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Correlation for estimation of hourly solar radiation

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Abstract
As the availability of solar radiation for a place depends upon the climatic conditions of the locality, a correlation for a place may not be suitable for other places of different climatic conditions. Therefore, an attempt has been made to develop a new model to evaluate hourly solar radiation on horizontal surface for Indian locations having different climatic conditions, using least square regression analysis based on the ASHRAE model. For this purpose measured diffuse and global solar radiation data from January 2001 to December 2005 of Ahmedabad, Calcutta, Bombay, Pune and Chennai cities of India have been used. Comparison between the estimated and the measured values shows that the constants derived for Indian locations provide good estimates of hourly solar radiation. The present estimated hourly solar radiation have also been compared with the estimates of the Liu and Jordan [7] and Singh et al [10] models which correlate hourly values and daily global radiation. In order to indicate the performance of the models, the statistical test methods of the mean bias error (MBE), root mean square error (RMSE) and t-test are used.

Keywords: Horizontal surface, Indian locations, Regression analysis, Solar radiation.

1. Introduction

Incoming solar radiation (insolation) is fundamental to most physical and biophysical process because of its role in energy and water balance [1]. In general, energy consumption can be examined under four main sectors such as industrial, building (residential), transportation and agriculture [2]. In this context, solar energy occupies one of the most important places among various alternative energy sources. In the studies of solar energy, data on solar radiation and its components at a given location are very essential [3]. Unfortunately, there are only a few solar radiation measuring stations in India. However, for locations where measured data are not available, empirical correlation proposed by various researchers can be used to estimate the solar radiation.

Sometimes, the design of solar energy devices needs accurate estimations of hourly solar radiation values. Over the years, numerous models for evaluating the hourly solar radiation appeared in the literature. The first attempt to analyse the hourly global radiation data was made by Whiller [4] and Hottel and Whiller [5] on the basis of solar radiation data of various locations in U.S.A., to obtain the variation of hourly to daily radiation ratio against sunset hour angle [6].

The distribution of total radiation on a horizontal surface over a day was examined by Liu and Jordan [7], who showed that the ratio of hourly to daily radiation could be correlated with the local day length and hour angle. Collares -Pareira and Rabl [8] have developed an analytical expression for hourly to daily global radiation ratio in terms of sunset hour angle. A model for hourly solar radiation has also been

developed by Al-Sadah et al. [9] and Singh et al. [10] which is correlated with the local time of day. There are some other models [11, 12] to estimate the hourly solar radiation.
The purpose of this paper is to present an analysis of hourly solar radiation data and to develop new regression constants for estimating the hourly solar radiation on a horizontal surface, which is based on the ASHRAE model [12]. Performance of the developed correlation is checked by comparing with the measured data and the results estimated by Liu and Jordan [7] and Singh et al. [10] for five Indian cities viz. Ahmadabad, Calcutta, Bombay, Pune and Chennai, having different climatic conditions.

2. Data and methodology

The solar radiation data comprising monthly average hourly diffuse and global radiation for four Indian stations, viz. Ahmadabad (Latitude 23.07^0 N, Longitude 72.06^0 E), Calcutta (Latitude 22.65^0 N, Longitude 88.35^0 E), Bombay (Latitude 19.12^0 N, Longitude 72.85^0 E), Pune (Latitude 18.53^0 N, Longitude 73.91^0 E) and Chennai (Latitude 13^0 N, Longitude 80.28^0 E), have been collected from India Meteorology Department (IMD) Pune, India. For all locations, the data measured for a period of five years (2001-2005) have been used for the present analysis. We have average out the measured data of all the selected locations on an hourly basis for all days in each month of the year to get a monthly averaged hourly variation of the diffuse and global solar radiation. The measured data are further averaged individual hourly values for each month over a period of one to five years. Proper computer programs are prepared for the present analysis.

