A Study of Performance of Light Pipes Under Cloudy and Sunny Conditions in the UK

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ABSTRACT

This paper presents results of an experimental study on the performance of a light pipe in winter under the climatic condition of the UK. A light pipe with top dome and light-distribution diffuser was installed in a model-scale building. The specular interior surface of the 330mm diameter light pipe has a minimum reflectance of 95% and the reflectance of the model interior can be changed by adopting white, grey and black surfaces. The performance of the light pipe was tested in November, which is in the worst season for daylight, and for overcast and sunny conditions. Both the ratio of interior illuminance to outdoor illuminance and the absolute illuminance inside the model were measured. A typical value of illuminance ratio for a white interior was 14% under a cloudy sky and 7% for sunny conditions. The lower value of the latter is probably due to the low altitude of the sun in the month of the experiment. The absolute illuminance measured under the two conditions were 1600 and 2200 lx, respectively. In a zone of 3¥3m fitted with the same light pipe, the illuminance would be reduced to 100-140 lx. This may still represent a potential energy saving of 30% and the value will increase significantly towards the summer months.

INTRODUCTION

Increased global warming and deterioration of the ozone layer has stimulated interest in use of renewable energy systems. Daylighting is increasingly employed in modern buildings, underground spaces and tunnels to minimise energy consumption and release of harmful emissions to the environment. Innovative daylighting techniques including lightshelves, prismatic glazing, holographic films and light pipes have facilitated the effective use of daylighting in a wide range of spaces [1-8]. In addition to bringing energy savings, these daylighting technologies also help to create healthier interiors for occupants. Bouchet [5] suggested that as little as 50 lx of daylight may provide significant relief of the feeling of isolation for people working in underground spaces. Natural daylight has also been found to relieve seasonal affective disorder, cholesterol problems, chronic fatigue, jet lag as well as benefiting people in shift work and computer VDU work [9, 10]. The improved psychological well-being would lead to increasing morale, work performance and productivity [9]. It was reported that students attending a daylit school achieved better examination results (14% higher marks) and higher attendance rates compared to those in non-daylit schools, including newly built non-daylit schools. [11]

This paper presents an experimental study of daylighting performance of the light pipe under the climatic conditions of the United Kingdom. The light pipe is a simple and effective daylighting device used widely in North America and Australia but has so far found limited acceptance in the UK (and Europe). One of the main obstacles to its wider application is the belief held by some people that the light pipe would provide little light under the often cloudy skies in the UK. Despite this sceptical perception, light pipes have been applied to a range of buildings in the UK, including residential buildings, education buildings and commercial office buildings. The initial feedback from the occupiers, owners and designers of these buildings has been very positive and a field monitoring programme has been planned. The experiments reported in this paper aimed to provide quantitative performance information to architects, building services engineers and researchers.

THE LIGHT PIPE

The light pipe, lined with highly reflective material, is used to guide sunlight and daylight into occupied spaces (Figure 1). Highly reflective materials include anodised aluminium and coated plastic film such as Silverlux, which have reflectances greater than 95%. Commercial light pipe are available from a number of manufacturers, in straight and bend sections for on-site assembly and installation. They allow the light pipe to go through complex roof spaces to reach rooms that are not easily accessible to skylights. A light pipe is normally fitted with a clear top dome which removes harmful UV radiation and prevents the ingression of rain water and dust. A diffuser fitted to the bottom of the light pipe ensures that light is distributed around the room it illuminates. Compared to skylight or windows, the light pipe transmits less solar heat on to the illuminated surfaces. This is particularly valuable in summer for preventing inhabitable hot spots in a building. In winter, a light collector (e.g., a sun-scoop) could be mounted above the top opening to allow significantly more sunlight from low angles to be collected.

The light transmitting performance of the light pipes is given by Swift and Smith [8]:

$$T = \frac{4}{\pi}\int_{s=0}^{1} \frac{s^2}{\sqrt{1-s^2}} R^{\mathrm{int}[p\tan\theta/s]} \left(1-(1-R(p \tan \theta / s - \mathrm{int}\{p \tan \theta / s\})\right) ds \quad (1)$$

where:

T = transmitance of the light pipe = ratio of the amount of transmitted light to that of the incident light

R = reflectance of the interior surface of the light pipe

p = aspect ratio of the light pipe = ratio of the light pipe length to its diameter

θ = angle of incident light = angle between the incident light and light pipe axis

int = integer function; e.g., int[a] = the integer less than or equal to a.

