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Tracing of daylight through circular light pipes with anidolic concentrators

Thanyalak Taengchum [a], Surapong Chirarattananon [a,b,*], Robert H.B. Exell [a,b], Pipat Chaiwiwatworakul [a,b]

[a] *Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, Thailand*
[b] *Science and Technology Postgraduate Education and Research Development Office, Ministry of Education, Thailand*

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Abstract

Light pipes can bring both daylight from the sun and the sky into deep interior spaces of a building. Adding an anidolic concentrator at the entry port of a light pipe will increase daylight capture and may reduce the overall cost per unit of delivered daylight flux, especially for long pipes or pipes with bends. This paper presents results of modeling, experiments, and simulation of transmission of beam and diffuse daylight through tubular light pipes attached with an anidolic concentrator at the entry port. Analytic method is used for tracing light rays from the sun and sources in the sky zones through the anidolic concentrator to the straight section of a pipe through to the exit port. The vertical curvature surface of the anidolic concentrator is modeled as a parabolic section. The ASRC-CIE sky luminance distribution model is used to generate luminance of daylight from the sky. The algorithms are coded in a MATLAB program. The physical anidolic concentrator and pipe are fabricated from off-the-shelf materials commonly available. The interior surface of each section is lined with a film of reflectance of 99%. Results from calculation of transmission of global and diffuse daylight through the tubular pipe with anidolic concentrator match well with those from experiments.

Keywords: Daylighting; Light pipe; Anidolic concentrator; Sky luminance; Sunlight

1. Introduction

Electric lighting accounts directly for 20% of electricity consumption in air-conditioned buildings in Thailand while daylight is plentiful, (Chirarattananon et al., 2010). Daylighting is attractive and can greatly help reduce lighting energy. The common method of daylighting letting daylight in through windows is practical only for the areas near windows. Light pipes and reflector systems that can utilize direct sunlight have been shown to be more effective in bringing daylight into deeper interior spaces, (Rosemann and Kraase, 2005; Scartezzini and Courret, 2002). Light pipes commonly used are passive tubular pipes that comprise an entry port, a hollow tubular pipe for transmission of daylight, and an exit port for delivering it into the intended space. In most cases and in this paper, all sections of a light pipe possess specularly reflective interior surfaces.

It is often desirable to capture daylight from a large part of sky through a larger entry aperture, then concentrate the captured daylight and re-direct it to a smaller pipe section.

* Corresponding author at: Joint Graduate School of Energy and Environment, King Mongkut's University of Technology Thonburi, Bangkok, Thailand. Tel.: +66 (2) 4708309.

E-mail addresses: t.thanyalak@yahoo.com (T. Taengchum), surapong.chi@kmutt.ac.th (S. Chirarattananon), exell@jgsee.kmutt.ac.th (R.H.B. Exell), pipat_ch@jgsee.kmutt.ac.th (P. Chaiwiwatworakul).

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Nomenclature

ϕ_s	solar zenith angle, radian
γ_s	solar azimuth angle
α_s	solar altitude angle
ϑ	acceptance half-angle, radian or degree
ϕ	90° complement of the acceptance half-angle
θ_{ent}	entry angle, radian
A_{ent}	area of entry port, m^2
Φ	light flux, lumen
ρ	surface reflectance
E	illuminance, lux
ΔE_{ext}	incremental illuminance at exit port
%Nrt	percentage of number of rays transmitted
CR	concentration ratio
θ_{ext}	exit angle, radian
A_{ext}	area of exit port, m^2
Evg	total illuminance, lux
Evd	diffuse illuminance, lux
Evtap	total daylight illuminance transmitted through the straight pipe with concentrator, lux
Evtp	total daylight transmitted through the pipe with no concentrator, lux
Evdap	diffuse daylight transmitted through a pipe with anidolic concentrator, lux
Evdp	diffuse daylight transmitted through a pipe with no concentrator, lux
Evdap-exp	measured transmitted diffuse illuminances, lux
Evdap-cal	calculated transmitted diffuse illuminances, lux
Evbap-exp	measured transmitted beam illuminances, lux
Evbap-cal	calculated transmitted beam illuminances, lux

Performance of such light collector can be improved if it is designed using the principle of anidolic, or non-imaging, optics, Scartezzini and Courret (2002). Molteni et al. rationalizing that basement and underground spaces were increasingly used in urban areas, studied the use of anidolic collectors connected to a vertical pipe, (Molteni et al., 2000). Two collectors were designed separately, one to capture and concentrate daylight from the sky, and one to capture summer sunlight. The authors used a scanning artificial sky as light source for a light pipe and collector model and found that the collectors increase transmitted light fluxes considerably. Wittkopf (2006), reports the use of Photopia, a raytracing calculation tool, to study comparative performance of a façade installed with an 'anidolic integrated ceiling', or AIC, against two other common configurations when the facades are illuminated with different sky luminance distributions. The author concludes that the façade with AIC performs better in terms of improving illuminance ratio and reducing glare. Wittkopf et al. (2010), used Photopia to study comparative luminous intensity distributions of light that passes through seven collectors of an anidolic integrated ceiling. Light uniformly distributed from a half hemisphere in front of the collector is simulated to enter each collector. The collector with a main anidolic concentrator and an opposite de-concentrator was found to offer the least spread of luminous intensity distribution. This is deemed to transmit light along the pipe with least attenuation. Linhart et al. (2010), modeled a 'virtual sky dome' that emanates daylight whose luminance distribution represents that of Singapore sky and used Photopia to simulate transmission of light from such model. The authors tested comparative performance of daylight transmission through the AIC against change in the reflectance of the surfaces, change in dimensions of the AIC, and extent of shading by objects above the collector.

Raytracing and flux transfer have been applied to the study of a facade-mounted rectangular pipes by Hien and Chirarattananon to obtain results that agree well with those from experiments, (Hien and Chirarattananon, 2009). Dutton and Shao (2008), use long thin rectangular sections to form approximate circular shaped pipes and simulate light transmission by the use of Photopia. Swift et al. (2008), develop theoretical model of transmission of light through rectangular pipe for collimated rays and report that results from the model agree well with experimental results. Zastrow and Wittwer (1986), considered transmission of light beam across cylindrical light pipes and offers a simple relationship for light transmission as a function of the length and diameter of the pipe, and the entry angle of the light beam. Kocifaj et al. (2008), developed a method called HOLIGILM for calculation of illuminance on an incremental area at the exit port of a circular light pipe by considering backward tracing of a light ray through the entry dome or port to a sky zone. Kocifaj et al. (2010), extends the HOLIGILM method to the case where two straight pipes are connected to form a bend. Kocifaj and Kundracik (2011), introduce an asymmetrical parameter and apply it with the HOLIGILM method to characterize the spread of luminous intensity of light exiting a pipe. Darula et al. (2010), applies the HOLIGILM method to study daylight transmission through a bended pipe on a roof and examines the patterns of illuminance distributions at exit port and at the work plane below for a standard sky luminance distribution (CIE Sky 12, clear with sun) and a number of room orientations. The authors conclude that effective design of bended tubular light pipe requires a study of interrelation between tube azimuth orientation and the angle of incidence of the sun beam. Kocifaj (2009) applies the HOLIGILM method to modeling of light transmission through hollow light guide with transparent exit port,