Lighting Res. Technol. 34,1 (2002) pp. 39–52

The measured and predicted performance of passive solar light pipe systems

DJ Carter MSc PhD CEng FCIBSE FILE FSLL
School of Architecture, University of Liverpool, Liverpool, UK

Received 06 January 2001; in final form 23 May 2001

Passive hollow tubes consist of a light pipe transport section with, at the upper end, some device for capturing natural light and, at the lower end, a means of distribution of light within the interior. The wider use of the systems is currently limited by the lack of quantitative design methods other than those based on empirical data. This paper presents results of laboratory and field measurement of luminous flux output and luminous intensity distribution for various configurations of passive solar light pipes. The results indicate quantitative performance and form the basis of a number of methods of performance prediction for a wide range of passive light pipe system configurations.

1. Introduction

Over the past few years considerable research has been undertaken on the use of light pipes as transport devices or light emitters in buildings. The majority of systems in use employ electric lamps or sun tracking devices as light sources and thus rely on expensive equipment to capture, transport and distribute light. Recent interest has focused on passive light pipes as a means of lighting interiors. These devices operate according to the same physical principles as electric or sun tracking systems to transport and distribute light but, due to their simplicity, are cheaper to construct and maintain.

Passive hollow pipes consist of an essentially vertical light pipe transport section with, at the upper end, some device for capturing natural light whilst preventing ingress of wind and rain and, at the lower end, a means of distribution of light within the interior. The upper end of the tube may be horizontal or inclined at some angle to the tube axis. The tube is lined with highly reflective silvered material but contains no lenses or other devices to redirect the light. The hollow tube wall uses multiple specular reflection at the inner wall to transmit light. In general terms overall light transmission is a function of surface reflectance, input angles of the incident light, and the proportions of the tube in terms of the ratio of length to diameter (aspect ratio). If the light paths are long compared with the axial length the number of reflections are necessarily large, and light loss therefore depends to a great extent on reflectance of the wall material. To minimize the number of reflections light should enter the tube as a near collimated axial beam.

A number of passive pipe systems are commercially available. They consist of a clear polycarbonate dome, rigid or flexible tubes coated with a reflective material, and a light diffuser made of opal or prismatic material. Rigid tubes may include bends or elbows. A modification to the basic systems cuts the upper end of the tube at an oblique angle and inclines the cut toward the equator. This ‘light scoop’ has the effect of increasing the luminous flux output of the tube by a factor to up to two under clear sky plus sun but has a negative effect on output under overcast conditions.

Address for correspondence: DJ Carter, School of Architecture and Engineering, Leverhulme Building, Abercromby Square, Liverpool L69 3BX, UK. E-mail: eb09@liverpool.ac.uk

 10.1191/1365782802li029oa

A number of studies of passive pipe systems have produced empirical performance data for particular cases of system configuration and local daylight conditions, and this data may be applied to design of similar systems. The studies indicate that passive pipe systems have considerable potential as a primary light source for some types of building interior.

This paper presents results of luminous flux output and luminous intensity distribution for configurations of passive solar light pipes, based on laboratory and field measurements. As well as indicating quantitative performance of passive light pipes, analysis of the results enables prediction of performance of a wide range of system configurations.

2. Passive light tubes as a lighting solution

The first theoretical work on mirrored pipes by Zastrow and Wittwer[1] established an approximate expression for light transmission of a pipe of arbitrary cross section:

$$T = R^{l \tan\gamma / d} \tag{1}$$

where R is the reflectivity of the pipe, l the pipe length, γ the angle of incident radiation with respect to the pipe axis, and d the effective diameter of the entrance aperture of the pipe. Subsequent work by Swift and Smith[2] established that this theory was generally limited to pipes having a low aspect ratio, high reflectivity, and near collimated incident light. In particular their work demonstrated the sensitivity of reflectance of mirror material to performance, with variations of as little as 0.1% causing noticeable changes in pipe performance. They also showed that transmission along a mirrored pipe could induce large variations in spectral properties of the light – that from silver coated pipes exhibiting a red shift and that from aluminium coated pipes being blue shifted.

Early investigations into performance of passive light pipes were made using both laboratory and field measurement. Love *et al.*[3] compared the transmittance of the transport section (not including collectors or emitters) of a number of commercially available mirror light pipes. The pipes were mounted above an integrating chamber and illuminance measured simultaneously within the integrator and externally, thus enabling the transmittance of various combinations of bends and straight pipe to be determined. Harrison *et al.*[4] measured nadir illuminance and simultaneous external illuminance from a single pipe under laboratory conditions. The results indicated that nadir daylight factor (inside/outside illuminance ratio) ranged from 0.5% for overcast skies to 0.2% for clear skies at a point 1.7 m below the pipe.

A field study enabled data for working plane and/or nadir illuminance and simultaneous external illuminance to be gathered for actual installations.[5] A further study extended this work to suggest basic information on light transmission properties of some configurations of pipe and on quantities of planar illuminance delivered under certain circumstances.[6] The published data on pipe transmission could with the addition of information on collectors and emitters make a possible estimation of luminous flux output. However, there appears to be no information on spatial distribution of light emitted from the systems. The above information could, with some difficulty, serve as 'rule of thumb' design guidance. This does not however address the problem of prediction of performance of installations that do not resemble those measured.

