

AN ANALYSIS OF DAYLIGHTING
PERFORMANCES IN OFFICE
BUILDINGS AND APPLICATIONS
OF LIGHT-GUIDE SYSTEM
COUPLED WITH REDIRECTING
DEVICE

TSANG KIN WAI

DOCTOR OF PHILOSOPHY
CITY UNIVERSITY OF HONG KONG

August 2010

CITY UNIVERSITY OF HONG KONG
香港城市大學

An Analysis of Daylighting Performances in
Office Buildings and Applications of
Light-guide System Coupled with
Redirecting Device
商用樓宇採光環境及揉合轉向裝置的光導
管應用之分析

Submitted to
Department of Building and Construction
建築學系
in Partial Fulfillment of the Requirements
for the Degree of Doctor of Philosophy
哲學博士學位

by

Tsang Kin Wai
曾建偉

August 2010
二零一零年八月

ABSTRACT

Daylight is a valuable natural resource and plays a crucial role in passive solar building design. Appropriate daylighting design not only provides a connection with outside, ensuring an adequate illuminance level with high uniformity and a glare-free environment but also provides an opportunity for energy saving and carbon reduction. However, in metropolitan Hong Kong, vast high-rise buildings are built closely together resulting in a severely indoor daylight environment.

To acquire in-depth understanding of the daylight environment of current buildings in Hong Kong, a survey on the daylighting performance of local buildings was conducted. In total, 35 air-conditioned non-residential buildings built from 1962 to 2004 spreading over different districts were selected for the study. The findings suggest that the rear part of rooms rarely receives adequate amount of daylight and the average obstruction angle for buildings in Hong Kong is between 30° and 60°. It is envisaged that traditional daylighting designs are not able to fulfil the needs of occupants and there is a potential to use novel daylighting devices to transmit light from the zenith of a sky dome to interior part of the buildings.

And therefore, the performance of several daylighting systems was investigated. The first one was a vertical light-pipe system. It was studied through field measurements and its performance was promising. For nearly half of the operating hours, the internal illuminance design level can be achieved by daylight alone. However, vertical light pipes are usually installed in floors near the roof and reduces its usability in high-rise non-residential buildings.

The second type of system being studied was the laser cut panel (LCP). Its installation is simple and redirects daylight into deeper parts of a room. LCP can improve the indoor daylight environment under most sky conditions. Both uniformity and the illuminance of the rear part of rooms have significant improvement. The performance of LCP is highly dependent on the internal layout of the room. Any obstruction which intercepts redirected daylight seriously affects the performance of LCPs.

Subsequently, horizontal light pipe (HLP) seems to be able to remedy the situation. However, the HLP cannot transmit light from high elevations effectively, and hence, another system integrating the LCP with a HLP (LLP) is of interest. To investigate the performance of this system, experimental works were conducted to identify the transmission characteristics of this system. The LCP can reduce the number of reflection with light pipes and hence it can increase the overall transmittance for light from high elevations. Through a simulation study, it is found that for most sky conditions, the LLP have a larger transmittance than conventional the HLP.

Annual performance of a daylighting system is an important parameter to assess a design. However, even though computational power is improving, conducting an annual assessment of daylighting systems is still not feasible. Fortunately, employing daylight coefficient concepts can greatly reduce the simulation time for long-term system evaluation. In this study, a two-step daylight coefficient simulation approach is proposed. Its performance was validated against measured data. And finally, a simple daylighting assessment tool was developed. Its major algorithms are discussed. It is believed that this study can provide a better understanding and more accurate design method of daylighting systems for architects and engineers.

