Light Guides as Energy Saving Alternative for Windowless Interiors

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Abstract: - The paper is focused on evaluation of internal illuminance from tubular light guides. The light guides present modern ways of illumination of internal windowless parts of buildings. Their function is based on the principle of light transport from outdoor to distant indoor places due to multi-reflections on their high reflective internal surfaces. This study describes a method for evaluation of internal illumination from light guides on the basis of determined luminance of the light guide ceiling diffuser. A calculation module was developed for the evaluation of indoor illuminance on the basis of data from monitoring of the ceiling diffuser luminance. The described method presents a design tool for an operative estimation of indoor daylighting in rooms illuminated by tubular light guides.

Key-Words: - Light guides, Illuminance, Daylight, Light transmittance, Reflectance, Visual comfort, Luminance, Solar radiation, Overcast and clear sky.

1 Introduction

Indoor visual comfort is one of leading requirements in building design process [1]. Many existing buildings need the window retrofit to increase indoor visual comfort. Newly designed buildings should be optimized with respect of sufficient indoor illuminance, protection against glare effect and solar overheating.

The paper is focused on evaluations of special daylight systems - light guides. These systems represent not only daylighting but also energy saving alternative to compare standard artificial lighting [2]. They consist of roof transparent domes, highly reflective tubular ducts and ceiling transparent cover - the diffuser is very often used to scatter daylight uniformly into the illuminated room (Fig. 1).

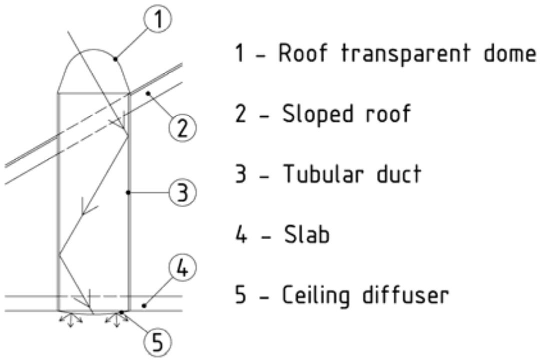

Fig. 1 Scheme of light guide

Evaluation of indoor illuminance from light guides is actual task and it has been topic of many experimental studies and theoretical models [3], [4], [5]. A new calculation module was completed for the determination of indoor illuminance - daylight component from the light guide. Indoor illuminance in any positions in the investigated room can be calculated in the program for a determined value of luminance of the ceiling diffuser. The program can evaluate internal illuminance with the respect of direct component from sky which is transmitted through the light guide itself. Internally reflected component from reflected light on internal surfaces in rooms is not included into calculations.

Light guides of different diameters were investigated. The method can be used for the length of the light guides up to 5 m (the light guide going through one floor). Illuminance was calculated on a mesh of nodal points (distance between neighbouring nodal points is 500 mm) on the work plane 850 mm above floor level in a reference room (in the distance 2 m under the light guide ceiling diffuser).

2 Input data

The evaluation of interior daylighting and internal illuminance from light guides require specification of boundary conditions, it means type of sky – overcast, partly cloudy or clear sky. Room geometry together with surface characteristics as colour, roughness, reflectance or transmittance are needed. Dimensions and position of light guides must be determined for the internal illuminance calculations.

Luminance on the ceiling diffuser of the light guide system was monitored for the detail study of illuminance availability on the work plane. The average value of the ceiling diffuser luminance is adequate to external sky conditions and depends on the length of the light guide.

The practical application of a light guide was selected for the determination of input data for the calculation. The light guide is installed in a windowless internal corridor of a school building. The light guide has a diameter of 520 mm and it goes through one floor – the total length is 4.8 m. The corridor with the light guide is shown in Fig. 2.

Internal illuminance was measured on the work plane 2 m under the light guide (T-10, serial no. 32521004, Konica Minolta, serial no. 51511084 was used for measurements). On the basis of internal illuminance measured during the outdoor illuminance between 3800 and 5000 lx, the Daylight factors as the ratio between value of internal illuminance and external illuminance were calculated in particular nodal points on the selected working plane. Internal and external illuminances were measured simultaneously for outdoor conditions of overcast sky with sky luminance gradation from horizon to zenith 1:3 (CIE overcast sky).

