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L. MAŇKOVÁ, J. HRAŠKA, M. JANÁK

SIMPLIFIED DETERMINATION OF INDOOR DAYLIGHT ILLUMINATION BY LIGHT PIPES

Lucia Maňková
lmankova@gmail.com
Research fields: daylighting in buildings

Jozef Hraška
jozef.hraska@stuba.sk
Research fields: solar energy, daylighting, energy efficiency and sustainability of buildings

Milan Janák
milan.janak@ stuba.sk
Research fields: building simulation – daylighting, energy and CFD

Department of Building Structures
Faculty of Civil Engineering
Slovak University of Technology in Bratislava
Radlinského 11 813 68 Bratislava, Slovakia.

ABSTRACT

This paper presents some results of experimental research conducted on daylight transmission through vertical straight light pipes with highly reflective inner surfaces. It deals with a method for evaluating the transmission efficiency of a tube and subsequently sets out an evaluation method for an assessment of the average illuminance of internal spaces with light pipes. The method was verified by dynamic daylight simulations made by the Radiance program (Larson – Shakespeare 1998) with its photon map extension (Schregle 2003). This evaluation method is based on the Bratislava Daylight Reference Year (DRY) (Darula – Kittler 2004) and could be used for light pipes with various length and diameters.

KEY WORDS

- *light pipes*
- *daylight*
- *daylight simulations*
- *illumination*

1. INTRODUCTION

The task of daylight transmission through a light pipe is relatively unknown in Slovakia, even though a great deal of research has been conducted all over the world. Because light pipes have been manufactured for only 30 years, research on their properties is still underway. The interest in these daylight devices has increased on the part of researchers and users during recent years, and there are many questions connected to the possibilities for their utilization, design criteria and the financial aspects of these daylight devices.

A large number of mathematical models and experimental studies for evaluating light pipes have been generated during the past two decades. These experimental and theoretical methods were usually developed for specific configurations and local daylight conditions. Therefore most of the achieved data could only be used for similar systems and daylight conditions. As an example, the first model made by Zhang (Zhang – Muneer 2000) could be mentioned. This author introduced the term ´daylight penetration factor´ (DPF), which represents the ratio of internal to external illuminance for light pipes. The author subsequently developed an equation for straight vertical light pipes and one for vertical light pipes with bends for all types of skies (Zhang – Muneer 2002). Another example is the research performed by Callow (Callow 2003). This author investigated the influence of the parameters of light pipes on the daylight efficacy of these devices. Measurements in Nottingham and Singapore were made and, according to these measurements, the author developed models for an assessment of the daylight efficacy of light pipes. He paid a great deal of attention to changes in daylight efficacy coupled with changing external conditions and determined that daylight efficacy was not always directly proportional to external illuminance.

All of these studies prove the specialists´ interest in light pipes and the necessity to deal with the problem of the design criteria of these devices. Even though thousands of these systems are sold annually, a general method of assessment for light pipes has still not been completed. The assessment of light pipes consists of two main parts, i.e. an estimation of the amount of light leaving the pipe (light pipe efficacy) and an analysis of the distribution of light in internal space.

2. AN ASSESSMENT OF THE TRANSMISSION EFFICACY OF DAYLIGHT THROUGH A TUBE

Daylight efficacy is the main parameter of the evaluation of a light pipe, and it depends on the geometric parameters (length and diameter of the tube), reflectance of the internal surface, climate conditions and the sun´s altitude. Light pipe efficacy is defined as the ratio of luminous flux leaving the pipe to an internal space and the luminous flux entering the pipe. As daylight conditions change, light pipe efficacy changes with them.

