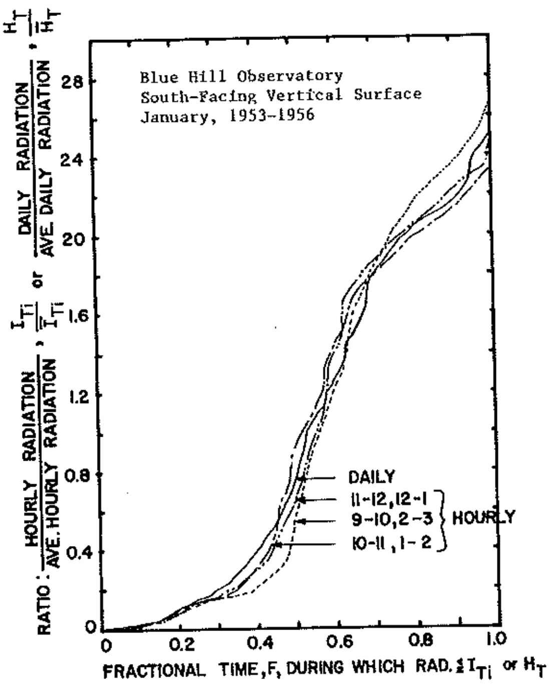

Fig. 4 Hourly and daily cumulative frequency curves for a southfacing vertical surface at Blue Hill, MA. (From Liu and Jordan (1963)).

Bhatia (1984) proposed an analytical correlation based on the Liu & Jordan original curves by which hourly utilizability fractions can be computed. Clark et al. (1983), instead of resorting to the generalized cumulative frequency curves of daily global radiation values on horizontal surfaces, generated hourly utilizability curves from actual data of several U.S. cities. A subsequent regression correlation for these curves has also been proposed. Both these studies seem to yield compatible estimates of hourly utilizability fractions, especially in the low and intermediate range of critical radiation ratios $X_{C,i}$. However at high values of $X_{C,i}$ certain deviations in ϕ_i were noticed.

The generalized hourly utilizability curves as well as the generalized K curves were generated from limited radiation data of only a few temperate locations (mostly in the U.S.). That they should be applicable as such to tropical locations is by no means obvious. Moreover subsequent studies (for example Theilacker & Klein (1981)) have shown them to be inaccurate for certain temperate locations as well.

The objective of Liu & Jordan was to suggest a computational procedure for directly determining Q_M. Their hourly utilizability method achieves this, but at the expense of having to perform a summation over n hours of the day. Subsequent workers have proposed the daily utilizability method which enables Q_M to be directly determined by the following equation.

$$Q_M = F_R\, \bar{\eta}_o\, \bar{H}_T\, N\, \bar{\phi}(I_C), \tag{2.15}$$

where $\bar{\phi}$ is the daily utilizability fraction defined as

$$\bar{\phi}(I_C) = \frac{\sum_{j=1}^{N} \sum_{i=1}^{n} [I_{T,i,j} - I_C]^+}{\sum_{j=1}^{N} \sum_{i=1}^{n} I_{T,i,j}}. \tag{2.16}$$

The daily utilizability concept is inherently limited to the case when the solar collector operates over the entire month under conditions such that T_{Ci} is constant during operation. On the other hand, though the hourly utilizability concept can equally well be used for the above case, it has a more general usage in the sense that it permits diurnal variation of T_{Ci} provided the variation is identical over all the days of the month.

Klein (1978) and later Theilacker & Klein (1981), making use of the Liu & Jordan generalized K curves, generated the daily utilizability curves for different values of $\bar{K}, I_C$ and collector tilts and proposed analytical equations for computing daily utilizability fractions.

Evans et al. (1982) based on actual measured radiation data from several U.S. cities have also developed empirical correlations for the daily utilizability factor wherein explicit account has been taken not of the critical radiation I_C but of the collector performance parameters $F_R\ \bar{\eta}_o$ and $F_R\ U_L$. A direct comparison of both methods is difficult to make and consequently either one (or even both, for comparison purposes) can be used. Finally, it must be borne in mind that such generalized correlations are bound to exhibit an inherently uncertainity range, and consequently a greater degree of accuracy than this range can never be achieved.

On the other hand, if detailed irradiation data are available at the location, it is possible to obtain a higher degree of accuracy by repeating the computational procedures on which the hourly and daily utilizability methods are based than by using generalized correlations. However, locations where such detailed measured irradiation data are available are not numerous, and this highlights the necessity of having empirical correlations.

The main objective of this article is to present a reassessment of a study done by Kumar (1984) on solar irradiation data in Bangkok (a tropical location near the sea and subject to a strong monsoonic influence), with a view to proving (or disproving) the validity of using these generalized correlations for tropical locations. The study could also serve as a model for studies of a similar type at other locations, which would subsequently lead to the use of correlations whose generality would be beyond dispute. Such correlations would then prove very useful for solar system design purposes.

CASE STUDY: APPLICABILITY TO BANGKOK

Preparatory analysis

Five years irradiation data at Bangkok of hourly global irradiation values on a horizontal surface formed the raw data base for our analysis. We could have equally used Exell's radiation model for our analysis, but use of raw data was deemed more appropriate since our basic objective was to discuss differences in the irradiation fluctuation pattern in tropical as opposed to temperate locations, and we did not wish to introduce other uncertainties, even of minor magnitude, by using Exell's model.

