AN ANALYSIS OF DAYLIGHT LUMINOUS EFFICACY

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In Hong Kong, there have been growing concerns about energy consumption, particularly in buildings, and its likely adverse effects on the environment. Recent energy audits and surveys of commercial buildings have indicated that lighting accounts for 20-30% of the total electricity use. Daylighting has been identified as a priority area in energy-efficient design strategy and energy conservation programme. In cooling-dominated region, daylighting is always accompanied by unwanted solar heat gain. To have a good understanding of the relative importance of outdoor illuminance and solar radiation, daylight luminous efficacy under different sky conditions and for different surfaces has been investigated. Six-year (1991-1996) measured outdoor illuminance and solar radiation data have been gathered and analysed. Three sky conditions, namely overcast, partly cloudy and clear, have been examined. Correlations between luminous efficacy and solar altitude have been conducted, and cumulative frequency distribution of luminous efficacy is derived and presented. About 80% of the year, the global luminous efficacy exceeds 100 lm/W, which is much higher than most electric lighting systems. Implications for energy efficiency in building designs and operations are discussed.

Introduction

Daylighting is particularly attractive in hot climates since it reduces electricity use, not only for artificial lighting but also for air-conditioning due to less heat dissipation from electric light fittings [Ref.1]. A recent study in Hong Kong has revealed that very few buildings in Hong Kong have incorporated daylighting schemes, and daylighting has been identified as one of the key areas in energy-efficient design strategy [Ref. 2].

The objective of daylighting design is to maximize the utilization of available outdoor illuminance without imposing excessive cooling load and causing glare. In subtropical Hong Kong, solar heat gain is a major component of building cooling load, accounting for nearly half of the total building envelope load for office buildings [Ref.3]. To evaluate daylighting design, we need to know the incident solar irradiation data and the corresponding outdoor daylight illuminance, so that the trade-off between solar heat gain and daylighting benefits can be properly assessed. This paper presents work on solar radiation and daylight illuminance measurements and analysis.

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The measuring station

Hourly data of solar radiation and outdoor illuminance on the horizontal plane have been measured since 1991. The measuring station is located on the roof of the City University of Hong Kong, free of obstruction. Two pyranometers (CM11) manufactured by Kipp and Zonen, Netherlands, are used to measure the solar radiation. The diffuse radiation pyranometer is fitted with a shadow-ring (CM121) to shade the thermopile from the direct sun. The two pyranometers are connected to an integrator (CM12) which calculates radiation over selected periods. A Pascal program has been written to capture the data from the integrator and store the data in a micro-computer. Details

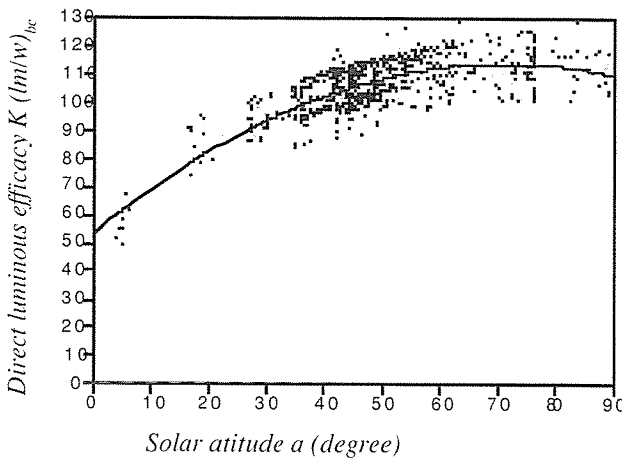

Figure 1. Direct luminous efficacy for clear sky against solar altitude

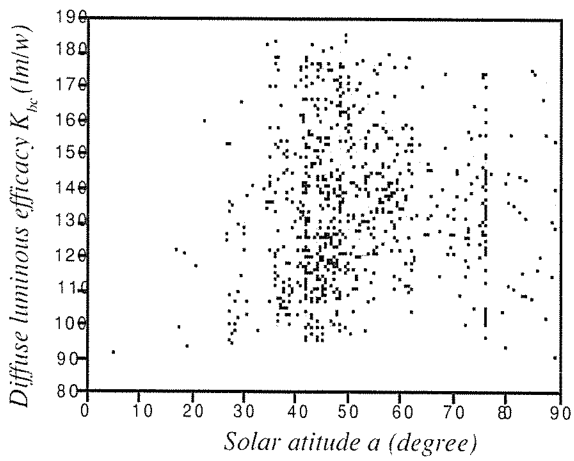

Figure 2. Diffuse luminous efficacy for clear sky against solar altitude

of the solar radiation measurement can be found in [Ref. 4].