2.1. Method specification

The Radiance simulation program combined with a photon map algorithm (Schregle 2003) was used to assess the transmission efficacy of a tube. This efficacy was thereafter compared with the efficacy calculated by the use of two existing equations (1) (2) – (according to ref. Swift – Smith 1995, CIE 173:2006) and subsequently with other two generated equations.

$$\eta_{t,i} = \rho^{\frac{l.\tan\gamma}{d}} \tag{1}$$

$$\eta_{t,i} = \frac{e^{\,l/d\,.\,tg\gamma\,.\,\ln\rho}}{(1 - l/d\,.\,tg\gamma\,.\,\ln\rho)} \tag{2}$$

Radiance, a well established program in the research community, works following a backward ray tracing method and enables accurate and physically valid lighting simulations. However, developments in light redirecting materials have caused new challenges in their simulation; their specular nature makes them difficult to simulate with the backward ray tracing principle of Radiance and often merely results in a noisy mess. The phenomenon of caustic (i.e. bright, iridescent highlights on a diffuse surface caused by specular reflection or refraction) causes a serious problem for this simulation program. Traditional ray tracing methods do not account for all kinds of indirect illumination in the investigated model. This is the reason why the photon map algorithm (Schregle 2003) was used as an extension to the classic version of Radiance to achieve a realistic model of a light pipe.

The entire simulation model inserted into Radiance consisted of a tube with the diameter (d = 0.2 m – 0.8 m) and length (l = 1 m – 5 m) lined by material with a high specular reflectance (ρ = 0.94 – 0.99) and a flat diffuser placed at the bottom of the tube. It should be noted that the main purpose of this part of the research was to evaluate the daylight transmission efficacy of the tube without the influence of the dome and the diffuser. The resulting daylight transmission efficacy was stated just above the diffuser (the reflectance of the diffuser was 10%; when a lower degree of reflectance was adjusted, the daylight transmission efficacy did not change).

Simulations were made separately for sunlight conditions and diffuse light conditions. During the first part of the simulation (sunlight conditions), this virtual model was exposed to direct solar radiation predetermined into the program with different sun altitudes ($h_s = 30° – 60°$). Note that γ is an incident angle, i.e. the angle between the ray of light and light pipe axis. It is calculated as follows: $\gamma = 90° – h_s$. This angle (γ) was later set at 30° during calculations under diffuse light conditions. Combinations of the mentioned parameters (l, d, ρ, γ) were selected randomly, whereby just one parameter was changed every time (Tab. 1). During the second part of this simulation (diffuse light conditions) the same model was exposed to diffuse light represented by a CIE standard overcast sky (steep luminance gradation towards the zenith), and randomly selected combinations of parameters (l, d, ρ) were investigated.

A point scanner was placed above the top of the tube to record the direct horizontal illuminance E_s (during the first part of the simulation – direct sunlight) and diffuse horizontal illuminance E_{ob} (during the second part of the simulation – diffuse light). The illuminance at the end of the tube (above the diffuser) was computed as an average illuminance E_p as follows: There was a picture of the tube´s bottom, i.e. a parallel view of the diffuser, made for every selected combination of parameters. The resolution of the picture was set up as 64 x 64 pixels, seeing that a picture with a higher resolution (128 x 128 pixels) brings only a negligible difference in the resultant illuminance. The illuminance of each pixel was recorded, and the resultant illuminance was calculated as an average value. Note that every picture is square in shape (there is a circular illuminated diffuser and 4 black ´corners´, see Fig. 1)

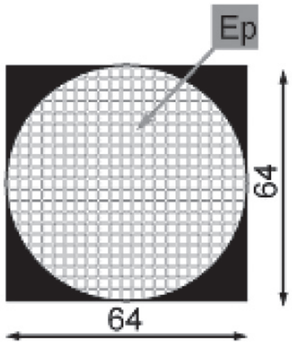

Fig. 1 *Parallel view of the upper part of the diffuser – scheme of generated picture (64 x 64 pixels) used for average illuminance (E_p).*

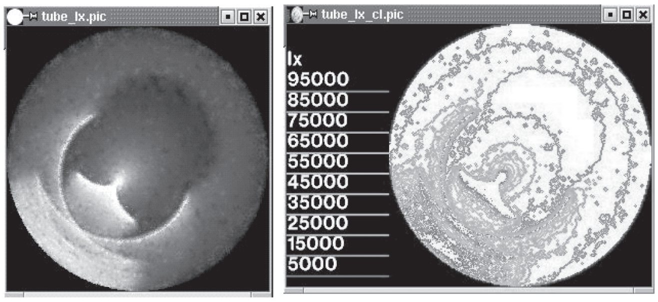

Fig. 2 *Parallel view of the upper part of a diffuser under a direct light condition used for the calculation of average illuminance (left) and illuminance isolines (right), γ = 60°, l = 1 m, d = 0.8 m, ρ = 0.98.*

Pixels creating ´black corners´ (i.e., with a zero value of illuminance) were left out of the calculation. One example of the rendered picture can be seen in Fig. 2.

