DEVELOPMENT OF AN ALGORITHM FOR PREDICTING THE PERFORMANCE AND OPTIMIZING THE DESIGN OF AN ENERGY EFFICIENT LIGHTING SYSTEM

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ABSTRACT

This paper describes part of the research that is being done on the prediction of the performance of light pipes and the ways to optimize their design, in order to house artificial lighting, able to supplement daylight in a space. The research has up to date resulted in an algorithm for the easy and quick calculation of the interior illuminance provided by light pipes and in a procedure for the calculation of the power of the necessary artificial lighting (LEDs) and the energy savings for lighting, due to the daylight provided by the light pipes and the daylight linked controls of the LEDs.

KEYWORDS

Light pipes, performance algorithm, LEDs, energy savings

1. INTRODUCTION

Lighting is one of the most important energy consumers among the building mechanical systems, especially in public buildings and office premises located in city centres. During the last decades, daylight systems, more sophisticated than the usual side windows, are commonly used both in new and in renovated buildings, in order to satisfy the users' requests for access to daylight and to provide for reduced energy consumptions. One of the most common daylight systems, mainly used in the countries of north-western Europe is a category of Tubular daylight guidance systems, the passive zenithal guidance system, more commonly referred to as light pipe. Light pipes permit the entrance of skylight and sunlight through a transparent dome, placed on the building roof, into a highly reflective tube. After internally reflected, light is guided at ceiling level, where an opal or prismatic diffuser, diffuses the light emitted in the space. The tubes can either be straight or have bends, and the system diameter and length may vary significantly, depending on application.

A respectful number of scientists has studied the performance of passive light pipes and developed algorithms for the calculation of the light emitted by this type of daylight system. The Luxplot method, for example, can be applied to pipes of any size, with any number of bends of any angle, with a diffuser (Jenkins and Muneer, 2003). It calculates the luminous flux and then estimates the illuminance distribution at any point on the reference plane. The method does not involve solar altitude and sky clearness parameters. From this methodology, the authors have developed a tool with an output of a colour luxplot (Jenkins et al 2005). The tool developed by Zhang and Muneer (Zhang and Muneer, 2002) is for use with light pipes with opal or cloudy diffuser, straight or elbowed. The input parameters are more than those of the Luxplot method, as it requires solar altitude and sky clearness. The quantity used to describe the light pipe performance is the "Daylight Penetration Factor" (DPF). A third methodology, which is included in the Technical Report CIE 173:2006, is described in the following paragraphs, as it was used for the development of the proposed algorithm.

The following paragraphs include part of a study conducted within the framework of the European project HERB (Holistic energy efficient retrofitting of residential buildings), aimed to develop an algorithm for the calculation of the performance of light pipes and for the integration of energy efficient artificial lighting controlled by daylight linked controllers.

2. DEVELOPMENT OF AN ALGORITHM FOR THE CALCULATION OF THE ILLUMINANCE PROVIDED BY LIGHT PIPES

2.1 General

The methodology for defining the specifications of an optimum light pipe with integrated artificial lighting (LEDs in particular) for a certain space with specific lighting requirements, would lead to the appropriate light pipe sizing and/or number of pipes and the number/wattage of the LEDs required for the system to provide the minimum illuminance needed on the reference plane. The two main parameters that have to be determined are:

a. The illuminance E_{pipe} that the light pipe can provide under specific external conditions. The daylight availability from other natural light sources (for example windows, skylights, etc) is not investigated in this paper.

b. The illuminance E_{LED} that the artificial lighting sources will provide, in order to supplement the natural lighting.

These terms are associated with the following relation:

$$E_{LED}= E_{int} - E_{pipe} \text{ (lux)} \quad (1),$$

where E_{int} is the desired illuminance level on the reference plane.

2.2 Description of the TTE method and of the simulation procedure

CIE Technical report 173:2006 "Tubular Daylight Guidance Systems" describes one analytical method for the performance calculation of passive zenithal systems, based on the concept of Transmission Tube Efficiencies (TTE). TTE is a term that expresses the efficiency of the tube, taking into account the losses on the output of a light pipe due to the light absorbed by the guide material, the multiple reflections of light that occur within the tube, the tube length, the presence of pipe elbows, etc, under overcast sky conditions. The relationship for the TTE calculation incorporates the length, diameter and reflectance of the guide. However, the Technical Report provides TTE values for different pipe diameters, lengths and reflectances, as well as for various angles and number of elbows, in a tabulated form for a more straightforward application.