The above equation is based on the assumption that the surface reflectance is independent of light incident angle and wavelength. Transmission calculation for surfaces which do not have this characteristics can be found in [8]. Equation 1 is not integrable and the transmitance of light pipes have to be obtained using numerical techniques. The results obtained by Edmonds et al [4] indicated that the transmitance of a light pipe is critically dependent on the incident light angle, the reflectance of its interior surface and its aspect ratio.

A simpler equation [12] is also available which may be used to obtain an estimation of the transmitance of a light pipe:

$$T = R^{l \tan\theta / d_{eff}} \quad (2)$$

where:

l = length of the light pipe

d_{eff} = $\pi d/4$

= diameter of the light pipe.

Measurement of light pipe performance carried out in Australia has shown that an illuminance of 300 lx can be achieved in a room of 3x3x2m fitted with a single light pipe of 255mm diameter without using any device to enhance light collection [4]. The aspect ratio of the light pipe, the reflectivity of the interior surface and the solar altitude were 7, 95% and 60° respectively. The corresponding external illuminance value was not reported. Information on light pipe performance in Europe is limited. Bouchet and Fontoynont [5], in France, analysed performance of light wells lined with a specular and highly reflective material using a Monte-Carlo based ray-tracing technique. Their computer simulation predicted a minimum illuminance of 100 lx for over 70% of the period between 9am and 6pm under overcast conditions. The corresponding external illuminance had a minimum value of 10,000 lx. The simulation was based on a light well of 1x1x6m, which was sealed at the top using glass blocks with a transmission of 0.6 and had a glare reduction cover. The separation between the light wells was 4.5 m.

The attractiveness of the light pipe, compared with skylights, lies in its flexibility in going through roof spaces, lower heat loss during the winter season, more uniform light distribution and its potential for application in multistorey buildings (using large diameter pipes). Interiors with only side windows are often perceived as gloomy even on sunny days when there is sufficient indoor daylight. A light pipe would reduce the luminance contrast between the room and the bright exterior thus reduce the possibility of occupants resorting to electric lighting to correct the perceived gloom.

EXPERIMENTAL ARRANGEMENT

The experimental set up is shown schematically in Fig. 2. A light pipe produced by the SunPipe Company inc. was mounted to the top of a sealed light box. The cylindrical light pipe has a length of 1.2 m and a diameter of 330 mm. A highly reflective film is laminated, using adhesives, to the interior surface which has a minimum reflectivity of 95%. The top of the pipe was sealed with a clear anti-yellowing acrylic dome. A pearl white diffuser was fitted to the lower opening of the light pipe for even light distribution within the light box. The box, 0.7x0.7x0.5m, was constructed using plywood and had removable side panels for easy access to the interior. The reflectance of the internal surfaces could be changed by lining them with white, grey or black paper to allow the effect of reflectance to be evaluated. Wheels were fitted to the light box to facilitate the daily transfer of the rig between its indoor storage to the test site on an open field.

Illuminance measurement was carried out using a Megatron DA10 light meter which had a range of 0.05-100,000 lux . The meter was based on a Selenium photovoltaic cell which has a spectral response very similar to that of a standard human eye thus avoids the need for correction for various types of light sources. Cosine correction was by means of a clear perspex dome, which produced zero error up to a incidence angle of 65°. For the solar angles around noon in November in Nottingham, the error produced was approximately 5%.

Illuminance of the sun on the open field and that within the light box were obtained using two separate photocells. The readings were recorded manually and cares were taken to ensure that there was no passing clouds or other significant changes of lighting condition between reading the two cells. The photocell within the box was normally placed in the centre of its floor. It was also placed in various other locations within the box to examine spatial distribution of illuminance. These include the corners of the floor, centre of the side walls and corners in the ceiling.

The measurements were carried out on a patch of grass field away from major buildings to minimise the amount of reflected light reaching the light pipe. The field had trees to the south and west and parapet walls to the north and east. The trees to the south were sufficiently low to allow direct sunlight to reach the light pipe. Although the trees to the west were fairly high, they did not block direct sunlight at the time of the tests and their effect on diffuse skylight is small. It was estimated that the light pipe would receive all direct sunlight and 95% of diffuse sky light. There was also a temporary building close to the north parapet wall and its external facades and other surfaces around the field visible from the light pipe had dominantly low reflectances.