The tube transmission efficacy η_t for sunlight conditions was afterwards calculated as the ratio of average internal illuminance E_p on the top of the diffuser and the direct horizontal illuminance E_s entering the light pipe ($\eta_t = \frac{E_p}{E_s}$). In the case of the diffuse light conditions, the tube transmission efficacy η_t was calculated as the ratio of the average internal illuminance E_p on the top of the diffuser and the diffuse horizontal illuminance E_{ob} entering the light pipe ($\eta_t = \frac{E_p}{E_{ob}}$).

All the resulting data of η_t were afterwards compared with the data calculated according to the two different known equations (1) (2) inserted above. Note that in the case of diffuse light, parameter γ in the equations (1) (2) always represents 30° (assuming that it is the only light within a cone subtending an angle of 30° from the zenith entering the tube).

2.2 Results

The impact of particular parameters on the tube transmission efficacy of light (η_t) (assessed by simulation and calculation according to equations (1) (2)) is illustrated in Fig. 3. It could basically be said that the data calculated by the use of equation (1) are overestimated in comparison with the simulated data, and the data calculated by equation (2) are, on the other hand, underestimated. In the case of diffuse light all the calculated data are overestimated in comparison with the simulated data.

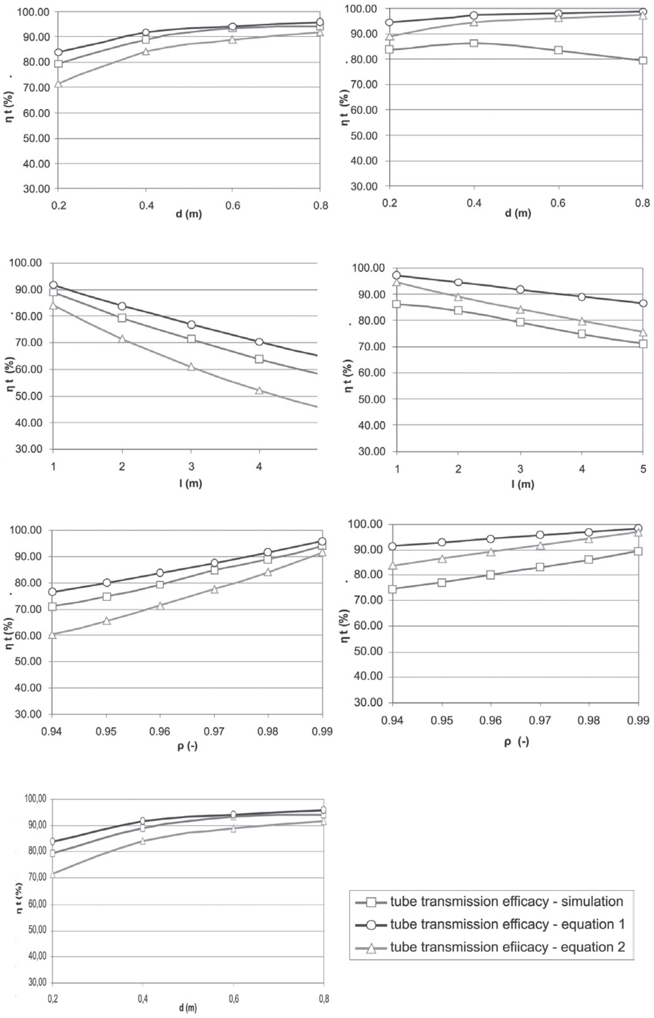

Fig. 3 *The impact of parameters (d, l, ρ, γ) on the tube transmission efficacy under direct light conditions (left column) and diffuse light conditions (right column); data achieved by the simulation and calculation according to equations (1) (2).*

