Relation between direct and diffuse daylight illuminance

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Abstract

Building interiors are variously illuminated during the whole year by skylight and sunlight. Levels of indoor illuminance are changing in dependence on the sky luminance conditions and solar altitudes. To model global illuminance in terms of utilization and verification of interior daylighting the relation between sunlight and skylight is needed to be known. Under an artificial sky the proportion of both these components should be calibrated to measure correctly daylighting effects in scale models.

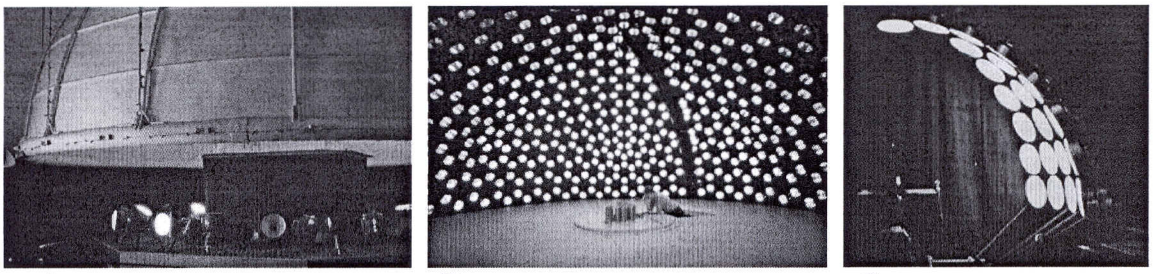
This paper discusses the relation between global, diffuse/skylight and direct/sunlight illuminances under ISO/CIE sky standards by model means using an artificial sky.

Keywords. Daylighting, skylight, Daylighting, skylight, artificial sky, sunlight, artificial sun

Introduction

Daylighting in building interiors can be evaluated either by calculations or by measurements in situ or in scale models under artificial sky. Several artificial skies and scanning sky simulators were built and are operated worldwide simulating conditions of exterior illuminace under the standard sky luminance distribution on the hemisphere or its lunes. The advantage of model measurements in laboratory conditions is in the simulation of same, stable and comparable daylight conditions to test and evaluate daylight distribution indoors at any time. Artificial skies offer to choose stable and defined lighting conditions for research purposes and technical solutions in the illuminating engineering and architectural design.

Artificial skies and simulators are either the hemispherical dome type with an illuminated/reflective or translucent inner surface or as partial sky lune simulators with or without an artificial sun. For example two artificial skies and one sky lune simulator in operation are shown in Fig. 1. The first hemispherical sky with a white diffuse inner surface and with luminaires located under the measuring table is at the Institute of Construction and Architecture, Slovak Academy of Sciences (ICA SAS) in Bratislava, Fig. 1.A, [1] and [2]. Artificial sky at ICA SAS in Bratislava models the CIE overcast sky luminance distribution (with luminance gradation from horizon to zenith 1 : 3) and the CIE clear sky after the recommendations published in [3] and [4] as well as the unity, so called Lambert sky with the same luminance in all sky elements. The second sky on Fig. 1.B, [5] has also a hemispherical shape but its luminaires are installed in its inner surface. Due to changing intensity of light sources the sky luminance distribution is controlled to achieve desired sky patterns. Probably, the simulation of all ISO/CIE general sky is possible to simulate in this device although the smooth luminance distribution is missing. The construction of hemispherical domes requires laboratories with large spaces and investments. To save expenses the sky simulators of partial sky lunes were developed and such example is shown in Fig. 1.C which was built in EPLF in Lausanne in Switzerland [6]. Due to controlled and dimmable luminaires installed in the 1/6 of the hemispherical lune this simulator mocks up standard luminance in the 24 circular elements. If the model is rotated in 60° steps the sky luminances can be adjusted in appropriate sectors and the final exterior and indoor illuminace can be obtained by the summation of partial measured values.



A. B. C.

Figure 1. Daylight simulators.
A. Artificial sky with highly diffuse inner plaster, Institute of Construction and Architecture, SAS in Bratislava, B. Artificial sky at the Welsh School of Architecture in Cardiff, UK, C. Sky lune simulator at the EPFL in Lausanne, Switzerland.

Methodology

Building interiors are illuminated by various levels of skylight when the sun disc is shaded by clouds or when coupled effects of skylight and sunlight during sunny situations appear. Values of diffuse illuminance during overcast and cloudy sunless situations are occurring commonly with different solar altitudes resulting due to low light transmission through clouds and can be determined by the diffuse clearness index k_{vdd}. During sunny situations the penetrating sun rays are scattered and attenuated in the atmosphere and this process can be described generally by the luminous turbidity factor T_v. Studies [7] - [9] show that skylight/diffuse illuminance and sunlight/direct illuminance occurring in the nature can be modelled by both parameters k_{vdd} and T_v and their representative values can be found by measurements.