Since diffuse radiation measurements were not available, the analysis was limited to total radiation values, hourly and daily, on a horizontal surface. It was found that the monthly mean diurnal distribution was symmetrical about solar noon for the months of November, December, January, February, March and April (which correspond to the dry season), while for the remaining six months the afternoon irradiation was always less than that in the morning. The monthly and yearly mean climatic data for Bangkok obtained from our analysis are given in Table 1.

Table 1
Monthly and yearly mean climatic data for Bangkok

Month	$\bar{H}$ (MJ/m^2 day)	$\bar{K}$	$\bar{T}_a$ (°C)
January	17.2	0.58	30.8
February	17.3	0.53	31.3
March	19.4	0.54	33.1
April	19.0	0.51	34.2
May	18.7	0.49	32.9
June	16.9	0.45	32.3
July	15.6	0.41	31.7
August	16.3	0.43	31.0
September	15.6	0.43	31.7
October	15.5	0.46	31.1
November	16.6	0.55	30.9
December	16.0	0.56	29.7
Yearly mean	17.01	0.495	31.72

Cumulative frequency curves of daily total radiation

Though the analysis would have been more accurate if probability distributions had been considered, it was found that 5 years' data was not enough to obtain proper probability density curves. Moreover, though the probability density and the cumulative frequency distributions were mathematically correlated, the latter's dampening or moderating effect (due to its being an integral of the former) on the variation in basic irradiation data can be particularly helpful when analysing raw irradiation data for the purpose of evaluating the long-term performance of solar collectors.

On drawing the monthly cumulative frequency curves based on the measured values of H at Bangkok, it was found that the curves for each of the twelve months are markedly different from the corresponding generalized K curves of Liu & Jordan, as given analytically by either Bendt et al. (1981) or Hollands & Huget (1983). Figure 5 depicts this difference for the two months having extreme values of $\bar{K}$, i.e., January ($\bar{K} = 0.58$, dry season) and July ($\bar{K} = 0.41$, wet season).

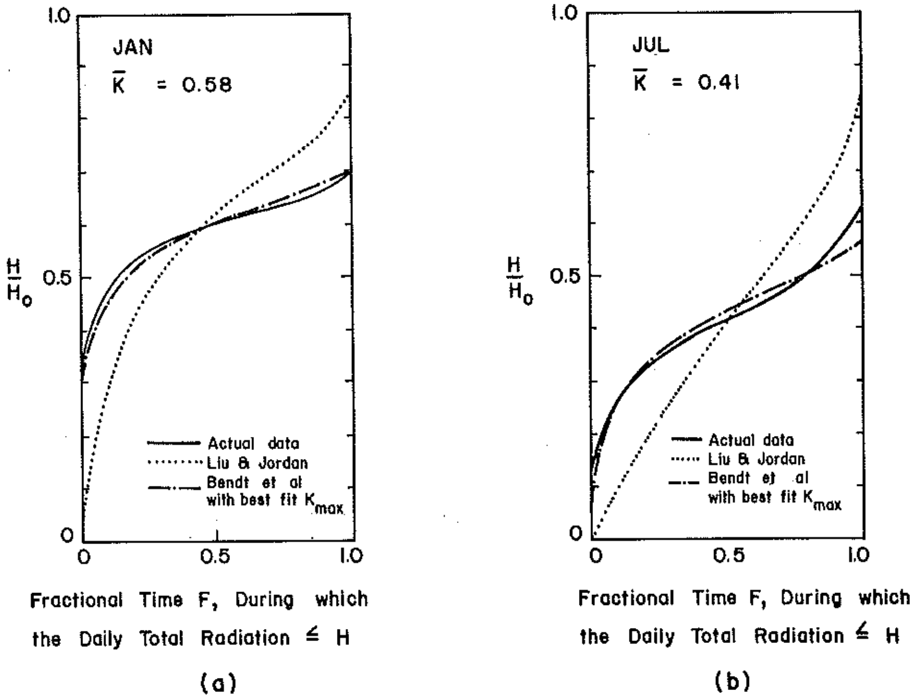

Fig. 5 Cumulative frequency curves of daily total radiation ratios on a horizontal surface in Bangkok.
——— Actual data .... Liu and Jordan . – . – . – . – . – Bendt et al. with best fit K_{max}.

It will be noted that the values of K_{max} of the Liu & Jordan curves are higher than those at Bangkok. Thus the same analytical correlation by Bendt et al. was reused, but instead of assigning a fixed value of K_{max}, as given by eq. 2.11, its value was made to float, and the corresponding value of K_{max} which resulted in the minimum least square fit to the cumulative frequency curve was determined. It can be noted from Fig. 5 that the resulting fit to the Bangkok cumulative frequency curves seems very good. This, as well as comparisons done with the cumulative curves of several Indian cities (Gupta et al. (1979)), indicate that the basic probability density functions chosen by Bendt et al. and Hollands & Huget (eq. 2.10) seem equally applicable to tropical locations provided the value of K_{max} is modified. It has also been found that for the rainy months, the actual probability density distribution is more skewed than that predicted by the above two distributions. Thus taking n = 2 in equation 2.10 seems to lead to a closer fit, especially during rainy months (Saunier et al. (1984)).

