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An Analysis of Global, Direct and Diffuse Solar Radiation

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Abstract

The paper studies the horizontal global, direct-beam and sky-diffuse solar radiation data measured in Hong Kong from 2008 to 2012, reports some of the general findings, evaluates mathematical model for predicting direct-normal solar radiation and computes various climatic variables. The findings can help to establish a more reliable and comprehensive solar radiation database for further building energy designs and assessments.

Keywords: Solar radiation; Diffuse radiation; Model validation; Hong Kong

Nomenclature

BSR	Direct solar radiation on a horizontal surface, Wh/m^2
DSR	Diffuse solar radiation on a horizontal surface, Wh/m^2
ESR	Extraterrestrial solar radiation on a horizontal surface, Wh/m^2
GSR	Global solar radiation on a horizontal surface, Wh/m^2
T_L	Irradiance based turbidity of an arbitrary sky, dimensionless
a_v	Rayleigh atmosphere extinction coefficient, dimensionless
m_v	Air mass, dimensionless

1. Introduction

Solar radiation data are crucial to the active solar energy facilities [1] and passive energy-efficient building designs [2]. However, solar radiation readings vary with geographic latitude, season and time of

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day, due to the various positions of the sun under unpredictable weather conditions [3]. Long-term data measurement is the most effective and accurate way of setting up such databases. In many parts of the world, however, the basic solar radiation data for the surfaces of interest are not always readily available [4]. Horizontal global solar radiation (GSR) is made up of direct (BSR) and diffuse (DSR) components. The conventional method involves developing empirical correlations between BSR or DSR components and GSR [5]. In interpreting sky conditions, meteorological data are used as weighting factors to show the degree of sky clearness[6]. Recently, the Hong Kong Observatory (HKO) has recorded the hourly GSR, DSR and BSR. This paper analyses the recorded solar radiation data, evaluates a prediction model and computes the meteorological parameters based on the horizontal measured solar radiation data [7].

2. Data measurement and general performance

In July 2008, the HKO established a station to measure the horizontal global, sky-diffuse and direct-beam solar radiation in Kau Sai Chau, Hong Kong (22.3 ° N, 114.3 ° E). The data collection started just before sunrise and ended after sunset each day. The measurements were recorded hourly in local civil time. For the present study, the data collected between July 2008 and December 2012 were employed. To eliminate spurious data and erroneous measurements, stringent quality-controls tests based on the CIE guidance were adopted [8]. Table 1 summarizes the tests and results. Over 2000 data with a solar altitude of less than 4 ° or the GSR less than 20 W/m² which were near sunrise and sunset were rejected. No and 226 data were rejected under Level 1 and Level 2 tests, respectively. After the 3-level test, around 17,620 hourly readings for each solar radiation component (GSR, DSR and BSR) were retained for subsequent analysis.

Table 1. Quantity of data accepted for each CIE test level

CIE Test Level	Criterion	Number of data record (Hour)	
		Rejected	Accepted
Total	Solar Angle > 0		19,852
Level 0	Solar Angle > 4	2,009	17,843
	GSR > 20W/m^2		
Level 1	0 < GSR < 1.2ESR	None	17,843
	0 < DSR < 0.8ESR		
	0 ≤ DSR < ESR		
Level 2	85%(BSR+DSR) < GSR < 115%(BSR+DSR)	226	17,617
	DSR < GSR		

Figure 1 shows the correlations between GSR and the sum of DSR and BSR. An examination of the figure shows that a clustered band can be clearly noticed at most parts of the graph. There is a slight scatter around certain parts of the graph at high radiation values. Since the GSR, DSR and BSR were measured by three independent meters, the results indicate that all the three sets of solar radiations should be correctly recorded. The peak value can be more than 1,080 Wh/m² which is quite good for active solar applications. However, such a high value has an implication to the building thermal design. Most roofs in Hong Kong have 40-50mm thermal insulation with no skylight. The main purpose is not to reduce heat conduction but to minimize the risk of a ‘hot’ ceiling during sunny summer days.