CONTENTS

<i>Abstract</i>	<i>i</i>
<i>Acknowledgements</i>	<i>iii</i>
<i>Contents</i>	<i>iv</i>
<i>List of Figures</i>	<i>viii</i>
<i>List of Tables</i>	<i>xiii</i>
<i>List of abbreviations and acronyms</i>	<i>xv</i>
<i>Nomenclature</i>	<i>xvii</i>
Chapter 1 Introduction	1
1.1 Background	1
1.2 Objectives	6
1.3 Outline of original contributions	7
1.4 Outline of the thesis	7
Chapter 2 Survey on daylighting performance of office buildings in Hong Kong....	10
2.1 Regulations and guidelines related to daylighting design in Hong Kong...	11
2.2 Building survey and parameters affecting daylighting	13
2.2.1 Building area and orientation	14
2.2.2 Glass type	18
2.2.3 Window Area	19
2.2.4 Shading	19
2.2.5 External Obstruction	20
2.3 Computer simulation approach	21
2.3.1 Building Description	21
2.3.2 Simulation settings	25

2.4	Daylighting performance	28
Chapter 3 Evaluation of Light-pipe system in Hong Kong		39
3.1	Daylighting system and light-pipe system	40
3.1.1	Overview of daylighting system	40
3.1.2	Overview of light-pipe system	44
3.2	Building description and measurement	47
3.3	Measured data analysis	50
3.3.1	Interior illuminance	51
3.3.2	Sky conditions	55
3.4	Light-pipe model analysis	62
3.4.1	Zhang and Muneer Model (Zhang and Muneer, 2000)	64
3.4.2	Jenkins et al. Model (Jenkins et al., 2005)	66
3.4.3	CIE Model (Al-Marwaei and Cater, 2006)	67
3.5	Model assessment	68
3.6	Energy Savings	69
Chapter 4 Study of laser cut panel performance under real sky via scale model measurement.....		76
4.1	Laser cut panel descriptions	77
4.2	Field measurement and equipment	83
4.3	Data analysis	86
4.3.1	Overcast sky conditions	87
4.3.2	Non-overcast sky conditions	90
4.4	Simulation study	95
Chapter 5 Analysis of the performances of a light-pipe system incorporating a laser-cut panel.....		103
5.1	Horizontal light-pipe system	104

5.2	Scale model measurement.....	105
5.3	Simulation package validation	112
5.4	Case study	115
Chapter 6 Long-term assessment method of daylighting systems under various sky conditions using a simulation technique..... 123		
6.1	Daylight coefficient approach	125
6.1.1	Theory of the daylight coefficient.....	125
6.1.2	Simulation technique for traditional window.....	128
6.2	Simulation technique for daylighting systems	140
6.2.1	Calculation Procedures.....	142
6.3	Validation study.....	148
6.3.1	Data measurement.....	149
6.3.2	Simulation procedures and settings.....	150
6.4	Approximating light-pipe efficiencies for multiple directions.....	153
6.5	Demonstration of applying the daylight coefficient and pipe transfer coefficient for long-term study.....	165
6.5.1	Calculation algorithm.....	165
6.5.2	Generic office building and simulation settings.....	167
6.5.3	Data analysis	171
Chapter 7 Development of simplified software for indoor daylight environment assessment 183		
7.1	The CIE standard sky	185
7.2	Methodology and calculation procedures	188
7.2.1	Daylight coefficient module.....	190
7.2.2	Daylighting device module	204
7.2.3	Illuminance calculation module	207

7.3	Data analysis	209
Chapter 8	Conclusions and recommendations	215
8.1	Summary of major findings	215
8.1.1	Daylighting performance for commercial building in Hong Kong.....	
		215
8.1.2	Performance of innovative daylighting systems	216
8.1.3	Simulation method for light-pipe systems for long-term assessment .	
		220
8.2	Limitation of studies	221
8.3	Suggestions for future work	223
References		225
Appendix A	Proposed Software Source Code	238
Appendix B	List of Publications.....	304

