Horizontal and Vertical Illuminance Correlations in a Case Study for Shaded South Facing Surfaces

S. Matour, M. Mahdavinejad, R. Fayaz

***Abstract*—**Daylight utilization is a key factor in achieving visual and thermal comfort, and energy savings in integrated building design. However, lack of measured data related to this topic has become a major challenge with the increasing need for integrating lighting concepts and simulations in the early stages of design procedures. The current paper deals with the values of daylight illuminance on horizontal and south facing vertical surfaces; the data are estimated using IESNA model and measured values of the horizontal and vertical illuminance, and a regression model with an acceptable linear correlation is obtained. The resultant illuminance frequency curves are useful for estimating daylight availability on south facing surfaces in Tehran. In addition, the relationship between indirect vertical illuminance and the corresponding global horizontal illuminance is analyzed. A simple parametric equation is proposed in order to predict the vertical illumination on a shaded south facing surface. The equation correlates the ratio between the vertical and horizontal illuminance to the solar altitude and is used with another relationship for prediction of the vertical illuminance. Both equations show good agreement, which allows for calculation of indirect vertical illuminance on a south facing surface at any time throughout the year.

***Keywords*—**Tehran daylight availability, horizontal illuminance, vertical illuminance, diffuse illuminance.

I. Introduction

In conventional building design, attention is often focused on thermal performance, ignoring illuminance and luminance distribution in daylit interiors, which not only affects the human comfort criteria in buildings (visual comfort, psychological comfort, fulfilling the physiological needs of residents), but also increases energy consumption. Daylight integrated design of buildings requires detailed information about the local environment [1]; particularly knowledge of the diffuse light entering the windows is very important, since the building rooms are mostly lit by diffuse light [2]-[4], and as well, diffuse daylight has a higher luminous efficacy than most artificial lighting [5]. Since the accurate assessment of building facade illumination is a key factor in active utilization of renewable solar energy [6], the starting datum for this calculation is obviously natural incident illuminance on the outside surfaces of windows, so that, the current research deals with this topic. An influential step towards the development and promotion of daylighting technology is a study on daylight availability and sky luminance [7].

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Daylight availability data are essential for effective design of daylit buildings. These data not only provide the basis for specifying illuminance on a given surface in specified time rates (hourly, daily and monthly) and location, but also describe the maximum and minimum illuminance scenarios on vertical and horizontal surfaces under various sky conditions [8]. In addition, the information of diffuse skies and the direct sunlight from the vertical plane are essential in creating a comfortable working environment and a healthy indoor environment [9]. Such information can be obtained either by measurements or calculations from other meteorological quantities. One of the crucial problems in predicting the role of daylight in energy efficient buildings is the need for reliable local data on daylight availability [10]. Due to the lack of adequate measurements available for sky luminance and illuminance in Tehran, external illuminations are estimated by the equations proposed by “Illuminating Engineering Society of North America” (IESNA). Then, the primary data and beam normal illuminance as well as solar altitude and azimuth are calculated using these equations [11].

Daylight illuminance and daylight availability have been measured and studied in different countries since the 1920s [8]. In a previous study in Eshtehard, Hamadan and Kerman stations in Iran, the horizontal and vertical global illuminance were measured within only 15 days, and an equation was developed between the measured and calculated data, which has been proposed for all cities of Iran (r2 = 0.796) [12].

In this paper, the mean hourly and monthly illuminance data on south facing vertical and horizontal surfaces are obtained using a linear model in order to estimate the daylight variations for a whole business year in Tehran. Also, frequency curves of vertical illuminance on the same surface are drawn in addition to the horizontal surface versions.

II. Methodology

Daylight measurements were carried out at a station located on the roof of the Faculty of Architecture at Tarbiat Modares University in Tehran, Iran. Illuminance values on south facing vertical and horizontal surfaces have been obtained using two illuminance measuring equipment of TES, 1339R model. A measurement setup consisting of a vertical stand to assemble the vertical sensor on the south orientation and a horizontal surface on the roof is considered.