Some aspects of the thermal properties of passive light pipes have been investigated. Transmittance of infra-red radiation is generally of the same order of magnitude as visual radiation but the majority of ultra violet radiation is filtered at the collector.[7] The results of thermal resistance measurements produced an average value of 0.28 m^2 K/W – of the same order of magnitude as a double pane insulated roof-light.[4]

A range of prismatic materials are widely used as an alternative to mirrored materials as the light transmission medium in light pipe installations powered by electric sources.[8] These materials are generally not used in the type of systems described in this paper. Their characteristic is that they only accept light within a defined cone (usually 27.6 degrees) and although high transmissions can be obtained by total internal reflection for radiation from some incident directions, there may be very little from others. Since the range of incident directions necessarily utilized in daylight systems is large, and will include many angles from directions outside the acceptance cone, this may be seen as a major drawback. However there may be a case for investigating the use of these materials in passive pipe systems since; firstly although these materials only accept light from a narrow range of incident angles, daylight entering at near axial incidence is more efficient because it bounces less; secondly daylight from the zenith is likely to come from the relatively bright part of the sky, and thirdly buildings are commonly overshadowed meaning that in practice little horizontal light reaches the light-pipe collector in the first place.

3. Experimental investigation

The work investigated luminous flux output, luminous intensity, and planar illuminance distribution for a number of configurations of passive solar light pipes by a combination of laboratory and field measurement.

3.1 Equipment

An apparatus was designed and built, based on an optical length of 1 m, to measure luminous intensity in the γ plane for the quadrant 0°–90°. The apparatus was installed beneath a 330 mm diameter pipe in the roof space of the Mulberry Building (a general purpose teaching building) at Liverpool University (see Figure 1). Due to space restrictions the apparatus could be used only for pipe lengths 610 and 1220 mm and for two C-planes, namely, 0° and 30°. Light was measured using recently calibrated photocells connected to a datalogger which also recorded simultaneous external illuminance. The measurement area was blacked-out so as to prevent stray light affecting the cell readings.

Luminous flux output from the pipes was measured using a cubical box that approximated the characteristics of a photometric integrator. The box consisted of a hardboard cube 0.8 m long, with interior joints sealed and, coated on the inside with matt white emulsion paint. Three separate lids were constructed for the box with different sized holes in the centre to accommodate the three main sizes of pipe. A calibrated photocell, centrally mounted on a 20 cm bracket facing the base of the box was used to measure illuminance whilst acting as its own baffle to light directly from the source. The box was calibrated in the laboratory of a major lamp manufacturer using lamps of known output with each of the lids. The integrator is shown in Figure 2.

Data on nadir illuminance and luminous flux output was collected from 11 pipe configurations mounted in a 2 m × 1.5 m garden shed, which was lined with hardboard to prevent light penetration to the test area, and painted matt black (see Figure 3). The pipes were installed at roof level 1600 mm above the floor on which measurements were made. Matt black curtains were hung to separate each of the pipes to prevent them contributing to the measurements taken from adjacent areas, thus allowing the measurement of the direct component of illuminance at nadir. There was also a facility to black out any area in order to record data from combinations of pipes. The pipes were all 610 mm long and were of the following diameters: 200 mm, 330 mm, 450 mm and 530 mm.

3.2 Results

The apparatus described was used to measure luminous intensity from two 330 mm diameter pipes of 610 and 1220 mm length each equipped with opal diffusers. Readings were taken (not continuously) through the period September 1999 to November 1999 with the apparatus aligned South (C = 0°). For a period in December 1999 the apparatus was positioned for C = 30° (approximately SSE). Sky conditions for the period were predominately overcast or cloudy with external horizontal illuminance only exceeding 25 000 lux for about 10% of the readings. Using spreadsheet software the readings for