2.1 Mathematical models

2.1.1 Liu and Jordan model

Liu and Jordan [7] proposed the following correlation to estimate the monthly mean hourly global radiation ($\bar{I}$) on a horizontal surface from the monthly mean daily radiation ($\bar{H}$) on a horizontal surface:

$$\frac{\bar{I}}{\bar{H}} = \frac{\left(\frac{\pi}{24}\right)(\cos W - \cos Ws)}{\sin Ws - \left(2\pi \frac{Ws}{360}\right)\cos Ws} \tag{1}$$

where W is the hour angle in degrees and Ws is the sunset hour angle.

2.1.2 Singh et al. model

Singh et al. [10] developed the following correlation to estimate the ratio of monthly mean hourly ($\bar{I}$) to monthly mean daily ($\bar{H}$) global radiation on horizontal surface for Lucknow, India:

$$\frac{\bar{I}}{\bar{H}} = a_1 + b_1 t + c_1 t^2 \tag{2}$$

2.1.3 Present model

The present model is based on ASHRAE model [12]. Since the evaluated constants of the ASHRAE model are not validating the data for Indian climate, hence the expression for hourly solar radiation has been modified to give more accurate results and is given as:

$$I = I_b + I_d \tag{3}$$

$$I_b = A\, I_N \cos\theta_z + B \tag{4}$$

$$I_N = C \exp\left[-\frac{D}{\cos\theta_z}\right] \tag{5}$$

$$I_d = E I_N + F \tag{6}$$

where I_b, I_d and I_N are hourly beam, hourly diffuse and hourly beam radiation in direction of rays respectively. The values of the constants A, B, C, D, E and F are given in Table 1.
θ_z is the zenith angle, which depends upon the latitude of the location (ϕ), hour angle (ω) and solar declination (δ), and can be evaluated from the following equation:

$$cos\theta_z = sin\emptyset . sin\delta + cos\emptyset . cos\delta . cos\omega \quad (7)$$

The accuracy of correlations is tested by calculating the mean bias error (MBE), root mean square error (RMSE) and t- test error. The MBE, RMSE and t-test are defined as follows:

$$MBE = [\sum \{(I)_{i,c} - (I)_{i,m}\}/P] \quad (8)$$

$$RMSE = [\sum \{(I)_{i,c} - (I)_{i,m}\}^2/P]^{1/2} \quad (9)$$

$$t = [(P-1)\ MBE^2/(RMSE^2 - MBE^2)]^{1/2} \quad (10)$$

where $(I)_{i,c}$ and $(I)_{i,m}$ are the ith calculated and measured values and p is the total number of observations. In general, a low RMSE is desirable. The positive MBE shows overestimation while a negative MBE indicates underestimation.

Table 1. Correlation constants for present model

Months	Present constants (modified ASHRAE model)					
	A	B	C	D	E	F
January	1.259	73. 51	1175	0.785	0.3313	51.03
February	1.117	65.99	1382	0.8464	0.3061	71.55
March	1.003	79.68	1636	0.9669	0.2900	64.18
April	0.889	105.7	1810	1.1050	0.3030	88.40
May	0.9142	80.38	1777	1.1740	0.3579	98.47
June	0.9113	29.84	1038	1.1560	0.7719	84.17
July	1.407	50.2	602	1.1190	1.4670	73.19
August	0.9036	31.19	531	1.0230	1.6480	56.72
September	0.9618	42.15	816	0.9955	0.9439	55.21
October	1.069	56.60	1103	0.9955	0.4878	48.69
November	1.176	60.29	1370	0.8599	0.2748	57.16
December	1.186	70.85	1189	0.7876	0.3405	49.92