Global vertical and horizontal illuminance values are measured over 20 days in the period from June 21 to July 10, 2011 from 8 a.m. to 4 p.m. at one minute intervals. The collected data are entered in to the statistical sheet of SPSS software and regression models are applied to develop a relationship between the calculated and measured illuminance data. The measured data are presented as follows; first, the results obtained from the equations for average horizontal and vertical illuminance on south facing surfaces for each month in the full business year, and then the probability to exceed a given illuminance level during hot and cold months for global and indirect illuminance on vertical south facing surfaces from 9:00 a.m. to 3:00 p.m. (typical business hours in Tehran) are indicated. Finally, the relationship between the global horizontal illuminance, solar altitude angel and diffuse vertical illuminance is obtained. The properties of clear sky in IESNA equations are used for illuminance calculations for a 64% clear sky scenario through the year in Tehran. Based on this data set, the behavior of the exterior horizontal and vertical illumination levels (south facing vertical surface) are analyzed.

III. Results and Discussions

A. Vertical Global Illuminance

Comparison of the mean measured and the mean calculated hourly illuminance levels on the south facing surfaces is shown in Table I. The maximum mean value of the measured illuminance is 43.86 klx at 12 p.m., while the value is 48.11 klx for calculated illuminance at the same hour. The minimum values for the measured and calculated illuminance at 4 p.m. are 18.95 klx and 19.46 klx, respectively.

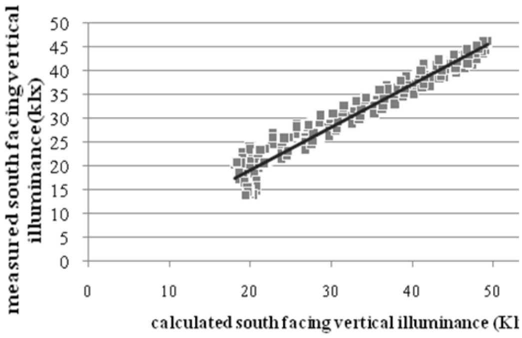

Fig. 1 Relation between the measured and calculated values of south facing vertical illuminance (r2=0.9535)

Patterns of comparative curves of mean measured and mean calculated hourly illuminance on the south facing surfaces illustrate that IESNA equations do not exactly estimate the vertical illuminance as the measured values at the mentioned time interval. For this reason, a linear relationship is defined between the measured and calculated values. Considering the obtained regression coefficient of r2 = 0.9535 for this linear equation (Fig. 1), it can be used as a complimentary equation to the IESNA equations for the purpose of determining vertical illuminance on south facing surfaces in Tehran.

$$Evsm = 0.9022\, Evsc + 0.9845 \quad (1)$$

where *Evsm* and *Evsc* are the measured and calculated vertical south facing illuminance in Kilolux, respectively. Fig. 2 illustrates the comparative curves of the measured and calculated mean hourly values on the south facing surfaces

TABLE I
Mean Hourly Values of Measured and Calculated Vertical Illuminance Levels on South Facing Surface

	Mean measured illuminance	Mean calculated illuminance
9	23.07	24.21
10	32.42	35.71
11	40.22	44.50
12	43.86	48.11
13	42.48	45.54
14	36.58	37.50
15	27.88	26.25
16	18.95	19.46

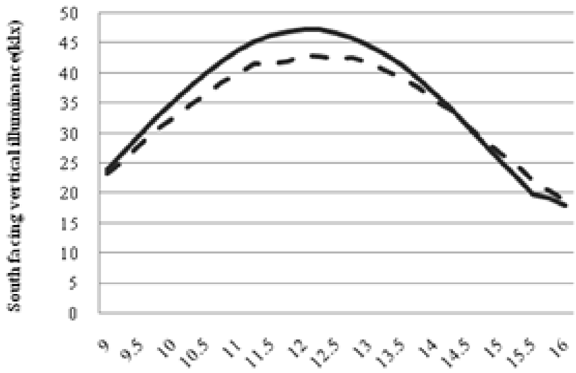

Fig. 2 Comparison of the measured and calculated mean values on the south facing vertical. _ _ _ Measured Vertical Illuminance, ___ Calculated Vertical Illuminance

B. Horizontal Global Illuminance

According to the method used for estimation of the vertical illuminance on south facing surfaces, a similar process is applied for estimation of the annual horizontal illuminance. The data for these two parameters are collected in the same days and hours. Comparison of the measured and calculated mean hourly illuminance on the horizontal surface is shown in Table II. The maximum values for the mentioned parameter in the measured and calculated data at 12 p.m. are 112.31 and 114.32, respectively.