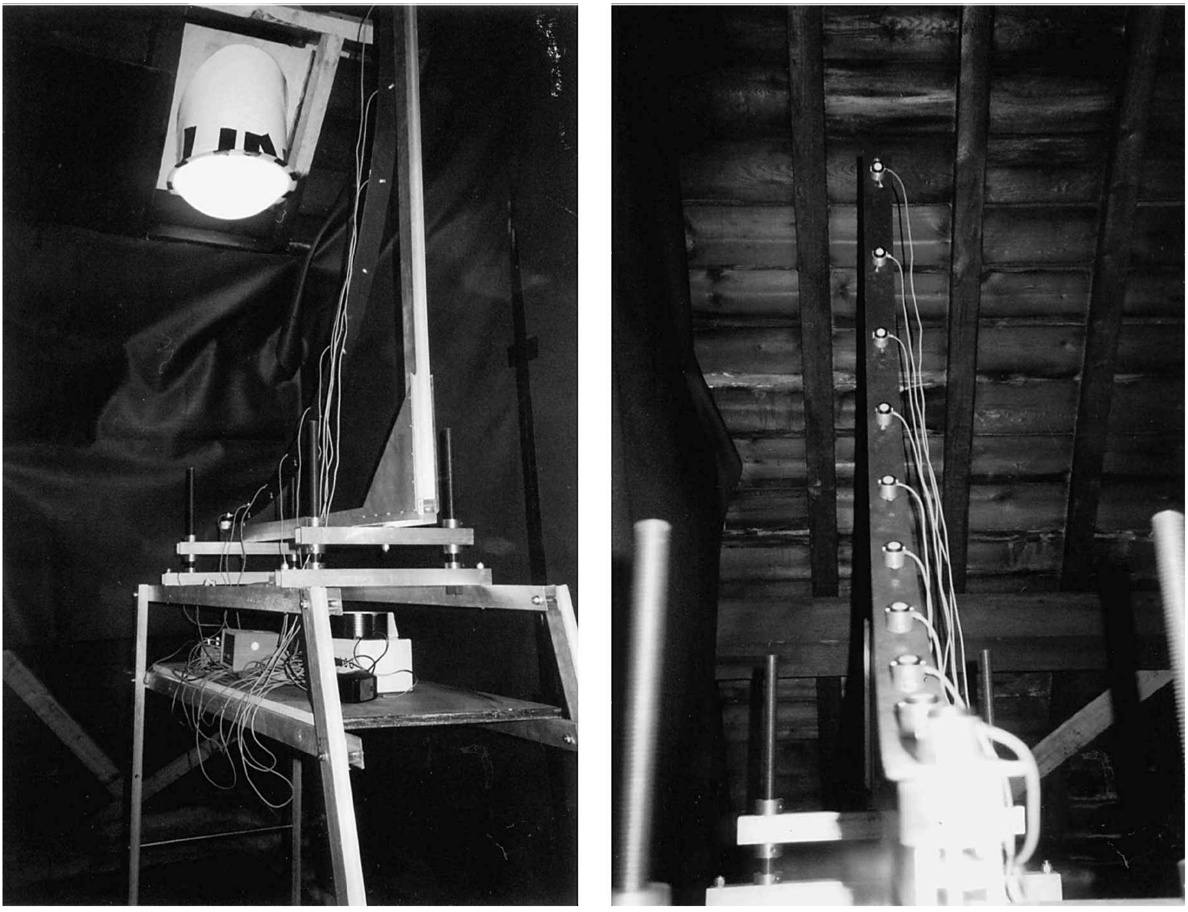


Figure 1 Apparatus to measure luminous intensity distribution from pipe emitter

the γ plane for the overcast and cloudy conditions were averaged and plotted on the same scale. The resulting polar curve, shown in Figure 4, applies to pipes of both lengths. Application of the same technique to the data for the 30° azimuth gave similar results.

Measurements of luminous intensity over a period of some 10 weeks produced a consistent pattern of distribution from a 330 mm diameter pipe under overcast and cloudy skies. The apparatus was used during the period June to August 2000 to investigate luminous intensity distribution for clear sky/sun conditions using the methods described above. A polar curve very similar to Figure 4 resulted for pipes of both lengths. A series of supplementary measurements were then made for clear sky/sun conditions for the pipe without the diffuser. The distribution in this case was skewed depending on sun position, a phenomenon previously noted in similar measurements for rooflights.[9] Since a diffuser is an integral part of generic passive pipe systems, Figure 4 is used for design purposes for either sky condition later in this work. No measurements of luminous intensity were made for pipes of other diameters, but since the geometry of pipe and diffuser are proportionate for other sizes produced by this manufacturer it has been assumed for subsequent work in this paper that the same distribution applies.

The integrator apparatus was used to measure pipe output luminous flux from two installations:

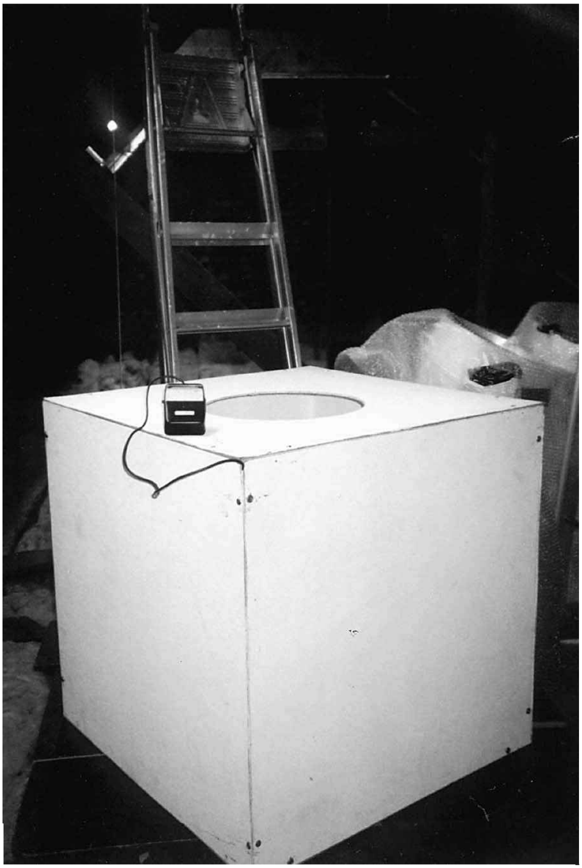


Figure 2 Photometric integrator for luminous flux measurement

the Mulberry Building and Pleasant Street School, Liverpool. The nadir illuminance at a vertical distance greater than five times the diameter of the emitter was also measured and used to calculate nadir luminous intensity for each pipe. Using this, total luminous flux output was calculated by the zone factor method for symmetric luminaires set out in CIBSE TM5.[10] The results, shown in Table 1, indicate differences between the data sets not exceeding 10% which may be considered within the acceptable accuracy of the essentially field measurement methods used in this work. Nadir illuminance can therefore be used for determination of luminous flux output for in locations where the use of the calibrated integrator apparatus is inconvenient.

The techniques of luminous flux measurement and calculation were used to investigate the relationship of pipe efficiency and aspect ratio for 25 pipes, variously of 330, 450 and 530 mm diameter, all lined with material having a specular reflectance of 95%. This data set consisted of measurements from the experimental installations illustrated in Figures 1 and 3, field measurements from Pleasant Street School and an office building, and data taken from Reference 3. Note that the latter were for aspect ratios 2.1, 4.6 and 8.4. Pipe input was calculated as a function of external horizontal illuminance and pipe cross-section area. Pipe output was either measured (Mulberry and Pleasant Street) or calculated as described previously.