The deviations (in absolute values) were calculated, and the final deviation was stated as an average value. As can be seen from *Tab. 1*, the average deviation between the data of the tube transmission efficacy achieved by simulation (η_t) and the calculated data according to equation 1 ($\eta_{t,1}$), is 3.67% under direct light conditions, whereas a comparison of the same simulated data (η_t) with the data calculated according to equation 2 ($\eta_{t,2}$) showed an average deviation of 6.91 %. The data in Tab. 2 represent the same comparison for diffuse light. The simulated data are compared to the data produced by equation 1 (eq. 1) and equation 2 (eq. 2), whereas the calculated deviations are 13.22% (eq. 1) and 8.28% (eq. 2).

In the case of direct light we can say that the simulated data of the tube transmission efficacy lies between the data calculated

Tab. 1 *Data of the tube transmission efficacy of light achieved by simulation (η_t) in comparison with the data calculated by eq. 1 ($\eta_{t,1}$) and eq. 2 ($\eta_{t,2}$) under direct sunlight conditions.*

γ (°)	d (m)	l (m)	ρ (-)	η_t (%)	$\eta_{t,1}$(%)	$\eta_{t,}2$ (%)	dev.1(%)	dev.2(%)
40	0.4	1	0.98	95.31	95.85	91.95	0.54	3.36
50	0.4	1	0.98	92.85	94.16	88.81	1.31	4.04
60	0.4	1	0.98	89.03	91.62	84.25	2.60	4.78
70	0.4	1	0.98	83.08	87.04	76.44	3.96	6.64
60	0.2	1	0.98	79.29	83.95	71.45	4.66	7.84
60	0.4	1	0.98	89.03	91.62	84.25	2.60	4.78
60	0.6	1	0.98	93.44	94.33	89.14	0.89	4.31
60	0.8	1	0.98	94.07	95.72	91.71	1.65	2.36
60	0.4	1	0.98	89.03	91.62	84.25	2.60	4.78
60	0.4	2	0.98	79.33	83.95	71.45	4.62	7.88
60	0.4	3	0.98	71.28	76.92	60.93	5.63	10.36
60	0.4	4	0.98	63.67	70.47	52.21	6.80	11.47
60	0.4	5	0.98	57.54	64.57	44.92	7.03	12.62
60	0.4	1	0.94	70.90	76.50	60.33	5.60	10.57
60	0.4	1	0.95	75.00	80.08	65.53	5.08	9.47
60	0.4	1	0.96	79.16	83.80	71.21	4.64	7.95
60	0.4	1	0.97	84.81	87.64	77.43	2.83	7.38
60	0.4	1	0.98	89.03	91.62	84.25	2.60	4.78
60	0.4	1	0.99	94.01	95.74	91.75	1.73	2.26
Average value of deviation							3.67	6.91

Tab. 2 *Data of the tube transmission efficacy achieved by simulation (η_t) in comparison with the data calculated by eq. 1 ($\eta_{t,1}$) and eq. 2 ($\eta_{t,2}$) under diffuse light conditions.*

γ (°)	d (m)	l (m)	ρ (-)	η_t (%)	$\eta_{t,1}$(%)	$\eta_{t,2}$ (%)	dev.1(%)	dev.2(%)
30	0.2	1	0.98	83.64	94.33	89.14	10.70	5.50
30	0.4	1	0.98	86.23	97.13	94.37	10.90	8.15
30	0.6	1	0.98	83.60	98.07	96.20	14.47	12.60
30	0.8	1	0.98	79.15	98.55	97.14	19.40	17.98
30	0.4	1	0.98	86.23	97.13	94.37	10.90	8.15
30	0.4	2	0.98	83.71	94.33	89.14	10.62	5.43
30	0.4	3	0.98	79.22	91.62	84.25	12.40	5.03
30	0.4	4	0.98	74.75	88.99	79.69	14.24	4.94
30	0.4	5	0.98	70.98	86.43	75.43	15.46	4.46
30	0.4	1	0.94	74.37	91.46	83.96	17.09	9.59
30	0.4	1	0.95	77.23	92.86	86.46	15.63	9.23
30	0.4	1	0.96	80.32	94.28	89.03	13.96	8.72
30	0.4	1	0.97	83.11	95.70	91.67	12.59	8.56
30	0.4	1	0.98	86.23	97.13	94.37	10.90	8.15
30	0.4	1	0.99	89.50	98.56	97.15	9.06	7.65
Average value of deviation							13.22	8.28