The methodology firstly calculates the flux Φ_i emerging from the diffuser of a light pipe, for specific external global illuminance, TTE and dome and diffuser transmittances. In order for an indication of the interior lighting levels, provided by a number of light pipes N in a space, to be provided, the Technical report provides a relation for the Daylight Penetration Factor (DPF).

After the flux Φ_i emerging from the output device of the light pipe is calculated, it can be used with any lighting software, in order to simulate the illuminance levels on the reference plane. The procedure includes finding (or constructing) a luminaire with circular polar diagram, setting the diameter of the luminaire the same as the light pipe diameter, replacing the lumen output of the original luminaire with the flux derived from the TTE method and replacing the luminaire Utilization Factor with the light pipe Utilization factor (UF). This is a Utilization factor for passive light guides, based on the assumption that the light pipe output devices can resemble flush mounted luminaires, with an approximate cosine luminous intensity distribution. The values of Lower Flux Utilance can be used as Utilization factors (Carter, 2002), which are given by the Technical report, according to the room index and reflectances of the interior surfaces.

2.3 Calculations performed with the TTE method

The TTE method was applied to light pipes of two reflectance values (0.95 and 0.98) five diameters (0.25, 0.35, 0.53, 0.65, 0.9 m) and seventeen lengths (0.25, 0.5, 0.75, 1, 2, 3, 4, 5, 6, 8, 10, 12, 14, 15, 16, 18, 20, 25 m) in order for the flux Φ_i to be determined, for an external illuminance of 5,000lux. The transmission of both the clear dome and the diffuser was considered to be 0.82.

For the light pipe characteristics previously described, the TTE values were read from the table of the CIE technical report. For any length that is not included in the CIE technical report, the TTE value of the light pipes with one of the diameters mentioned above and of tube reflectances 0.92, 0.95, 0.98 or 0.995, can be derived from Table 1. These relations emerged from regression analysis, estimating the relationships between the length (L), the diameter (D) and the reflectance (R) of the tube.

Table 1: Relationships for the calculation of the TTE values

D \ R	**0.92**	**0.95**	**0.98**	**0.995**
0.25	$-0{,}235\ln(L) + 0{,}678$	$0{,}9268e^{-0{,}144L}$	$0{,}9817e^{-0{,}063L}$	$0{,}9985e^{-0{,}017L}$
0.35	$0{,}9007e^{-0{,}164L}$	$0{,}9504e^{-0{,}12L}$	$0{,}9901e^{-0{,}046L}$	$0{,}999e^{-0{,}012L}$
0.53	$0{,}9502e^{-0{,}114L}$	$0{,}9768e^{-0{,}074L}$	$0{,}9949e^{-0{,}031L}$	$1{,}0004e^{-0{,}008L}$
0.65	$0{,}9679e^{-0{,}096L}$	$0{,}9795e^{-0{,}073L}$	$0{,}9958e^{-0{,}025L}$	$e^{-0{,}007L}$
0.9	$0{,}9767e^{-0{,}071L}$	$0{,}9875e^{-0{,}045L}$	$0{,}9985e^{-0{,}019L}$	$1{,}0009e^{-0{,}005L}$

After the flux values for the aforementioned cases were calculated with the TTE method, they were assigned to a luminaire with cosine luminous intensity distribution and simulations were performed with the IES VE pro software. The light pipes were simulated in eight different types of rooms of varying sizes which are commonly met in residential buildings (Room Length/Width/Height (m): 4/4/3, 4/4/5, 6/4/3, 4/7/3, 5/5/4, 6/6/2.5, 4/3/3, 4/5/3). The reflectance values of the interior surfaces were considered to be: walls: 50%, ceiling: 70%, floor: 30%. The working plane on which the illuminance levels were calculated was 0.85m above the room floor and was 0.50m offset to the walls. In total, 1,728 scenarios were calculated.