Investigations to determine how the value of K_{max} can be predicted, especially for tropical locations, without having to use real measured values of H have also been carried out. One could use atmospheric attenuation models to estimate clear day irradiation values (Saunier et al. (1984)); but since accurate meteorological data is often not available, an empirical approach was used in this study. Joshi (1984), basing his procedure on a study of various tropical locations (mostly Indian), has proposed an empirical correlation between K_{max} and $\bar{K}$ which can subsequently be used with the Bendt et al. probability function, and is given by

$$K_{max} = 0.362 + 0.597\,\bar{K}. \tag{3.1}$$

Finally, it should be noted that for certain applications, the daily values of irradiation H for all the days of a month may be needed. Such values can be generated from eq. 2.12 by assigning to $F(X)$ as many equally spaced values from 0 to 1 as there are days in the month and calculating the corresponding values of K from which the values of H are easily deduced. Finally, from this set of H values, random sampling without replacement can be done in order to assign a value of H to each particular day of the month. This procedure implicitly assumes that there is no interaction between successive days – a statement which, though not strictly accurate, nevertheless gives accurate enough estimates of most solar system performance. The following example should make this procedure clear:

Example 1

Generate the daily total horizontal irradiation values for all the days of the month of January in Bangkok, Thailand.

From Duffie and Beckman (1980) the mean day of the month (i.e. the day for which the solar declination is closest to the monthly average value) for January is:

n = 17, January = 17.

From Table 1, for January in Bangkok

$\bar{H}$ = 17.2 MJ/m^2 -day,

and $\bar{K}$ = 0.58.

Thus from eq. 3.1, K_{max} = 0.708

From eq. 2.12, with n = 0 and K_{max} as calculated above, the values of $H/\bar{H}$, for different values of fractional time $F(X)$, can be calculated. The results are tabulated in Table 2. For the sake of comparative evaluation, the actual (measured and averaged) values of H are also given in the table and it can be seen that the accuracy of prediction is good enough for all practical purposes, thereby indirectly justifying the use of the Bendt et al. probability distribution function as well as the linear correlation between $\bar{K}$ and K_{max} given by eq. 3.1.

Table 2
Table giving the results of Example 1

S. No.	Fractional time	Calculated $H/\bar{H}$	Values arranged in ascending order	
			Calculated H (MJ/m^2 day)	Actual data H (MJ/m^2 day)
1	0/30	0.086	1.483	10.279
2	1/30	0.485	8.345	12.603
3	2/30	0.623	10.712	13.195
4	3/30	0.708	12.179	13.892
5	4/30	0.770	13.245	14.254
6	5/30	0.819	14.083	15.484
7	6/30	0.859	14.774	15.954
8	7/30	0.893	15.361	16.230
9	8/30	0.923	15.872	16.701
10	9/30	0.949	16.324	16.898
11	10/30	0.973	16.729	17.083
12	11/30	0.994	17.097	17.268
13	12/30	1.014	17.433	17.379
14	13/30	1.031	17.984	17.450
15	14/30	1.048	18.276	17.801
16	15/30	1.064	18.297	17.938
17	16/30	1.078	18.547	18.051
18	17/30	1.092	18.783	18.226
19	18/30	1.105	19.005	18.354
20	19/30	1.117	19.215	18.447
21	20/30	1.129	19.415	18.488
22	21/30	1.140	19.605	18.731
23	22/30	1.150	19.786	18.957
24	23/30	1.160	19.959	19.129
25	24/30	1.170	20.125	19.279
26	25/30	1.179	20.284	19.396
27	26/30	1.188	20.437	19.467
28	27/30	1.197	20.584	19.614
29	28/30	1.205	20.726	19.796
30	29/30	1.213	20.864	20.115
31	30/30	1.221	20.996	20.687

It must finally be noted that the values of H thus deduced do not correspond to the number of days of the month as given by the serial number. A random selection without replacement has to be made to assign particular values of H for each day. This is not given in the table since the number of permutations is very large indeed.

Hourly utilizability function

As mentioned earlier, Liu & Jordan reported that the cumulative frequency curves of particular hour pairs, i.e. $F(I_i/\bar{I}_i)$ for a month are not substantially different from those based on daily irradiation, i.e. $F(H/\bar{H})$. For Bangkok it was observed that:

i) For the six months (November to April) corresponding to the dry season, the claim made by Liu & Jordan is more or less justified. It should be recollected that for these six months, the monthly mean irradiation over the day is symmetric about solar noon.

ii) For the remaining six months, covering the rainy season, Liu & Jordan's claim was found to be invalid. Moreover, the cumulative frequency curves for the morning hours of each of these six months are close to one another but markedly different from those of the afternoon hours, which in turn are close to one another.

The above observations are illustrated in Fig. 6, which gives the cumulative frequency curves of daily irradiation values and the range of variation of the corresponding curves for individual hours for the months of March and April (clear months) and August (cloudy month).