LIST OF FIGURES

Figure 1.1	Primary Energy Requirements of Hong Kong from 1979 to 2009	2
Figure 1.2	Electricity uses of Hong Kong from 1979 to 2009	3
Figure 2.1	Elevation of Building 30	22
Figure 2.2	Typical floor plan with simulation points for Building 30.....	23
Figure 2.3	Elevation of Building 20	24
Figure 2.4	Typical floor plan with simulation points for Building 20.....	25
Figure 2.5	Simulation model for Building 30.....	27
Figure 2.6	Simulation model for Building 20.....	28
Figure 2.7	Daylight factors at the various floors facing northeast for Building 30..	29
Figure 2.8	Daylight factors at the various floors facing southeast for Building 30 .	30
Figure 2.9	Daylight factors at the various floors facing southwest for Building 30	30
Figure 2.10	Daylight factors at the various floors facing northwest for Building 30.	31
Figure 2.11	Daylight factors at the various floors facing west for Building 20	31
Figure 2.12	Daylight factors at the various floors facing south for Building 20.....	32
Figure 2.13	Daylight factors at the various floors facing north for Building 20.....	32
Figure 3.1	Typical construction of a light-pipe system	45
Figure 3.2	Interior view of the corridor	48
Figure 3.3	The seven-sensor layout for the light pipe measurement.....	50
Figure 3.4	Plan view and section of the five measuring points in the corridor	50
Figure 3.5	Cumulative frequency distributions for the measured illuminance at various rings of the light pipe.....	53
Figure 3.6	Cumulative frequency distribution for F_{out}	54
Figure 3.7	Cumulative frequency distribution for τ	55
Figure 3.8	The interior for the 5 points measured on Day 1 (an overcast sky)	57

Figure 3.9	The interior for the 5 points measured on Day 2 (a clear sky).....	58
Figure 3.10	The interior for the 5 points measured on Day 3	59
Figure 3.11	The interior for the 5 points measured on Day 4	59
Figure 3.12	The interior for the 5 points measured on Day 5	60
Figure 3.13	The interior for the 5 points measured on Day 6	60
Figure 3.14	The interior for the 5 points measured on Day 7	61
Figure 3.15	Correlation of outdoor illuminance measured on the roof-top of the building and our measuring station	70
Figure 3.16	Cumulative frequency distribution for daylight availability in the corridor	73
Figure 3.17	Lighting energy consumption for various months	74
Figure 4.1	Cross-section of laser cut panel	78
Figure 4.2	Principle of light deflection by laser cut panel	78
Figure 4.3	The fraction of light deflected for laser cut panel with a D/W ratio of 0.6.	81
Figure 4.4	Daylight redirection for various panel tilt angles.....	82
Figure 4.5	Plan, front and section of model and measurement points arrangement.	85
Figure 4.6	Measured daylight illuminance and RI under an overcast sky when $\alpha_U=71.6^\circ$	89
Figure 4.7	Measured daylight illuminance and RI under an overcast sky when $\alpha_U=71.6^\circ$	90
Figure 4.8	Measured daylight illuminance and RI at sunlit surface under a non-overcast sky when $\alpha_U = 71.6^\circ$	92
Figure 4.9	Measured daylight illuminance and RI at sunlit surface under a non-overcast sky when $\alpha_U = 56^\circ$	92
Figure 4.10	Measured daylight illuminance and RI at sunshade surface under a	

	non-overcast sky when $\alpha_U = 71.6^\circ$	94
Figure 4.11	Measured daylight illuminance and RI at sunshade surface under a non-overcast sky when $\alpha_U = 56^\circ$	94
Figure 4.12	Simulated daylight illuminance under the CIE overcast sky when $\alpha_U = 71.6^\circ$	98
Figure 4.13	Simulated daylight illuminance under the CIE overcast sky when $\alpha_U = 56^\circ$	98
Figure 5.1	Plan and section of the light pipe scale model	106
Figure 5.2	Arrangement of illuminance sensors at the bottom of diffuser (view from bottom)	108
Figure 5.3	Cases showing light coming from different elevations.....	111
Figure 5.4	Isotropic view of the room used for the case study.....	116
Figure 6.1	Relationship between sky element and change of indoor illuminance .	126
Figure 6.2	Aimed ray directed to the sky element.....	135
Figure 6.3	Indirect sky component calculation by the sky element	136
Figure 6.4	Fine-scale sub-sky element used for indirect sky simulation	137
Figure 6.5	Calculation procedure of the daylight coefficient approach for daylighting systems	143
Figure 6.6	Measurement setup for a light pipe with obstruction under real sky	150
Figure 6.7	Step in calculating the exiting luminous flux for light pipe calculation	151
Figure 6.8	The luminous flux output obtained by measurement and simulation ...	152
Figure 6.9	Subdivision scheme for daylighting system.....	155
Figure 6.10	Comparison of HLP exiting luminous flux from the sky using the NN and standard method	159
Figure 6.11	Comparison of HLP exiting luminous flux from the sky using the "interpolated" and standard method	159

