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Research Paper :

Estimation and experimental validation of solar radiation by ASHRAE method for Bhubaneswar (India)

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ABSTRACT

The reliability of ASHRAE (American Society of Heating, Refrigerating and Air-conditioning Engineers) model for estimation of hourly solar radiation on earth's surface was tested with the measured data of bright sun shine hours throughout the year 2007 for Bhubaneswar (Latitude 21.12^0 N and Longitude 85.65^0 E) located in south-east India. Comparing the observed and predicted values of hourly solar radiation, a clearness number (correction factor) has been found out in this model for the place to estimate the solar radiation for design of solar energy devices without going through sophisticated measuring instruments. It was found that on clear day or cloudless skies, the predicted solar radiation by ASHRAE method was about 20 per cent higher than the observed value at Bhubaneswar. Thus, for the prediction of solar radiation at Bhubaneswar a clearness number of 0.8 was taken for further calculations. The observed and predicted values of solar radiation for different seasons at Bhubaneswar showed close agreement when the clearness number was taken as 0.8.

Key words : Solar radiation, Thermal modeling, Experimental validation

The amount of solar radiation incident on earth's surface is an important and important data for solar energy applications (Duffie and Beckman, 1991). This Solar radiation has temporal and spatial variation. To obtain these data, a net work of solar monitoring stations equipped with pyranometers and data acquisition systems are generally established in a target area. However, the number of stations in the network are usually not sufficient to provide solar radiation data of the area especially in developing countries. This is mainly due to the high equipment and maintenance costs. Though solar radiation can be estimated from sunshine duration and cloud cover data, the accuracy of estimation is relatively low (Iqbal, 1983) and the correct data from measuring stations are very rare. Therefore, a suitable correlation becomes important to predict the solar radiation data for a particular place with a view to design a solar energy device for optimum performance.

Hence, looking at the importance of theoretical models, many researchers have predicted different types of models to predict solar radiation data (ASHRAE, 1985; Garg and Garg, 1987; Singh *et al.*, 1997). ASHRAE model is one such method in the literature to predict hourly values of solar radiation and it is deterministic and independent of climatic parameters such as temperature and humidity. With the help of ASHRAE model, the solar radiation can be predicted on hourly basis on any day of the year at any latitude. It also provides the values at different inclinations of the surface facing in any direction. The constants used in this model was developed for United States conditions. Hence, there is a need to validate them for different cities under study for obtaining the accurate performance of various solar gadgets. An effort in this paper has, therefore, been made to test their validity for a place of interest like Bhubaneswar (Latitude 21.12^0 N and Longitude 85.65^0 E) city of India.

METHODOLOGY

Estimation of solar radiation:

The total irradiation on a surface is the sum of the direct solar radiation, I_D, the diffuse sky radiation, I_d and solar radiation reflected from surrounding surfaces, I_r.

Estimation of direct solar radiation:

The intensity of the direct component is the product of the direct normal irradiation, I_{DN} and the cosine of the angle of incidence θ between the incoming solar rays and a line normal to the surface. Angle of incidence is calculated using the relationship.

Cos ¯ = l Cos Z + m Cos W + n Cos S .... (1)

where,

θ= Incident angle on a surface

l, m, n are the direction cosines of the normal to the surface which are calculated as below:

Let, the reference axes are vertical line, horizontal line pointing west and horizontal line pointing south. Thus, for a horizontal surface: l = 1, m= 0, n = 0 and for a vertical surface: l =0, m= ± Sin(WAZ), n =Cos (WAZ) where, WAZ = wall azimuth angle

m and n depend on orientation of the surface and n is positive when wall faces west of south. Cos Z, Cos W and Cos S are the direction cosines of solar beam which are calculated as:

$$\mathbf{Cos\ Z = Sin\ L.Sin\ D + Cos\ L\ Cos\ D.\ Cos\ H} \quad ....(2)$$

$$\mathbf{Cos\ W = Cos\ D.Sin\ H} \quad ...(3)$$

$$\mathbf{S = \pm (1 - Cos^2\ W - Cos^2 Z)^{1/2}} \quad ...(4)$$

where, L = Latitude angle; H = Hour angle; D = Sun's declination angle; Cos S is positive, if

$$\mathbf{cos\ H\ [\ \frac{Tan\ D}{Tan\ L}} \quad ...(5)$$

Latitude angle (L) is fixed for a particular place. Declination angle (D) varies each day.

where, n = Day of the year.