Subsequently, as is shown in Fig. 7, it was found that the most convenient way of grouping the individual cumulative frequency curves for each hour so as to decrease their number while at the same time retaining a certain degree of accuracy was to represent:

a) all the hourly curves for the six dry months (November to April) by one single curve;

b) all the curves for the morning hours for the six wet months (May to October) by one single curve;

c) all the curves for the afternoon hours for the six wet months (May to October) by one single curve.

These three curves, which are more or less representative of all the cumulative frequency curves of each hour for all the twelve months of the year, are drawn together in Fig. 8. It will be noted that curves (a) and (b) are fairly close, and also that curve (c) is the steepest since it is subject to the most variation in hourly irradiation values as a result of the poorest weather being encountered in the afternoon hours during the rainy season.

Using the Bendt et al. function (eq. 2.12) for the cumulative frequency curves, the values of X_{max} (assuming $X_{min} = 0.0$) which best fit the above three curves are as follows:

a) $X_{max} = 1.27$ and hence $\gamma = 3.464$

b) $X_{max} = 1.33$ and hence $\gamma = 2.682$

c) $X_{max} = 1.44$ and hence $\gamma = 1.730.$ (3.2)

These values of γ and X_{max} can be introduced into eq. 2.14 to determine the corresponding hourly utilizability functions for horizontally-placed collectors at Bangkok.

Monthly cumulative frequency curves of hourly total radiation and the corresponding daily utilizability function

For horizontal surfaces, the radiation ratio can be taken as $Y = (I_{i,j}/\bar{I}_m)$, where $\bar{I}_m$ is the monthly mean hourly radiation averaged over the hours between 6:00 a.m. and 6:00 p.m. and equal to $(\bar{H}/12)$. The corresponding monthly cumulative frequency curves for all the twelve

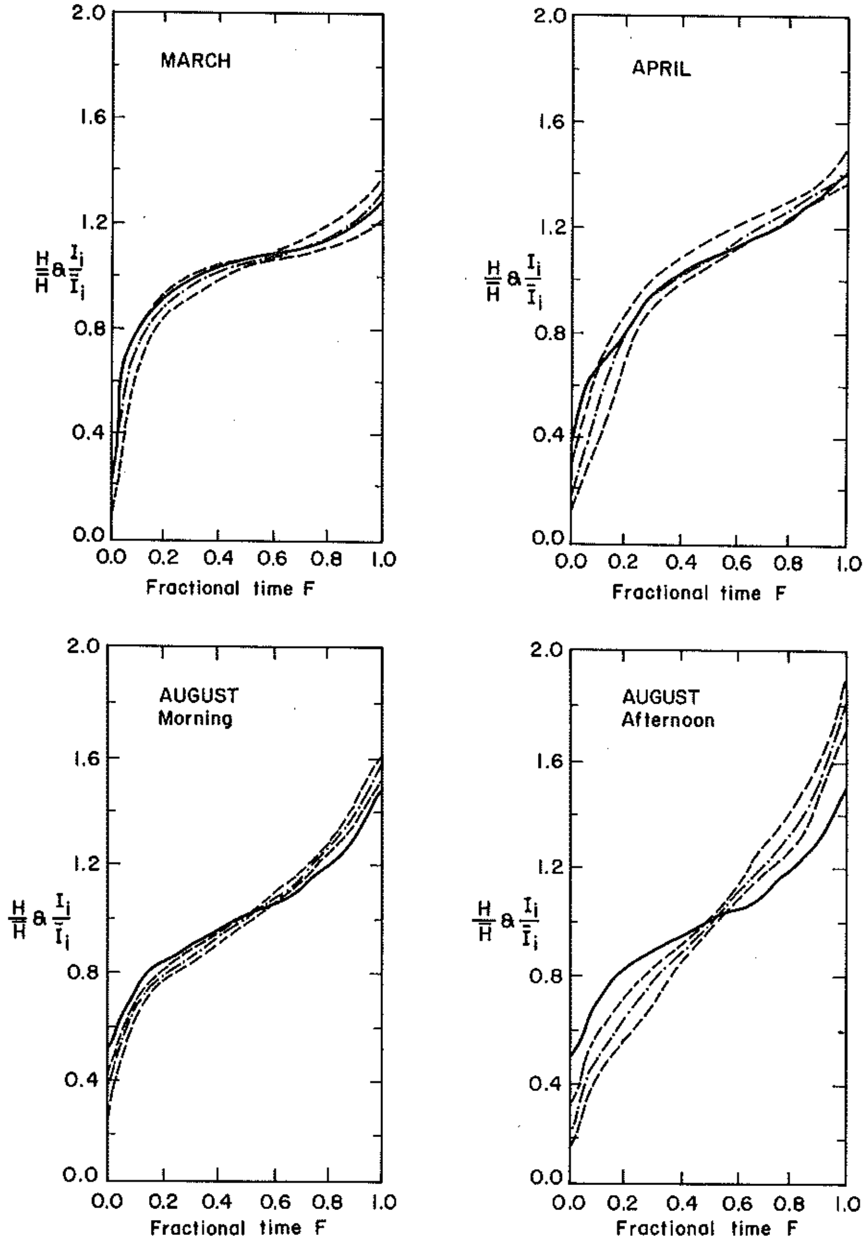

Fig. 6 Cumulative frequency curves of daily and hourly global radiation on a horizontal surface in Bangkok. ———— Daily frequency curve. – – – – – – Range of hourly CFC. . – . – . – . – Monthly mean hourly CFC. (From Kumar (1984)).