Figure 6.12	Comparison of LLP exiting luminous flux from the sky using the NN and standard method	160
Figure 6.13	Comparison of LLP exiting luminous flux from the sky using the "interpolated" and standard method	160
Figure 6.14	Comparison of HLP exiting luminous flux from the sun using the NN and standard methods.....	162
Figure 6.15	Comparison of HLP exiting luminous flux from the sun using the "interpolated" and standard methods	163
Figure 6.16	Comparison of the LLP exiting luminous flux from the sun using the NN and standard method	163
Figure 6.17	Comparison of LLP exiting luminous flux from the sun using the "interpolated" and standard methods	164
Figure 6.18	Calculation procedure for indoor illuminance level by the daylight coefficient and light transfer coefficient	166
Figure 6.19	Plan and section of the generic office building.....	169
Figure 6.20	Rendering for the model employed in the simulation.....	171
Figure 6.21	Annual mean RI at the first floor facing north.....	173
Figure 6.22	Annual mean RI at the first floor facing east.....	173
Figure 6.23	Annual mean RI at the first floor facing south.....	174
Figure 6.24	Annual mean RI at the first floor facing west.....	174
Figure 7.1	Calculation procedures adopted in the software	189
Figure 7.2	Calculation procedures for the daylight coefficient module	191
Figure 7.3	Calculation algorithm of $r_{\text{direct},i}$ for SC and ERC	195
Figure 7.4	Calculation algorithm of daylight coefficient for IRC	202
Figure 7.5	Calculation algorithm of determining the coefficient for daylighting devices.....	205

Figure 7.6	Flowchart for daylight illuminance calculation for each time step.....	208
Figure 7.7	The illuminances simulated by RADIANCE and Photopia and the simple software for skies nos. 2, 4 and 6	212
Figure 7.8	The illuminances simulated by RADIANCE and Photopia and the simple software for skies nos. 7 to 10.....	213
Figure 7.9	The illuminances simulated by RADIANCE and Photopia and the simple software for skies nos. 11 to 15	213

LIST OF TABLES

Table 2.1 Summary of building information and daylight parameters for surveyed buildings.....	16
Table 2.2 Ambient parameters setting for simulation	26
Table 2.3 Area for different daylight zone	34
Table 2.4 Room depth for different directions of Building 20 & 30	35
Table 2.5 Daylight glare index for Building 20 and Building 30	37
Table 3.1 Classification of daylighting systems according to (Ruck et al., 2000; Kischkoweit-Lopin, 2002)	43
Table 3.2 The uniformity and K_t for the seven measurement days.....	61
Table 3.3 Coefficients for Zhang and Muneer (2000) model against Hong Kong data..	66
Table 3.4 Errors summarised for different models	69
Table 4.1 Set of ambient parameters used for simulation	96
Table 4.2 Simulated results for various external obstruction angles under non-overcast skies.....	99
Table 4.3 External conditions and room parameters for simulation typical case studies	100
Table 4.4 The RI and uniformity for case studies	100
Table 5.1 Efficiencies (%) of the HLP for light coming from different directions	110
Table 5.2 Efficiencies (%) of the LLP for light coming from different directions	111
Table 5.3 Simulated efficiency (%) of the HLP for light coming from different directions by Photopia.....	113
Table 5.4 Simulated efficiency (%) of the LLP for light coming from different directions by Photopia	114
Table 5.5 Annual averaged modeled transmittance (%) for HLP and LLP	118