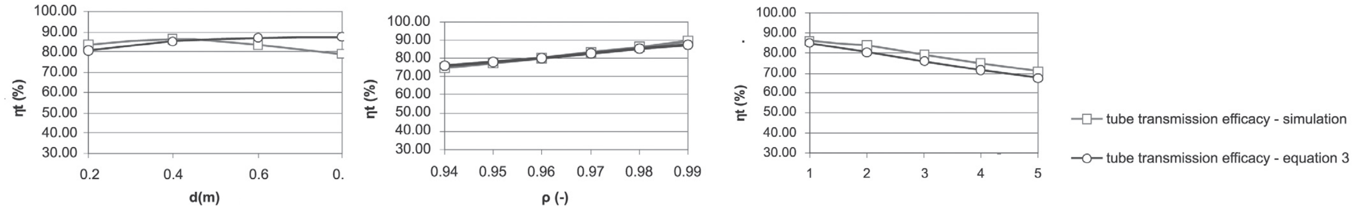

Fig. 4 *The impact of parameters (d, l, ρ) on the tube transmission efficacy under diffuse light conditions; data achieved by the simulation and calculation according to equation (3).*

by equations 1 and 2, whereas the results produced by eq. 1 are overestimated, and the results from eq. 2 are underestimated. According to the results achieved, we can basically say that eq. 1 is more suitable than eq. 2, and the resulting deviation (3.67%) could be negligible. Concerning the second part of the simulation (diffuse light), the results from both equations are overestimated in comparison with the simulated data, whereas the use of equation 2 brings a lower deviation (8.28%).

Equation (1) was modified (see eq. 3**)** in order to get closer to the simulation results (Tab. 3, Fig. 4) under diffuse light conditions.

$$\eta_{t,i} = \rho^{\frac{l}{d}} - 0{,}1 \qquad (3)$$

Tab. 3 *Data of the tube transmission efficacy of light achieved by simulation (η_t) in comparison with the data calculated by eq. 3 ($\eta_{t,3}$) under diffuse light conditions.*

d (m)	l (m)	ρ (-)	E_s	E_p	η_t (%)	$\eta_{t,3}$(%)	dev.3 (%)
0.2	1	0.98	16765	14022	83.64	80.39	3.25
0.4	1	0.98	16765	14456	86.23	85.07	1.15
0.6	1	0.98	16765	14016	83.60	86.69	3.09
0.8	1	0.98	16765	13270	79.15	87.51	8.35
0.4	1	0.98	16765	14456	86.23	85.07	1.15
0.4	2	0.98	16765	14034	83.71	80.39	3.32
0.4	3	0.98	16765	13282	79.22	75.94	3.28
0.4	4	0.98	16765	12532	74.75	71.71	3.04
0.4	5	0.98	16765	11899	70.98	67.68	3.29
0.4	1	0.94	16765	12468	74.37	75.67	1.30
0.4	1	0.95	16765	12948	77.23	77.96	0.73
0.4	1	0.96	16765	13465	80.32	80.30	0.02
0.4	1	0.97	16765	13933	83.11	82.67	0.44
0.4	1	0.98	16765	14456	86.23	85.07	1.15
0.4	1	0.99	16765	15004	89.50	87.52	1.98
Average value of deviation							2.31

The resulting average deviation was stated as 2.31 %, whereby it should be noted that equation (3) is suitable only for light pipes with a diameter of less than 600 mm. If the diameter is greater, the deviation will be more significant (Fig. 4).

