Daylighting and Energy Savings with Tubular Light Guides

JITKA MOHELNIKOVA
Faculty of Civil Engineering
Brno University of Technology
Veveri 95, 602 00 Brno
CZECH REPUBLIC
mohelnikova.j@fce.vutbr.cz, http://www.fce.vutbr.cz

Abstract: - Energy savings are actual tasks in many technical branches including the building industry. Buildings have to be design for low energy consumption. Energy savings in buildings can be achieved by reduction of energy consumption for heating, ventilation and artificial lighting. The design of buildings with respect of solar radiation and daylighting gives possibility for energy efficient buildings. Saving of electric energy for permanent artificial lighting is important technical problem in internal parts in buildings without daylighting. Modern technologies have brought possibility to solve these problems. Tubular light guides are systems which serve for natural 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. Advantage of these systems is in the possibility of dynamic daylighting in internal parts of buildings and electric energy savings for artificial lighting. Evaluation of indoor daylighting from a reference tubular light guide was completed. Light guides of different diameters and different light efficiency were compared with sources of artificial light. Energy saving for light guides of different efficiency was estimated.

Key-Words: - Energy savings, Solar radiation, Solar energy, Daylighting, Light guides, Indoor climate.

1 Introduction

Buildings have to be design for low energy consumption. Energy savings in buildings can be achieved by reduction of energy consumption for heating, ventilation and artificial lighting. The design of buildings with respect of solar radiation and daylighting gives possibility for energy efficient buildings. Saving of electric energy for permanent artificial lighting is important technical problem in internal parts in buildings without daylighting. Modern technologies have brought possibility to solve these problems.

Tubular light guides are systems which serve for natural 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. They consist of roof transparent domes, highly reflective tubular ducts and ceiling transparent cover - the diffuser which is very often used to scatter daylight uniformly into the illuminated room [1]. Light guides represent possibility of improvement of indoor visual comfort and also energy saving alternative to compare standard artificial lighting in buildings [2]. The topic of the paper is focused on daylighting and energy saving evaluations of these systems.

The investigation of indoor illuminance and energy efficiency of tubular light guides is actual task and it has been interest of many experimental studies and theoretical models [3], [4], [5]. The models of interior daylighting and internal illuminance from light guides require specification of input data; it means outdoor light conditions for overcast, partly cloudy or clear sky [6]. Room dimensions, geometry and surface characteristics as colour, roughness, light reflectance or transmittance are fundamental data. Optical properties of light guide components, their dimensions and position in a building must be determined for the internal illuminance calculations [7].

Light efficiency of tubular light guides was evaluated. A real practical installation of the light guide of standard dimensions and optical properties was selected for the daylight study. The estimation of energy savings was completed for light guides. These light guides were compared with incandescent and fluorescent sources of artificial lighting.

An evaluation of daylight distribution was completed for the determination of indoor illuminance – the daylight component from a light guide. Indoor illuminance in any positions in the investigated room can be calculated for a determined value of luminance of the ceiling diffuser. The internal illuminance was evaluated with the respect of the direct component from sky which is transmitted through the light guide. Tubular light guide advantages and disadvantages were compared to traditional daylight systems as windows and roof skylights.

2 Light Guide Efficiency Determination

Determination of luminous flux Φ [lm] going through light guides serves for the evaluation of electric energy savings. Luminous flux derived from solar radiant flux Φ_e [W] is expressed by the formula [8]

$$\Phi = K_m \int_{380}^{780} \frac{d\Phi_e}{d\lambda} V(\lambda) d\lambda \quad [\mathrm{lm}] \tag{1}$$

where

K_m = 683 lm.W^{-1} … photopic vision constant, max value of light efficiency for wavelength λ_m = 555 nm

V(λ) … relative light efficiency of visible light at the wavelength λ

The luminous flux $\Phi_o(\gamma)$ affecting the roof dome of the light guide at the angle of incidence γ is an input value for the determination of luminous flux $\Phi(\gamma)$ leaving the light guide. The equation 2 [8] represent the basic formula for light guides evaluation

$$\Phi(\gamma) = \Phi_o(\gamma).\rho^{\frac{l.\tan\gamma}{D}} \quad [\mathrm{lm}] \tag{2}$$

where

ρ … reflectance of internal surface of the light guide [-]

l … length of the light guide pipe [m]

d … light guide diameter [m]

In real situations the luminous flux passing the light guide has to be corrected by light loss coefficient which consists of

- light loss due to a transparent roof dome τ_1,
- light loss due to a ceiling diffuser τ_2,
- light loss due to other obstacles (shadings, blinds, roof structures etc) τ_3.