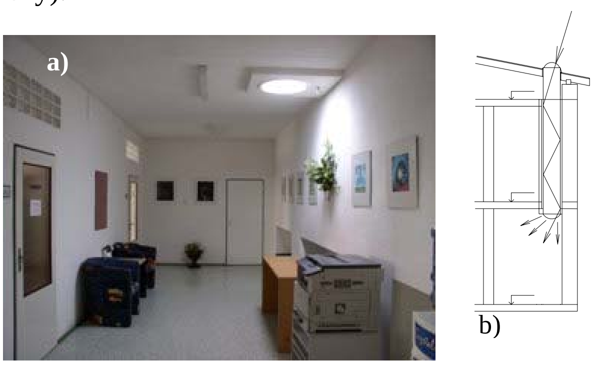

Fig. 2 The room illuminated by the light guide
a) photograph, b) section

The scheme of the studied room drawn in the plan and two sections which include distribution of internal illuminance - daylight factor DF % is presented in Figure 3.

In addition to illuminance measurements and the Daylight factor determination luminance of the ceiling diffuser of the light guide was monitored under different outdoor sky conditions (for cloudy, partly cloudy and clear sky). Values of the ceiling luminance monitored for different sky conditions are presented in Table 1. The luminance was monitored by the luminance camera Vario LMK (monitored in October 2006).

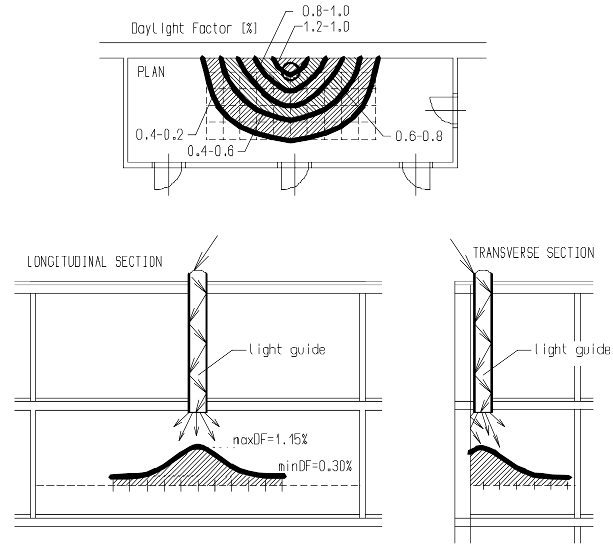

Fig. 3 Studied light guide – scheme in plan and longitudinal and transverse section including the daylight factor distribution

Table 1 Luminance of the ceiling diffuser

Type of sky	Measure-ment	Ceiling diffuser luminance L [cd.m^{-2}]			
		Min value	Max value	Mean value	Standard deviation
Overcast	First	1094.0	1917.0	1541.0	114.0
	Second	988.6	2016.0	1589.0	153.6
	Third	866.4	1903.0	1562.0	141.2
	Average value	**983.0**	**1945.3**	**1564.0**	**136.3**
Partly cloudy	First	2540.0	4512.0	3485.0	364.0
	Second	306.7	4574.0	3568.0	340.0
	Third	2025.0	4700.0	3489.0	438.4
	Average value	**1623.9**	**4595.3**	**3514.0**	**380.8**
Clear	First	5679.0	17130.0	13790.0	1622.0
	Second	6515.0	17220.0	13910.0	1549.0
	Third	6762.0	17690.0	14310.0	1387.0
	Average value	**6318.7**	**17346.7**	**14003.3**	**1519.3**

On the basis of monitoring of the ceiling diffuser of the installed light guide, the characteristic values of luminance L_d were selected for the following internal illuminance determination:

- L_d = 1000 cd.m^{-2} for overcast sky conditions,
- L_d = 4000 cd.m^{-2} for partly cloudy sky,
- L_d = 14 000 for clear sky conditions.

3 Illuminance calculations

Values of the ceiling luminance were taken as input data for the following evaluations. Internal illuminance [6], [7] in any point on the work plane under the ceiling diffuser could be calculated after the formula

$$E_i = L_d . d\omega_i = L_d \frac{dA_i}{\left(\frac{l}{\cos \gamma_i}\right)^2} \quad [\text{lx}] \qquad (1)$$

where:
l is vertical distance of the centre of the diffuser to the working plane
$d\omega$ is element of solid angle
γ is angle from the vertical axis of the light guide to the direction centre of the ceiling diffuser – the investigated nodal point on the work plane,
dA is area of an elementary perpendicular projection of the ceiling diffuser

$$dA_i = \pi \, r^2 \cos \gamma_i \qquad (2)$$

where r is the diameter of the light guide.