The reproduction of real illuminance levels in a laboratory is not ease to simulate because real sunlight has high intensities which cannot be achieved by artificial light sources. The standard sky luminance distribution can be modelled by setting intensities of artificial light sources but illuminance levels are sometimes evaluated not in physical units but respecting standard requirements for minimum daylighting expressed by relative daylight factors. However, future development of daylighting and illuminating engineering is oriented to methods working with photometric variables in physical units avoiding relative values.

Diffuse illuminance E_{vd} for ISO/CIE sky standards 1 – 6 which generally represent sunless situations and can be calculated after [10] and [11] as follows:

$$E_{vd} = k_{vdd}\, \varepsilon\, E_{voh} \sin \gamma_s, \qquad \text{[lx]} \qquad (1)$$

where $k_{vdd} = E_{vd} / E_{voh}$, diffuse clearness index,
ε – eccentricity correction factor,
γ_s – solar altitude,
E_{vo} – luminous solar constant equal to 133,8 in klx, [12] and [13],
$E_{voh} = \varepsilon E_{vo} \sin \gamma_s$, extraterrestrial illuminance on the horizontal plane.

The eccentricity correction factor ε can be calculated with satisfactory accuracy after equation (2) published by [14]:

$$\varepsilon = 1+0{,}034 \cos (2\, \pi\, (J - 2)/365), \qquad (2)$$

where J – the number of a day within a year.

After [10] and [11] the ratio of zenith luminance L_{vz} to diffuse illuminance E_{vd} is taken as a classification parameter of ISO/CIE general skies while the value of L_{vz} can be calculated after equation (3) and the diffuse illuminance after (4). Standard sunny situations are defined by sky types 7 – 12 in the [15].

$$L_{vz} = (A1\,T_v + A2)\sin\gamma_S + 0{,}7(T_v + 1)\frac{(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + 0{,}04\,T_v, \quad [\text{kcd/m}^2] \qquad (3)$$

$$E_{vd} = \frac{L_{vz}\,E_{voh}}{B\frac{(\sin\gamma_S)^C}{(\cos\gamma_S)^D} + E\sin\gamma_S}. \quad [\text{klx}] \qquad (4)$$

During sunny situations the total illuminance consists of the coupled influence of skylight and sunlight. Levels of sunlight/direct illuminance are influenced by scattering and attenuation of sun rays penetrating atmosphere from universe to earth's ground is expressed by luminous turbidity factor T_v. In regard to these effects the value of direct illuminance E_{vs} can be calculated in relation to the extinction coefficient a_v and the relative optical air mass of the atmosphere m as follows:

$$E_{vs} = E_{voh}\ \varepsilon\ exp(-\,a_v\ m\ T_v), \quad [\text{klx}] \qquad (5)$$

whereas after [16] is:

$$m = \frac{1}{sin\,\gamma_s + 0{,}50572(\gamma_s + 6{,}07995°)^{-1{,}6364}}, \qquad (6)$$

and for an ideal clear and dry Rayleigh atmosphere the value of extinction coefficient av in the visible spectrum after [17] is

$$a_v = \frac{1}{9{,}9 + 0{,}043\,m}. \qquad (7)$$

Then the global/total illuminance E_{vg} is determined as a sum of diffuse and direct components

$$E_{vg} = E_{vd} + E_{vs}. \quad [\text{klx}] \qquad (5)$$

If values of global, diffuse and direct illuminance for various sun heights will be determined the possible availability of daylighting in the exterior is given. For the purpose of daylight simulation in artificial skies these values will have to be reduced to attainable levels of the artificial lighting system. Very important is to consider the minimum measurable indoor illuminance in the model. This limit level depends on the accuracy and sensitivity of the illuminance meter as well as on the scale of the model. It is assumed that the illuminance limit of 0,3 lx should be satisfactory when laboratory illuminance meters are applied.

Because the daylighting varies in relation to sun height the simulation of sky luminance distribution for many sun positions on the hemisphere should be appropriate for architectural design. I this paper are presented results of modelling exterior and scaled interior illuminance for only referenced solar altitude γ_s = 30°. The parameters k_{vvd} and T_v in Tab. 1 were recommended for the simulation of the ISO/CIE general sky in artificial skies after study Darula and Kittler, (2004a, 2004b and 2005). All components of exterior illuminances were based on application of these parameters in Tab. 1 resulting in illuminances presented in Tab. 2.