The final light loss coefficient is determined as

$$\tau_T = \tau_1 \tau_2 \tau_3 \tau \quad [-] \tag{3}$$

The total luminous flux $\Phi_T(\gamma)$ leaving the light guide is derived as

$$\Phi_T(\gamma) = \Phi_o(\gamma)\tau_T \rho^{\frac{l.\tan\gamma}{D}} \quad [\mathrm{lm}] \tag{4}$$

Light efficiency of the tubular light guide system can be determined as a ration between the total luminous flux leaving the light guide and luminous flux entering into the light guide in accordance with the formula

$$\eta = \frac{\Phi_T}{\Phi_o} [-] \tag{5}$$

Efficient and optimal design of tubular light guides depends on their optical properties and dimensions – length l and diameter d. Common tubular light guides are efficient in dimensions l/d ≤ 10, for example light guide of diameter 0.5 m is efficient to length of 5 m. Longer light guides of the same diameter have very low light efficiency. The ratio l/d=20 means light efficiency is lower than 0.2 for light guides with tube of internal reflectance ρ=0.95.

Light guides of the same dimensions must have very high reflectance for higher efficiency, for example ρ = 0,96 → η = 0,225, ρ = 0,97 → η = 0,301, ρ = 0,98 → η = 0,370, determined for l/d = 20.

Recommended dimensions of tubular light guides are: diameters between 0.3 and 0.7 m, length to 5 m. Tubular light guides of small diameters (smaller than 0.15 m) are not ecenomical because of low light transmittance and high investment price.

The following table 1 presents results of light efficiency calculation for light guides of different dimensions (diameters from 0.1 to 1.0 m and lengths between 1 and 5 m).

Table 1 Light guide efficiency of tubular light guides

diameter [m]	light guide length l [m]				
	1.0	2.0	3.0	4.0	5.0
0.1	0.332	0.199	0.119	0.071	0.043
0.2	0.429	0.332	0.257	0.199	0.157
0.3	0.467	0.394	0.332	0.280	0.236
0.4	0.487	0.429	0.377	0.332	0.292
0.5	0.500	0.451	0.407	0.368	0.332
0.6	0.509	0.467	0.429	0.394	0.361
0.7	0.515	0.478	0.445	0.423	0.384
0.8	0.520	0.487	0.457	0.429	0.402
0.9	0.523	0.494	0.467	0.441	0.417
1.0	0.526	0.500	0.485	0.451	0.429

Illuminance in a position of the light guide ceiling diffuser E_d is determined in a following way

$$E_d = \frac{d\Phi_T(\gamma)}{dA} \quad [lx] \tag{6}$$

where

dA … area of an element of the light guide ceiling diffuser

Luminance of the ceiling diffuser L_d can be calculated on the assumption of uniformly overcast cloudy CIE sky and for perfectly diffusive ceiling diffuser

$$L_d = E_d/\pi \quad [\mathrm{cdm}^{-2}] \tag{7}$$

The light guide efficiency could be determined as the following ratio

$$\eta = \frac{\Phi_T}{\Phi_o} \cong \frac{L_d}{L_s} [-] \tag{8}$$

where L_s … sky luminance [cdm^{-2}]

Light efficiency was determined for a light guide of diameter 520 mm. Total length of the guide is 4.8 m. Luminance photographs of the ceiling diffuser under cloudy, partly cloudy and clear sky were monitored by the luminance camera LMK. The sky luminance was monitored by multimeter CEM DT 8823. Average light efficiency of the investigated light guide system is about 30% (η=0,3-0,4). Example of the luminance photograph of the ceiling diffuser is presented in Figure 1.