3. Results and discussion

Least squares regression analysis was used to fit equations (4), (5) and (6) to the data for each hour of the day to obtain values of the regression constants A, B, C, D, E and F for each month of the year. The regression constants A, B, C, D, E and F for each month of the year are given in Table 1. Validation of the present constants was made by comparing the present estimated results of monthly mean hourly global radiation, as a function of the Zenith angle with the estimated values of Liu and Jordan [7] and Singh et al. [10] correlations along with the measured values. These comparisons are made for all twelve months from January to December for each location under consideration; however for scarcity of space in presenting the paper, the comparison is shown only for January and June months of all five stations through Figures. 1-10. From these Figures a close agreement has been observed between the present theoretical and measured values. The present correlation is found more appropriate than the other correlations for all selected locations. The MBE, RMSE and t-test values for present and Liu and Jordan [7] and Singh et al. [10] correlations for the months of January and June for all five locations are summarized in Table 2. We observe that in comparison to others, the present MBE, RMSE and t-test values are very low, indicating fairly good agreement.

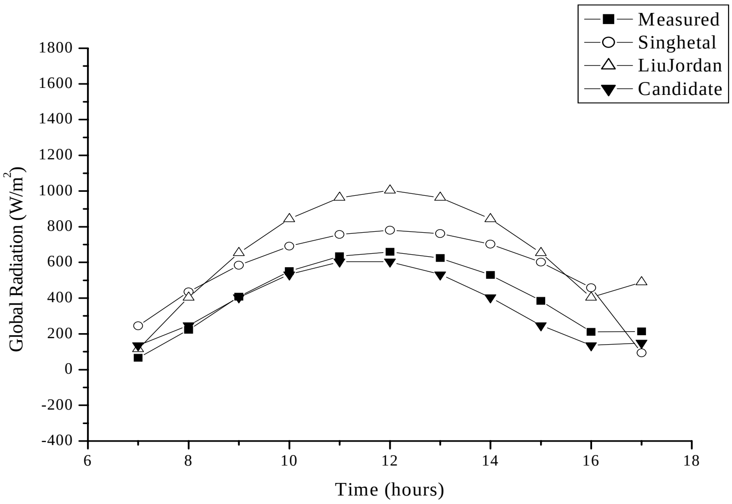

Figure 1. Hourly variation in global solar radiation with time for Ahmedabad (January month), India

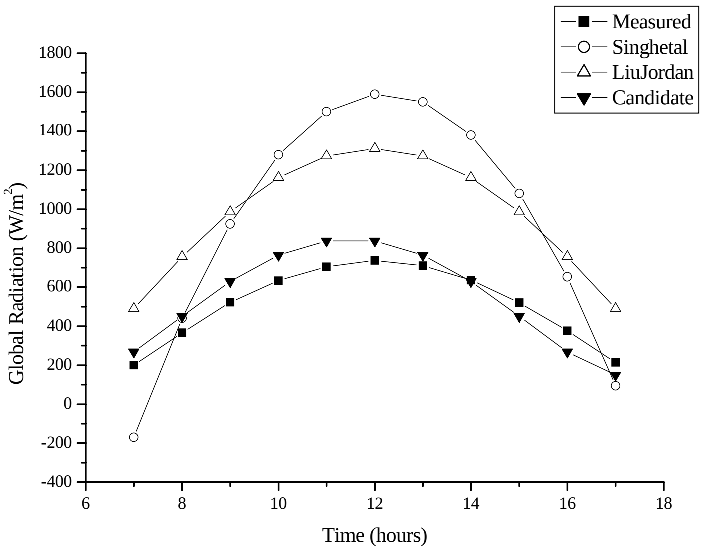

Figure 2. Hourly variation in global solar radiation with time for Ahmedabad (June month), India