For outdoor illuminance measurement, silicon photovoltaic cells with cosine and colour correction, measuring outdoor illuminance level up to around 150klux are used. Measured data are converted into digital signals by an analogue/digital converter, captured and stored in a micro-computer. All measurements are referred to true solar time. This facilitates computations which involve solar altitude and extraterrestrial radiation on a unit horizontal surface and comparison of data for different locations.

Data analysis

Kittler et al. [Ref.5] suggested a number of formulae as well as graphical methods for the evaluation and presentation of solar radiation and outdoor illuminance data. For building energy analysis, many researchers use the luminous efficacy to correlate solar irradiance and daylight illuminance [Refs.6-8]. In the calculation of daylight availability and lighting energy use in buildings, the luminous efficacy enables daylight data to be generated from the more widely measured solar radiation data for places where measured outdoor illuminance data are not available.

In this study, six-year (1991-1996) of measured hourly data were sorted into three categories according to the clearness index K_t: clear, partly cloudy and overcast sky conditions as follows:

(a) clear sky ($K_t > 0.7$)

(b) partly cloudy sky ($0.15 < K_t$ 0.7)

(c) overcast sky ($0 < K_t$ 0.15)

where K_t = global solar radiation / extraterrestrial solar radiation.

Clear sky

Hourly direct illuminance and solar radiation data at $K_t>0.7$ were used to determine the direct luminous efficacy K_{bc}, which is defined as the ratio of illuminance to solar irradiance. Figure 1 shows the variation of K_{bc} with respect to solar altitude α. Regression analysis has been carried out and K_{bc} can be expressed in terms of a as follows:

$$K_{bc} = 53.5 + 1.7a - 0.012a2 \text{ (lm/W)} \quad (1)$$

(R=0.76, R2=0.58, RMSE=6.4 lm/W and RMSE=6 percent),

where R, R2 and RMSE are the correlation coefficient, coefficient of determination and root-mean-square error, respectively. An R2 of 0.58 indicates that 58 percent of the variation in direct luminous efficacy can be explained by changes in solar altitude. Figure 1 also indicates that K_{bc} increases with a. Similar findings have been reported by Littlefair [Refs.7 and 8] for the U.K. and other locations.

Diffuse efficacy was calculated as the ratio of diffuse illuminance to its corresponding diffuse radiation. The diffuse efficacy under clear sky K_{dc} has an average value of 134.2 lm/W with a standard derivation of 20.3. Figure 2 plots K_{dc} against a. It can be seen that data are very scattered and no clear pattern or relationship can be observed. Generally, K_{dc} is much higher than K_{bc} particularly at low solar altitude. Figure 3 shows the plot of global efficacy K_{gc} against a. Through regression analysis, K_{gc} can be expressed as:

$$K_{gc} = 60.6 + 1.7a - 0.013a2 \text{ (lm/W)} \quad (2)$$

(R=0.70, R2=0.49, RMSE=6.8 lm/W and percentRMSE = 6percent)

The correlation between global efficacy and a is not so strong as that between direct efficacy and a as R2 is only