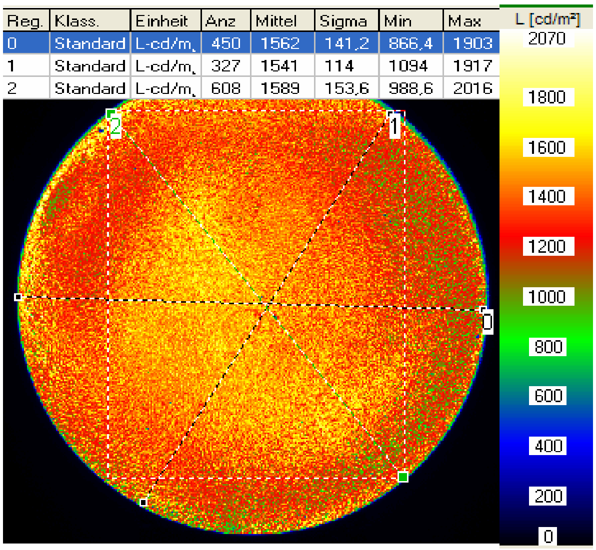


Fig. 1 Luminance photograph of the monitored ceiling diffuser of the light guide. (monitored by the luminance camera LMK)

3 Energy Savings Assessment

Evaluation of energy savings due to light guides as a substituting lighting element for standard artificial lighting was completed. Luminous flux transmitting through light guides of different diameters was determined for the evaluation. Light guides were compared to incandescent and fluorescent sources of artificial lighting [9] with different luminous efficacy - see table 2. The comparison of the selected light guides witch are frequently used in buildings – light guides of diameters 0.32 and 0.52 and 0.72 m, length of the light guide ducts about 1 m (light efficiency 0.5) is included in Table 3.

Table 2 Luminous efficacy of the lighting sources

Artificial light source	Luminous efficacy
Incadescent bulb lamp	12 lmW^{-1}
Fluorescent lamp (standard)	50 $lm.W^{-1}$
Fluorescent lamp (HF)	100 $lm.W^{-1}$

The selected light guide evaluations was determined for different external illuminance from 5000 lx to 100 000 lx, it means from overcast sky to clear sunny sky conditions which are characteristic for Central Europe region - characteristic daily profiles of external illuminances monitored this region are presented in Fig. 2 (monitored in Bratislava at the Slovak Academy of Sciences by *Kittler, Darula, 2004*) [10].

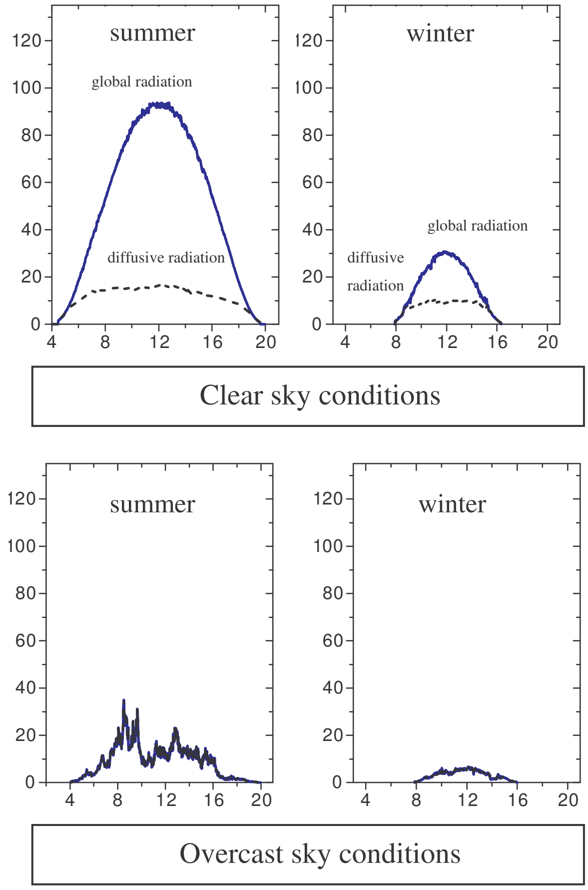


Fig. 2 External illuminance – characteristic daily profiles for summer and winter seasons, Bratislava [10]

Mean external illuminance in this climatic region is 20 000 lx. Conditions of overcast sky evaluations are considered for external luminance 5000 lx.