The measurements were made around noon during November to monitor the performance of the light pipe under both cloudy and sunny conditions. In addition, the effect of surface reflectance on illuminance levels and the distribution of illuminance within the light box were also examined.

RESULTS AND DISCUSSION

Table 1 shows a set of reading taken under overcast conditions. The external illuminance at noon reached 11,500 lx which is very low even for November. The corresponding illuminance inside the measurement box with white interior was 1600-1700 lx, representing approximately 14% of the external level. If the light pipe were fitted to a room of 3x3x2m, i.e., 4 time larger in all three dimensions than the light box, the transmitted light would be spread to an area 16 times larger and the resultant light level would be approximately 100 lx. This would still represent a potential energy saving of 20-30% depending on the design illuminance of the room (350-500 lx) and the saving would increase substantially towards the summer months when the available daylight would be up to 8 times higher.

Data for black interiors in Table 1 shows that the internal illuminance was more than 3 times lower than that for a white interior and the values for the grey interior are similarly low with internal/external illuminance ratios of about 5. In addition, the internal illuminance on black surfaces decreased from 600 to 580 lx while the external level increased from 12,000 to 19,000 lx. The measurement error was probably due to cloud movement which was less noticeable against a cloudy sky. Although significant errors like this happened only once during the test, it illustrates the necessity of simultaneous reading, using data loggers rather than manual recording, of illuminances at multiple points under a fast changing sky, which is not uncommon in the UK. To minimise the effect of errors in individual readings, average values of three separate readings were calculated and presented in the tables.

Figure 2 shows the performance of the light pipe under sunny conditions. Clear sunny skies did not occur frequently in November in the UK thus skies with scattered thin clouds were deemed acceptable for this measurement. The external illuminance increased to about 30,000–40,000 lx but the internal level increased by a much smaller rate to about 2,200 lx. The internal/external illuminance ratio actually decreased substantially to 7–8%. This lower value is probably due to the low altitude of the sun in November. In contrast, diffuse light from an overcast sky originates mostly from the area around the apex of the sky and therefore would pass through the light pipe with fewer number of reflections and less loss. The effect of internal surface reflectance was similar to that found under an overcast sky: the internal illuminance falls by more than 3 times.

Monitoring of illuminance in the light box showed that its distribution was uniform on the floor for white, grey and black interior surfaces. As a result, only one photocell placed in the centre of the floor was used for measurement of horizontal illuminance. It was also shown that illuminance was virtually uniform on all surfaces of the light box for the white interior but illuminance decreased significant on the ceiling and the side panels for grey and black interiors.

Table 3 shows the effect of interior reflectance of the light pipe on light transmission. The light pipe was lined with grey paper which resulted in a reduction of interior illuminance to a negligible level: 0.36% of the exterior illuminance.

CONCLUSIONS

The performance of a light pipe was tested in November for cloudy and sunny conditions. Both the ratio of interior illuminance to outdoor illuminance and the absolute illuminance inside the light box were measured. A typical value of illuminance ratio for the white interior was 14% under a cloudy sky and 7% for sunny conditions. The lower value of the latter was probably due to the low altitude of the sun at the month of the experiment. The absolute illuminance for the two conditions were 1600 and 2200 lx, respectively. In a zone of 3x3m fitted with the same light pipe, the illuminance would be reduced to 100-140 lx. This may still represent a potential energy saving of 30% and the value would increase significantly towards the summer months. It was also found that the reflectance of the interior surfaces had a pronounced effect on internal illuminance.

Table 1. Light pipe performance under cloudy conditions.

Internal Surface	External Illuminance(lx)	Internal Illuminance(lx)	Internal/External Ratio
WHITE	12000	1600	13%
	11500	1700	15%
	11500	1600	14%
average	11667	1633	14%
BLACK	16000	600	4%
	12000	600	5%
	19000	580	3%
average	15667	593	4%
GREY	13800	750	5%
	14000	740	5%
	14000	730	5%
average	13933	740	5%

Table 2. Light pipe performance under sunny condition.

Internal Surface	External Illuminance(lx)	Internal Illuminance(lx)	Internal/External Ratio
WHITE	32000	2200	7%
	26000	2200	8%
	31000	2200	7%
average	29667	2200	7%
BLACK	36000	680	2%
	44000	680	2%
	44000	680	2%
average	41333	680	2%

Table 3. light transmission in ligh tpipe with low reflectivity.