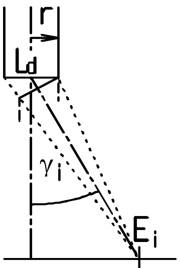

Fig. 4 Scheme of the calculation relations

The calculation module under MS Excel was completed for the internal illuminance calculations. The program serves for the operative determination of internal illuminance under the light guides of different diameters and length up to 5 m. The program can evaluate internal illuminance with the respect of direct sky component only internally reflected component is not included in the calculations.

There are presented data from calculation for overcast sky conditions, for the ceiling luminance 1000 cdm^{-2}. Data of calculated illuminance are in agreement with data from measurements, table 2 and figure 5. For example illuminance directly under the light guide, in the axis, on the work plane – calculated value 51.9 lx and measured value 57.5 lx (DF = 1.15%, for external illuminance 5000 lx – see Fig. 3).

Table 2 Illuminance E [lx] on the work plane

E [lx]	1	2	3	4	5	6	7	8	9
x/y	**2.00**	**1.50**	**1.00**	**0.50**	**0.00**	**0.50**	**1.00**	**1.50**	**2.00**
S9/2.0	0,76	1,50	2,72	4,10	4,75	4,10	2,72	1,50	0,76
S8/1.5	1,50	3,56	7,64	12,9	15,6	12,9	7,64	3,56	1,50
S7/1.0	2,72	7,64	18,8	32,4	38,0	32,4	18,8	7,64	2,72
S6/0.5	4,10	12,9	32,4	48,5	51,9	48,5	32,4	12,9	4,10
S5/0.0	4,75	15,6	38,0	51,9	53,1	51,9	38,0	15,6	4,75
S4/0.5	4,10	12,9	32,4	48,5	51,9	48,5	32,4	12,9	4,10
S3/1.0	2,72	7,64	18,8	32,4	38,0	32,4	18,8	7,64	2,72
S2/1.5	1,50	3,56	7,64	12,9	15,6	12,9	7,64	3,56	1,50
S1/2.0	0,76	1,50	2,72	4,10	4,75	4,10	2,72	1,50	0,76

Graphical presentation of the calculation results from table 2 is shown in Fig. 5. The figure presents isolines which connect nodal points with the same illuminance level on the selected work plane.

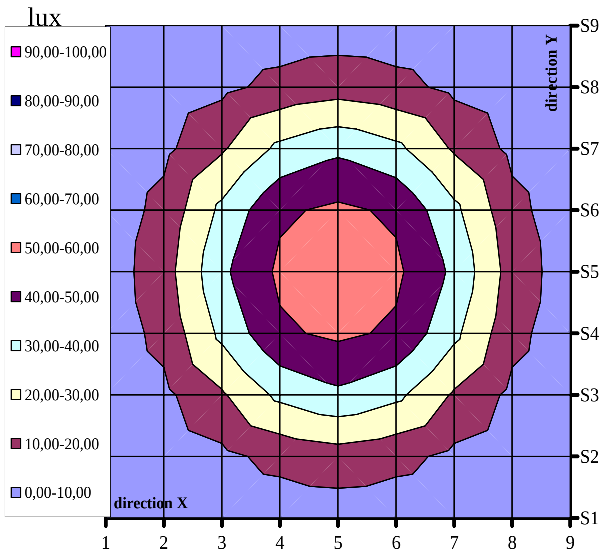

Fig.5 Isolines of the illuminance on the work plane

Light guides of different radiuses were selected for the following calculations. Seven light guide radiuses were used r1=0.3, r2=0.4, r3=0.5, r4=0.6, r5=0.7, r6=0.8, r7=0.9 m. Illuminance distribution in the height 2 m under the light guide - the work plane (clear sunny sky, L_d = 14 000 cd.m^{-2}).