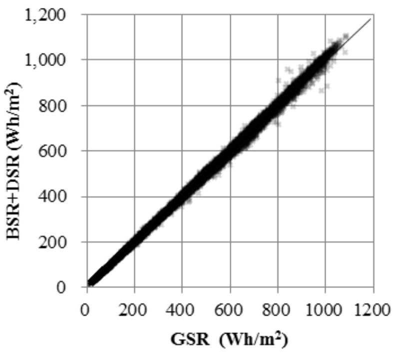

Fig. 1. Result of measurement (GSR and sum of BSR and DSR)

Daily solar radiation data are useful for evaluating the performance of solar electric and solar thermal systems. Figure 2 presents the monthly-average-daily BSR and DSR. It can be seen that the DSR varies ranging from 1,510 Wh/m² in December to 2,690 Wh/m² in June and BSR ranges between 690 Wh/m² in March and 3,150 Wh/m² in July. The average GSR, DSR and BSR are 3,870, 2,150 and 1,720 Wh/m², respectively. The maximum GSR observed in July is mainly due to the high solar altitude and long day-length in summer. The below average GSR recorded from December to April are due mainly to the low solar altitude in winter and unstable weather conditions in spring. It can also be noted that the months receive low GSR containing a high portion of DSR. Generally, the variation in DSR is comparatively less than that in BSR. The annual averages of DSR and BSR are around 55.6% and 44.4%, respectively. The findings are in good agreement with our previous work [9].

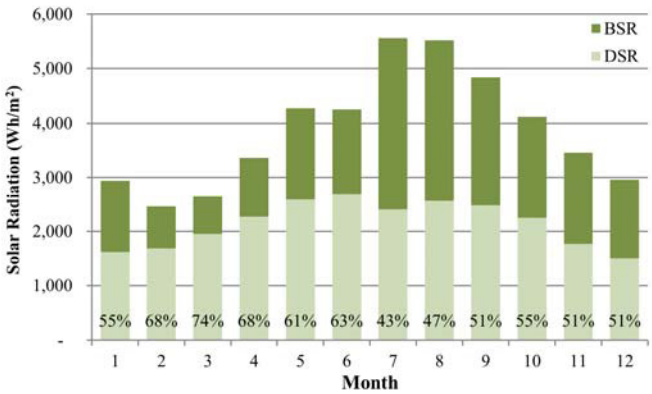

Fig. 2. Monthly average daily BSR and DSR for each month

Hourly data would be more appropriate for examining cooling load. Figure 3 plots the monthly-average-hourly GSR and DSR in February and July representing respectively the lowest and largest recorded monthly-average-daily GSR. The peak solar radiation appears at solar noon for both GSR and DSR. The GSR of just over 700 Wh/m² and less than 400 Wh/m² are observed at noon in July and February, respectively. The DSR values are , however, quite close for these two months.

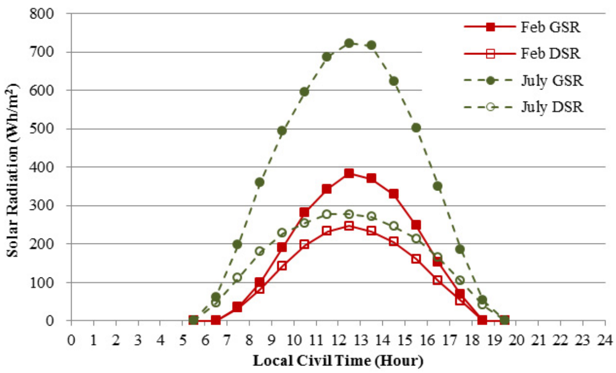

Fig. 3. Average hourly GSR and DSR for February and July

3. Prediction models

In the absence of DSR or BSR, the most common approach is the diffuse fraction (the ratio of DSR to GSR) or direct-beam normal as a function clearness index (K_t) which is the ratio of GSR to extra-terrestrial solar radiation (ESR) [10]. A well-known mathematical approach namely Boland-Ridley-Lauret (BRL) model [11] was employed for the evaluation. The required input parameters for calculating the diffuse fraction and the direct normal solar radiation include clearness index, appearing solar time, solar altitude angle and persistence. The performance for the model was assessed by three widely used statistics: mean bias error (MBE), root mean square error (RMSE) and mean absolute error (MAE). Table 2 presents the results. The BRL tends to underestimate the solar radiation with the %MBE of -3.4% and %MAE of 16.8%. The RMSE is 41.1 W/m² which is 29.1% of the mean measured value.