Then hour angle is calculated as:

$$\mathbf{H = 15\ x\ (hours\ from\ solar\ noon)} \quad ...(6)$$

Direct normal irradiation in W/m^2 is given as:

$$\mathbf{I_{DN}\ Z\ \frac{A}{exp\ (B/cosZ)}} \quad ...(7)$$

where, A = Apparent solar irradiation in W/m^2 at air mass = 0

B = Atmospheric extinction coefficient (air mass)$^{-1}$

Cos Z is calculated by Eq. (2)

The values of A and B vary during the year because of seasonal changes in dust and water vapour contents of the atmosphere, and also because of changing earth-sun distance.

Thus, from Eqs. (1) and (7) the intensity of direct solar radiation in W/m^2 is

$$\mathbf{I_D = I_{DN}\ .Cosq} \quad ...(8)$$

Estimation of diffuse sky radiation:

The diffuse solar radiation in W/m^2 from a clear sky that falls on any surfaces is given approximately by:

$$\mathbf{I_d = C.\ I_{DN}.\ F_{SS}} \quad ...(9)$$

where,

I_{DN} is the direct normal solar intensity (W/m^2) calculated in Eq (7). C is diffuse radiation factor (dimension less) available for 21st of each month (Table 9). F_{SS} is the angle factor between the surface and sky, *i.e.* the fraction of the radiation emitted by the surface that goes directly to the sky. F_{SS} can be calculated as:

$$\mathbf{F_{SS} + F_{Sg} = \quad 1} \quad ...(10)$$

where,

F_{Sg} is the angle factor between ground and inclined surface which is given as

$$\mathbf{F_{Sg} = 0.5\ (1 - Cos\ q)} \quad ...(11)$$

where, q is the tilt angle of the surface from horizontal

Estimation of reflected solar radiation:

Reflected solar radiation, I_r, can be calculated as:

$$\mathbf{I_r = I_{DN}.\ R_G\ .F_{Sg}} \quad ...(12)$$

where, I_{DN} is direct normal solar intensity in W/m^2 as calculated in Eq. (7). R_G is the reflectance value of the surrounding ground surface.

Estimation of total irradiation falling on a surface:

The total irradiation on a surface is the sum of the direct solar radiation, I_D, the diffuse sky radiation, I_d, and solar radiation reflected from surrounding surfaces, I_r. Thus, total irradiation in W/m^2 is

$$\mathbf{I_t = I_D + I_d + I_r} \quad ...(13)$$

A computer-based model in FORTRAN-77 has been developed for prediction of total solar radiation on different wall surfaces and horizontal surfaces, direct radiation and diffuse radiation reaches at the earth surface.

The performance of a solar energy drying system depends upon the intensity of solar radiation falling on the collector surface. The availability of solar radiation on a particular place depends upon geographical location, orientation of surface, radiation characteristics, operating time, day and weather conditions (Mani and Rangarajan, 1982). A computer simulation model is developed to predict the intensity of solar radiation on hourly basis at various orientations. The predictions of the model have been verified with the recorded or observed data of the representative days.

The sun's position in the sky at a particular time can conveniently be expressed in terms of solar altitude, solar azimuth, hour angle, solar declination angle, angle of incidence, surface solar azimuth and solar constants. Values of solar constants for the 21st day of each month were obtained from ASHRAE fundamentals and Langrage's interpolation was used for estimating their values for each day. As the model's prediction is limited to the clear sky day, the sky clearness number (CLNO) of unity (1) was used. To consider the effect of ground reflectivity in the total global radiation, the ground reflectivity was taken as 0.2.

Software description:

For prediction of direct and diffuse solar radiation for the place of Bhubaneswar, Fortran-77 has been used to solve the ASHRAE method. The predicted and observed values of solar radiation for 21st day of March, June, September and December, 2007 are mentioned in Table 1, 2, 3 and 4.

RESULTS AND DISCUSSION

On a clear days or cloudless skies, the predicted solar radiation was calculated by ASHRAE method for March 21, June 21, September 21 and December 21. The observed solar radiation was recorded for these days with the help of a precision pyranometer. It was observed that on March 21, the predicted solar radiation varied from 664 W/m^2 at 9 hr to 452 W/ m^2 at 16 hr. The maximum predicted solar radiation was 964 W/ m^2 at12 hr. While the observed solar radiation varied from 420 W/ m^2 at 9 hr to 640 W/ m^2 at 16 hr. The maximum observed value was 850 W/ m^2 at 12 hr. Thus, it was found that for March 21, 2004 the predicted value was 17.95 per cent higher than the observed value (Table 1). On June 21, the predicted solar radiation varied from 768 W/ m^2 at 9 hr to 585 W/ m^2 at 16 hr (Table 2). The maximum predicted solar radiation was 1026 W/ m^2 at 12 hr. While observed value varied from 630 W/ m^2 at 9 hr to 410 W/ m^2 at 16 hr. The maximum observed value was 910 W/ m^2 at 12 hr. It wasfound that for June 21, the predicted value was 20.32 per cent higher than observed value.

