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Straight light pipes' daylighting: A case study for different climatic zones

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ABSTRACT

A comprehensive study of straight light pipe efficiency and illuminance distribution below ceiling level is performed using HOLIGILM tool. The recommendations for light guide systems can be made for different latitudes and sky luminance patterns using the data computed here. The computational results show that the light pipe transmittance is a monotonic function of solar altitude, except for low-sun angles. Redistribution of photons at the light pipe base can be characterized by a scalar value called "asymmetry parameter", *g*. A use of *g* is an efficient attempt to the classification of a large number of luminous intensity distributions. The minimum value of *g* is at low solar elevations (between 10° and 30°) because of balanced contribution of diffuse light of a sky and the direct sunbeams. The low values of *g* indicate the redistribution of light is more uniform. Luminous intensity solid determined by means of HOLIGILM tool is used to compute illuminance distribution at a working plane. The peak intensity and intensity gradient of a bright ring projected onto a working plane can be used to characterize the optical properties of different light pipes in different climatic zones.

1. Introduction

Indoor visual comfort is leading demand for building design. Light pipes transmit daylight via multi-reflections on highly reflective surfaces, thus having a possibility of natural light illumination of internal and windowless parts in buildings. The light tubes are subject of many research projects focused on theoretical modelling as well as experimental evaluations. For instance, the hollow light guides were analysed by Shao et al. (1997) who performed daylight measurements on the test box with light pipe installations. In his later study Shao (1998) has also determined luminous transmittance of the light pipes in dependence on the tube configuration and optical properties. The experimental research conducted by Oakley et al. (2000) was to monitor illuminance levels, while Elmualim et al. (1999) studied light pipes connected with a ventilation system.

A vast database of measured data would not be useful without numerical tools and models that both are necessary for successful prediction of illuminance levels under different light-pipe installations. Jenkins and Muneer (2003) developed a numerical tool for modelling illumination levels on a working plane below the bottom interface of a light pipe. They also compared a few of light-pipe prediction methods (Jenkins and Muneer, 2004) without giving any preference arguing that each method has its own advantages and disadvantages. However, some methods may suffer from distortion effects if optics of light beams is heavily simplified or even ignored. The light beams travelling through a pipe interact with a mirror reflective internal surface and lose their preferred direction, thus showing a complex light distribution curve. No doubt a performance assessment is a native attempt to evaluation of different light pipe systems. Zhang and Muneer (2000) has made a set of computations for overcast and clear sky conditions and introduced a daylight penetration factor that relates the internal illuminance to the external global illuminance. Of course, the efficiency of a light pipe depends on pipe photometry as documented by Rosemann et al. (2002) in Arthelio project experiments. The curve as well as the performance of the passive solar light pipe systems was predicted by Carter (2002), who later contributed to the field by 3-year experiments on practical installations of light pipes (Carter 2004; Marwaee and Carter, 2006).

An analytic solution to the problem was introduced by Kocifaj et al. (2008) who developed a tool called HOLIGILM – Hollow Light Guides Interior Illumination Method. The numerical implementation of the method was used first for the evaluation of straight light pipes (Kocifaj,

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2009) and then in modelling a bended pipe (Kocifaj et al., 2010). A general need for optimized design of ducted daylight systems (Robertson et al., 2010) has been a motivation for a targeted study on the availability of luminous flux below a bended light-pipe (Kocifaj et al., 2012). This study has documented that the light transmission efficiency increases if an upper tube is slightly deflected from the sun. Schou (2012) has investigated the algorithms for the progressive photon mapping and stochastic progressive photon mapping methods. His results and also the results from EnergyPlus (Malet-Darmour et al, 2014) were both compared against HOLIGILM.

Recommendations for zenith systems and light pipes have been issued in the document CIE 173 Tubular Daylight Guidance systems (2012) that also introduces a simplified light guide efficiency method. However, a reasonable predictions under different exterior conditions can be only made using accurate tools that incorporate the physics of beam propagation in its complexity. Results of research focused on the performance prediction of tubular daylighting devices (Laouadi, 2013) show in-depth look inside tubular daylight devices.

A comprehensive evaluation of straight-pipe efficiency is presented in this article for different sun elevations. The wide scope evaluation for different sky types and locations would be useful for specification of differences among light pipe designs. Light pipes contractors′ recommendations for installation in buildings are very often based on data from local investigation. For this reason a holistic approach considering different sun positions in the light pipe evaluation is useful.

2. Computer simulations

The concept of straight vertical metal tube is commonly used in many types of buildings (office buildings, warehouses, etc.), and evaluations are focused on the determination of design recommendations for the light pipes applied in different climatic zones.

The HOLIGILM-based simulations are made here aiming to obtain the optical properties of different light pipes under different exterior conditions. Specifically, the input parameters to the modelling are as follows:

(1) latitudes: 0°, 20°, 40°, 60°.