The tube transmission efficacy could also be calculated according to equation (4), which was made through the use of a non-linear regression. The average deviation between the computed data and simulation was then stated as 5.37% (Tab. 4, Fig. 5)

$$\eta_{t,i} = -0.26152 + 0.17333\,.\,\sin(\ln(5.82691.\mathrm{d})) + \\ + 0.377.\mathrm{e}(\rho^{8}) + 0.07899.\sin l \qquad (4)$$

Tab. 4 *Data of the tube transmission efficacy of light achieved by simulation (η_t) in comparison with the data calculated by eq. 4 ($\eta_{t,4}$) under diffuse light conditions.*

d (m)	l (m)	ρ (-)	E_s	E_p	η_t (%)	$\eta_{t,4}$ (%)	dev.4 (%)
0.2	1	0.98	16765	14022	83.64	71.41	12.23
0.4	1	0.98	16765	14456	86.23	81.75	4.48
0.6	1	0.98	16765	14016	83.60	85.22	1.62
0.8	1	0.98	16765	13270	79.15	86.09	6.94
0.4	1	0.98	16765	14456	86.23	81.75	4.48
0.4	2	0.98	16765	14034	83.71	82.28	1.43
0.4	3	0.98	16765	13282	79.22	76.21	3.01
0.4	4	0.98	16765	12532	74.75	69.12	5.63
0.4	5	0.98	16765	11899	70.98	67.52	3.45
0.4	1	0.94	16765	12468	74.37	62.83	11.54
0.4	1	0.95	16765	12948	77.23	66.66	10.57
0.4	1	0.96	16765	13465	80.32	71.03	9.28
0.4	1	0.97	16765	13933	83.11	76.02	7.08
0.4	1	0.98	16765	14456	86.23	81.75	4.48
0.4	1	0.99	16765	15004	89.50	88.33	1.16
Average deviation							5.37

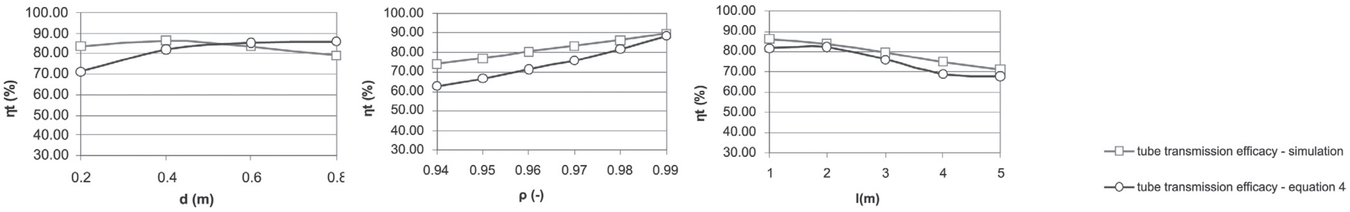

Fig. 5 *The impact of parameters (d, l, ρ) on the tube transmission efficacy under diffuse light conditions; data achieved by the simulation and calculation according to equation (4).*

It is necessary to say that these results are valid just for the tube transmission efficacy and not the efficacy of the overall light pipe. The dome and the diffuser were not included in this part of the calculation (the transmission factors of the dome and diffuser change with the type of dome and diffuser, i.e., according to the material and shape used). The combinations of the parameters of the tube (l, d, ρ, γ) were selected randomly; therefore, the results achieved and new equations are valid within the range of the assessed data. The objective was to acquire data of the tube transmission efficacy by the simulation and compare them with the calculated data in order to find an equation which corresponds with the simulation results the most. These equations (3 and 4) were afterwards used in the evaluation method for the light pipes presented below.

3. THE CALCULATION METHOD FOR THE AVERAGE ILLUMINANCE ASSESSMENT OF INTERNAL SPACES WITH LIGHT PIPES

The calculation method, also known as the zonal cavity method, has arisen as an adaptation of the European standardised method for the average illuminance of a working plane (STN EN 13032-2. 2005, Stockmar 2005). The aim was to utilize the daylight climate data from the Bratislava Daylight Reference Year and assess the illuminance of the working plane of spaces illuminated by vertical straight light pipes under dynamic daylight conditions. This DRY, a meteorological database lasting one year, was therefore statistically processed to reach a form which is easy to use. The average illuminance data calculated by the use of this method were subsequently compared with the results made by the Radiance simulation program

