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Analysis of the experimental performance of light pipes

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ABSTRACT

Light pipes can provide daylight and improve lighting conditions in buildings. Knowledge of their optical performance is a prerequisite for their successful integration into buildings. This article presents and analyses the experimental performance and the specific efficiency characteristics of a light pipe as integrated into an experimental test-cell. Extensive measurements are performed for eight continuous months under clear, cloudy and intermediate sky conditions. The spatial and temporal variability of the indoor illuminance is analysed using clustering techniques. It is found that there is an almost exponential relation between the average and the maximum indoor illuminance with the exterior illuminance levels. In parallel, a strong spatial inhomogeneity is observed under all sky conditions. The transmissivity or Daylight Penetration Factor of the light pipe is found to present a strong daily variation during the clear days while it was almost constant under cloudy sky condtions. A clear correlation of the light pipe's Daylight Penetration Factor is found against the solar azimuh and solar altitude especially under clear sky conditions.

1. Introduction

Passive zenithal light guides, commonly referred to as light pipes, are the most widely known and commercially available type of light guidance systems, used for channeling daylight in parts of interiors with no or little daylight availability from windows. Light pipes consist of an external element which collects daylight and sunlight and is usually a transparent dome, the guide, made from a highly reflective metal sheet which transports light and a diffuser or other means of light distribution element. Other variations of daylight guidance systems include the zenithal type with active collection and the horizontal guide systems, where the collector is integrated in the building façade [1].

The study of the performance of light pipes started on the 1980's, when the daylight guidance systems were considered to be innovative. Since then, many scientists have experimented with the various components of the system and have even integrated other functions, such as ventilation. Shao and Riffat [2] have investigated the possibility of combining light pipe technology with natural stack ventilation and solar heating by integrating the light pipe with an air stack and passive heat pipes. Canziani et al. presented a horizontal light pipe, with a trapezoidal shape and with an active reflector which followed the sun rays, depending on the season and the time of the day [3]. Their study showed that the system can increase the daylight levels in the deepest parts of side-lit spaces and it can also improve uniformity. Baroncini et al. proposed a double light pipe, consisting of an internal tube similar to that of common light pipes and an external transparent tube, which enables the flow of daylight in the spaces that the tube meets until it reaches the lowest floor [4]. Kennedy and O'Rourke studied the possible usability and the performance of a light pipe with apertures on the tube, in the appropriate positions in order to allow daylight flow in various floors [5]. Gracia-Hansesn and Edmonds also studied the potential of light pipes lighting more than one spaces, in a vertical layout [6]. They designed and assessed an extractor system that provides equali lighting levels in the various levels of a building.

However, the experimental analysis and the calculation of the performance of common passive zenithal light guides has been the main subject of research on this scientific field. Zhang and Muneer in 2000 [7], used data from a real application in Scotland, to produce two models for the calculation of the illuminance due to a light pipe. They reported that the parameters that influence the performance of a light pipe with specific characteristics (diameter, length,

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Nomenclature

DPF	Daylight penetration factor
Kd	Diffuse solar radiation clearness index
AC	Air conditioning
LED	Light emitting diode

reflectances, etc) are the sky clearness index, the position of the sun in the sky and the distance between the diffuser and a specific point in the studied space. The term "daylight penetration factor" (DPF) of light pipes was introduced in the same paper, which describes the relation of the internal illuminance due to a light pipe, with the total external illuminance, in accordance to the widely used term of Daylight Factor. Later, in 2003, Jenkins and Muneer proposed a semi-empirical prediction method for the calculation of light pipe performance under overcast sky conditions [8]. P.J. Carter in 2002 [9] described a number of predictive methods for the performance of light pipes, based on real applications. The measuring of the luminous intensity of a light pipe enabled the construction of a polar curve which shows that light pipes can be simulated as flush mounted luminaires. Based on that principle, Vasilakopoulou et al. [10], produced simple relations for the average interior illuminance for various light pipe diameters. Li et al. [11] have also studied the experimental performance of light pipes, this time in the sub-tropical climate of Hong-Kong, with good results on the levels and the uniformity of the resulting lighting environment. Other similar studies describe the light pipes' performance in Korea [12], in Beijing [13], in Instanbul [14] and in Jordan [15].

Presently, experimental data have been used and processed in order to identify the decisive parameters that affect the light pipe performance in mediterranean climates.

2. Experimental set-up

The experiment described in the following paragraphs was set up as a European Project deliverable. Apart from the light pipe the performance of which is analysed in this study, artificial lighting and daylight linked controls were also installed and the energy consumption of the integrated system was monitored. The artificial lighting equipment is only briefly described, to the extent to which it affects the natural lighting performance of the light pipe.

2.1. The test room

The experiment was conducted in a test room, which is a prefabricated, light-construction room, located in the campus of the Kapodistrian University of Athens (lat, long: 37.97, 23.79). The room is 5.76 m long by 2.75 m wide, with a height of 2.35 m. All the surfaces of a space of 4.00 m by 2.75 m inside this room were covered with black matte fabric, with a reflectance value lower than 0.1, in order to prevent intereflections and to avoid the need to measure the surfaces' reflectances. Even though the room has one window, this is also covered with horizontal fins and with the same black fabric, so as no light was coming through it. The ceiling of the room was painted black, with a matte paint, with a reflectance value of 0.1 approximately.

The light pipe has been installed in the center of this 4.00 m by 2.75 m space. The space below the light pipe is occupied by desks, with a height of 0.74 m. The desks are covered with the same black fabric, as the one covering the walls.

Because of the construction material of the room (from outside: metal plate, 5 cm of insulation, plastic interior surface), the temperatures inside the test room can be relatively high, especially during the summer months. An air-conditioning unit that was switched on when the temperatures went over 40 °C, or when someone was inside the room, was installed, mainly to protect the artificial lighting equipment. The AC unit is the only element inside the room with a light colour (white).

Fig. 1. The test room.

Fig. 2. The layout of the illuminance sensors.

The test-cell is located in a rural environment, surrounded by low plants and a few trees that do not shade the light pipe dome (Figs. 1 and 2).

2.2. Measuring equipment

Thirteen sensors measuring illuminance were placed on the desks, inside the test-cell, in the layout that is shown in Fig. 3. The distance of the peripheral sensors is about 50 cm from the curtains that cover the room walls. The largest horizontal distance between a sensor and the center of the diffuser is 1.75 m, approximately. The sensor that measures the exterior illuminance is placed horizontally on the roof of the room, on an unobstructed spot. The silicon head was regularly cleaned, in order to avoid loss of performance. The characteristics of the illuminance sensors are presented in Table 1.

All the illuminance sensors are connected to a data logger, which takes measurements every 15 s and records average, maximum and minimum values every minute. Temperature is also recorded every minute from a sensor placed inside the data logger case. The data logger is connected to a multiplexer and a wireless modem, making the data retrieval from a distant computer possible.

The measurements started on the 28th of November 2014 and continued for eight months, until the 7th of August 2015.