2.4 Deriving relationships for a simplified algorithm for illuminance calculation

The above described calculations and simulations were aimed to provide data for the development of an algorithm that would enable the calculation of the light output of light pipes in a certain room, in order to estimate the interior lighting conditions that are established and for the artificial lighting equipment to be defined and sized, in terms of wattage and/or number of LED lamps.

The correlation of the calculated illuminance values with the room dimensions and the TTE, led to the following relationships, depending on the light pipe diameter (D):

$$\text{For } D=0.25,\ E_i = 5{,}73 - 0{,}64 \times L - 0{,}31 \times W - 0{,}95 \times H + 4{,}34 \times TTE \quad (3)$$
$$\text{For } D=0.35,\ E_i = 14{,}22 - 0{,}90 \times L - 1{,}30 \times W - 2{,}30 \times H + 7{,}59 \times TTE \quad (4)$$
$$\text{For } D=0.53,\ E_i = 34{,}63 - 2{,}96 \times L - 2{,}29 \times W - 6{,}02 \times H + 19{,}03 \times TTE \quad (5)$$
$$\text{For } D=0.65,\ E_i = 59{,}79 - 4{,}52 \times L - 4{,}08 \times W - 10{,}06 \times H + 25{,}53 \times TTE \quad (6)$$
$$\text{For } D=0.90,\ E_i = 101{,}68 - 6{,}26 \times L - 9{,}59 \times W - 18{,}08 \times H + 58{,}22 \times TTE \quad (7)$$

where L= the room length, considered to be larger than the room width (m),W= the room width (m), H= the room height (m) and TTE= the transmission tube efficiency.

The particular relations are valid for specific conditions (E_{ex}=5,000lux, τ_c=0,82, etc), however they can be easily transformed to take into account different exterior and interior conditions and light pipe characteristics, by multiplying the result with the following product:

$$k= (Eex/5,000) \times (\tau_{dome} \times \tau_{diffuser}/0,82) \times (MF/0.9) \quad (8)$$

where MF is a maintenance factor, participating in the flux calculation, related to the positioning of the light pipe dome and the pollution of the specific location.

3. DEVELOPMENT OF A METHOD FOR THE OPTIMISATION OF THE DESIGN OF LED ASSISTED LIGHT PIPES

3.1 Calculation of the illuminance from the LEDs

Since daylight levels are not stable throughout a certain time period, the light emitted from a light pipe, should be supplemented by artificial lighting, in order to achieve a certain interior design illuminance E_{int}. The design interior illuminance on a reference plane, is determined by the space’s function and the users’ needs. Usually, indicative illuminance values for interior spaces, depending on their use, are given by Standards. For domestic environments, such limits are not provided by Standards, so the design illuminance value should be set depending on the users’ needs and activities. The design illuminance E_{int} is given by relation (1).

The illuminance from the light pipes of a room can be calculated from the algorithms described previously, for a given external illuminance. However, the maximum illuminance from the LEDs, needed to reach the design illuminance in a room, is the value that defines the installed power of the lamps used in the light pipe system. The maximum E_{LED} should be adequate in order to provide the necessary supplementary illuminance levels to the illuminance levels provided by the natural light sources of a room, at the time when the external illuminance is relatively low for the location where the room is situated. One such external illuminance could be the average external global illuminance $E_{ex,min}$, of the month with the lowest average external global illuminance, compared to the rest of the eleven months of the year, for a specific location. This data can be obtained from organizations that perform climatic measurements in every country, or by climatic files included in software databases.

By calculating the emitted flux Φ_i for external illuminance $E_{ex,min}$, the illuminance values provided by a light pipe $E_{pipe,min}$ under relatively low levels of external illuminance can be simulated or calculated by relations 3-7. If $E_{pipe,min}$ is then used in relation (1), the $E_{LED,max}$ that is calculated, is going to cover the needs for supplementing the natural light in order for the design illuminance to be achieved in a room, in the majority of the sky conditions.