Tab. 1 Recommended parameters for simulation of the ISO/CIE general sky in artificial skies

Situation	Parameter	Sky type														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Sunless	k_{vvd}	0,1	0,2	0,2	0,2	0,3	0,2									
Sunny	T_v							5	5	4	4	2,5	2,5	2,5	3	3

Tab. 2 Diffuse, direct and global exterior illuminance, solar altitude 30 °

ISO/CIE sky standard		Illuminance in klx		
		E_{vd}	E_{vs}	E_{vg}
1	I.1	6,690		6,690
2	I.2	13,380		13,380
3	II.1	13,380		13,380
4	II.2	13,380		13,380
5	III.1	20,070		20,070
6	III.2	13,380		13,380
7	III.3	13,470	24,646	38,116
8	III.4	14,157	24,646	38,803
9	IV.2	11,130	30,095	41,224
10	IV.3	14,326	30,095	44,420
11	IV.4	9,526	40,606	50,132
12	V.4	12,016	40,606	52,622
13	V.5	9,451	40,606	50,057
14	VI.5	14,074	36,747	50,821
15	VI.6	15,330	36,747	52,077

Dimensions of the artificial sky, the measuring table and the light sensitive spot of illuminance meter head determine the scale of the physical model construction. The Bratislava artificial sky has 8 m diameter and a square area of the measuring table is 2.4 x 2.4 m. The effective scales of the model rooms for the Bratislava artificial sky are in the range from 1 : 10 to 1 : 20. The reduction of modelled illuminances in sky simulators can be different with respect to the scale of the room model. It seems that for LED luminaires the reduction 1:13 - 1:20 of the real outdoor illuminances could be satisfactory for application of this lighting systems in the Bratislava artificial sky.

Tab. 3 Recommended illuminance in the artificial sky and limiting illuminances in models for sunless ISO/CIE sky standards 1-6, solar altitude 30°

Diffuse exterior illuminance		k_{vvd}	Illuminance in the artificial sky		Limit illuminance in the model			
E_{vd}			Scale	$scaledE_{vd}$	D	$scaledE_i$	D	$scaledE_i$
lx				lx	%	lx	%	lx
6000	min	0,10	15	400	0,50	2,00	0,10	0,40
			20	300		1,5		0,30
30000	max	0,44	15	2000	0,50	10,00	0,10	2,00
			20	1500		7,50		1,50

The daylight factor method was used in these calculations and in Tab. 3 is documented the range of illuminances applicable for model measurements in the artificial sky for simulated ISO/CIE sky standards 1 - 6 if sun height is 30°. During these situations global illuminance has the same value as diffuse illuminance. In this study under sunless situations the scale factors 1:15 and 1:20 for all illuminances seems to be suitable.

For all sunny situations were investigated scales 1:13, 1:15 and 1:20 and separately were determined the indoor global, diffuse and direct illuminances as reduced values $scaledE_{vg}$, $scaledE_{vd}$ and $scaledE_{vs}$ in Tab. 4.

Tab. 4 Recommended diffuse and direct illuminance in the artificial sky for sunny ISO/CIE sky standards 7 - 15, solar altitude 30°

Diffuse exterior illuminance		Illuminance in the artificial sky		Direct exterior illuminance		Direct illuminance in the model	
E_{vd}		Scale	$scaledE_{vd}$	E_{vs}		Scale	$scaledE_{vs}$
lx			lx	lx			lx
12000	min	13	923	6000	min	13	462
		15	800			15	400
		20	600			20	300
26000	max	13	2000	41000	max	13	3154
		15	1733			15	2733
		20	1300			20	2050

In Tab. 5 are presented results of illuminances for sunny situations classified as sky type 7 – 15 in the standard [15], when additional contribution of direct illuminance in minimum and maximum values of global illuminance are rather higher than values under sunless situations. These indoor illuminance results are quite higher if windows are designed without shading devices. The last column in the Tab. 5 indicates, that there is a surplus circa to 80% reduction when entering daylight is shaded or redirected by devices in the window aperture.

Tab. 5 Recommended global illuminance in the artificial sky and limiting illuminance in the model for sunny ISO/CIE sky standards 7 - 15, solar altitude 30°

Global exterior illuminance		Global Illuminance in the artificial sky		Limit interior illuminance in model			
E_{vg}		Scale	$scaledE_{vg}$	D	$scaledE_i$	D	$scaledE_i$
lx			lx	%	lx	%	lx
32000	min	13	2462	0,50	12,31	0,10	2,46
		15	2133		10,66		2,13
		20	1600		8,00		1,60
53000	max	13	4077	0,50	20,38	0,10	4,08
		15	3533		16,66		3,53
		20	2650		13,25		2,65

Conclusions

Relation between diffuse and direct illuminance occurring in the nature is different under sunny and sunless situations and these vary with sun height. If there is a task to model exterior illuminances in the laboratory a possible scaling of these levels should be determined and calibrated to the same scale factor and should be reduced in accordance to the technical parameters of designed artificial lighting system. It seems that the scaling factor in the range of 1 : 13 – 1 : 20 can be used for illuminance levels in artificial skies to achieve satisfactorily performing daylight measurements in scale models. The simulation of daylight under sunny situations require the application of controlled artificial light sources with high luminous intensities due to the rise of real global illuminance up to 114 000 lx under sun height 75° above the horizon. For practical architectural measurements and verification of building design solutions using the artificial sky the daylight situations determined by [15] with sun position 30° above horizon as a reference condition could be applied.

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