

An investigation of the vertical diffuse efficacy of solar irradiance for Thailand's climate

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Abstract. This paper presents a study result of the luminous efficacy of diffuse solar irradiance on vertical plans using records from a daylight measurement station located in Bangkok, Thailand. Hourly mean values of the vertical diffuse efficacy are first introduced. Variations of the efficacy are also presented for different sky conditions. Our results indicate that the tropical diffuse efficacy was higher than those in high latitude regions. In this study, the authors proposed a method for the efficacy prediction. The proposed method was evaluated its performance against some selected existing models. The results show that the authors' method predicted well the tropical efficacy value and outperformed other evaluated models with their original coefficients.

1. Introduction

Daylighting is perceived to be a key measure that makes buildings towards environmental and energy sustainability. Appropriate daylighting technologies help reduce substantial electrical energy for both lighting and air-conditioning in buildings particularly those in tropical region where the sky is highly luminous and daytime is long throughout a year [1-2]. Different from practical electric lighting for indoor illumination, the daylighting is more complicate as amount of light from its sources varies in natural with geography and outdoor climate. Hence, daylight data presents its essence for establishing solutions in order to reap a full benefit from the available daylight in a location. Unfortunately, the daylight data is still scarce today, as the routine observation program at most meteorological station includes only solar irradiance. An alternative method to produce illuminance data is via the use of luminous efficacy. The efficacy can be thought simply of a multiplicative factor of the solar irradiance. Not a constant, the efficacy value varies with prevalent climate condition. A number of researches have been conducted in Europe and North America to establish the accurate efficacy models [3-5]. The main objective of this paper is to investigate the luminous efficacy of solar irradiances on vertical planes of the north, east, south, and west in Thailand. To fulfil the objective, the specific activities carried out in the study include: (i) characterization of the luminous efficacy of the vertical diffuse solar irradiances, (ii) modeling of the vertical diffuse efficacy and (iii) performance evaluation of the developed efficacy models against some selected existing models. At present, the scope of this efficacy study was limited only to the diffuse component of the solar irradiance.

2. Daylight and solar irradiance measurement



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A daylight measurement station was established under a graduate program in Energy Division of the Joint Graduate School of Energy and Environment (JGSEE), King Mongkut's University of Technology, Thonburi (KMUTT), Thailand. The station is located on a roof deck of a seven-story building in Bang Khun Tien campus of the university. The campus is situated in southern suburban area of Bangkok (latitude 13.58°N and longitude 100.44°E). The station has measured solar irradiance and daylight illuminance of global, diffuse horizontal and beam normal components; including total irradiance and illuminance on vertical planes facing the four cardinal orientations (N, E, S, and W). All the mentioned data have been recorded every five minutes.

3. Characteristics of the tropical vertical efficacy

The hourly data aggregated from the five-minute illuminance and irradiance records in year 2015-2016 from the station were used for the analysis. Values of diffuse efficacy (K_d) were derived by dividing the hourly values of diffuse illuminance (lux) with its corresponding diffuse irradiance (W/m^2). This section presents results from statistical analysis of the vertical diffuse efficacy data. Correlations between the diffuse efficacies and sky conditions will be presented next.

Hourly mean values of the vertical diffuse efficacy were analysed for four cardinal orientations. However, in this paper, only that of the south surface was presented as shown in Table 1. It can be observed that the diffuse efficacy on the south varied from about 107.1 lm/W to 172.5 lm/W. The efficacy values were relatively high during noon. The efficacy was also high during November-February when the sky was rather clear compared to other period. The yearly average of diffuse hourly mean value was approximately 138.6 lm/W.