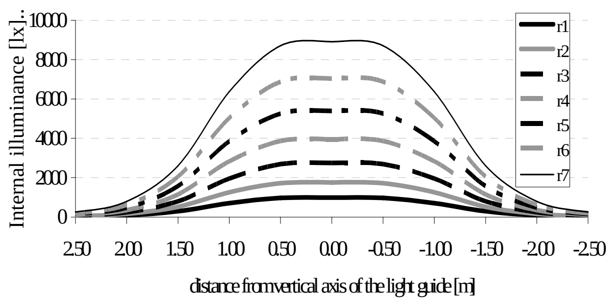

Fig. 6 Illuminance on the work plane (vertical section) from light guides of different radiuses (r1 to r9)

The evaluation is determined for light guides of different diameters from 0.3 to 0.9 m. The calculation procedure of the described method can be used for light pipes of length up to 5.0 m, longer light guides can be evaluated but new values of ceiling diffuser should be monitored.
Results of the calculation of internal illuminance on the horizontal plane directly under the light guide vertical axis, 2 m under the ceiling diffuser, with

different luminance (from L01 = 1 500 cdm^{-2} to L09 = 15 000 cdm^{-2} - see Fig. 6 and Table 3).

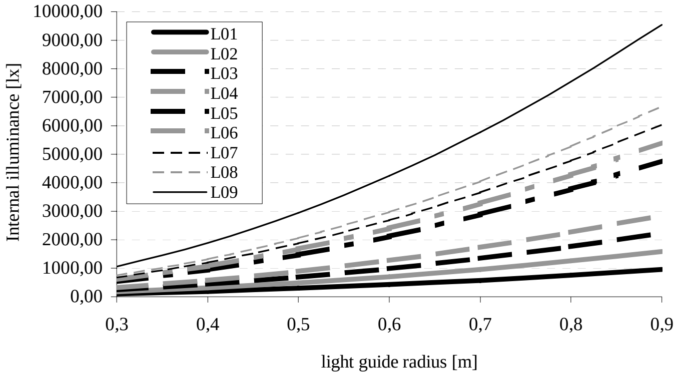

Fig. 7 Illuminance on the work plane (dependence on the light guide radius and luminance of the ceiling diffuser)

Table 3 Internal illuminance calculated for the light guides of radius from 0.3 to 0.9 m and luminance of diffusers from 1500 cd.m^{-2} up to 15000 cd.m^{-2}

r [m]	The ceiling diffuser luminance L [cd.m^{-2}]								
	L01	L02	L03	L04	L05	L06	L07	L08	L09
	1500	2500	3500	4500	7500	8500	9500	10500	15000
0,3	106,0	176,7	247,4	318,1	530,1	600,8	671,5	742,2	1060,3
0,4	188,5	314,2	439,8	565,5	942,5	1068,1	1193,8	1319,5	1885,0
0,5	294,52	490,87	687,22	883,57	1472,6	1669,0	1865,3	2061,7	2945,2
0,6	424,12	706,86	989,60	1272,3	2120,6	2403,3	2686,1	2968,8	4241,2
0,7	577,27	962,11	1347,0	1731,8	2886,3	3271,2	3656,0	4040,9	5772,7
0,8	753,98	1256,6	1759,3	2262,0	3769,9	4272,6	4775,2	5277,9	7539,8
0,9	954,3	1590,4	2226,6	2862,8	4771,3	5407,5	6043,6	6679,8	9542,6

The evaluation of illuminance on the horizontal work plane from one, two and four light guides was carried out. Results of these calculations are presented in graphs in Fig. 8, Fig. 9 and Fig. 10. The internal illuminance on the work plane were calculated for the ceiling diffuser of radius 0.3 m and luminance L_d=14 000 cd.m^{-2}.