Figure 5a shows attenuation of light output with aspect ratio under overcast skies for vertical pipe systems including a clear 'light capture' dome and an opal diffuser. The points that fall outside a 10% margin of experimental error are all from the field measurement of actual installations. All of the measurements from the 'test rig' installations described in Section 3.1 were within 10% margin of experimental error. Love *et al.*[3] produced measured pipe efficiency and aspect ratio for pipes lined with 95% reflectance material but without collector or diffuser and their results for overcast sky conditions are plotted on Figure 5b. This Figure also shows Love's values corrected for the transmission losses of collecting dome and diffuser used in the present work (respectively 0.88 and 0.6) and indicates agreement well within 10%. It would thus appear that this and similar graphs can be used to estimate luminous flux output for a given pipe configuration and sky condition.

4. Design tools

Prediction methods for passive light pipes can conveniently be broken down into two parts, the first being an estimation of the amount of light exiting the pipe system, and the second an analysis of the likely distribution of this light within the installation.

Figure 3 Test rig used for measurement of nadir illuminance and luminous flux output

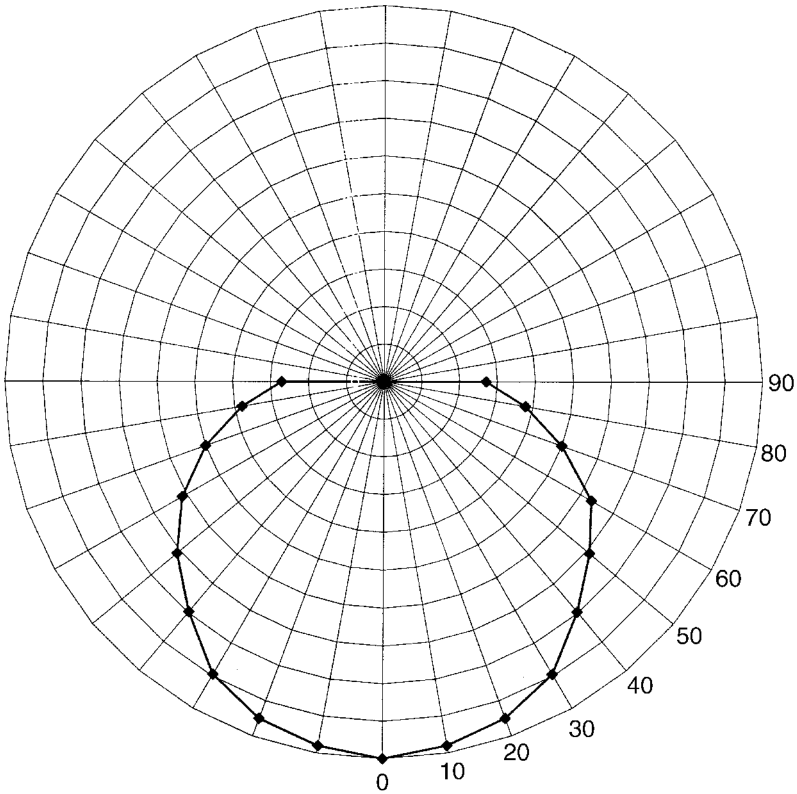


Figure 4 Polar curve of average luminous intensity distribution for overcast sky (Nadir intensity = 295 cd/10001 m)

Table 1 Comparison of measured and calculated luminous flux output

Installation	Measured luminous flux	Calculated luminous flux
Mulberry Building 1	585	578
Mulberry Building 2	371	414
Pleasant Street School 1	569	523
Pleasant Street School 2	540	500

4.1 Amount of light delivered by a pipe

The quantity of light delivered by a passive light pipe to an interior will depend on the incident external illuminance and the configuration of the pipe. The designer of a passive light pipe system must estimate appropriate external daylight conditions for the site in a manner similar to that for conventional daylight calculations. Typically for UK conditions a designer would use the mean horizontal diffuse illuminance.[11,12] The quantity of light entering the pipe depends on the illuminance incident on the collector and its cross-sectional area. Light loss will occur at each optical process in the passage of light through collector, straight pipe lengths, diffuser and bends. The attenuation due to the first three as a function of aspect ratio is shown in Figure 5. Note that this graph is for the most commonly used type of pipe – those lined with a material with a 95% specular reflectance. Light loss in bends will be higher than for the equivalent length of straight pipe. The graph in Figure 6 (derived from Reference 3) plots efficiency against bend angle for bend length equal to pipe diameter.

The application of the data may be illustrated for a 330 mm diameter pipe of 4m overall length containing three bends of 70, 40 and 30 degrees respectively. The length of straight pipe (including collector and diffuser) is 3 m giving an aspect ratio of 9:1. From Figure 5 the efficiency is 0.3. From Figure 6 the efficiencies of the bends detailed above are 0.77, 0.79 and 0.81 respectively. Thus the overall efficiency of the system is the product of those of the four components, namely 0.147. The luminous flux exiting the pipe can then be estimated as a product of external illuminance, pipe cross-sectional area and system efficiency.