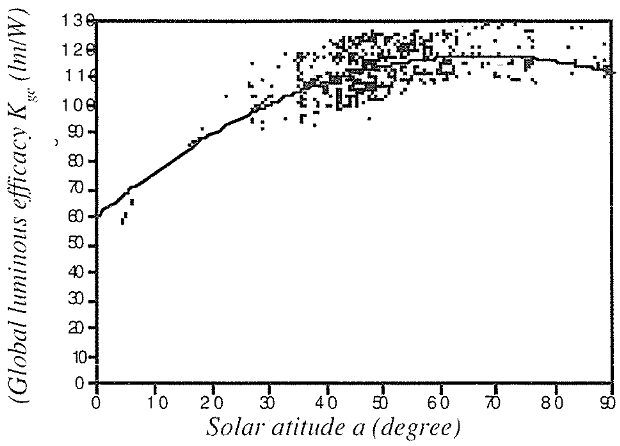

Figure 3. Global luminous efficacy for clear sky against solar altitude

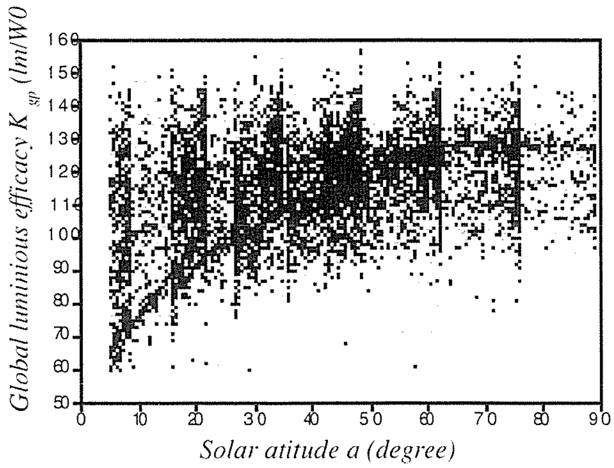

Figure 4. Global luminous efficacy for partly cloudy

0.49. This is due to the influence of diffuse component on the global efficacy. Global radiation has direct and diffuse components, and K_{gc} can be regarded as a combination of direct luminous efficacy K_{bc} and diffuse luminous efficacy K_{dc}, and can be written as:

$$K_{gc} = \frac{E_{gc}}{I_{gc}} = \frac{E_{bc}+E_{dc}}{I_{gc}} = \frac{K_{bc}I_{bc}+K_{dc}I_{dc}}{I_{gc}}$$

$$= Kbc(1-K)+KdcK \qquad (3)$$

Where E_{gc}, E_{dc} and E_{bc} are the global, diffuse and direct illuminance; I_{gc}, I_{dc} and I_{bc} the corresponding solar irradiance; and K_{gc}, K_{dc} and K_{bc} their respective luminous efficacies. The diffuse fraction K is the ratio of diffuse to global radiation. For clear sky, K_{bc} dominates as K is very small. Thus, K_{gc} increases with a, but more gradually than K_{bc}.

Overcast sky

Overcast sky means no direct solar component is measured. Global efficacy K_{go} is very close to diffuse efficacy K_{do} under overcast sky conditions, ranging from 70 to 150 lm/W. Similar to diffuse efficacy under clear sky, K_{do} does not correlate well with a. Average luminous efficacy under overcast sky is 113.2 lm/W with a standard derivation of 17.5, which is close to the 115 lm/W reported for the U.K. [Ref.8]. Luminous efficacy under an overcast sky is generally less than K_{dc}. This may be due to the interreflections between the clouds near the horizon and the buildings surrounding the measuring station.

Partly cloudy sky

Global luminous efficacy K_{gp} plotted against solar altitude is shown in Fig.4. The scatter of data points, especially at low solar altitude, can be observed. This is due to different cloud conditions for a given value of clearness index K_t. Partly cloudy sky can be treated as a combination of clear and overcast skies: the direct component in the clear sky and the diffuse component scattered in both the clear and cloudy parts of the sky. Thus, the direct luminous efficacy can simply be determined from Eq.(1), and the diffuse luminous efficacy under partly cloudy sky conditions can be considered as a linear combination of the diffuse efficacy under clear and overcast sky conditions with cloud cover C as an indicator of the actual sky condition. Hence:

$$K_{dp} = (1-C)K_{dc} + CK_{do} \qquad (4)$$

For subtropical Hong Kong, averaged measured K_{dc} and K_{do} have been found to be 134.2 and 113.2 lm/W, respectively. Substituting these values into Eq.(4) gives:

$$K_{dp} = 134.2 - 21C \text{ (lm/W)} \qquad (5)$$

As shown in Eq.(3), the global luminous efficacy can be obtained from the direct and diffuse efficacies with the diffuse fraction K as an indicator of the relative importance of the direct and diffuse components under a particular sky condition. Therefore, from Eqs. (1), (3) and (5), the global luminous efficacy is given by:

$$K_{gp} = K(134.2-21C)+(1-K)(53.5+1.7.a-0.012a2) \text{ (lm/W)} \qquad (6)$$

Equations (1), (5) and (6) were used to predict, respectively, the direct, diffuse and global efficacies under partly cloudy sky conditions. The predicted efficacies were compared with the measured data for 1996. The RMSE values are 20.3, 19.6 and 12.4 lm/W for direct, diffuse and global efficacies, respectively; representing 24.2, 14.8 and 10.8 percent of the mean measured values.