On September 21, the predicted solar radiation varied from 649 W/ m^2 at 9 hr to 441 W/ m^2 at 16 hr (Table 3). The maximum predicted value was 941 W/ m^2 at 12 hr. While the observed value varied from 550 W/ m^2 at 9 hr to 320 W/ m^2 at 16 hr. The maximum observed value was 810 W/ m^2 at 12 hr. It was observed that the predicted value was 20.76 per cent higher than the observed value.

Table 1 : Comparison of predicted and observed solar radiation on the horizontal surface (March 21, 2007)

Time (hrs)	Predicted solar radiation intensity (Watt/m^2)	Observed solar radiation intensity (Watt/m^2)	% Difference
09.00	664	420	58.0
10.00	827	600	37.8
11.00	929	640	45.1
12.00	964	850	13.4
13.00	929	780	19.2
14.00	827	760	8.81
15.00	664	740	-10.2
16.00	452	640	-29.3

Average deviation in a day=17.95

Table 2 : Comparison of predicted and observed solar radiation on the horizontal surface (June 21, 2007)

Time (hrs)	Predicted solar radiation intensity (Watt/m^2)	Observed solar radiation intensity (Watt/m^2)	% Difference
09.00	768	630	21.9
10.00	909	780	16.5
11.00	996	860	15.8
12.00	1026	910	12.7
13.00	996	860	15.8
14.00	909	775	17.2
15.00	768	640	20.0
16.00	585	410	42.68

Average deviation in a day = 20.32

Table 3 : Comparison of predicted and observed solar radiation on the horizontal surface (Sept. 21, 2007)

Time (hrs)	Predicted solar radiation intensity (Watt/m^2)	Observed solar radiation intensity (Watt/m^2)	% Difference
09.00	649	550	18.0
10.00	808	710	13.8
11.00	907	790	14.8
12.00	941	810	16.1
13.00	907	800	13.3
14.00	808	690	17.1
15.00	649	480	35.2
16.00	441	320	37.8

Average deviation in a day = 20.76

Table 4 : Comparison of predicted and observed solar radiation on the horizontal surface (Dec. 21, 2007)

Time (hrs)	Predicted solar radiation intensity (Watt/m^2)	Observed solar radiation intensity (Watt/m^2)	% Difference
09.00	392	290	35.1
10.00	548	470	16.5
11.00	645	550	17.2
12.00	678	580	16.8
13.00	645	540	19.4
14.00	548	430	27.4
15.00	392	300	30.6
16.00	189	140	28.5

Average deviation in a day = 23.93

On December 21 the predicted solar radiation varied from 392 W/ m^2 at 9 hr to 189 W/ m^2 at 16 hr (Table 4). The maximum predicted value was 678 W/ m^2 at 12 hr. While the observed solar radiation varied from 290 W/ m^2 at 9 hr to 140 W/ m^2 at 16 hr. It has been found that the predicted value was 23.93 per cent higher than the observed value. Average deviation between predicted and observed value was about 20 per cent. Thus, for the prediction of solar radiation at Bhubaneswar a clearness number of 0.8 has been taken for further calculations.

On March 21, at clearness number 0.8, the predicted solar radiation on horizontal surface at Bhubaneswar varied from 175 W/ m^2 at 7 hr to 793 W/ m^2 at 12 hr and then decreased to 175 W/ m^2 at 17 hr. It has been seen that 78 per cent direct radiation and 20 per cent diffused radiation reached at the earth surface (Table 5). On June 21, the predicted solar radiation at Bhubaneswar on horizontal surface varied from 123 W/ m^2 at 6 hr to 846 W/ m^2 at 12 hr and then decreased to 123 W/ m^2 at 18 hr. It was found that 75 per cent direct radiation and 24 per cent diffused radiation received at the earth surface (Table 6).

