# 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
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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

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by

Tsang Kin Wai
曾建偉

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# 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.

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# LIST OF ABBREVIATIONS AND ACRONYMS

| | |
|---|---|
| CIBSE | The Chartered Institution of Building Services Engineers |
| CIE | Commission Internationale de I’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 |

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|---|---|
| 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

| | |
|---|---|
| $\alpha_s$ | Solar altitude (degree) |
| $\alpha_u$ | Upper obstructed angle (degree) |
| $\beta$ | Elevation of laser cut panel (degree) |
| $\varepsilon$ | Transmission efficiency (dimensionless) |
| $\varepsilon_{gd}$ | Transmission efficiency of ground patch (dimensionless) |
| $\varepsilon_{sky}$ | Transmission efficiency of sky patch (dimensionless) |
| $\varepsilon_{sun}$ | Transmission efficiency of sun (dimensionless) |
| $\theta$ | Elevation angle of sky element (degree) |
| $\theta_c$ | Angle of laser cut to the normal (degree) |
| $\theta_i$ | Angle of incidence (degree) |
| $\theta_{i,max}$ | Maximum angle of incidence (degree) |
| $\theta_{i,min}$ | Minimum angle of incidence (degree) |
| $\theta_o$ | Angle of vertical obstruction (degree) |
| $\theta_v$ | Angle between light-pipe diffuser normal and point of interest (m) |
| $\iota$ | Rotation angle around x-axis (dimensionless) |
| $\kappa$ | Rotation angle around y-axis (dimensionless) |
| $\lambda$ | Rotation angle around z-axis (dimensionless) |
| $\xi_1$ | Pseudo azimuth of sky element (degree) |
| $\xi_2$ | Pseudo elevation of sky element (degree) |
| $\rho_{ave}$ | Average Reflectance of internal surface (dimensionless) |
| $\rho_{cw}$ | Average Reflectance of ceiling and upper wall above the mid-height of the window (excluding window wall) (dimensionless) |
| $\rho_{fw}$ | Average Reflectance of floor and lower wall below the mid-height of |

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|---|---|
| | the window (excluding window wall) (dimensionless) |
| $\rho_{obs}$ | Reflectance of obstruction (dimensionless) |
| $\rho_b$ | Reflectance of pipe body (dimensionless) |
| $\phi$ | Azimuth angle of sky element (degree) |
| $\tau$ | Transmittance(dimensionless) |
| $\varphi$ | Angle of bend for light pipe (degree) |
| $\chi$ | Scattering angle (degree) |
| $\Omega$ | 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) |
| $\omega$ | Solid angle (steradians) |
| $\omega_{gd}$ | Solid angle of ground patch (steradians) |
| $\omega_i$ | Solid angle for sky patch i (steradians) |
| $\omega_s$ | Solid angle of the source seen from the point of observation (steradians) |
| $\omega_{sky}$ | Solid angle of sky patch (steradians) |
| $\omega_{sun}$ | 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 |

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|---|---|
| | 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) |
| $\mathbf{C}$ | Matrix for total luminous from sky element (dimensionless) |
| c | Adjustable coefficient for the CIE standard skies model (dimensionless) |
| D | Cut space (m) |
| $D_{direct\ sky}$ | Matrix of daylight coefficient for direct sky component (dimensionless) |
| $D_{indirect\ sky}$ | Matrix of daylight coefficient for indirect sky component (dimensionless) |
| $D_l$ | Distance (m) |
| d | Adjustable coefficient for the CIE standard skies model (dimensionless) |
| $d_\phi$ | Light pipe diameter (m) |
| dc | Daylight coefficient (dimensionless) |
| dc’ | Daylight coefficient for obstruction (dimensionless) |
| $dc_{direct\ sky}$ | Daylight coefficient for direct sky component (dimensionless) |
| $dc_{direct\ sun}$ | Daylight coefficient for direct sky component (dimensionless) |
| $dc_{indirect\ sky}$ | Daylight coefficient for direct sky component (dimensionless) |
| $dc_{indirect\ sun}$ | Daylight coefficient for direct sky component (dimensionless) |
| $d_{eff}$ | Effective diameter (m) |
| $E_a$ | Illuminacne of light coming directly above horizon on a vertical surface (lux) |
| $E_b$ | Illuminacne 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) |

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|---|---|
| Erg | 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 illuminace 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) |

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|---|---|
| $F_{indirect\ sky}$ | Luminous light flux for light coming from indirect sky (lm) |
| $F_{indirect\ sun}$ | 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) |
| $\mathbf{F}$ | 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) |

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|---|---|
| $n_{air}$ | Refractive index of air (dimensionless) |
| $n_{panel}$ | Reflective index of panel (dimensionless) |
| $\mathbf{P}_{set}$ | 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) |
| $pc_{direct\ sky}$ | Pipe transfer coefficient for direct sky (dimensionless) |
| $pc_{direct\ sun}$ | Pipe transfer coefficient for direct sun (dimensionless) |
| $pc_{indirect\ sky}$ | Pipe transfer coefficient for indirect sky (dimensionless) |
| $pc_{indirect\ sun}$ | 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) |

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|---|---|
| **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) |