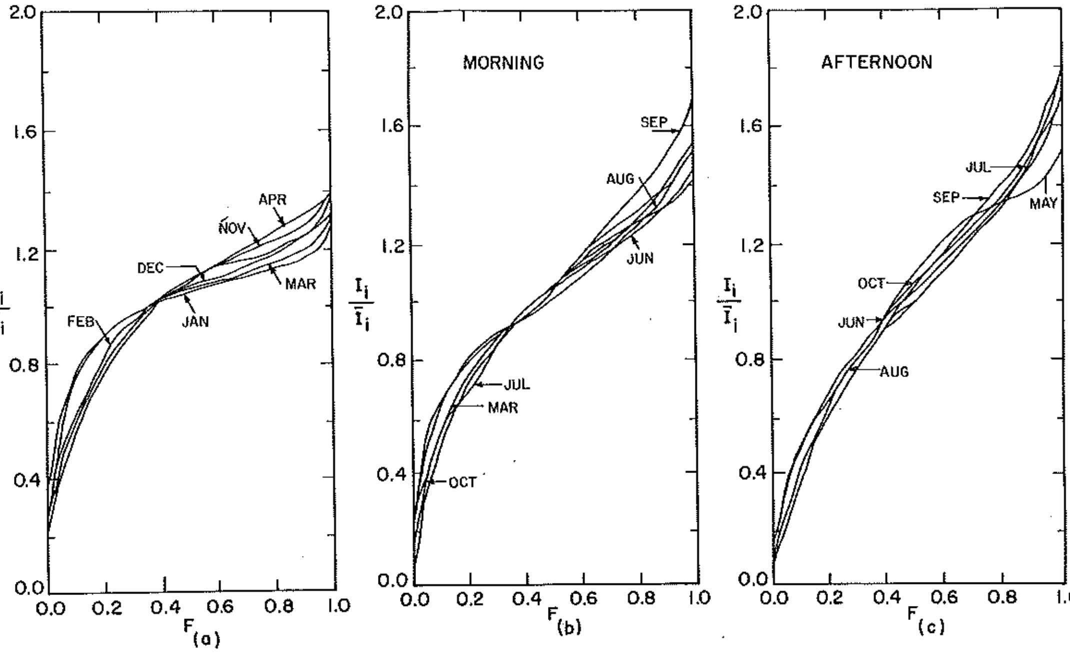

Fig. 7 Cumulative frequency curves of hourly total radiation on a horizontal surface in Bangkok.
a) For dry months, November to April
b) For rainy months (morning hours), May to October
c) For rainy months (afternoon hours), May to October

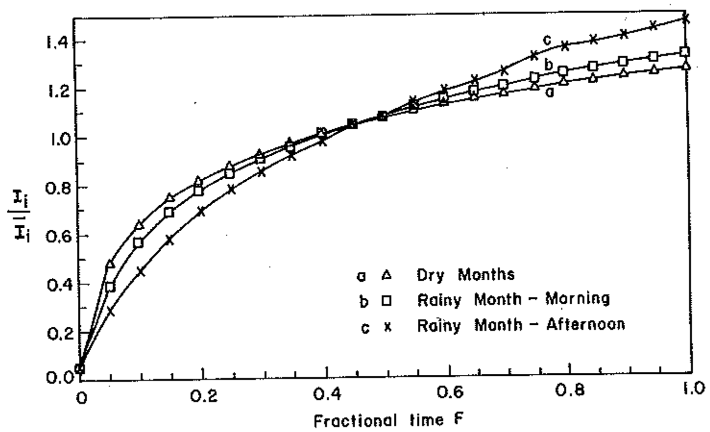

Fig. 8 The three representative cumulative frequency curves of individual hour pairs of radiation on a horizontal surface for all the months in Bangkok.

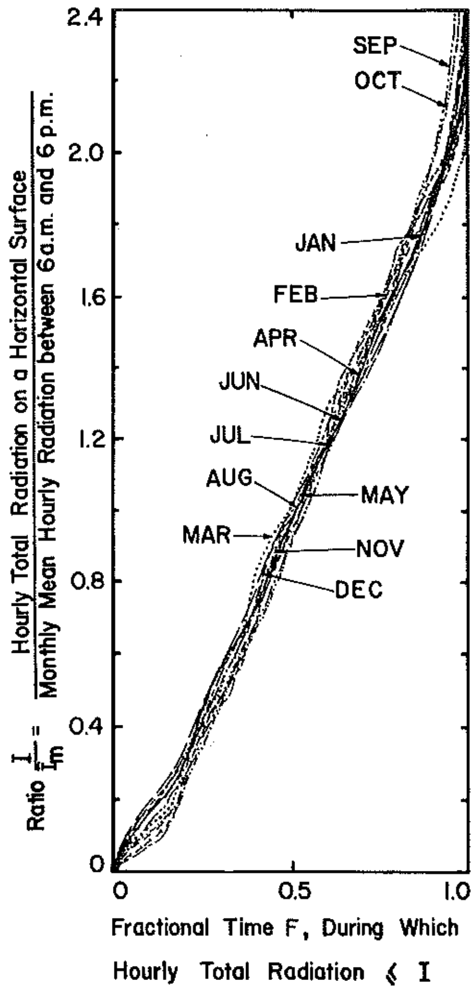

Fig. 9 Monthly cumulative distribution curves of hourly total radiation on a horizontal surface in Bangkok.