Average sky conditions

Average efficacy under all sky conditions for different times of the day and different seasons will be useful to

Month	6	7	8	9	10	11	12	13	14	15	16	17	18
Jan	-	86	98	105	109	111	111	111	109	106	100	84	-
Feb	-	87	102	109	114	115	115	115	113	110	104	88	-
Mar	-	98	109	114	118	120	120	120	118	115	109	99	-
Apr	82	109	116	120	121	121	120	121	121	121	117	108	88
May	91	116	122	125	125	120	118	120	123	124	122	115	102
Jun	90	110	115	118	117	117	116	117	118	119	117	112	101
Jul	88	115	121	122	120	119	118	119	122	122	121	117	103
Aug	83	113	120	124	122	120	119	120	122	124	120	113	93
Sep	79	102	110	114	117	118	118	119	121	120	116	112	94
Oct	-	98	107	111	114	117	117	117	115	112	107	98	-
Nov	-	94	105	108	111	114	114	113	111	109	106	100	-
Dec	-	92	100	105	109	111	113	112	109	107	101	95	-

Table 1. Average Global Luminous Efficacy (lm/W).True Solar Time

Month	6	7	8	9	10	11	12	13	14	15	16	17	18
Jan	-	92	109	117	120	121	121	121	120	117	112	90	-
Feb	-	92	109	118	123	122	122	124	124	120	112	94	-
Mar	-	102	115	121	124	126	127	126	124	122	117	105	-
Apr	84	112	120	125	126	127	126	127	127	127	123	114	91
May	93	122	127	132	131	130	128	130	130	131	129	121	105
Jun	94	117	121	124	124	124	123	126	125	126	124	120	105
Jul	91	122	129	131	132	131	131	131	134	134	131	124	107
Aug	86	119	127	131	132	129	128	130	132	132	129	120	97
Sep	83	111	121	126	129	129	127	128	130	129	126	118	97
Oct	-	107	118	123	126	128	129	127	124	123	118	105	-
Nov	-	108	117	123	125	125	127	129	126	122	118	111	-
Dec	-	103	115	122	125	126	127	128	128	125	114	102	-

Table 2. Average Diffuse Luminous Efficacy (lm/W). True Solar Time

architects and building engineers. This will give designers an indication of the prevailing relationship between daylight illuminance and solar irradiance. Tables 1 and 2 show the average values of global and diffuse luminous efficacies on a horizontal plane, respectively. Each value is the ratio of the measured average illuminance for that hour to the corresponding average radiation. Knowing the average radiation data, the corresponding average illuminance level can be readily determined by using these luminous efficacies.

The yearly average global luminous efficacy is 110.7 lm/W with a standard deviation of 10.4 and the yearly average diffuse luminous efficacy is 119.6 lm/W with a standard deviation of 11.5. Diffuse luminous efficacy is generally higher than global luminous efficacy, indicating that the diffuse component in daylighting design is more energy-efficient. Data at low altitude (i.e. near sunrise and sunset) are the major contributors to the standard deviation. Global luminous efficacies from May to September are higher than those of the same hour in other months, mainly due to high direct luminous efficacy at high solar altitude in the summer.