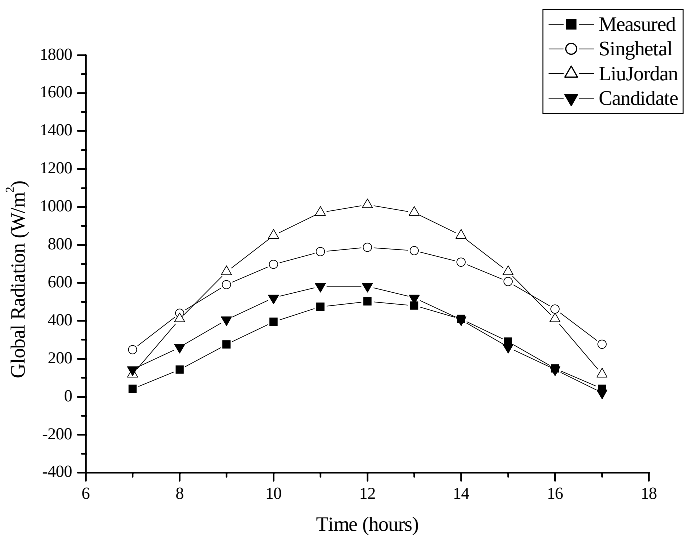

Figure 3. Hourly variation in global solar radiation with time for Calcutta (January month), India

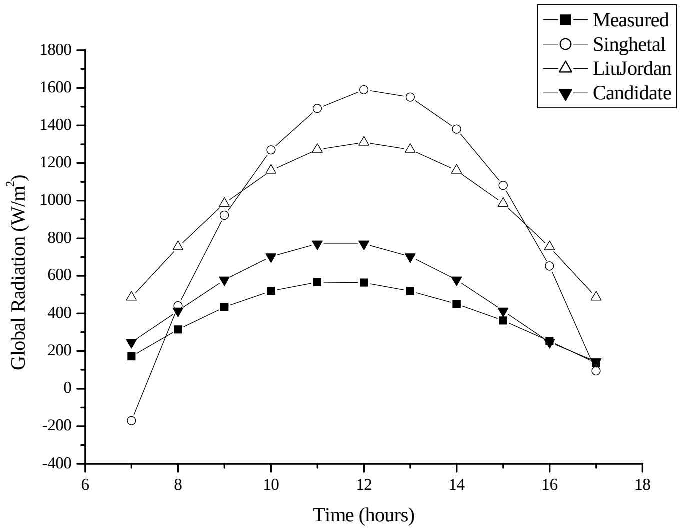

Figure 4. Hourly variation in global solar radiation with time for Calcutta (June month), India

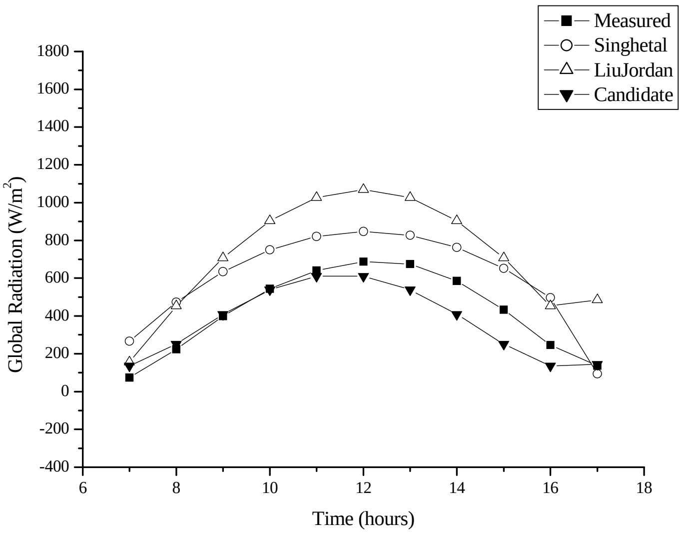

Figure 5. Hourly variation in global solar radiation with time for Bombay (January month), India