months in Bangkok are shown in Fig. 9. It can clearly be seen that all these distribution curves, except for the rainy months of September and October, which deviate slightly at higher values of $F(Y)$, are linear and surprisingly very close to each other. This leads to the inference that the probability distribution is rectangular (i.e. $P(Y)$ = constant) and unvarying for all the months of the year. It has been found that these curves could be represented by the following linear function:

$$F(Y) = 0.063 + 0.438Y \tag{3.3}$$

for the range $0.1 < F(Y) < 0.9$.

The value of Y_{max} is calculated by putting $F(Y) = 1$ in eq. 3.3 and thereby $Y_{max} = 2.14$.

The daily utilizability function for a horizontally-placed flat plate collector is easily derived by integration of eq. 3.3 Thus

$$\bar{\phi}_H(Y_C) = 1 - 0.94Y_C + 0.22{Y_C}^2, \tag{3.4.a}$$

which can also be written as

$$\bar{\phi}_H(Y_C) = [1 - \frac{Y_C}{Y_{max}}]^2, \tag{3.4.b}$$

where $Y_C = I_C/\bar{I}_m$.

In terms of $\bar{H}$, this simplifies to

$$\bar{\phi}_H(Y_C) = [1 - \frac{I_C}{0.178\bar{H}}]^2, \tag{3.4.c}$$

where I_C is in MJ/m^{2}h, and $\bar{H}$ is in MJ/m^2 day.

From Fig. 10 it can be seen than the use of a quadratic correlation gives satisfactory results

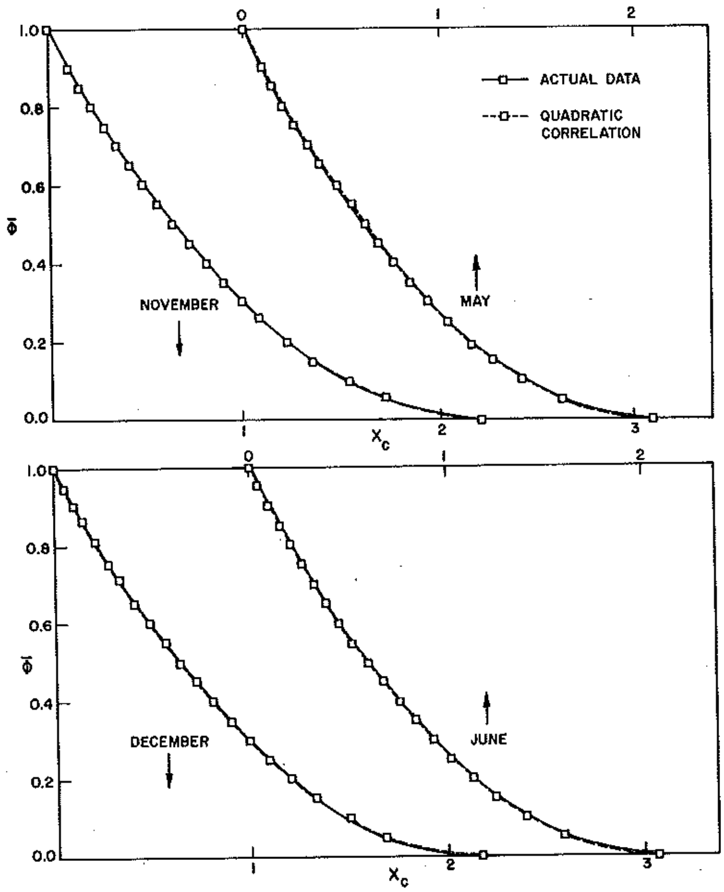

Fig. 10 Daily utilizability vs. critical radiation ratio obtained from actual data and the quadratic correlation for Bangkok.

as compared to actual data. This illustrates the fact that the utilizability function is relatively less sensitive than the cumulative function to differences or fluctuations in raw irradiation data.

Thus it is found that the daily utilizability function reduces to a very simple expression for Bangkok, or more generally to locations at which the monthly cumulative frequency curves of hourly total radiation are linear and close together. The same trend has also been observed for Chiang Mai (Asokan (1985)), another tropical location in northern Thailand.

Equation 3.4 is valid only for horizontal surfaces. Asokan (1985) and Reddy and Asokan (1985), basing their findings on the Bangkok solar irradiation model of Exell (1980), have generated monthly cumulative frequency curves of hourly total irradiation on south-facing surfaces of various tilts, and have observed that these curves exhibited the same properties as those on horizontal surfaces, in the sense that the frequency curves could still be assumed linear and very close to each other. However the slopes of these curves differed with surface tilt. Corresponding empirical correlations by regression have also been proposed and compared with Klein's generalized utilizability curves.

