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Experimental analysis of a scaled, multi-aperture, light-pipe, daylighting system

David M. Kennedy [a], Fergal O'Rourke [b,*]

[a] School of Mechanical and Design Engineering, Dublin Institute of Technology, Bolton Street, Dublin 1, Ireland
[b] Department of Electronic and Mechanical Engineering, Dundalk Institute of Technology, Dundalk, Co. Louth, Ireland

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Abstract

This paper presents a daylighting experimental analysis of a novel vertical light-pipe which incorporates side apertures serving multiple levels to a deep-plan building. A light-pipe system that serves three floors has been developed in which the ground floor is illuminated via a light-pipe by a conventional ceiling mounted diffuser while the first and second floors are lit with daylight outlets on the sidewalls. Illuminance at each level of the three storey building relative to a work plane height, as well as the distance from the luminance source have been determined. The relationship between illuminance level on the work plane and the aperture area for different vertical apertures has been found and the results are presented. To determine the ratio of aperture opening area, A_o, to the work plane height, H_{wp}, that produces the same illuminance at representative points on a desk at each level, a 1:13 scale model was built to avoid sensor sensitivity problems. A 75 mm-diameter tubing was used to construct a scaled-model designed to emulate the largest 1000 mm-diameter light pipe available, yielding the largest aspect ratio, and thus light transmission at a scale of 1:13. Experiments with outdoor illuminance levels of 11,000 and 14,000 lux gave illuminance at specified reference points of 532 and 80 lux respectively. Importantly, the methodology used in this research can be adopted by architects and building engineers when developing case-specific designs or redevelopment of existing buildings.

Keywords: Light-pipe; Daylighting; Illuminance

1. Introduction

The UK and Ireland has an over-reliance on fossil fuel imports to meet energy demand (O'Rourke et al., 2009). The issues associated with combusting fossil fuels have led to alternative measures being developed in how energy is being delivered and consumed, namely energy conversion technologies and energy management techniques (Canziani et al., 2004). Efficient energy management practice, particularly in buildings, has grown over the past decade, with architects and engineers opting for techniques to reduce the energy consumed within a building (Tsangrassoulis et al., 2005). Throughout the 1990s the demand for deep-plan air-conditioned and artificially-lit buildings expanded rapidly across the UK and Ireland. Furthermore, these buildings can consume, on average, twice as much energy as narrow-plan buildings (Building Research Energy Conservation Support Unit, 1993; Steamers, 2000). Artificial lighting accounts for approximately 16% of total energy consumption of buildings and

* Corresponding author. Tel.: +353 4293 70200x2695.
E-mail address: fergal.orourke@dkit.ie (F. O'Rourke).

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Nomenclature

A_o	aperture opening area (m^2)
θ	angle from the reference illuminance point to the normal of the work plane (°)
A	area (m^2)
α	angle of light intensity to the normal of the work plane (°)
A_r	reference area (m^2)
C	illuminance reference point in the work plane
d	distance between a point light source and a point where illuminance is measured (m)
v	distance between a point light source and a point directly below the light source, where the illuminance is measured (m)
w	distance across the work plane normal to the vertical aperture (m)
D_F	daylight factor (%)
E	illuminance (lux)
E_r	reference illuminance (lux)
H_{wp}	work plane height (m)
I	point source intensity (cd)
P	reference luminance point source (cd/m^2)
S	aperture area scale factor
F	illuminance flux (lm/m^2)

Suffixes

1	first set of measurements
2	second set of measurements
FF	first floor
GF	ground floor
HA	horizontal aperture position
SF	second floor
o	outside
VA	vertical aperture position

up to a third of total heat gains in open-plan offices (Samuels and Prasad, 1994). This translates to 34% of the energy consumed for typical air-conditioned offices in the UK and Ireland (Steamers, 2000). Furthermore, with the limitations of natural resources and the development of new lighting technologies, energy consumption and utilisation has become a topical issue (Jenkins and Muneer, 2003). Daylighting is an effective and efficient sustainable approach to reduce the need for artificial lighting in buildings. Daylighting can be defined as introducing natural light to a building (Sharp et al., 2014). Daylighting technologies are generally divided into three categories: skylights, light-pipes and solar concentrators/collectors.

The use of daylighting technologies reduces the energy consumption of building while improving the quality of visual comfort and health (Li et al., 2010). Numerous studies have shown that daylighting systems provide a solution to illuminate deep-plan buildings and provide increased energy efficiency in addition to physiological benefits (Hamzah et al., 2003; Paroncini et al., 2007). The light-pipe or light-tube has become popular in the development of daylighting technology. Moreover, the technology is an efficient method of transporting light to areas of a building with limited daylight exposure (Baroncini et al., 2010).

The aim of this research is to design, develop and evaluate a natural lighting system for deep-plan buildings to make use of the daylight available during working hours and thus reduce energy consumption. Importantly, this paper presents the findings of the performance evaluation of a scaled-model light-pipe. The findings presented in this paper can be used to develop sophisticated natural lighting control strategies for building design.

1.1. State-of-the-art

A case study on an atrium building showed that continuous daylight-linked controls resulted in 46% annual savings in electrical-lighting energy consumption (CIBSE, 1991). It was also found that integrating an exhaust-ventilation-duct concentric to a light-pipe, with the annular volume, forming the natural ventilation stack has been shown to provide both sufficient daylight and exhaust ventilation for buildings (Atif and Galasim, 2003; Elmualim et al., 1999). Bouchet and Fontoynont (1996) reported that by using specular reflectors, light may be transmitted to depths of 10–15 times the width of a light well (Bouchet and Fontoynont, 1996). However, the use of diffusing reflectors reduces the transmission depth to just four times the width of the light well. Tests carried out on light-pipe ventilation stacks in the UK show luminance losses of typically 98–99% as the light travels from the clerestory inlets to room outlets just 10 m below due to dull white surfaces, poor inlet design, and low aspect ratios (Bouchet and Fontoynont, 1996).

A number studies, based on the performance and analysis, have been undertaken for hollow mirror light-pipes and atria. Critically, all of these systems were hollow light-pipes with only one emitter at its base (Carter, 2002; Edmonds et al., 1995; Jenkins and Muneer, 2003; Kristl, 1994; Oakley et al., 2000; Shao et al., 1998b; Zhang and Muneer, 2000). It was found that for multi-storey buildings several light-pipes are generally required one for each level. Zastrow and Wittner (1986) presented a conventional mirror light-pipe system that has a continuous side opening slit, for artificial lighting applications including lighting shops, railway stations, and industry (Zastrow and Wittner, 1986). In a different study, AyersBeng and