TABLE II
Comparison of the Mean Hourly Values of the Measured and Calculated Horizontal Global Illuminance

	Mean hourly horizontal global illuminance at standard time (klx)	
	Mean measured illuminance	Mean calculated illuminance
9	80.68	85.54
10	96.60	100.31
11	108.10	110.47
12	112.31	114.32
13	108.51	111.60
14	96.94	102.48
15	81.51	87.61
16	61.68	68.05

The minimum values for the measured and calculated illuminance at 4 p.m. are 61.68 klx and 68.05 klx, respectively. In order to enhance the accuracy of the IESNA equations (Fig. 3), a linear equation has been proposed between the measured and calculated values (Fig. 4).

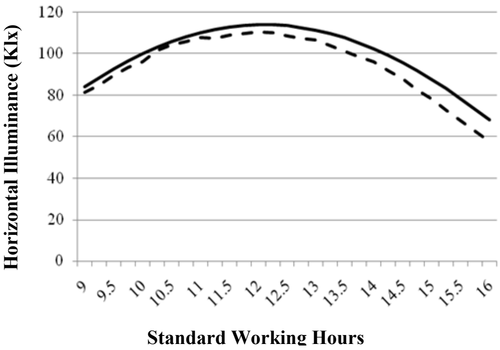

Fig. 3 Relation between the measured and calculated values of horizontal illuminance (r2=0.981). _ _ _ Measured Vertical Illuminance, ___ Calculated Vertical Illuminance

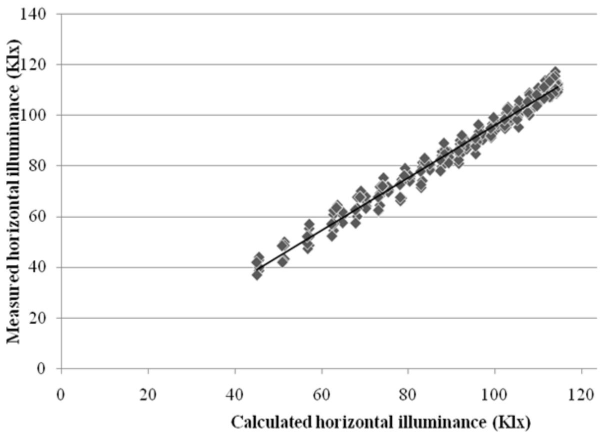

Fig. 4 Comparison of the measured and calculated mean values on horizontal illuminance

Due to the high regression coefficient of r2 82 = 0.9535 obtained for this linear equation, it is shown that the equation is valid for the whole year.

$$Ehm = 1.037Ehc - 7.648 \quad (2)$$

where *Ehm* and *Ehc* are the measured and calculated horizontal global illuminance in Kilolux, respectively. Based on the above equation, the horizontal global illuminance can be obtained for all business days and hours in a complete year.

C. Daily Variation of the Illuminance Levels

Temporal distribution of the horizontal and vertical global illuminance on the south facing surface during a day is shown in Fig. 5 for two representative cases of 23rd June and 23rd December, which investigated clear sky conditions on both days. Representing the summer (June) and winter (December) solstices, the dates were selected in order to present a daily variation of illuminance; the maximum values were obtained at noon and range from 111.14 klx for 23rd June to 52.17 klx for 23rd December.

In winter time, the south facing vertical surfaces receive significantly more illumination than the horizontal surfaces with a maximum daily value ranging from 44.13 klx on 27th of June to 90.16 klx on 27th of December at noon; that is, the ratio between the vertical and horizontal illuminance is about 0.4 in summer and 1.7 in winter at around midday.

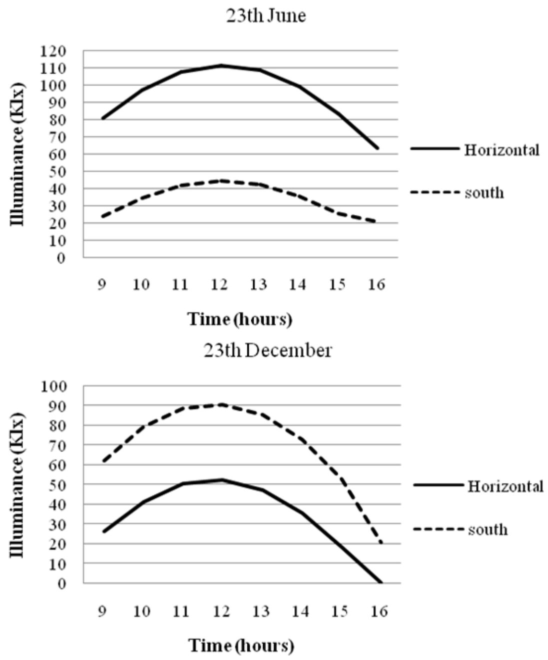

Fig. 5 Global horizontal and south facing vertical illuminance values for two clear days in summer (23rd June) and winter (23rd December) in Tehran, Iran