Figure 11 illustrates the difference between the values calculated using Klein's correlation and those for Bangkok for the months of January and July. It is seen that Klein's correlation sys-

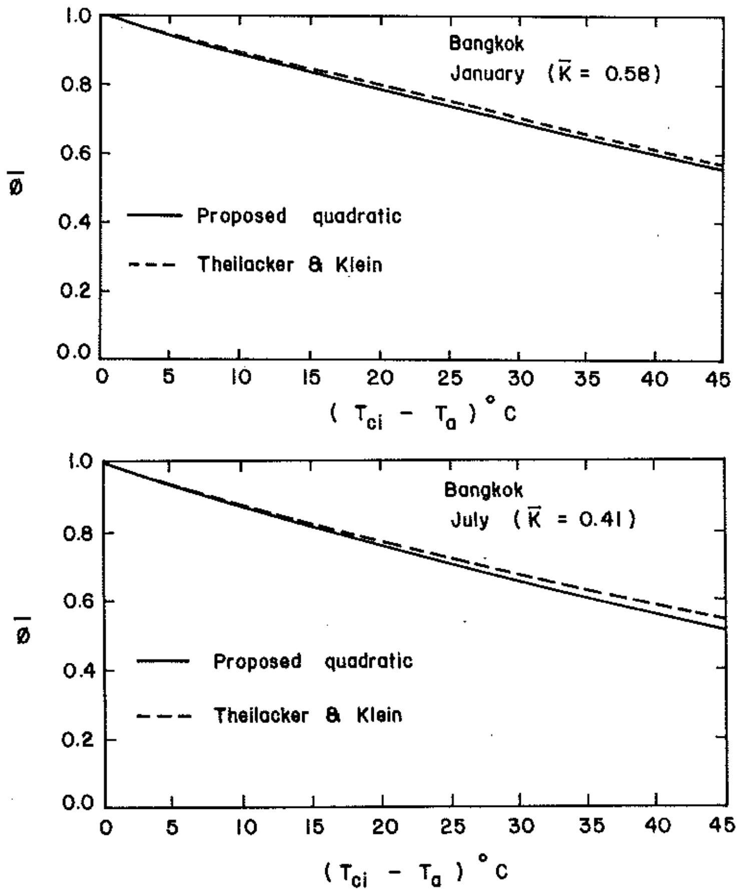

Fig. 11 Plots of daily utilizability factor for Bangkok according to different relationships.

tematically over estimates $\bar{\phi}$, which is to be expected since the generalized Liu and Jordan's cumulative frequency curves are steeper than those obtained for Bangkok.

For tilted surfaces, Reddy & Asokan (1985) reported higher differences between the generalized curves of Klein and those of Bangkok data generated from Exell's model, especially for higher critical irradiation values. However, since properly designed solar systems, i.e. those which are to be economically competitive with other sources of energy, are made to function under conditions where the solar energy collected is important (i.e. there are low values of critical radiation), it was concluded that the resulting error on system performance was not particularly important.

Example 2

A flat plate solar collector of unit surface area is placed horizontally in Bangkok. Its performance parameters are

$$F_R\ U_L = 4.0\ \text{W/m}^2\,{}^\circ\text{C and } F_R\ \eta_o = 0.8.$$

If the temperature of the fluid inlet to the collector is 60°C and is assumed to be constant over the entire year, compute the monthly and yearly total useful energy which will be collected by using the various hourly and daily utilizability relationships.

For simplicity assume $F_R\ \eta_o$ to be constant throughout the year. The values of $\bar{H}$ and $\bar{T}_a$ for each month in Bangkok are given in Table 1.

(a) The monthly total collected energy can be computed by using the daily utilizability concept directly as given by eq. 2.15. The factor $\bar{\Phi}_H$ can be computed using three different relations:

(1) eq. 3.4 which has been deduced from an analysis of the actual irradiation data of Bangkok;

(2) the correlation proposed by Theilacker and Klein (1981) from Liu and Jordan's generalized K curves;

(3) the correlation proposed by Evans et al. (1982) based on an analysis of the actual data from several U.S. cities.

The monthly total values of the collected energy Q_M are tabulated in the first three columns of Table 3.

(b) The monthly total collected energy can also be computed by using the hourly utilizability concept as given by eq. 2.6 and then performing a summation of the operational number of hours during a day, as expressed by eq. 2.3. The hourly utilizability fraction $\phi_{H,i}$ can be computed using three different relations:

(4) the correlation proposed by Bhatia (1984) to fit the original Liu and Jordan hourly utilizability curves;

(5) the correlation proposed by Clark et al. (1983), based on the actual irradiation data of several U.S. cities;

(6) eq. 2.14 using the empirical constants deduced from an analysis of actual Bangkok data, which are given by eq. 3.2.