On September 21, the predicted solar radiation at Bhubaneswar on horizontal surface varied from 172 W/ m^2 at 7 hr to 776 W/ m^2 at 12 hr and then decreased to 172 W/ m^2 at 17 hr. It has been seen that 77 per cent direct radiation and 22 per cent diffused radiation received at the earth surface (Table 7). On December 21, the predicted solar radiation at Bhubaneswar on horizontal surface varied from 164 W/ m^2 at 8 hr to 562 W/ m^2 at 12 hr and then decreased to 164 W/ m^2 at 16 hr. It was found that 75 per cent direct radiation and 24 per cent diffused radiation received at the earth surface (Table 8 and 9). Thus, it was concluded that around 75-80 per cent direct and 15-20 per cent diffused radiation received

Table 5 : Predicted solar radiations (Watt/m^2) on March 21 with clearness number 0.8

Time (hr)	Direct radiation (I_D)	Diffuse radiation (I_d)	Total radiation (I_t)	I_D/I_t	I_d/I_t
7.00	109	66	175	0.622	0.377
8.00	289	90	379	0.762	0.237
9.00	452	100	552	0.818	0.181
10.00	578	104	682	0.847	0.152
11.00	658	106	764	0.861	0.138
12.00	686	107	793	0.865	0.134
13.00	658	106	764	0.861	0.138
14.00	578	104	682	0.847	0.152
15.00	452	100	552	0.818	0.181
16.00	289	90	379	0.762	0.237
17.00	109	66	175	0.622	0.377

Table 6 : Predicted solar radiations(Watt/m^2) on June 21 with clearness number 0.8

Time (hr)	Direct radiation (I_D)	Diffuse radiation (I_d)	Total radiation (I_t)	I_D/I_t	I_d/I_t
6.00	65	58	123	0.528	0.471
7.00	221	94	315	0.701	0.298
8.00	381	110	491	0.775	0.224
9.00	521	117	638	0.816	0.183
10.00	630	121	751	0.838	0.161
11.00	698	124	822	0.849	0.150
12.00	722	124	846	0.853	0.146
13.00	698	124	822	0.849	0.150
14.00	630	121	751	0.838	0.161
15.00	521	117	638	0.816	0.183
16.00	381	110	491	0.775	0.224
17.00	221	94	315	0.701	0.298
18.00	65	58	123	0.528	0.471

Table 7 : Predicted solar radiations(Watt/m^2) on September 21 with clearness number 0.8

Time (hr)	Direct radiation (I_D)	Diffuse radiation (I_d)	Total radiation (I_t)	I_D/I_t	I_d/I_t
07.00	104	68	172	0.604	0.395
08.00	277	95	372	0.744	0.255
09.00	434	106	540	0.803	0.196
10.00	557	111	668	0.833	0.166
11.00	635	114	749	0.847	0.152
12.00	661	115	776	0.851	0.148
13.00	635	114	749	0.847	0.152
14.00	557	115	668	0.833	0.166
15.00	434	106	540	0.803	0.196
16.00	277	95	372	0.744	0.255
17.00	104	68	172	0.604	0.395

Table 8 : Predicted solar radiations(Watt/m^2) on December 21 with clearness number 0.8

Time (hr)	Direct radiation (I_D)	Diffused radiation (I_d)	Total radiation (I_t)	I_D/I_t	I_d/I_t
8.00	101	63	164	0.615	0.384
9.00	246	85	331	0.743	0.256
10.00	363	94	457	0.794	0.205
11.00	438	97	535	0.818	0.181
12.00	464	98	562	0.825	0.174
13.00	438	97	535	0.818	0.181
14.00	363	94	457	0.794	0.205
15.00	246	85	331	0.743	0.256
16.00	101	63	164	0.615	0.384

Table 9 : Values of different Solar constants in various months of a year

Date	Declination, D (deg)	A (W/m^2)	B ($Airmass^{-1}$)	C (Dimensionless)
January 21	-20	1202	0.141	0.103
February 21	-10.8	1187	0.142	0.104
March 21	0	1164	0.149	0.109
April 21	+11.6	1130	0.164	0.120
May 21	+20.0	1106	0.177	0.130
June 21	+23.45	1092	0.185	0.137
July 21	+20.6	1093	0.186	0.138
August 21	+12.3	1107	0.182	0.134
September 21	0	1136	0.165	0.121
October 21	-10.5	1136	0.152	0.111
November 21	-19.8	1190	0.144	0.106
December 21	-23.45	1204	0.141	0.103

at earth surface.

Fig. 1, 2, 3 and 4 illustrate the values of solar radiation on horizontal surface and different walls of a room at Bhubaneswar on 21st day of March, June, September and December, 2007, respectively. From the figures it is found that the predicted and observed solar radiations show a fair agreement with each other.