For maximum energy savings for lighting, the lamps’ output should be controlled by a dimmer, receiving input from a daylight sensor. The control pattern would turn the artificial lighting on, when E_{pipe} is less than the E_{int} that has been set for the specific room and increase the output of the LEDs as E_{pipe} falls. When $E_{pipe} \leq E_{pipe,min}$, the LEDs are going to work in maximum output. As users of rooms usually forget to turn off the lights of systems that are daylight linked when the daylight is adequate, it is important for the control system to automatically turn off the lamps when they are not needed. When emitting 1% of their maximum output, artificial lighting systems consume 8% of their full power, leading to unnecessary waste (Reinhart, 2004).

An alternative way to define the $E_{LED,max}$, is to set it equal to the design illuminance E_{int}, so that the light pipe system can provide the necessary light levels in the room, even during the nighttime. However, this approach is not followed here, as it would not result in an optimized design of the daylight system comprised from the light pipe and the LEDs.

3.2 Calculation of necessary installed power of the LEDs

The calculation of the necessary installed power of the light pipe LEDs that are going to supplement the natural lighting provided by the light pipes of a space, requires the steps analyzed in the following paragraphs.

1. Calculation of the flux (lm) emitted by the lamps.

After the maximum light output from the LEDs in terms of illuminance is known, the $E_{LED,max}$ value can be used with the following relation of the lumen method, in order for the necessary LED lumens to be calculated.

$$E_{LED}=(\Phi_{LED} \text{ x } N \text{ x } UF \text{ x } MF)/A \tag{9}$$

Where Φ_{LED}= the flux emitted by all the LED lamps included in one light pipe, N=the number of light pipes in the room, UF =the utilization factor of the luminaire, MF= the maintenance factor of the luminaire, A= the area of the working/reference plane.

From relation (9) the flux Φ_{LED} of the LEDs that will be included in one light pipe can be calculated.

2. Estimation of the LEDs luminous efficacy (lm/W). This step is needed only when the lamps of the system have not yet been precisely specified, in which case, the luminous efficacy is provided by the manufacturer. If, however, an estimate has to be made, the parameters that have to be considered are the desired correlated colour temperature (CCT) of the lamps, the losses due to temperature and the losses caused by the optical system -lenses or diffusers- and from the light that reaches some part of the luminaire and never reaches the reference plane.
3. Calculation of the LEDs wattage.

By dividing the total flux Φ_{LED} coming from the LEDs of one light pipe with the luminous efficacy value of a LED lamp η, the wattage P_{LED} of the lamps of one light pipe is calculated (10).

$$P_{LED}= \Phi_{LED}/\eta \text{ (W)} \tag{10}$$

3.3 Energy savings for lighting

The energy savings for lighting can be calculated with a number of ways. A simplified but indicative way has been selected, in order to calculate the percentage of the energy saved by the use of the LED lamps and a daylight linked-dimming profile.

Relation (10) gives the wattage of the LEDs that have to be installed in each light pipe of a space, in order to provide the supplementary lighting, when natural lighting is not enough for the needs of the users. Since the mean monthly external global illuminance of a specific location is known, the wattage of the LEDs that is needed to provide for the supplementary illuminance can be calculated for every month. By multiplying this wattage P_{LED} to the average daylight hours of each month of the year, the energy consumption for lighting (if the LEDs were on during all the daylight hours) is calculated. From this value and from the energy consumption for the same external conditions but with no daylight availability, the percentage of energy savings can be calculated.

This method gives a rough estimate for the energy savings that result from the use of light pipes and artificial lighting controlled to supplement the daylight systems, employing only the necessary wattage.

3.4 Application of the procedure for the LED power specification and of the calculation of energy savings for lighting

The procedure analyzed in the previous chapters, has been implemented in four rooms, of dimensions frequently met in residences, with different light pipe characteristics (diameter, length) and different window areas. The calculations were performed for seven European cities: Nottingham-UK, Geneva-Switzerland, Lisbon-Portugal, Madrid-Spain, Amsterdam-Netherlands, Bologna-Italy and Athens-Greece. The mean daylength of every month in hours and the monthly mean of daily sums of global illuminance in kluxh, were obtained by www.satel-light.com. December was for every city the month with the less hours of day and with the lowest mean global illuminance value. By dividing the global illuminance of December with the hours of day of the same month, the $E_{ex,min}$ for which the sizing of the artificial lighting system will be calculated, was obtained.