Table 5.6 Percentage (%) of working hours in excess of the designed lighting level ..	120
Table 5.7 Annual lighting energy consumption (kWh) for different daylight-linked control systems for the HLP and LLP	120
Table 6.1 Ambient parameter settings for model uses in the validation study of the pipe transfer coefficient	152
Table 6.2 Summary of RMBE and RRMSE for skylight of the NN and "interpolated" alignment schemes for the HLP and LLP	158
Table 6.3 Summary of RMBE and RRMSE for sunlight of the NN and "interpolated" alignment schemes for the HLP and LLP	162
Table 6.4 Brief description of the generic office building	168
Table 6.5 Ambient parameter settings for the study in the generic office building	171
Table 6.6 Percentage of operating hours exceeding 100lux.....	176
Table 6.7 Percentage of operating hours exceeding 300lux.....	177
Table 6.8 Percentage of operating hours exceeding 500lux.....	178
Table 6.9 Energy Consumption (MWh) of different control strategies for different daylighting devices.....	180
Table 7.1 A set of fifteen standard sky types and their parametrisation	187

LIST OF ABBREVIATIONS AND ACRONYMS

CIBSE	The Chartered Institution of Building Services Engineers
CIE	Commission Internationale de l'Eclairage
DF	Daylight factor
DGI	Daylight Glare Index
DPF	Daylight penetration factor
EMSD	Electrical and Mechanical Services Department
ERC	Externally reflected component
GFA	Gross floor area
GHG	Greenhouse Gas
HLP	Horizontal light pipe
HOE	Holographic optical elements
IEA	International Energy Agency
IGU	Insulated glass unit
ILE	The Institution of Lighting Engineers
IRC	Internally reflected component
LED	Light-emitting diode
LLP	Laser cut panel coupled with horizontal light pipe
MBE	Mean bias error
MF	Maintenance factor
NN	Nearest neighbour
OTTV	Overall thermal transfer value

RI	Relative illuminance
RMBE	Relative mean bias error
RMSE	Root mean square error
RRMSE	Relative root mean square error
SC	Sky component
SLL	The Society of Light and Lighting
TTE	Tube-transmission efficiency
UF	Utilisation Factor
UVA	Unobstructed vision area
VDF	Vertical daylight factor
VT	Visible transmittance
WWR	Window-to-wall ratio

NOMENCLATURE

α_s	Solar altitude (degree)
α_u	Upper obstructed angle (degree)
β	Elevation of laser cut panel (degree)
ε	Transmission efficiency (dimensionless)
ε_{gd}	Transmission efficiency of ground patch (dimensionless)
ε_{sky}	Transmission efficiency of sky patch (dimensionless)
ε_{sun}	Transmission efficiency of sun (dimensionless)
θ	Elevation angle of sky element (degree)
θ_c	Angle of laser cut to the normal (degree)
θ_i	Angle of incidence (degree)
$\theta_{i,max}$	Maximum angle of incidence (degree)
$\theta_{i,min}$	Minimum angle of incidence (degree)
θ_o	Angle of vertical obstruction (degree)
θ_v	Angle between light-pipe diffuser normal and point of interest (m)
ι	Rotation angle around x-axis (dimensionless)
κ	Rotation angle around y-axis (dimensionless)
λ	Rotation angle around z-axis (dimensionless)
ξ_1	Pseudo azimuth of sky element (degree)
ξ_2	Pseudo elevation of sky element (degree)
ρ_{ave}	Average Reflectance of internal surface (dimensionless)
ρ_{cw}	Average Reflectance of ceiling and upper wall above the mid-height of the window (excluding window wall) (dimensionless)
ρ_{fw}	Average Reflectance of floor and lower wall below the mid-height of