4.2 Lighting analysis within an installation

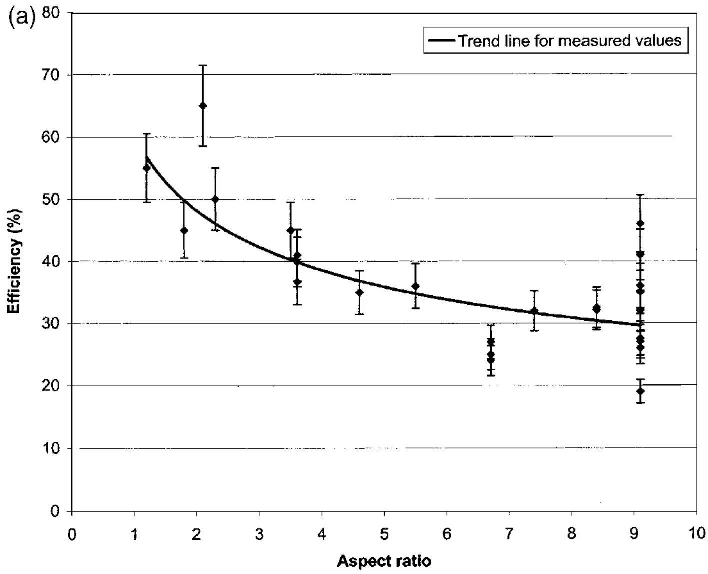
The combination of luminous flux output from the pipe and its luminous intensity distribution can be used as the basis of a number of methods of prediction of illuminance in installations lit by passive light pipes.

4.2.1 Point by point calculation

The cosine law of illuminance can be used to estimate light distributions from passive pipe systems by hand calculation. Table 2 shows both measured and calculated values of illuminance for a section of the 2.5 m wide internal corridor at Pleasant Street School, Liverpool. The calculations were made using a known luminous flux output and a luminous intensity curve in Figure 4. The installation consisted of 450 mm diameter pipes located 2.4 m above the floor and spaced centrally 7.7 m apart. Room surface reflectance was measured and weighted average values calculated for ceiling (0.7), walls (0.41) and floor (0.09). The values in Table 2 are for points on the floor. The calculated values are for direct light only and hence are slightly lower than measured. Despite this the general agreement between the sets is below 10% until the distance of 2 m, and only exceeded where illuminance magnitudes are very small and difficult to quantify using field measurement techniques.

4.2.2 Utilization factors for passive light pipes

The lumen method is presently the most widely used interior average illuminance calculation procedure for electric lighting systems. The method is based on determination of the total luminous luminous flux reaching the work plane made up of a component that comes direct from the luminaire and an indirect component that is multiply reflected from the room surfaces. The Utilization Factor describes the fraction of initial lamp luminous flux which ultimately reaches the working plane and is a calculated quantity based on luminous intensity distribution



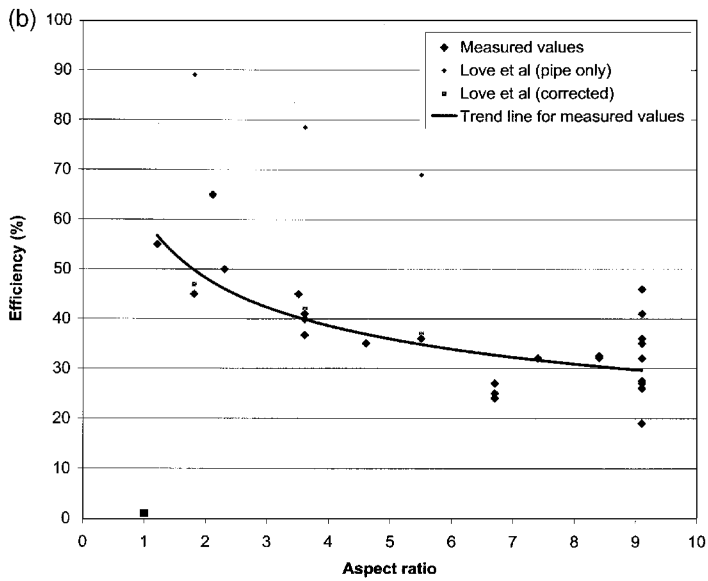


Figure 5 (a) Graph of pipe efficiency against aspect ratio. (b) Graph of pipe efficiency against aspect ratio

and efficiency of the luminaire used, room proportions and room surface reflectance.

It is difficult to apply this approach to most conventional daylight installations since factors such as variability of source and the asymmetric manner in which light is admitted result in great differences between various parts of the room and make any attempt to calculate average illuminance meaningless. There have however been a number of proposals to apply the lumen method to installations comprising regular arrays of diffusing rooflights for which a luminous intensity distribution was known. One approach was to measure luminous intensity distributions for a range of commercially available rooflights and derive tables of utilization factors for each type.[9]

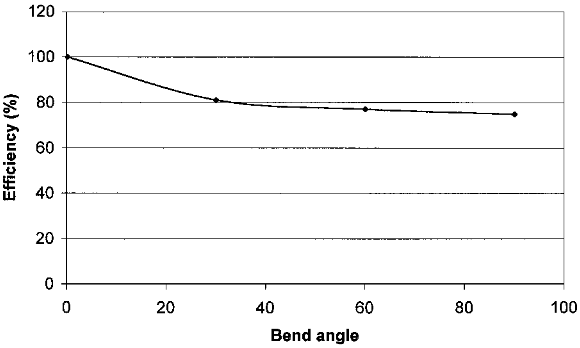


Figure 6 Graph of efficiency against bend angle for bend length equal to pipe diameter

A more generic approach was to consider rooflights as flush mounted luminaires which could be classified using the BZ system. Tabulated values of Lower Flux Utilance apply to each BZ class and since there is no upward luminous flux these values can be used directly as Utilization Factors for design purposes.[13,14]

This paper extends the above concept to passive light pipes. Using the measured luminous intensity distribution (see Section 3.2) the passive light pipes emitter was classified using its direct ratio as BZ6. Spacing to Height Ratio (Nominal) was confirmed as 1.5. The Lower Flux Utilance table for BZ6 luminaires can thus be used for calculations for regular arrays of passive light pipes. An extract is shown in Table 3. Luminous flux output per pipe is estimated as described in Section 4.1. An example of the method is shown in the next section.