Table 2. MBE, RMSE and MAE of the BRL models

MBE (Wh/m^2)	% MBE	RMSE (Wh/m^2)	% RMSE	MAE (Wh/m^2)	% MAE
-4.9	-3.4%	41.1	29.1%	23.8	16.8%

4. Climatic parameters

The GSR, DSR and BSR can be used to form various climatic parameters for indicating the sky conditions. The three common climatic parameters are K_t, diffuse coefficient (K_d) and Linke turbidity factor (T_L) which can be expressed as:

$$K_t = GSR/ESR \quad (1)$$
$$K_d = DSR/ESR \quad (2)$$
$$T_L = \ln(ESR/BSR)/(a_v m_v) \quad (3)$$

where a_v is Rayleigh atmosphere extinction coefficient; m_v is air mass

Figure 4 depicts the frequency of occurrence (FOC) for K_t. The pattern of K_t is fairly evenly distributed, with two peaks centered at 0.12 and 0.72. The maximum K_t is up to 0.84. It is perhaps logical using K_d to indicate the state of the sky as the sky-diffuse radiation for the whole sky is being considered. [12]. Low K_d data stand for overcast and clear days and high K_d values represent partly cloudy skies. Figure 5 displays the FOC for K_d. The peak occurrence of around 10% appears at K_d of 0.275. Small K_d values ($K_d < 0.275$) occur more frequent than large K_d ($K_d > 0.275$) indicating overcast and partly cloudy skies are more than clear days. The T_L is a quantity used for expressing the atmospheric turbidity [13]. When there is no BRS, T_L tends to be infinite. Likewise, the frequency of occurrence for T_L is exhibited in Figure 6. The frequent of occurrence is about 32% at $T_L \geq 39$ which corresponds to overcast skies with very small amount of BSR. With more direct component, T_L decreases. A peak frequency of occurrence of 8.25% is observed when T_L=5.

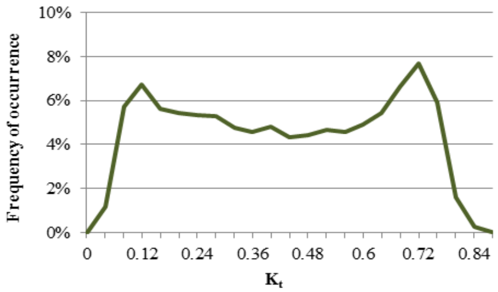

Fig. 4. Frequency of occurrence for K_t

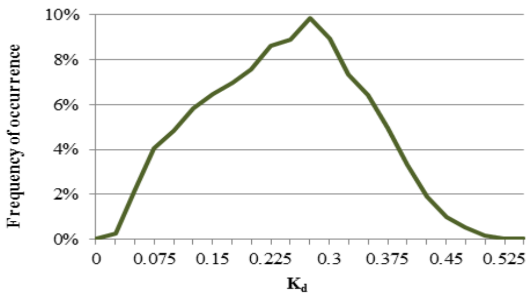

Fig. 5. Frequency of occurrence for K_d

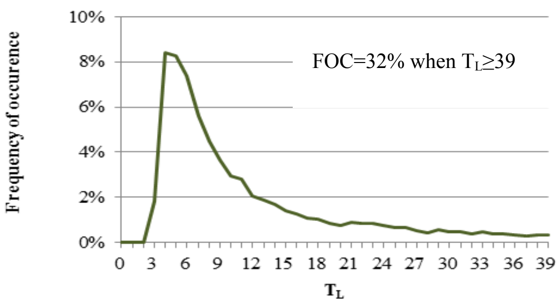

Fig. 6. Frequency of occurrence for T_L

5. Conclusions

An analysis of horizontal global, direct-beam and sky-diffuse solar radiation solar radiation was conducted. The annual daily averages of horizontal global, diffuse and direct radiation are 3.87, 2.15 and 1.72 kWh/m², respectively. The performance of the BRL model was evaluated and the %MBE, %MAP and %RMSE were -3.4, 16.8 and 29.1%, respectively. The solar radiation data were also used to compute various climatic parameters including K_t, K_d and T_L. The results are in good agreement with our previous findings. The study can help to establish a comprehensive solar radiation database for subsequent building designs and energy scheme evaluations.

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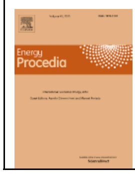

Biography

Dr. Danny Li is currently an Associate Professor in Department of Architecture and Civil Engineering at the City University of Hong Kong. His research areas include building, energy and the environment in general and solar radiation and daylighting in particular.