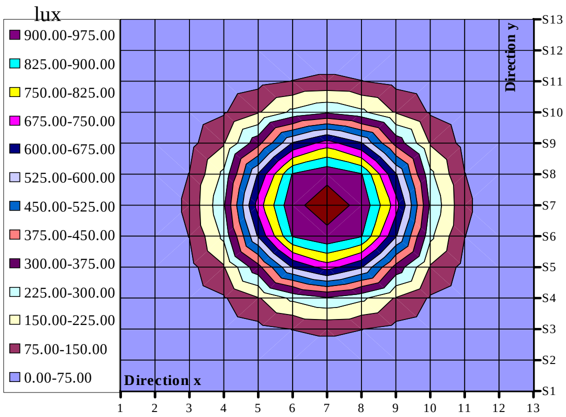

Fig. 8 Isolines of illuminance from one light guide

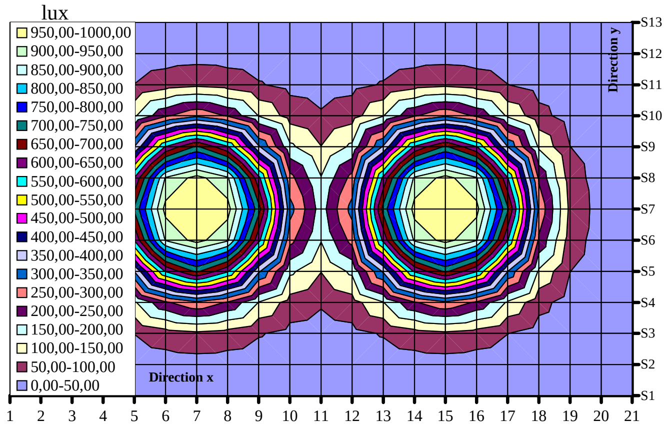

Fig. 9 Isolines of illuminance from two light guides

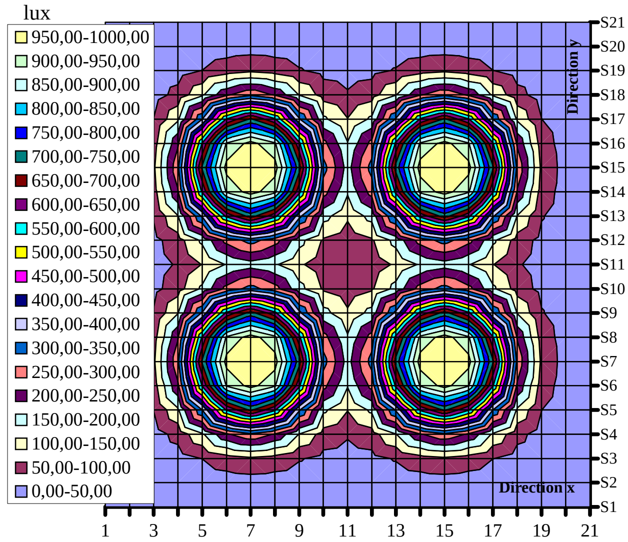

Fig. 10 Isolines of illuminance from four light guides

4 Conclusion

Visual comfort in rooms with light guides depends on their dimensions and position in the room. Light transmittance through light guides is influenced by optical properties of their components. Very high light reflectance of internal surface of the light guide duct and high light transmittance of the transparent roof dome and ceiling diffuser is required.

Daylighting in rooms from light guides is influenced by climatic conditions - external illuminance during different sky conditions (overcast, partly cloudy or sunny sky) and actual time (day and hour). It can be expected that highest internal illuminance is during sunny clear sky days - summer period with the highest sun altitudes.

Dimensions of light guides are recommended:

- diameters from 0,2 to 1,0 m. Smaller diameters than 0,2 m are not economical because they serve low luminance flux, low internal illuminance. Wider diameters than 1.0 m can be substituted in buildings by light shafts.

- length 1.0 to 5.0 m. Light guides of lengths up to 5 m and of the above mentioned diameters can serve for appropriated daylighting. Longer light guide require very high reflectance of internal surface of the light pipes.

Generally it can be recommended to design light guides no longer than 10 m. Light transmittance through light guides depends mainly on optical properties of light guide components (as light transmittance of the roof dome a ceiling diffuser, light reflectance of light pipe) and also on the aspect ratio between length and diameter of the light guide. The optimal solution is to design light guides to aspect ration to 10:1 (for example light guide of

The highest light efficiency of the tubular light guides can be achieved in summer season in time of clear sky and direct solar radiation. In time of cloudy and overcast sky conditions the light guide efficiency is very small. Light guides have small transmittance for diffusive light. For this reason the roof domes of light guides are completed with reflecting mirrors or concentrating optical lenses oriented to the South for concentration of direct solar radiation into light guide pipe.

The method of evaluation of internal illuminance on the work plane under the light guide with the help of the described calculation program serves for optimisation of positioning of light guides of different diameters. The ceiling diffuser luminance monitored under different climatic conditions is the input value for evaluation of light guides of various dimensions.

Light guides represent energy saving systems for lighting of buildings with natural light spectrum which has dynamic changes compared to standard artificial lighting systems. 1]

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