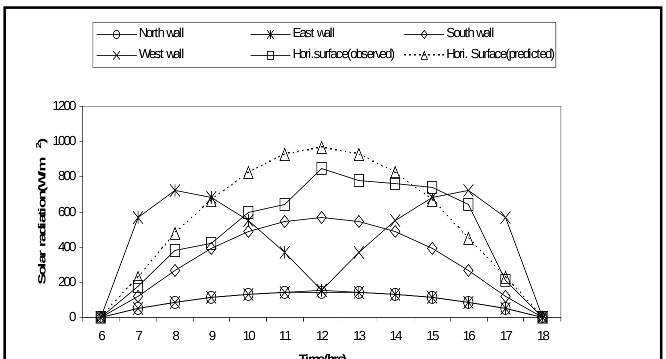

Fig. 1: Design of total solar radiation on different wall surfaces for Bhubanewar during 21 March

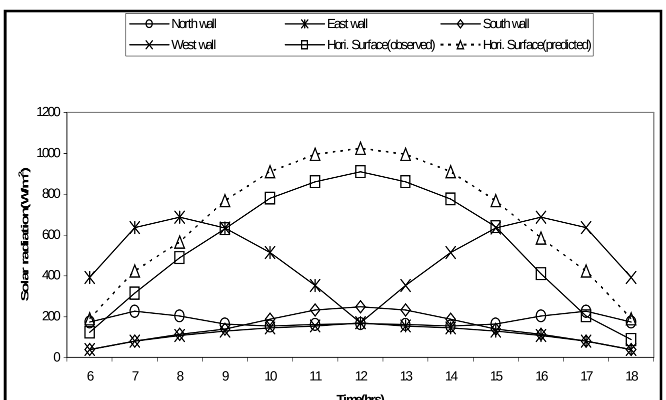

Fig. 2: Design of total solar radiation on different walls for Bhubanewar during 21 June

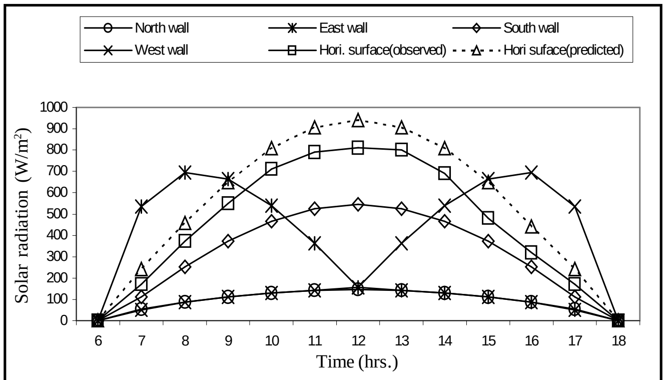

Fig. 3: Design of total solar radiation on different walls for Bhubanewar during 21 September

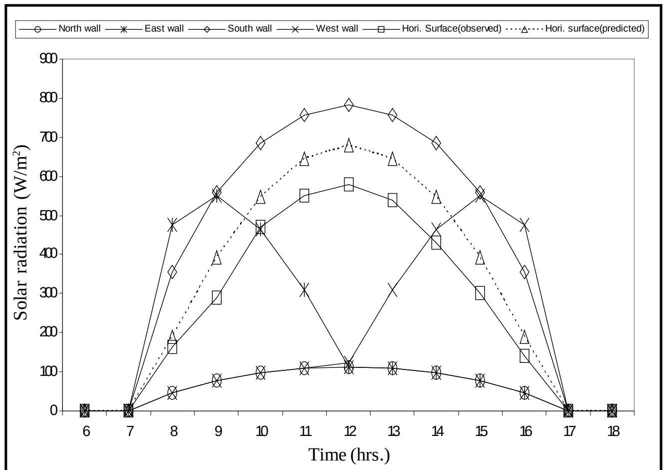

Fig. 4: Design of total solar radiation on different walls for Bhubanewar during 21 December

Conclusion:

On clear days or cloudless skies, the estimated solar radiation by ASHRAE method is about 20 per cent higher than the observed values. Thus, for the prediction of solar radiation at Bhubaneswar, a clearness number of 0.8 has been taken for further calculations and designing different solar energy devices. It has also been seen that the percentage of direct solar radiation and diffuse solar radiation reaching to the earth's surface is around 75-80 per cent and 15- 20 per cent, respectively. The observed and predicted values of solar radiation for different seasons of the year at Bhubaneswar were found to be in close agreement when the clearness number was taken as 0.8.

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