$E_{ex,min}$, i.e. the global illuminance of December for every city, was used with equations (3)-(7) and the average illuminance from one light pipe was calculated for the “worst sky conditions”, on a reference plane covering the room area, with an offset to the walls of 0.50m. These values were subtracted from the E_{int} of each room and E_{LED} was obtained. Based on this illuminance that has to be provided by the LEDs, the flux of all the LEDs (Φ_{LED}) in one light pipe was calculated, from relation (9). The luminous efficacy η that was assumed for the LEDs was 70lm/W. By dividing Φ_{LED} with η, the watts P_{LED} of the LEDs that have to be installed in each light pipe were calculated.

In order to calculate the energy savings for lighting, P_{LED} was multiplied with the mean daylength of December. This consumption was compared to the consumption of a system that would provide E_{int} only with the use of the LEDs for the same time period. The same procedure was followed for the rest of the months, for every city.

Some indicative results of the application of the algorithm for the calculation of E_{pipe} and of the determination of P_{LED} and of the energy savings in various rooms, locations and months, are given in Table 2.

4. RESULTS & DISCUSSION

4.1 General

The methodologies and algorithms previously described are part of a more general study, aiming to provide easily and quickly applied tools for the optimization of daylight systems, that include light pipes with integrated LED lighting, within the framework of the European project HERB (Holistic energy efficient retrofitting of residential buildings). Specifically, the light pipes are intended to be installed in domestic environments, which explains the small size of the room types used for the above analysis. Analysis for light pipes with elbows has also been performed, but is not presented in this paper.

The TTE method, as the analytical methodology proposed by the Technical Report CIE:173:2006, was chosen as the most accurate theoretical algorithm for the calculation of light pipes' performance. The flux Φ_i that resulted, was used as the lumen output of a luminaire with a perfect diffuser, with a lighting software (IES VE pro). The assumption that the light pipe is a luminaire enabled the simulation of the average illuminance in the studied rooms. A forward Raytracing tool, which would be able to dynamically simulate the interior lighting conditions and the energy savings from the use of the daylight system, is going to be used in a later stage of the study. Also, an experiment under laboratory conditions is already prepared, in order to validate the results obtained by the previously mentioned methods.

4.2 Assessment of the developed algorithm

The algorithm that was developed was intended to calculate the average illuminance on the reference plane of residential rooms, which usually have small dimensions. The proportions of the rooms would probably make the light pipe diffuser an area and not a point source, to which the inverse square law applies. For that reason, the assumption that the lumen method can be applied, for the calculation of the E_{LED}, is considered to be acceptable. However, the results of the calculation of the LEDs' wattage were tested with simulations. An LED luminaire with a diffuser, of approximately the same luminous efficacy and wattage as the ones used for the calculations, gave approximately the same average interior illuminance.

The comparison of the illuminance levels, from the light pipes in a room, calculated with the TTE method and the above described simulations and with the algorithms that resulted from the correlation of the various parameters (relations 3-7), shows great consistency.

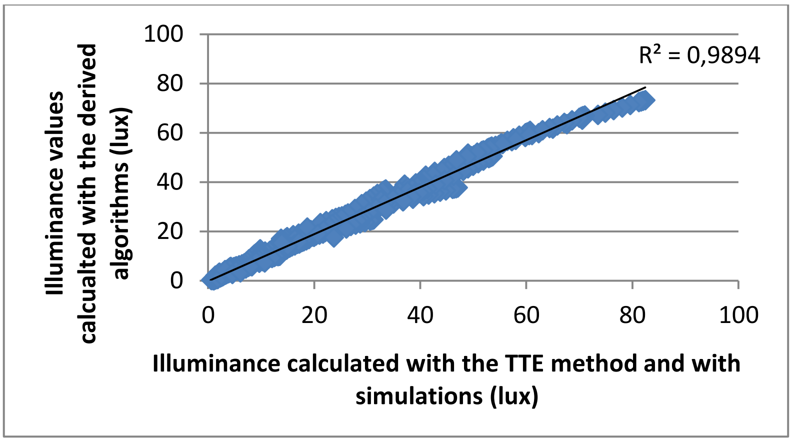

Figure 1.Correlation of the illuminance calculated with relations (3-7) and with the TTE methodology-simulation of the light pipe as a luminaire with “perfect diffuser”.