4.2.3 Computer simulation

Lighting analysis software may be used as an alternative to hand calculation methods for both the point by point and lumen methods. The general principle is to describe the passive light pipe diffuser as a conventional luminaire using, first, the measured luminous intensity distribution and, secondly, luminous flux output which is usually derived as described in Section 4.1. This approach may be used for a wide range of lighting analysis software and the illustrative examples that follow use Lumen Micro 2000.[15]

A simulation was made of the corridor of the Pleasant Street School described in Section 4.2.1. The results shown in Table 2 indicate that, like the hand calculation, there is general agree-

Table 2a Measured, calculated and simulated planar illuminance

Location	Measured	Hand calculation	Computer simulation	% Error Meas/Calc	% Error Meas/Sim
Nadir	31.5	30.7	29.9	2.5	5.0
1 m from nadir	22.5	22.0	22.3	2.2	2.2
2 m from nadir	11.5	10.5	12.6	8.6	9.5
3 m from nadir	6.0	5.5	8.1	8.3	35
4 m from nadir	5.0	4.4	7.3	12.0	46

Case 1: external illuminance = 14 000 lux, average luminous flux output from pipes = 585 lumens.

Table 2b Measured, calculated and simulated planar illuminance

Location	Measured	Hand calculation	Computer simulation	% Error Meas/Calc	% Error Meas/Sim
Nadir	22.5	21.7	21.6	4.4	4.0
1 m from nadir	17.3	17.3	16.1	0.0	6.9
2 m from nadir	7.5	7.3	8.5	2.6	13.3
3 m from nadir	5.0	4.3	5.9	14.0	18.0
4 m from nadir	4.0	3.4	5.3	15.0	32.5

Case 2: external illuminance = 9700 lux, average luminous flux output from pipes = 371 lumens.

Table 3 An extract of Lower Flux Utilance values for BZ6 luminaires

Room index	Effective ceiling reflectance (%)	Reflectance of floor or working plane 10%				Reflectance of floor or working plane 30%			
		Reflectance of wall				Reflectance of wall			
		50%	30%	10%	0	50%	30%	10%	0
0.8	70	0.51	0.43	0.37	0.34	0.54	0.44	0.37	0.35
	50	0.49	0.42	0.36	0.34	0.52	0.43	0.37	0.35
	30	0.48	0.41	0.36	0.34	0.50	0.42	0.37	0.34
1.0	70	0.57	0.49	0.43	0.40	0.61	0.51	0.44	0.41
	50	0.55	0.48	0.42	0.40	0.58	0.50	0.43	0.41
	30	0.54	0.47	0.42	0.40	0.56	0.49	0.43	0.40
1.25	70	0.63	0.55	0.49	0.46	0.68	0.59	0.51	0.48
	50	0.61	0.54	0.49	0.46	0.65	0.57	0.50	0.47
	30	0.59	0.53	0.48	0.46	0.62	0.55	0.49	0.47
1.5	70	0.68	0.60	0.54	0.52	0.74	0.64	0.57	0.54
	50	0.66	0.59	0.54	0.51	0.70	0.62	0.56	0.53
	30	0.64	0.58	0.53	0.51	0.67	0.60	0.54	0.52
2.0	70	0.75	0.68	0.62	0.59	0.83	0.74	0.66	0.63
	50	0.72	0.66	0.61	0.59	0.78	0.70	0.64	0.61
	30	0.70	0.65	0.60	0.58	0.74	0.68	0.62	0.60
2.5	70	0.80	0.73	0.68	0.65	0.89	0.80	0.73	0.70
	50	0.77	0.71	0.67	0.65	0.83	0.76	0.70	0.68
	30	0.75	0.70	0.66	0.64	0.79	0.73	0.68	0.66
3.0	70	0.83	0.77	0.72	0.70	0.93	0.85	0.79	0.76
	50	0.80	0.75	0.71	0.69	0.87	0.81	0.75	0.73
	30	0.78	0.74	0.70	0.68	0.82	0.77	0.73	0.70
4.0	70	0.88	0.83	0.78	0.76	0.99	0.92	0.86	0.84
	50	0.85	0.81	0.77	0.75	0.93	0.87	0.83	0.80
	30	0.83	0.79	0.76	0.74	0.87	0.83	0.79	0.77
5.0	70	0.91	0.86	0.82	0.80	1.0	0.97	0.92	0.90
	50	0.88	0.84	0.81	0.79	0.97	0.92	0.87	0.85
	30	0.86	0.83	0.80	0.78	0.91	0.87	0.83	0.82

ment with measured values to within 10% up to a distance of 2 m from nadir. Beyond this agreement is less good. This may be due to, on one hand, the difficulty of measuring the small magnitudes of illuminance and, on the other, with photometric representation of some of the room surfaces, particularly the walls which were decorated with children's art.