Table 1. Hourly mean values of the *south* diffuse efficacy (lm/W) by calendar months

Time	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
6-7			126.40	150.89	129.86	125.62	130.27	127.41	136.01	134.85	125.10	147.06
7-8	129.78	126.22	135.53	167.16	130.03	129.05	130.66	134.50	144.07	153.24	140.07	136.86
8-9	144.50	157.78	165.33	148.67	128.52	128.15	129.56	133.57	151.12	161.24	146.46	138.28
9-10	150.34	161.10	172.52	144.58	128.11	127.53	129.48	136.14	154.12	154.51	142.08	137.71
10-11	149.75	157.40	164.44	146.04	126.82	125.89	128.45	131.01	142.75	143.34	145.55	150.87
11-12	152.31	156.70	160.82	152.66	127.37	125.76	128.46	130.71	148.42	143.93	165.48	167.12
12-13	148.75	152.40	161.00	155.52	131.50	126.82	134.66	132.25	143.20	139.96	158.47	153.67
13-14	147.11	147.19	152.98	144.14	126.51	126.45	130.77	127.55	145.66	138.87	148.13	143.62
14-15	142.74	143.82	150.66	137.58	127.23	126.19	130.30	127.93	141.42	135.85	141.98	136.58
15-16	139.69	139.42	145.21	135.54	126.73	126.65	129.58	131.17	140.22	137.42	140.04	132.62
16-17	132.83	129.50	134.91	155.57	127.84	127.36	129.93	133.09	135.94	137.67	134.54	124.14
17-18	115.12	108.02	120.78	155.19	127.29	126.95	131.54	133.73	128.81	132.84	120.44	107.12
18-19			133.43	158.72	122.41	122.92	129.74	130.86	123.88			

4. Efficacy Modelling and Evaluation

In order to further the study, a method was developed to predict the tropical vertical efficacy for different sky conditions. Some existing models introduced by other researchers were chosen to evaluate against our tropical data. In this section, the authors also proposed a simple method for the vertical diffuse efficacy prediction. The authors' method was compared their prediction performance with the existing models.

Table 2 summarizes the existing efficacy models to be evaluated in this study. The first model DE1 was introduced by Muneer, Gul and Kubie [6] with a polynomial form. Ruiz, Soler and Robledo developed the three models from their studies denoted as DE2-DE4 [7, 8]. Among the three models,

DE3 and DE4 included solar altitude as their parameter input. The original coefficients of the models derived from the efficacy records in their study locations were included in Table 2.

In a step of the study, models DE1-DE4 were regressed with our tropical efficacy data to obtain the optimal local coefficient values. Table 2 also gives the local coefficient values of each model. As shown, models DE1-DE3 employed a single set of coefficients for the efficacy prediction, while model DE4 employed separate coefficient set each for a particular orientation. From comment of the earlier studies [9] that the coefficient separation offered a better prediction, the regression of the local coefficients was thus made for each of the orientations (north, east, south and west).

Table 2. The vertical diffuse efficacy models with their original coefficients and the local coefficient values regressed from the tropical data.

Model	Functional form	Coefficient	North	East	South	West
DE1	$K_d = a + b \cdot k_t + c \cdot k_t^2$	Original	a = 130.2 b = 39.83 c = 49.98			
		Local	a = 143.6 b = -19.88 c = 35.86	a = 138 b = 0.5676 c = 34.55	a = 140.1 b = -82.98 c = 146.1	a = 142.3 b = -80.38 c = 145.3
DE2	$K_d = a + b \cdot k_d + c \cdot k_d^2$	Original	a = 160.61 b = 47.05 c = 196.94			
		Local	a = 160.3 b = -38.29 c = 15.39	a = 166.8 b = -35.56 c = 5.068	a = 184.9 b = -125.4 c = 69.58	a = 197.2 b = -152.5 c = 86.89
DE3	$K_d = a \cdot (\sin \alpha)^b \cdot k_d^c$	Original	a = 86.97 b = -0.143 c = 0.218			
		Local	a = 133.3 b = -0.036 c = -0.0837	a = 134.7 b = -0.0348 c = -0.1087	a = 124.9 b = -0.0053 c = -0.1604	a = 123.4 b = -0.0291 c = -0.1927
DE4	$K_d = a \cdot (\sin \alpha)^b \cdot \Delta^c$	Original	a = 96.04 b = -0.08 c = -0.039	a = 112.2 b = -0.061 c = -0.009	a = 108 b = 0.088 c = -0.171	a = 112.63 b = -0.041 c = -0.027
		Local	a = 125.8 b = 0.0025 c = -0.0941	a = 136.3 b = 0.0084 c = -0.0575	a = 121.4 b = 0.0631 c = -0.1206	a = 116.9 b = 0.0569 c = -0.1611