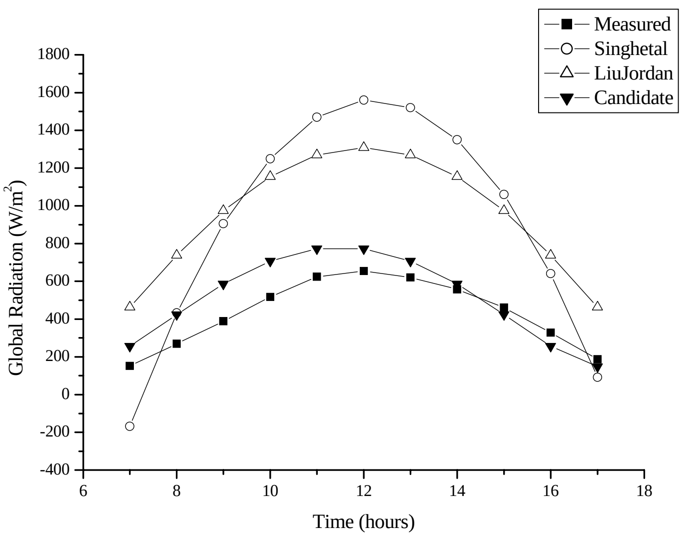

Figure 6. Hourly variation in global solar radiation with time for Bombay (June month), India

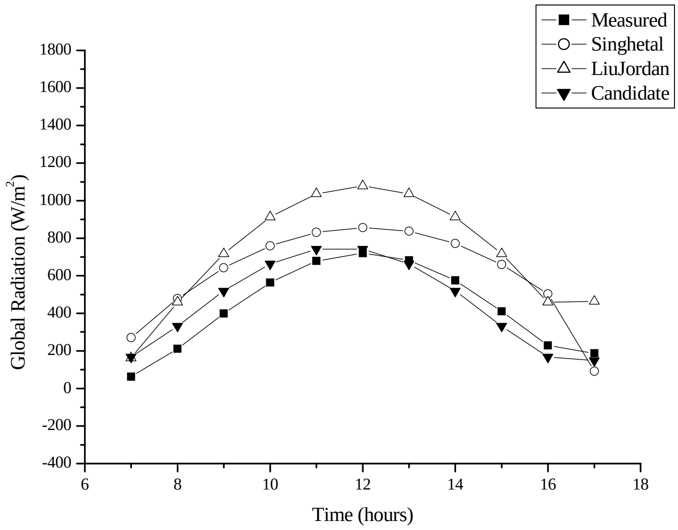

Figure 7. Hourly variation in global solar radiation with time for Poone (January month), India

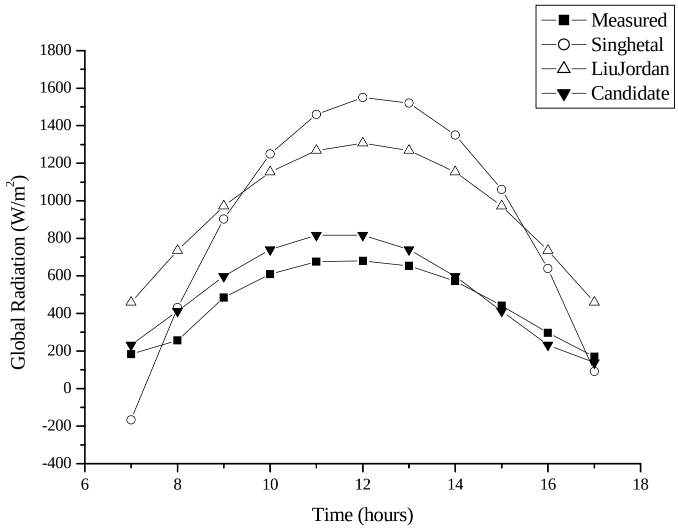

Figure 8. Hourly variation in global solar radiation with time for Poone (June month), India