	the window (excluding window wall) (dimensionless)
ρ_{obs}	Reflectance of obstruction (dimensionless)
ρ_b	Reflectance of pipe body (dimensionless)
ϕ	Azimuth angle of sky element (degree)
τ	Transmittance(dimensionless)
φ	Angle of bend for light pipe (degree)
χ	Scattering angle (degree)
Ω	Solid angle subtended by the source, modified by the position of the light source with respect to the field of view and Guth's position index (steradians)
ω	Solid angle (steradians)
ω_{gd}	Solid angle of ground patch (steradians)
ω_i	Solid angle for sky patch i (steradians)
ω_s	Solid angle of the source seen from the point of observation (steradians)
ω_{sky}	Solid angle of sky patch (steradians)
ω_{sun}	Solid angle of sun (steradians)
A_{in}	Input aperture area (m^2)
A_p	Aspect ratio (dimensionless)
A_{surf}	Total area of internal surface (m^2)
A_w	Area of working plane (m^2)
A_{win}	Area of window (m^2)
$\mathbf{A}$	Matrix of artificial light coefficient (dimensionless)
a	Adjustable coefficient for the CIE standard skies model (dimensionless)
alc	Artificial light coefficient (lux/lm)
b	Adjustable coefficient for the CIE standard skies model (dimensionless)
C_1	Configuration factors of the daylight flux incident on the mid-height of

	window pane from above the horizon (dimensionless)
C_2	Configuration factors of the daylight flux incident on the mid-height of window pane from below the horizon (dimensionless)
C_i	Coefficients for empirical model (dimensionless)
C	Matrix for total luminous from sky element (dimensionless)
c	Adjustable coefficient for the CIE standard skies model (dimensionless)
D	Cut space (m)
$D_{\text{direct sky}}$	Matrix of daylight coefficient for direct sky component (dimensionless)
$D_{\text{indirect sky}}$	Matrix of daylight coefficient for indirect sky component (dimensionless)
D_l	Distance (m)
d	Adjustable coefficient for the CIE standard skies model (dimensionless)
d_ϕ	Light pipe diameter (m)
dc	Daylight coefficient (dimensionless)
dc'	Daylight coefficient for obstruction (dimensionless)
$dc_{\text{direct sky}}$	Daylight coefficient for direct sky component (dimensionless)
$dc_{\text{direct sun}}$	Daylight coefficient for direct sky component (dimensionless)
$dc_{\text{indirect sky}}$	Daylight coefficient for direct sky component (dimensionless)
$dc_{\text{indirect sun}}$	Daylight coefficient for direct sky component (dimensionless)
d_{eff}	Effective diameter (m)
E_a	Illuminance of light coming directly above horizon on a vertical surface (lux)
E_b	Illuminance of light coming directly below horizon on a vertical surface (lux)
E_c	Minimum daylight level needed to reduce light output to minimum (lux)
E_d	Illuminance of direct sky and sun component on vertical surface (lux)

E_{rg}	Illuminance
$E_{direct\ sky}$	Illuminance from sky directly (lux)
$E_{direct\ sun}$	Illuminance from sky directly (lux)
E_{ex}	External illuminance (lux)
E_{ext}	External illuminance contributed by sky and externally reflected component (lux)
E_g	Global solar irradiance (W/m^2)
$E_{indirect\ sky}$	Illuminance from sky directly (lux)
$E_{indirect\ sun}$	Illuminance from sky directly (lux)
E_{mea}	Measured illuminance (lux)
E_{pred}	Predicted illuminance (lux)
E_{rg}	Illuminance by reflected light from ground (lux)
E_{rb}	Illuminance by reflected light from obstruction (lux)
E_{so}	Extraterrestrial solar irradiance (W/m^2)
E_{total}	Illuminance contributed by window and light pipe (lux)
$\mathbf{E}_{total}$	Matrix for total illuminance contributed by window and light pipe (lux)
E_{vg}	Horizontal global illuminance (lux)
E_{vd}	Horizontal diffuse illuminance (lux)
E_{vert}	Illuminance on vertical surface (lux)
E_{vs}	Horizontal direct illuminance (lux)
E_w	Indoor design illuminance (lux)
E_{win}	Illuminance due to window aperture (lux)
$\mathbf{E}_{win}$	Matrix of illuminance due to window aperture (lux)
e	Adjustable coefficient for the CIE standard skies model (dimensionless)
$F_{direct\ sky}$	Luminous light flux for light coming from direct sky (lm)
$F_{direct\ sun}$	Luminous light flux for light coming from direct sun (lm)