The prediction performance was first evaluated by comparing the calculated efficacy values of the models using the original coefficients with that using the local coefficients through scattered plots. Fig. 1 shows exemplarily that the local model DE1 gave higher predicted efficacy values than the original model. The difference became larger when the sky was clearer (higher value of k_t). In order to evaluate the model prediction performance, the two statistical parameters of Mean Bias Difference (MBD) and Root Mean Square Difference (RMSD) were employed. The parameter can be defined as:

$$MBD = \sum_{i=1}^N (C_i - M_i) / N \quad (1)$$

$$RMSD = \left[\sum_{i=1}^N (C_i - M_i)^2 / N \right]^{1/2} \quad (2)$$

where C_i is the calculated value, M_i is observed values and N is the number of data. By their definition, RMSD gives weight to points far away from the mean. RMSD gives only positive values. MBD can give positive or negative values, corresponding to that positive value implies an overestimation of the model.

From Table 3, the original model DE1 underestimated the tropical diffuse efficacy by 14.0-22.8 lm/W while the local model slightly overestimated by 0.28-0.69 lm/W. The local model gave RMSD value of 13.36-17.63 lm/W, lower than the original model. Table 3 also shows that the original model DE2 possessed large positive MBD and RMSD values, indicating it overestimated the efficacy values and performed worse compared with the original model DE1. The comparison also exhibits that the local model DE2 performed slightly better than model DE1 for all four orientations. This might imply that k_d is better for diffuse efficacy parameterization than k_t .

For the original model DE3, Table 3 shown that the model underestimated the tropical diffuse efficacy values. It performed worse than DE1 but better than DE2. For the local model DE3, its prediction performance was comparable with the local models DE1 and DE2; although the model included solar altitude as additional input parameter. However, the model DE3 offered the smallest discrepancy between the predicted values and the observed values. For the last model DE4, it had the functional form identical to that of model DE3, but brightness index (Δ) was used as the weather parametrization input. By observing the results in Table 3, models DE4 did not perform any significant prediction improvement.