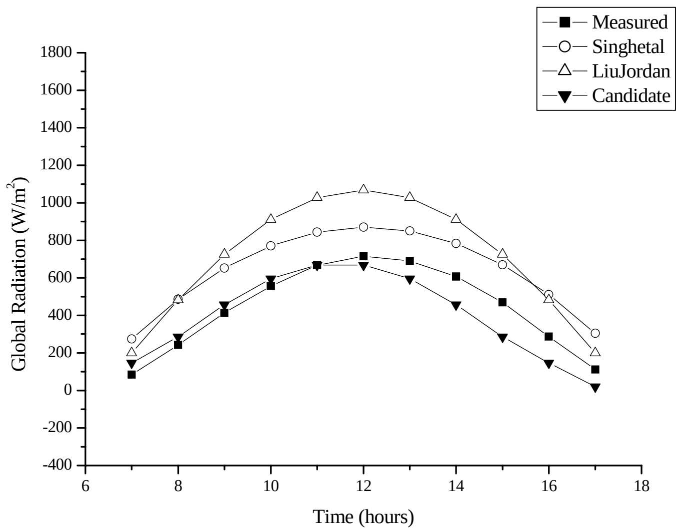

Figure 9. Hourly variation in global solar radiation with time for Chennai (January month), India

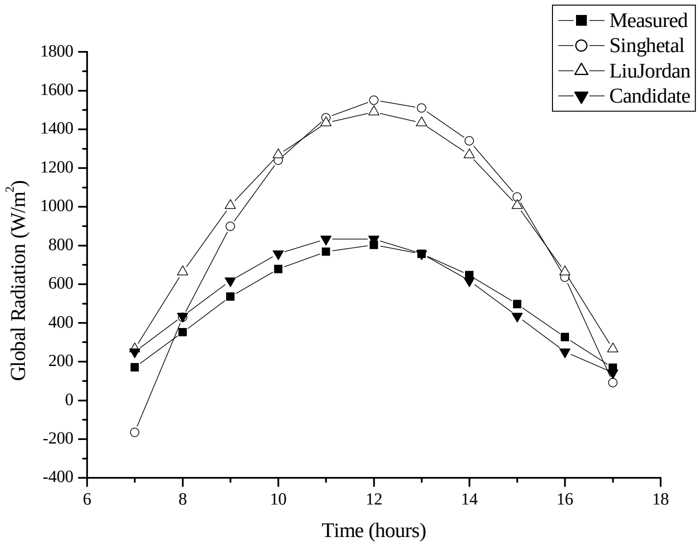

Figure 10. Hourly variation in global solar radiation with time for Chennai (June month), India

Table 2. The root mean square (RMSE), mean bias (MBE) and t- test errors for different models. The unit of RMSE and MBE is Wh. m $^{-2}$. day $^{-1}$.

		January			June		
Station		O.P. Singh	Liu & Jordan	Present model	O.P. Singh	Liu & Jordan	Present model
Ahamedabad							
	MBE	172.64	255	-44	427	457	39
	RMSE	177.46	270	76	583	469	91
	t-test	4.2	2.87	0.71	1.07	4.33	0.47
Calcutta							
	MBE	285.92	347	59	546	576	116
	RMSE	287.8	378	84	703	594	137
	t-test	8.7	2.31	0.98	1.63	3.96	1.59
Bombay							
	MBE	202.63	290	-61	487	522	80
	RMSE	205.45	304	102	630	538	118
	t-test	5.97	3.21	0.74	1.22	4.01	0.92
Poone							
	MBE	207.63	295	32	460	496	65
	RMSE	212.86	305	82	600	509	90.7
	t-test	4.42	3.69	0.42	1.19	4.34	1.02
Chennai							
	MBE	197.31	264	-47	394	459	21
	RMSE	199.39	280	97	527	505	62.12
	t-test	6.86	2.82	0.55	1.13	2.18	0.35

4. Conclusion

From the above discussion, we conclude that the remarkable variation in values of constants A, B, C, D, E and F are found for different months and locations. It may be due to the variations in the Indian climatic characteristics. Good agreement between the measured and the estimated values recommended the correlation for Indian climatic conditions. The MBE, RMSE and t-test values are remarkable low. Therefore, the modified of ASHRAE model with new constants can be used for any location in India or outstation with similar climatic characteristics.

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