$F_{\text{indirect sky}}$	Luminous light flux for light coming from indirect sky (lm)
$F_{\text{indirect sun}}$	Luminous light flux for light coming from indirect sun (lm)
F_{in}	Input light flux (lm)
F_{light}	Luminous flux from lighting system (lm)
F_{out}	Output light flux (lm)
F	Matrix of luminous flux output from light pipe (dimensionless)
f_d	Fraction of deflected light (dimensionless)
F_s	Fractional energy saving (fraction)
H_p	Vertical difference between light-pipe diffuser and reference point (m)
H_{rm}	Height of window head above floor level (m)
K_t	Clearness index (dimensionless)
L_{rm}	Depth of the room from window to back wall (m)
L	Luminance (cd/m^2)
L_b	Average luminance of the background excluding the glare source (cd/m^2)
L_{gd}	Luminance of ground (cd/m^2)
L_r	Luminance of aimed ray (cd/m^2)
L_s	Average luminance of glare source in the field of view (cd/m^2)
L_{sky}	Luminance of sky patch (cd/m^2)
L_{sun}	Luminance of sun (cd/m^2)
L_w	Average luminance of a window (cd/m^2)
L_z	Zenith luminance (cd/m^2)
l_p	Length of light pipe (m)
l_v	Relative luminance (dimensionless)
N	Total number of data (dimensionless)
N_g	Number of glare sources (dimensionless)
n	Number of sky element (dimensionless)

n_{air}	Refractive index of air (dimensionless)
n_{panel}	Reflective index of panel (dimensionless)
P_{set}	Set of ray belongs to direct sky pipe transfer coefficient (dimensionless)
P_z	Portion of the zenith overcast sky form which illuminance can enter the guide (degree)
pc	Pipe transfer coefficient (dimensionless)
$pc_{\text{direct sky}}$	Pipe transfer coefficient for direct sky (dimensionless)
$pc_{\text{direct sun}}$	Pipe transfer coefficient for direct sun (dimensionless)
$pc_{\text{indirect sky}}$	Pipe transfer coefficient for indirect sky (dimensionless)
$pc_{\text{indirect sun}}$	Pipe transfer coefficient for indirect sun (dimensionless)
Q_{in}	Entering luminous flux for light coming from particular direction (lm)
Q_{out}	Exiting luminous flux for light coming from particular direction (lm)
r	Radius (m)
r_i	Angle of refraction (degree)
r_{ext}	Ratio of indoor illuminance to external luminance (dimensionless)
r_{IRCA}	Ratio of E_a to external luminance (dimensionless)
r_{IRCB}	Ratio of E_b to external luminance (dimensionless)
r_{min}	Minimum angle of refraction (degree)
r_{max}	Maximum angle of refraction (degree)
r_{pipe}	Ratio of light pipe exiting light flux to external luminance (dimensionless)
R_b	Average reflectance of surface in the rear half of the room (dimensionless)
R_f	Minimum fraction of output level (fraction)
R_w	Minimum fraction of power consumption (fraction)
s	Arbitrary variable (dimensionless)

T	Set of ray belongs to direct sky daylight coefficient (dimensionless)
T_c	Transmittance of dome (dimensionless)
T_o	Transmittance of diffuser (dimensionless)
W	Cut Depth (m)
W_{rm}	Width of room measured parallel to the window (m)
x	Coordinate to x-axis (dimensionless)
x_o	Coordinate x of new origin (dimensionless)
x'	Transformed coordinate x (dimensionless)
x''	Coordinate x of shadow (dimensionless)
y	Coordinate to y-axis (dimensionless)
y_o	Coordinate y of new origin (dimensionless)
y'	Transformed coordinate y (dimensionless)
y''	Coordinate y of shadow (dimensionless)
Z	Zenith angle (degree)
Z_s	Solar zenith (degree)
z	Coordinate to z-axis (dimensionless)
z_o	Coordinate z of new origin (dimensionless)
z'	Transformed coordinate z (dimensionless)
z''	Coordinate z of shadow (dimensionless)