4.3 Assessment of the energy savings due to the daylight system

The application of the calculation procedure for the estimation of the wattage of the LEDs needed and for the energy savings that arise, show that light pipes can provide substantial savings in locations with high external illuminances and more moderate savings in locations with lower external illuminances, for the same time interval. However, countries with “darker” external conditions are probably going to use a daylight system with integrated artificial lighting for longer periods, which will lead to increased savings. The energy savings exceed 14%, even in the “darkest” month of the northest city of the study, for internal illuminance of 150 lux, which is a rather appreciable percentage for energy savings for lighting.

5. CONCLUSIONS

This paper describes part of the research that is being done on the performance of light pipes and the ways to optimize their design, in order to house artificial lighting, able to supplement daylight in a space. The research is performed within the framework of HERB, a European project that investigates the application of various innovative energy efficiency technologies in residential buildings.

The research has up to date resulted in an algorithm for the easy and quick calculation of the interior illuminance provided by light pipes (based on the methodology described in Technical Report CIE:173:2006 and lighting simulations) and in a procedure for the calculation of the power of the necessary artificial lighting (LEDs) and the energy savings for lighting, due to the daylight provided by the light pipes and the daylight linked controls of the LEDs. Much work needs to be done on the field, with simulations with forward Raytracing and optical design software and an experiment under laboratory conditions being currently prepared.

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Table 2.Results from the application of the algorithm for the illuminance from the light pipe and the LED power estimation process for different room types, months and European cities (tube reflectance=0.98, MF=0.8, room surface reflectances: ceiling/walls/floor=0.7/0.5/0.3, reference plane height=0.85, η_{LED} =70lm/W, τdome x τdif=0.72, reference plane at 0.85m above floor and 0.5m offset to walls)

Month	**City**	**Room length/ width/ height (m)**	**Pipe diameter/ length (m)**	**External illuminance (lux)**	**E_{pipe} (lux)**	**E_{int} (lux)**	**E_{LED} (lux)**	**P_{LED} (W)**	**Daylight hours (h)**	**Energy consumption for lighting (kWh)**	**Energy savings (%)**
Dec.	Amsterdam	4/7/3	0.65/3	8467,53	23,97	150	126,03	67,77	7,7	0,52	15,98
	Nottingham			8064,93	21,86		128,14	68,90	7,7	0,53	14,57
	Madrid			19273,68	52,25		97,75	52,57	9,5	0,50	34,83
	Lisbon			24115,79	65,37		84,63	45,51	9,5	0,43	43,58
	Bologna			14460,67	39,20		110,80	59,58	8,9	0,53	26,13
	Athens			20375	55,23		94,77	50,96	9,6	0,49	36,82
	Geneva			12034,09	32,62		117,38	63,12	8,8	0,56	21,75
Jun.	Amsterdam	6/4/3	0.53/6	34801,20	85,49	300	214,51	97,84	16,6	1,62	28,50
	Nottingham			30440,48	74,78		225,22	102,73	16,8	1,73	24,93
	Madrid			56880,79	139,72		160,28	73,10	15,1	1,10	46,57
	Lisbon			55026,85	135,17		164,83	75,18	14,9	1,12	45,06
	Bologna			47083,87	115,66		184,34	84,08	15,5	1,30	38,55
	Athens			55844,59	137,18		162,82	74,27	14,8	1,10	45,73
	Geneva			42987,34	105,60		194,40	88,67	15,8	1,40	35,20
Sept.	Amsterdam	5/5/4	0.375/5	26158,73	62,30	200	137,70	73,45	12,6	0,93	31,15
	Nottingham			24417,32	58,15		141,85	75,66	12,7	0,96	29,08
	Madrid			44888,89	106,90		93,10	49,65	12,6	0,63	53,45
	Lisbon			48298,39	115,02		84,98	45,32	12,4	0,56	57,51
	Bologna			39280,00	93,55		106,45	56,78	12,5	0,71	46,77
	Athens			45620,97	108,65		91,35	48,72	12,4	0,60	54,32
	Geneva			34642,86	82,50		117,50	62,67	12,6	0,79	41,25

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Satel light website: www.satel-light.com

HERB project website: http://www.euroretrofit.com/