D. Annual Variation of the Illuminance Levels

In Tables III and IV, the illuminance values for the south facing vertical and horizontal surfaces are shown separately. The mean hourly and monthly illuminances are illustrated in order to show the illuminance variation clearly. Tables III and IV also show the fluctuation of illuminance values on specific times of the year. According to Table III, the monthly maximum mean vertical illuminance occurs in January with 70.23 klx while the minimum corresponds to June, with 33.85 klx. The maximum illuminance occurs in January at 12 PM with 90.38 klx, and the monthly minimum mean vertical illuminance in July with 18.2 klx at 4 PM.

According to Table IV, the monthly maximum mean horizontal illuminance occurs in June with 93.63 klx and the minimum in December with to 35.23 klx. The maximum illuminance occurs in June at 12 p.m. at 111.28 klx and the monthly minimum mean vertical illuminance in December with 5.20 klx at 4 p.m.

TABLE III
MEAN HOURLY AND MONTHLY ILLUMINANCE ON THE HORIZONTAL SURFACE FOR A COMPLETE BUSINESS YEAR

	Mean hourly horizontal illuminance (klx)								
Month/ Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**MMI[1] (klx)**
Jan	31.6	46.8	55.7	57.6	52.2	40	22.4	5.8	39
Feb	44.9	60.8	70.2	72.1	66.4	53.7	34.9	12.6	52
Mar	60.6	77.2	87.0	89.2	83.8	71.1	52.1	28.5	68.7
Apr	73.2	89.9	99.9	102.7	98	86.2	68	45	82.9
May	79.7	96.0	106.2	109.5	105.7	95.1	78.4	56.8	90.9
Jun	80.9	97.1	107.5	111.2	108.2	98.5	82.9	62.4	93.6
Jul	78.5	95.1	105.9	110.1	107.4	97.9	82.4	61.9	92.4
Aug	72.0	89.5	100.8	105.3	102.4	92.5	76.3	54.9	86.7
Sep	60.7	78.6	90.1	94.4	91.1	80.5	63.4	41	75
Oct	45.9	63.3	74.3	78.0	74.1	62.9	45.4	23.2	58.4
Nov	32.7	48.8	58.8	61.6	57.2	45.8	28.5	8.1	42.7
Dec	26.6	41.7	50.8	53.0	48.1	36.5	19.6	5.2	35.2

TABLE IV
MEAN HOURLY AND MONTHLY ILLUMINANCE ON THE SOUTH FACING VERTICAL SURFACE FOR A COMPLETE BUSINESS YEAR

	Mean hourly vertical illuminance (klx)								
Month/ Hour	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**MMI (klx)**
Jan	65.1	79.8	88.6	90.3	85.1	73	53.5	26	70.2
Feb	64.2	78.3	86.4	88	83.2	72	54.9	29	69.5
Mar	57.1	70	77.6	79.4	75.2	65.2	50.4	30.1	63.1
Apr	44.1	56	63.1	65.4	62	53.4	40.5	24.8	51.2
May	31.2	42.3	49.4	51.7	49.1	41.7	30.3	21.3	39.2
Jun	24.3	35.1	42.1	44.8	42.6	36	25.5	20.1	33.8
Jul	25.9	37.1	44.5	47.4	45.5	39	28.5	18.2	35.8
Aug	35.4	47.5	55.6	58.8	56.7	49.7	38.3	24	45.7
Sep	48.1	61.4	70.1	73.4	70.9	62.9	50.1	33.7	58.8
Oct	58	72.7	81.8	84.9	81.6	68.1	57.5	37.6	67.8
Nov	61	75.1	87	89.7	85.6	69	52.1	31.4	68.8
Dec	61.9	78.7	88	90	85.2	73.1	53.1	24	69.3