The correspondong values of Q_M are also tabulated in Table 3. The values of Q_M, obtained from the actual irradiation data of Bangkok, have not been included in the table since they are

Table 3
Values of the monthly total solar energy collected (MJ/m^2) using various utilizability relationships for Example 2

Month	Daily Utilizability Relationships			Hourly Utilizability Relationships		
	Equation 3.4	Theilacker & Klein	Evans et al.	Liu & Jordan (Bhatia)	Clark et al.	Bendt et al.
January	294	304	296	263	296	293
February	268	279	270	248	272	267
March	355	361	355	323	351	347
April	340	349	338	316	339	333
May	337	339	333	306	328	323
June	283	289	280	262	279	272
July	258	263	253	239	253	243
August	270	277	268	252	268	259
September	246	261	250	237	252	244
October	253	264	257	238	256	249
November	265	282	276	247	257	270
December	258	272	266	236	266	261
Yearly (GJ/m^2)	3.43	3.54	3.45	3.17	3.44	3.36

almost identical to those of the first column (i.e. from values computed from eq. 3.4). It can be seen from the table that all the methods yield values which are within engineering tolerance, except perhaps the Liu and Jordan correlation as fitted by Bhatia. The Q_M values obtained by using the daily utilizability correlations are within 3%, with a maximum monthly variation of about 10%. However, based simply on the above results, one should not make a comparative evaluation of the accuracy of the various relationships over their whole range of potential application. It must also be noted that though the latter set of values requires more computational effort, use of such hourly utilizability correlations has to be resorted to in cases when T_{Ci} varies from hour to hour over the day but the variation is identical for the entire month.

CONCLUDING REMARKS

The study or analysis of solar irradiation data could be done on two different levels. The primary analysis, which is of a more fundamental nature, involves getting estimates of various solar radiation components over different time scales. This could be achieved by either developing a suitable radiation simulation model, like that done by Exell, or alternatively by proposing new or validating old empirical correlations.

There is, however, a secondary or complementary phase to this radiation analysis which involves looking into suitable condensed long-term irradiation fluctuations, in order that these may be used as the input forcing functions to long-term solar collector performance estimates. The aim of this article was to present work reported in the literature relating to the above objective. Since most of this work was done with irradiation data at temperate locations, it was deemed necessary that they be verified against tropical data. Consequently the manner in which the reassessment study was conducted has also been presented in this article.

The following are the important differences and conclusions reached from this reassessment study:

a) The generalized K distribution curves of Liu & Jordan are not valid for Bangkok, and other studies have shown them not to hold true for tropical locations in general. However the functional forms of the basic probability distribution can equally well be applied to both tropical and temperate locations provided suitable modification is made to K_{max}.

b) The pairs of cumulative frequency curves of particular hours can be taken as being similar to those of the daily irradiation values for the six months corresponding to the dry season at Bangkok. For the remaining six months covering the rainy season, this claim (originally made by Liu & Jordan) is no longer justified.

c) The cumulative frequency curves of all the hours over each of the twelve months of the year can be assumed to be linear, and sufficiently close to each other that a single straight line fit was found to yield daily utilizability curves which conform with those generated from actual data.

d) Though the cumulative frequency curves of daily irradiation in Bangkok differ appreciably from the Liu & Jordan generalized K curves, the derived daily utilizability curves for horizontal surfaces are sufficiently close for the generalized utilizability correlations to be equally applicable to Bangkok.

It is hoped that this study will serve as a model on which other such studies of a similar nature will be done for tropical locations of widely different climatological conditions, so that the generalized utilizability correlations can be verified both on an hourly and daily basis as well as for non-horizontal surfaces. It is also obvious that with the increase in raw radiation data in time, the empirical correlations concerning cumulative and utilizability distributions may be subject to change, thus requiring constant reverification and updating, even though the change may often be comparatively minor.

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NOMENCLATURE

$F(X')$ cumulative probability distribution of the stochastic variable X'

F_R heat removal factor of the solar collector

H daily total solar irradiation on a horizontal surface

H_o daily extraterrestrial solar irradiation on a horizontal surface

I hourly total solar irradiation on a horizontal surface

I_C threshold or critical radiation intensity of the solar collector

I_i hourly total solar irradiation on a horizontal surface of the i^{th} hour

$\bar{I}_m$ monthly average total solar irradiation on a horizontal surface between 6 a.m. and 6 p.m ($=\bar{H}/12$)

K daily clearness index

N number of days in the month

n number of sunshine hours in the day, day of the year counted from 1st January

$P(X')$ probability density distribution of the stochastic variable X'

Q daily total energy collected per unit collector area

Q_M monthly total energy collected per unit collector area

q hourly energy collected per unit collector area

q_m monthly total energy collected per unit collector area during a particular hour.

T_a ambient temperature

T_{Ci} fluid inlet temperature to the collector

U_L overall heat loss coefficient of the solar collector

X radiation ratio representing $(I/\bar{I})$ or $(I_T/\bar{I}_T)$ or $(H/\bar{H})$ or $(H_T/\bar{H}_T)$;

Y radiation ratio defined as $= (I/\bar{I}_m)$

η_o optical efficiency of the collector

ϕ hourly utilizability factor

$\bar{\phi}$ daily utilizability factor

Superscripts

$\bar{X}'$ denotes monthly average value of the quantity X', unless mentioned otherwise

Subscripts

C critical radiation

H horizontal surface

i specifies hour of the day

j specifies day of the month

max maximum

min minimum

T tilted surface

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