Lighting design and energy implications

The main applications of luminous efficacy data is to enable illuminance data to be generated from measured solar irradiance. For daylighting design and calculations, a cumulative frequency distribution of outdoor illuminance can indicate the percentage of the working year in which a given illuminance is exceeded. The cumulative frequency distribution has been calculated for the measured outdoor global illuminance and is shown in Fig. 5. The data are based on typical office hours from 08:00 to 18:00 in Hong Kong. Assuming a 500 lux indoor design illuminance for office space and a daylight factor of 2 percent, the required outdoor illuminance should be 25,000

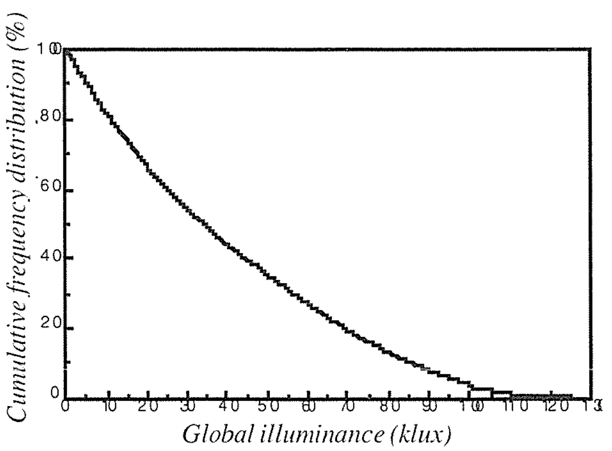

Figure 5. Cumulative frequency distribution for measured outdoor global illuminance

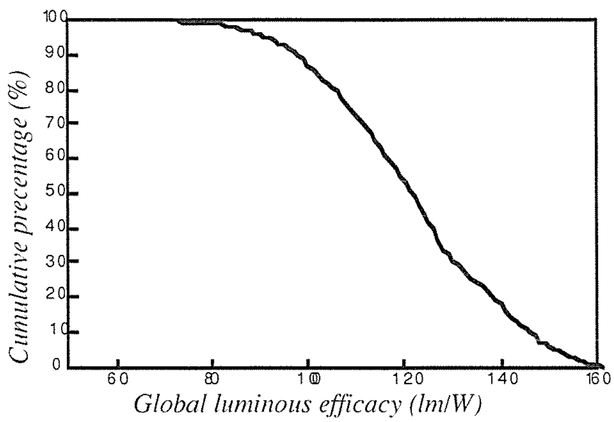

Figure 6. Cumulative frequency distribution for global luminous efficacy

lux. From Fig.5, it can be seen that about 60 percent of the time in a year, the outdoor illuminance would be above 25,000 lux. In other words, about 60 percent of the time daylighting alone would be adequate to achieve the 500 lux indoor design lighting level for offices with a 2 percent daylight factor design. This has significant implications for energy efficiency in office buildings in Hong Kong, where electric lighting accounts for 20-30 percent of the total electricity use and is a major component in total cooling load [Ref.9].

Figure 6 shows the cumulative frequency distribution of the global luminous efficacy. The cumulative percentage drops rapidly from about 100 to 140 lm/W, indicating that for most times of the year, the global luminous efficacy lies between these two values. In terms of energy efficiency, this is much better than the 16-40 lm/W for incandescent and 50-80 lm/W for fluorescent lamps commonly installed at homes and in office buildings [Ref.10], because less heat is introduced to achieve the same lighting level and less cooling will be required. This is particularly beneficial to places with subtropical climates like Hong Kong, where air-conditioning during hot summer months accounts for 40-60 percent of the total electricity consumption in buildings[Ref.9].

Conclusions

Six-year measured outdoor illuminance and solar irradiance data have been gathered and analysed. It has been found that direct luminous efficacy increases with solar altitude α. The diffuse efficacy under clear sky has an average value of 134.2 lm/W, and has no clear correlation with α. The global luminous efficacy under clear sky conditions increases with α, though more gradually than the direct luminous efficacy. The overcast sky luminous efficacy K_{dc} has an average value of 113.2 lm/W. For partly cloudy conditions, it is believed that global luminous efficacy K_{gp} can be estimated from its corresponding diffuse fraction, cloud cover and α. Yearly average global and diffuse luminous efficacies under average sky conditions are 110.7 and 119.6 lm/W, respectively. In subtropical Hong Kong, about 60 percent of the time daylighting alone will be adequate for office space with a 2 percent daylight factor design. About 80 percent of the year, the global luminous efficacy lies between 100 and 140 lm/W, which is much higher than the luminous efficacy of most electric lighting schemes. This has great implications for energy efficiency in building designs.

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