The results of computer simulation were also compared with that of the lumen method calculation for passive light pipes described in the previous section. A room of dimensions $15 \times 10 \times 3.03$ m, with surface reflectance of 70, 50, 20%, was lit using a regular array of 15 No 330 mm diameter pipes each having a luminous flux output of 408 lumens. The utilization factor from Table 3 is 0.91 and application of the lumen method gives an average work plane illuminance of 32.6 lux. A simulation of the same room using Lumen Micro yields a working plane illuminance of 33.2 lux. A contour plot is shown in Figure 7. Repeating the calculation using a 440 diameter pipe of luminous flux output 569 lumens gives working plane values of 45.5 lux by hand calculation and 46.2 lux by computer simulation.

4.2.4 Daylight factor

Quantitative performance of installations lit using conventional vertical or horizontal glazing can be specified by the 'daylight factor' concept, but the well documented Daylight Factor calculation based on its three components is of no use for passive light pipe installations.[11,12] However using the techniques developed in this paper it is possible to calculate internal illuminance at points within a passive pipe installation and then dividing by the external illuminance to give daylight factor. This result (also referred to as 'internal/external illuminance ratio') is fully compatible with that for conventional glazing. The software used in this study can be configured to perform both calculations simultaneously. Figure 8 shows the room illustrated in Figure 7 with the addition of conventional vertical windows.

5. Discussion

A number of limitations of the method must be stated. The calculation method is based on data from the most commonly used passive solar light pipe type – circular cross-section lined with 95% reflectance material with collector and diffuser. Since light transmittance is particularly sensitive to wall reflectance the information in Figure 5 cannot readily be applied to pipes lined with other materials. If appropriate data for other materials were available the techniques described in this paper could be applied to other configurations of passive light pipe systems. Figures 4 and 5 are based on measurement by the author and from other sources cited. In the absence of reliable standard test methods for measurement of the photometric performance of these devices accuracy appropriate to field measurement of ±10% must be assumed.

The actual performance of systems as installed may vary from those predicted by the method. The quantity of luminous flux delivered by a pipe will be influenced by the prevailing sky conditions, external obstructions, and alignment and state of cleanliness of the pipe, collector and emitter. Direct sun does not appear to have a major influence on luminous flux output and luminous intensity distribution in pipes sited in temperate latitudes. However this subject may need further investigation if pipes are to be used in regions where large magnitudes of direct radiation from high angle sun are common.

A number of other factors need to be considered in the design of a passive light pipe installation. The qualitative aspects of the visual environment in terms of luminance patterns, glare, or user opinions or preferences has received little attention. The desirability of linking passive pipe systems via the electric lighting control system to adjust electric lighting levels in a space as a function of external illuminance also warrants investigation.

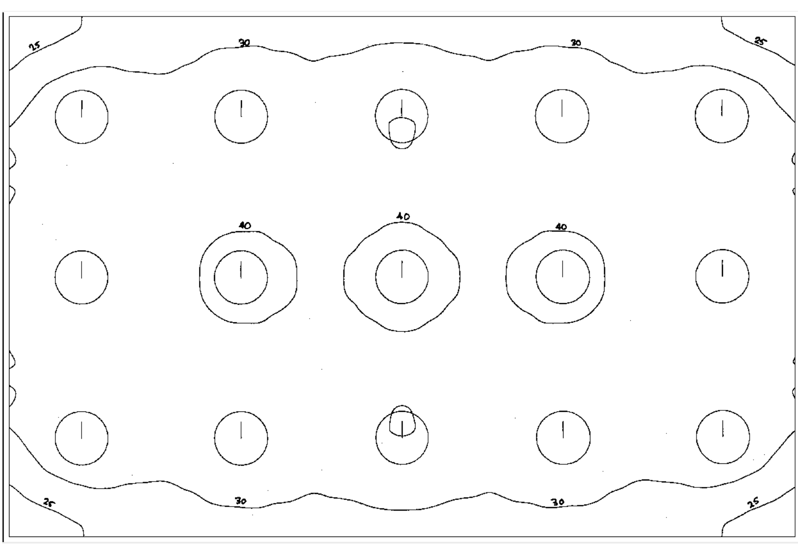


Figure 7 Contour plot of working plane illuminance (lux) in example room lit by passive pipes

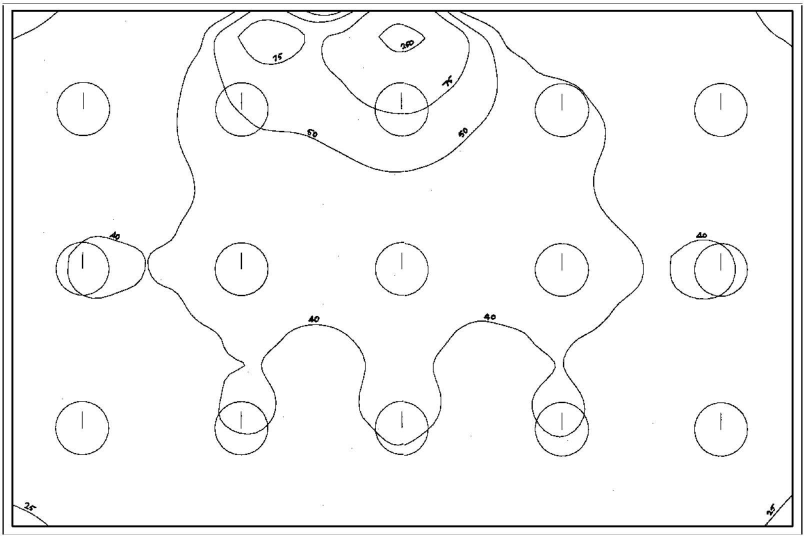


Figure 8 Contour plot of working plane illuminance (lux) in example room lit by passive pipes and vertical windows

6. Conclusions

The evidence to date suggests that passive solar pipe systems have potential as an electric light source substitute for a range of applications. This study develops a system of quantitative evaluation of passive solar pipes which enables answers to questions such as 'How many pipes are required to give a particular daylight factor distribution in a space?' to be framed. To this end the techniques advanced in this paper can be incorporated into, or used alongside, existing calculation methods for daylight factor.