3.1 Zonal cavity method

The zonal cavity method, which is also known as the lumen method (Steffy, 1963), is a simplified method mainly used in the artificial lighting sector. It should particularly be used as a tool in uniform settings of lighting designs if a simple, rough technique of illuminance quantification is desired. This method works on a utilization factor basis. The utilization factor is defined as the ratio between the total luminous flux falling on a working plane and the outgoing luminous flux from a light source. The method is based on the outgoing luminous flux, luminous intensity curve, space geometry and surface reflectances. The assessed space is an empty rectangle in shape, and the working plane is considered to be solid and calculated as any other surface in the space (it has an effective floor cavity reflectance ρ_{3e}). Every surface in the room (ceiling, working plane, walls) reflects light uniformly into the space

Tab. 5 *The input data for the room calculated.*

room parameters		light pipe parameters		sky conditions
width	5 m	length	2 m	CIE overcast sky global illuminance E_g = 20 000 lx
length	8 m	diameter	0.4 m	
height	2.85 m	reflectance of inner surface	0.96	
ceiling reflectance ρ_1	0.7	number of light pipes	6	
walls reflectance ρ_2	0.5	distance between light pipes	2 m	
floor reflectance ρ_3	0.3	luminous intensity curve	ideal diffuse	
position of working plane above the floor	0.85 m	light loss factor of the dome	0,9	
		light loss factor of the diffuser	0,7	

Tab. 6 *Input parameters for calculation and simulation.*

room	a (m)	b (m)	h (m)	ρ_1	ρ_2	ρ_3	l (m)	d (m)	ρ	n (pcs)	distance between light pipes (m)	E_g (lx)
1	5	8	2.85	0.7	0.5	0.3	2	0.4	0.96	6	2	20 000
2	5	8	2.85	0.7	0.5	0.3	1	0.65	0.96	6	2	20 000
3	8	8	3.5	0.7	0.5	0.3	2	0.4	0.96	4	4	20 000

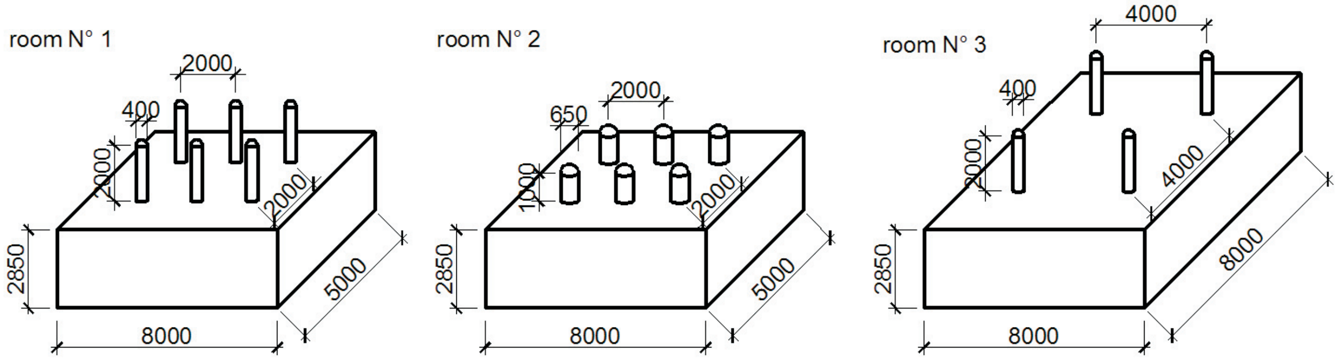

Fig. 6 *Schematic drawing of the three rooms assessed (geometric input data).*

according to Lambert´s law. Light sources are placed on the ceiling or suspended in a light source plane at a particular distance from the working plane.

3.2 A practical example of calculating the average illuminance on the working plane of a room

Below is an example of a calculation with the use of the zonal cavity method (according to STN EN 13032-2). The light pipe efficacy was assessed by the simulation and equation (4).