15th January, 15th February, 15th March, 15th April, 15th May, 15th June, 15th July, 15th August all at the local time of 10:00 AM. The 15th day in each month was chosen to characterize the given period of time evaluated.

(2) sky models in accordance with ISO 15469:2004 (CIE S 011/E:2003):

model 7: Partly cloudy with a brighter circumsolar effect and uniform gradation
model 8: Partly cloudy, rather uniform with a clear solar corona
model 12: Very clear/unturbid with a clear solar corona
These models represent a wide class of situations in which the intense sunlight can make the interiors well-lit. Note that passive illumination systems mostly profit of high levels of natural light, thus the above models are of great practical importance and deserve to be assessed separately.

(3) optical properties of the light pipe components:

- luminous transmittance of a glass cupola: 0.92,
- luminous transmittance of a transparent diffuser 0.7,
- light reflectance of the tube 0.95,
- tube lengths: 1.8 m, and 3.6 m,
- tube diameter: 0.52 m.

The above parameters are typical for many installations (Darula et al., 2009; Mohelníková, 2008).

The light pipe diameter of 0.52 m is frequently used for roof applications because it is convenient for sufficient daylight transmittance and easy installation in buildings. Light pipes of very small diameters are not very efficient. On the other hand light pipes of large diameters suffer from big opening in roof constructions and associated difficulties in practical realizations. The length we have chosen in our numerical experiment is adequate to the light guiding system transporting daylight through one floor headroom height or loft spaces. The basic parameters that controls the transmission of light through a vertically oriented pipe, graphical representation of the model and the coordinate system are described in their full complexity in the paper by Kocifaj et al. (2008).

3. Results and discussion

A series of simulations were conducted to identify the performances of light pipe under different solar positions, sky conditions and light-pipe (LP) configurations. Two light pipes with diameter d = 0.52 m and lengths D = 1.8 m (LP1) and D = 3.6 m (LP2) are considered. The aspect ratios computed as d/D are A_p = 3.46 (for LP1) and A_p = 6.92 (for LP2). The simulations wave been made under 3 different CIE General Skies (specifically for sky types 7, 8 and 12) and for 32 solar positions with solar altitude (α_s) ranging from 5.2° to 62°. The luminous transmittance, asymmetry parameter and indoor illuminance distribution for LP1 and LP2 are analyzed below.

3.1. Luminous transmittance

Luminous transmittance is known as the efficiency of light pipe system. It is expressed as a ratio of emitted luminous flux from the light pipe diffuser to the total light flux entering the transparent dome at the upper interface of the light guiding system. The transmittance of the light pipe strongly depends on both the position of sun disk and sky condition.

The luminous transmittance as a function of solar altitude was determined numerically for LP1 and LP2 under the CIE Standard Skies No. 7, 8 and 12. The data computed for sky type 7 tends to demonstrate greater similarity to that for sky type 8 (see Fig. 1). The transmittance ranges from 48% to 65% for LP1 and from 64% to 78% for LP2. The coefficient of variation (CoV) shown in Table 1 is expressed as standard deviation over the mean luminous transmittance for the two light pipes. A high value of CoV implies the transmittance would vary significantly. A light pipe with a low A_p usually has a low CoV. The CoVs for LP1 are 5.4% and 7.1% under Skies 7 and 8, respectively. For LP2, the CoV is 8.6% for Sky 7 and 11.2% under Sky 8. High value of A_p indicates the number of reflections is large, thus resulting in a low luminous transmittance value. Such phenomenon is more noticeable for clear skies. Under Standard Clear Sky 12, the CoVs for LP1 and LP2 are 13.9% and 21.3%, respectively. Therefore, CoV exhibits a strong correlation with the direct sunlight that dominates clear skies.

It is also important to analyze the light pipe luminous transmittance for different values of A_p, i.e. for different LPs. Note that LP1 is for A_p = 3.46, while LP2 is for A_p = 6.92. Fig. 2 depicts the transmittance ratio (LP2/LP1) as a function of solar altitude α_s for sky types 7, 8 and 12. The luminous transmittance for a longer pipe shows similarities for sky types 7 and 8, likewise it is shown in Fig. 1. The luminous transmittance ratio is between 75% and 85% for most of the sun positions. Since Sky 8 has a more distinct solar corona with a higher direct sun illuminance than those of Sky 7, the transmittance ratio for Sky type 8 is slightly below that for Sky type 7. The number of internal reflections in a tube reduces as α_s increases from 23° to 62°. As a consequence, the minimum luminous transmittance ratio is fount at α_s = 23°. As the α_s drops from 23° to 5°, the direct sun component decreases quickly, meaning that the transmittance becomes less important and the variation of the transmittance ratio is not substantial.

For CIE General Sky 12, the relative change of luminous