The prediction methods set out in this paper are applicable to the majority of passive solar light pipe systems used at present in the UK. New data sets, similar to those in Figure 5, would however be required for other types of system that differ markedly from those in current use. One of the issues that must be addressed in the future development of the systems is the need for standardized procedures for the production of design data. Whilst some aspects of these systems – notably measurement of reflectance and transmittance – have robust photometric methods, other aspects such as luminous flux and luminous intensity measurements for emitters, have no comparable standard. This work may be seen as a contribution to the debate on standards photometry that preferably should be conducted within CIE.

Passive solar pipe systems have great potential for innovative and exciting lighting for a range of applications. The imminent arrival on the market of materials with a specular reflectance of the order of 98% offers even greater possibilities in improved efficiencies or the use of longer length pipes. It is to be hoped that the techniques described in this paper go some way towards making these systems a more popular feature of modern low energy building design.

Acknowledgements

The financial and technical support of Monodraught Ltd., High Wycombe, Bucks HP12 3SE is gratefully acknowledged. The passive light pipe systems used in this work are SunPipes. The help of Craig Bajda with the measurements is acknowledged.

7. References

1 Zastrow A, Wittwer V. *Proceedings of the Society of Photo-optical Instrumentation Engineers*, 1986: 692, 227.
2 Swift PD, Smith GB. Cylindrical mirror light pipes. *Solar Energy Materials and Solar Cells* 1995; 36: 159–68.
3 Love JA, Dratnal P. Photometric comparison of mirror light pipes, *Unpublished report, University of Calgary*, 1995.
4 Harrison SJ, McCurdy GG, Cooke R. Preliminary evaluation of the daylight and thermal performance of cylindrical skylights. *Proceedings of International Daylight Conference*, Ottawa, Canada, 1998: 205–12.
5 Oakley G, Riffat SB, Shao L. Daylight performance of lightpipes. *Proceedings of the CIBSE National Conference*, Harrogate, (London: Chartered Institution of Building Services Engineers), 1999: 159–74.
6 Shao L, Elmualim AA, Yohannes I. Mirror light pipes: daylighting performance in real buildings. *Lighting Res. Technol.* 1998; 30: 37–44.
7 Salih A, Shao L, Riffat S. Study of daylight and solar infrared transmitted through light pipes under UK climate. *Proceedings of the CIBSE/ILE National Lighting Conference*, York, (London: Chartered Institution of Building Services Engineers), 2000: 198–207.
8 Whitehead L, Nodwell RA and Curzon FL. New efficient guide for interior illumination. *Applied Optics* 1982; 21: 2755–57.
9 Parent D, Murdoch JB. The expansion of the zonal cavity method of interior lighting design to include skylights. *J. Illumin. Eng. Soc.* 1988; 17: 141–73.
10 Building Research Establishment. *Estimating daylight in buildings: Part 1*. BRE Digest 309, HMSO, 1986.
11 Building Research Establishment. *Estimating daylight in buildings: Part 2*. BRE Digest 310, HMSO, 1986.
12 Chartered Institution of Building Services Engineers. *The calculation and use of utilization factors*. Technical Memoranda 5, (London: Chartered Institution of Building Services Engineers), 1980.
13 Paix D. Daylight with skylights – its prediction by artificial lighting techniques. *Light and Lighting* 1962; 55: 149–51.
14 Illuminating Engineering Society. *The calculation of utilization factors – The BZ method.* IES Technical Report 2, London, 1971.
15 Lighting Technologies Inc. *Lumen Micro 2000 Users Guide*, Boulder, USA, 2000.

Discussion

Comment on 'The measured and predicted performance of passive solar light pipe systems' by DJ Carter

Tariq Muneer (School of Engineeing, Napier University)

Solar light pipes are exotic devices that have firmly set their foot within the market place. Within Britain alone there are now a number of companies that are profitably trading these products and at an enviable growth rate.

Mr Carter's article is another welcome addition to the literature dealing with the performance reporting of light pipes. Historically, a number of such studies have appeared in the Australian, US, UK and Canadian journals and conferences, the most recent being in volume 32 of *Lighting Research and Technology*. In this issue, the findings of two research teams were presented. The team from Nottingham presented detailed aspects of the anisotropy of the light distribution of light-pipe systems, indirectly suggesting the influence of the Sun's position in the sky. The other contribution, by the Napier University team, comprehensively concluded that there was a significant effect of solar altitude and sky-clearness.

However, the article under discussion seems to suggest that the above factors may only have a minor influence on the delivery performance of light pipes. Perhaps the author would like to respond to this anomaly in the findings of the above cited references and the present study.

Author's response to T Muneer

DJ Carter

I thank Professor Muneer for his comments and additional information.