[1] Mean Monthly Illuminance

E. Estimation of Daylight Availability on Sunlit and Shaded South Facing Surfaces

To simplify the analysis, the vertical illuminance data are separated into two groups representing sunlit and shaded surfaces, as proposed by Li et al. [13] and Chirarattananon et al. [2]. The sunlit surfaces receive both direct beam illuminance from the sun and diffuse illuminance from the sky, occurring on the south facing surface. In the present article, daylight availability on the south facing surface is analyzed in the shaded case. Considering the climatography of Tehran, knowledge of solar energy and direct solar radiation is necessary for five months of the year (November to March) to decrease energy consumption in the buildings. However, in the other months, it is recommended to prevent the interior spaces from penetration of direct solar radiation [14]. Consequently, utilization of shading devices on the southern fenestration is required. At this stage, only indirect illuminance is observed on the southward vertical surface, which includes both the diffuse illuminance of the sky and the reflected illuminance from the ground. Direct solar illuminance is recommended to be avoided during seven months of the year. The indirect illuminance from the south direction is given by:

$$E_{v\,indirect} = (\rho .\ E_{hm}) + (0.9022\ E_{kv}) \quad (3)$$

where Ehm is the global horizontal illuminance in klx, ρ is the coefficient of ground reflection (0.17 in this case), Ekv is the diffuse vertical illuminance in klx and 0.9022 is the correction factor for the IESNA equation in Tehran based on (2).

Illuminance frequency curves on southward surfaces show that the total vertical illumination for 60% of business days throughout the year, exceed 40 klx and 65 klx for hot and cold months, respectively, while if indirect illumination is used for interior lighting, 60% of business days exceed 20.5 klx and 18.5 klx for hot and cold months, respectively. In these curves, total illuminance level is compared to the indirect illuminance level on the southward vertical surface for the whole year and can be used for estimation of the reduction in energy consumption by utilization of daylight in Tehran.

Generally, indirect illuminance on southward surfaces in warm months (April to October) is more than that in cold months (November to March), while the total illuminance level in cold months is more than that in warm months. With these illuminance levels on the southward surface in cold months, a glare problem may occur for residents and the use of advanced daylight systems are necessary for reducing the level of glare. Investigating a simple parametric model for prediction of daylight variables on shaded south facing surfaces, the relationship between the vertical and global horizontal illuminance is analyzed in the present research.

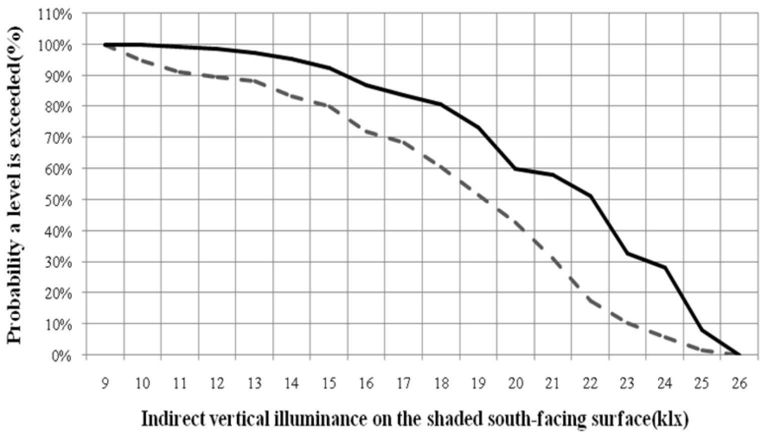

Fig. 6 Frequency curves for total vertical illuminance on south facing surfaces in Tehran. _ _ Cold months (November to March), ___ Hot months (April to October)

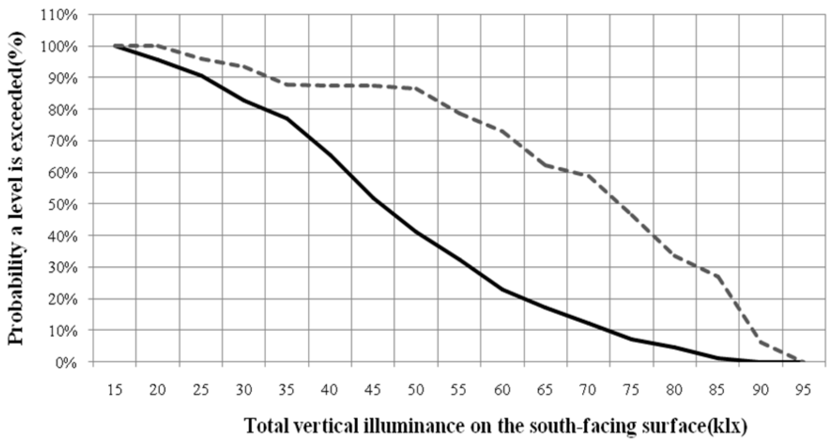

Fig. 7 Frequency curves for indirect vertical illuminance on south facing surfaces in Tehran. _ _ Cold months (November to March), ___ Hot months (April to October)

Following the model of Perez-Burgos et al. [15], as a function of the solar altitude as the only input parameter, a similar parameterization is involved in the present study. Specifically, the dependence of the Ev/Eh ratio versus sin (a) is analyzed; where, Ev is the indirect vertical illumination, Eh is the corresponding horizontal illumination and a is the solar altitude in Radians. In another model the relationship between the global horizontal illuminance and solar altitude has been analyzed with the following criteria applied to select the data in order to provide the information required for designing daylight systems in buildings.