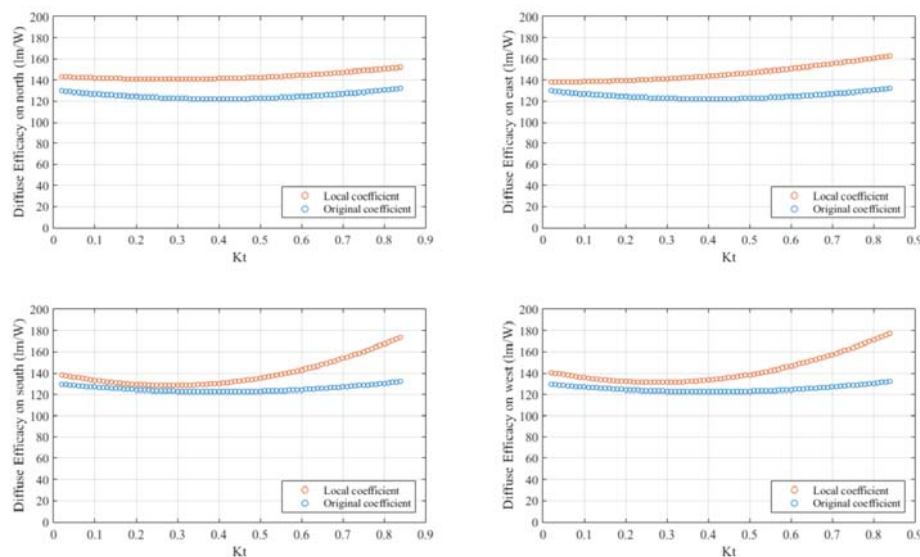


Figure 1. Comparison of diffuse efficacy from the original and local model DE1

Table 3. Evaluation of the vertical diffuse efficacy models

Model	North		East		South		West	
	Mean	143.4	Mean	147.0	Mean	138.2	Mean	141.5
	Dev	15.5	Dev	21.9	Dev	21.1	Dev	22.2
	MBD	RMSD	MBD	RMSD	MBD	RMSD	MBD	RMSD
Original coefficients								
DE1	-19.18	15.31	-22.79	21.66	-14.00	20.35	-17.28	21.50
DE2	75.97	53.95	72.37	58.13	81.15	59.97	77.87	61.49
DE3	-34.28	15.96	-37.89	21.46	-29.10	19.79	-32.38	19.34
DE4	-36.43	15.76	-28.73	22.39	-8.15	19.67	-21.37	22.44
Local coefficients								
DE1	0.44	13.36	0.28	20.09	0.69	15.76	0.59	17.63
DE2	0.40	12.88	0.18	19.78	0.65	15.34	0.21	16.66
DE3	0.30	13.00	0.17	19.69	0.60	15.48	0.17	16.54
DE4	0.35	12.87	0.55	20.30	0.79	16.87	0.51	18.40
DE5	0.26	13.17	0.28	20.62	0.43	15.85	0.05	16.27

As already mentioned, the authors aimed to introduce their own prediction methods. To be in line with our past daylight studies, Perez's clearness and sky brightness indices were to be used to parameterize insolation condition for the efficacy prediction. Table 4 summarizes the mean values of the vertical diffuse efficacy under eight Perez's clearness bins.

It can be observed that the efficacy value tended to increase with Perez's clearness. Under overcast condition (Clearness bin #1), the mean values of the diffuse efficacy ranged from 128.5 lm/W for south to 137.9 lm/W for east. The highest efficacy value would occur for clear sky condition with the mean values of 157.7 lm/W for north to 170.9 lm/W for west. The proposed prediction method was the direct use of the mean values of the diffuse efficacy in Table 4. In Table 3, this proposed method was denoted as the local model DE5. The table shows that the model could predict the diffuse efficacy values as comparable as model DE1-4. From the literatures, some studies introduced the use of a constant value to convert solar irradiance to its corresponding illuminance. However, Table 3 indicated that the author's method could improve the overall prediction performance by 5.8-26.7% (Reduced RMSD values) compared to the use of a constant efficacy value.

Table 4. The mean values of diffuse luminous efficacy on north, east, south and west surfaces

Clearness bin no.	North	East	South	West
1.Overcast	137.37	137.11	128.51	130.46
2	138.15	140.79	128.71	130.52
3	140.28	145.48	132.12	132.75
4	144.40	149.75	137.95	140.86
5	148.32	155.65	146.13	147.64
6	152.92	157.55	152.99	161.94
7	157.68	161.46	161.71	170.88
8. Clear	151.01	156.98	170.57	184.67

5. Conclusion

This paper characterized the vertical diffuse efficacy in Thailand's tropical climate. The statistical analysis showed that the mean values of the vertical diffuse efficacy were within a range of 107.1 lm/W to 172.5 lm/W. The evaluation of some existing efficacy models from higher latitude regions indicated that the tropical diffuse efficacy was comparatively high, and thus the daylight was more abundant. The characterization also showed that the diffuse efficacy value increased with clear sky condition. In the efficacy modeling, the existing models were regressed with our tropical efficacy records to obtain the optimal local coefficients. A prediction method was also introduced by the authors. The author's method determined the vertical efficacy values according to the eight Perez's clearness bins. The evaluation results showed that the author's methods and the existing model with local coefficients performed much better than the original efficacy models.

6. References

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