The resulting average illuminance was calculated according to eq. (5).

$$E_{pr} = \frac{n \,.\, E_g \,.\, A_d \,.\, \eta_t \,.\, UF \,.\, \tau}{A} \qquad (5)$$

where

n is the number of light pipes;
A_d – the area of the diffuser (m^2);
η_t – the tube transmission efficacy, calculated according to eq. 4 (-);
UF – the utilization factor for the working plane, calculated according to STN EN 13032-2 (-);
τ – the light loss factor, calculated according to CIE 173:2006 (-);
A – the area of the working plane (m^2).

$$E_{pr} = \frac{6 \times 20000 \times 0.126 \times 0.7156871 \times 0.95 \times 0.441}{40} = 113.14\ lx$$

3.3 Results

The calculation method mentioned above was also used for two other rooms. The parameters of all three rooms are listed in Tab. 6 (see also Fig. 6). The daylight efficacy of the tube η_t, which is one of the input parameters, was calculated with the use of two different equations (3 and 4) and also by the use of the simulation. Subsequently, the average illuminance of the working plane was assessed (Tab. 7).

As mentioned above, both the calculation and simulation were made under overcast sky conditions with a global illuminance E_g = 20 000 lx. The results of the average illuminances for the three rooms assessed on the working plane are listed below (Tab. 7). The calculated data and symbols in Tab. 7 are according to STN EN 130 32-2. 2005.

3.4 Comparison of simplified calculations with simulation results

The resulting average value of the illuminance on the working plane made by hand calculations was thereafter compared with the values derived by the Radiance simulation program with the

Tab. 7 *Main computed parameters and final average illuminances on the working plane for the three examples assessed.*

room	m_3	ρ_{3e}	k	DFL (lm)	UF	τ	η_t - Radiance	$\eta_{t,3}$ – eq. 3	$\eta_{t,4}$ – eq. 4
							E_{pr} (lx)	E_{pr} (lx)	E_{pr} (lx)
1	1.38	0.275	1.54	779.69	0.9514	0.441	111.1	113.1	113.14
2	1.38	0.275	1.54	779.69	0.9514	0.441	310.7	350.3	312.65
3	1.06	0.282	1.51	864.84	1.0203	0.441	49.61	50.53	50.56

Tab. 8 *Resulting values of the average illuminances evaluated by the calculation and simulation for the 3 assessed cases.*

room	simulation	calculation					
		η_t – Radiance		$\eta_{t,3}$ –eq. (3)		$\eta_{t,4}$ –eq. (4)	
	Epr (lx)	Epr (lx)	dev. (%)	Epr (lx)	dev. (%)	Epr (lx)	dev. (%)
1	104.3	111.1	6.52	113.1	8.44	113.14	8.48
2	290.9	310.7	6.80	350.3	20.40	312.65	7.48
3	54.5	49.6	8.96	50.5	7.27	50.56	7.21

photon map algorithm. In the first two cases, the values from the evaluation method were higher than the values achieved by the simulation (deviations 6.52 – 20.4 %). In the third case, when the assessed room was square in shape, the calculated values were 7.21 – 8.96 % lower than the values achieved by the simulation (Tab. 8). The deviations probably mainly originated from the simplified evaluation calculation method according to STN EN 13032-2. The highest deviation (20 %) arose from the use of equation (3) for the tube transmission efficacy in the assessed case Nº 2. This deviation probably arose from enlarging the diameter of the tube into the value 650 mm (see section 2.2). It should be noted that the equations for the light pipe efficacy assessment arose following the simulation results, and it is still necessary to deal with this problem.

4. CONCLUSION

In conclusion it can be stated that simulations with the use of the photon map algorithm can be used to evaluate the daylight tube's transmission efficacy. The method of the dynamic simulations of light pipes was developed, and the results were verified by the use of Radiance. The European normalized method for evaluating the average illuminance on a working plane (according to STN EN 13032-2) was converted into the daylight conditions of a room illuminated by light pipes. The equations for the tube transmission efficacy assessment, which were generated according to simulation results (3) and (4), are suitable for vertical short straight light pipes with a diameter of less than 0.6 m.

Through the use of this method the approximate value of the average illuminance of internal spaces illuminated by vertical straight light pipes can be assessed for an arbitrary day and hour during a year following the statistically processed data from the Bratislava Daylight Reference Year. The method could also be applied for mixed lighting, i.e., it is possible to evaluate rooms illuminated by light pipes and artificial light sources at the same time.

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