Internal Surface	External Illuminance(lx)	Internal Illuminance(lx)	Internal/External Ratio
GREY	11000	40	0.36%
	11000	40	0.36%
	11000	38	0.35%
average	11000	39	0.36%

An extended programme of light pipe experiments is underway at the University of Nottingham and monitoring of light pipes installed in a range of UK buildings will also be carried out. Results of these investigations will be reported in future publications by the authors. ●

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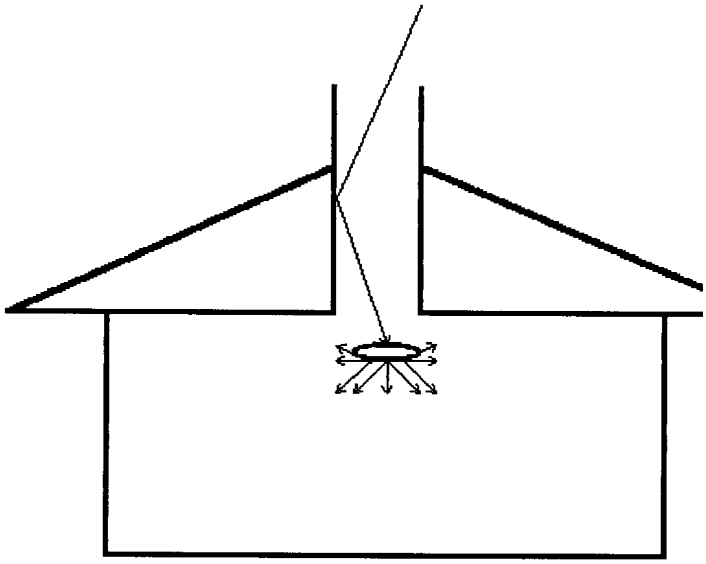

Fig.1. Light Pipe for daylighting of buildings.

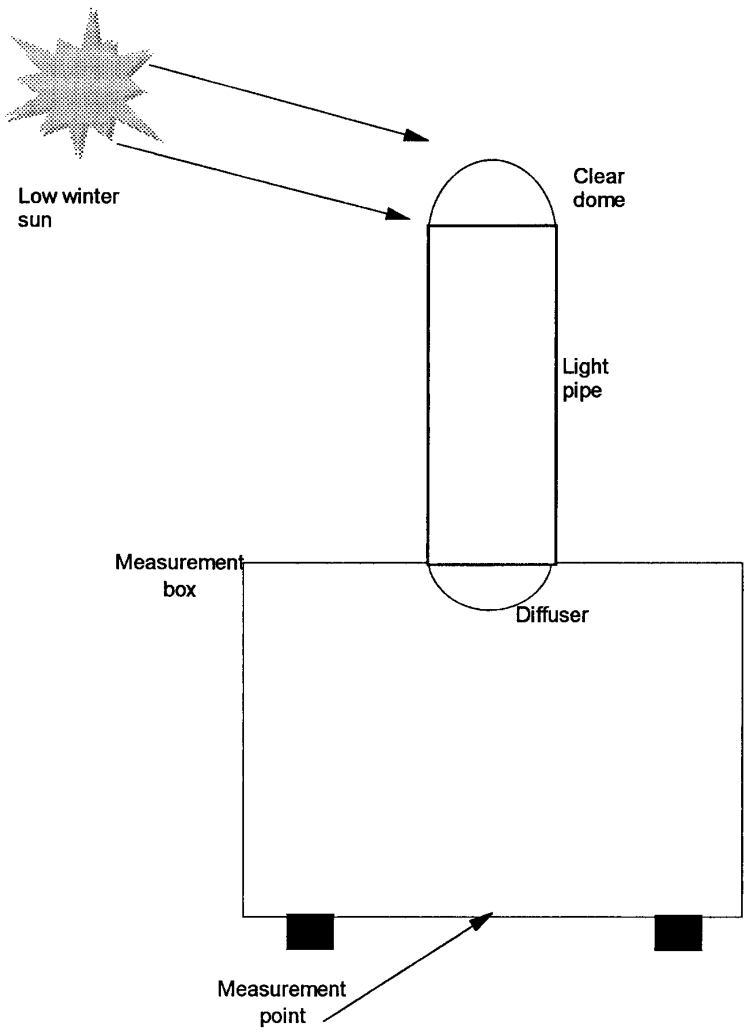

Fig. 2. Light pipe performance under cloudy conditions.

Lighting & Daylighting Systems and Applications