The experiment is performed in normal business hours of most buildings such as offices and schools, that is, in the range between 9:00 a.m. to 3:00 p.m., through which spaces are also significantly illuminated in winter and summer. From this selection, a regression process over a total of 2550 data is carried out. Data points and the fitted line are shown in Figs. 8 and 9. The equations obtained from the regression calculation are as follows:

$$Eh = 130.1 \sin(a) - 15.09 \quad (R2 = 0.998) \tag{4}$$

$$Evi/Eh = 0.211 \sin(a) - 0.78 \quad (R2 = 0.947) \tag{5}$$

Equations (4) and (5) are applicable to the whole year under clear sky conditions. They allow for calculation of the vertical illuminance on shaded southward surfaces, Evi, in daylight conditions corresponding to specific global horizontal illuminance and solar altitude. Due to the high correlation factor obtained for (4) and (5), it can be concluded that the equations are reliable in prediction of vertical clear sky illuminance for shaded southward surfaces.

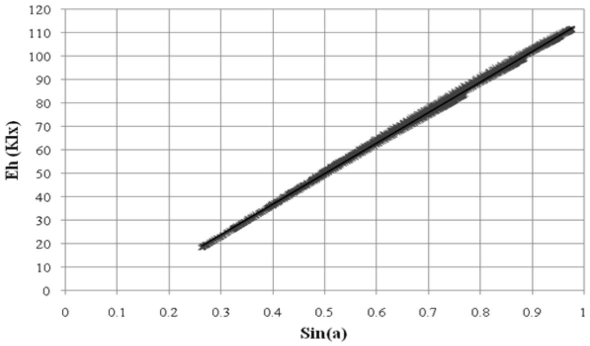

Fig. 8 Regression analysis: the horizontal illuminance versus sin of the solar altitude in Tehran, Iran

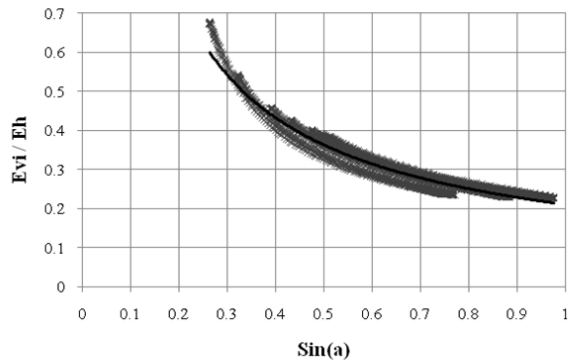

Fig. 9 Regression analysis: Ratio of the vertical to the horizontal illuminance versus sin of the solar altitude in Tehran, Iran

IV. Conclusion

Illuminance measurements are carried out in one station in Tehran, Iran. Illuminance values on southward vertical and horizontal surfaces are obtained through 20 days at one minute intervals between 21st June and 10th July, 2011 from 8 a.m. to 4 p.m. Using this data, the IESNA model is calibrated for Tehran with clear sky condition, and then illumination for the whole year is calculated. These data have been reported for the complete business year with several graphs and tables for horizontal and vertical global illuminance on southward surfaces.

For estimation of energy consumption reduction by utilization of daylight illuminance in buildings located in Tehran, illumination frequency curves are drawn for indirect and total vertical illumination in hot and cold months. As daylight availability is strongly affected by the local prevailing climate, the reported values of illuminance can be useful for daylight design of the buildings in Tehran and areas with similar climatic conditions.

When no indirect vertical illuminance measurements are available, the proposed methodology allows for calculation of this factor as a function of the corresponding horizontal illuminance and solar altitude. The methodology includes a simple parametric expression that simultaneously considers the southward facing of the vertical surface whenever it is shaded. Values of the horizontal illuminance are also required, which in the absence of measurements can be calculated from the equation of the solar altitude. In order to receive high quality daylight in the interior of buildings, utilization of indirect or diffuse daylight instead of direct sunlight is recommended in most cases.

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