Figure 3 compares luminous flux through tubular light guides of selected diameters for different external illuminances, the light guide efficiency η=0.5.

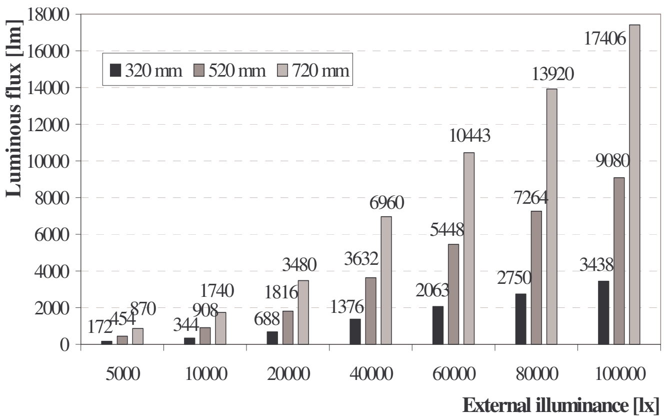


Fig. 3 Luminous flux through tubular light guides of diameters 320, 520 and 720 mm

Table 3 compares light guides of the selected diameters with artificial light sources. For example light guide of diameter 0.5 m and light efficiency 0.5 (shorter light guide 1 m long) can substitute incadescent lamp even during overcast sky external conditions.

Table 3 Comparison of light guides with sources of artificial lighting

External illuminance	Light guide diameter [m]		
	0.32	0.52	0.72
Incadescent bulb lamp			
5 000 lx	-	1x40 W	1x85W
20 000 lx	1x60W	1x100W+ 1x75W	3x100W+1x40 W
60 000 lx	2x100W	5x100W (+30 W)	10x100
100000 lx	3x100W (+1x35)	8x100W+ 1x85W	~17x100W
Fluorescent lamp (standard)			
5 000 lx	-	-	20 W
20 000 lx	-	1x36W	1x75W
60 000 lx	1x36W	1x100W+ 1x30W	2x100W+1x36 W
100000 lx	1x80W	2x100W	4x100W
Fluorescent lamp (HF)			
5 000 lx	-	-	-
20 000 lx	-	1x21W	1x35w
60 000 lx	1x21W	3x21W	3x35W
100000 lx	1x35W	3x35W	5x35W+1x28W

Utilisation of light guides in buildings with permanent artificial lighting could bring important energy savings. Evaluation of electric energy savings for light guide installations of different light efficiency from 0.5 to 0.2 was carried out. The evaluation was completed on the basis of determined luminous flux transmitted through the light guide under overcast sky with average external illuminance 5 000 lx, it means the most unfavourable conditions. Calculated values of luminous flux are presented in Table 4.

Table 4 Luminous flux through the light guides of different diameters from 0.1 to 1.0 m

Diameter [m]	Light efficiency	
	0.5	0.2
0.1	78.5	31.4
0.2	314.0	125.6
0.3	706.5	282.6
0.4	1256.0	502.4
0.5	1962.5	785.0
0.6	2826.0	1130.4
0.7	3846.5	1538.6
0.8	5024.0	2009.6
0.9	6358.5	2543.4
1.0	7850.0	3140.0

For the same conditions the electric energy savings were estimated for sources of artificial lighting – fluorescent lamps which can be substituted by 100 light guides (for example for lighting of the large assembly hall in a factory), see Fig. 4.

Energy savings due to the light guides were estimated for two determined limits:
- maximal possible energy savings of the light guides: light guide efficiency 0.5 (shorter light guides - length about 1 m [11]), maximal possible utilization of the light guide is 8 hours per day.
- average possible savings of the light guides: light guide efficiency 0.2 (longer light guides – max. length to 5 m [12]), possible utilization of the light guide is 5 hours per day.

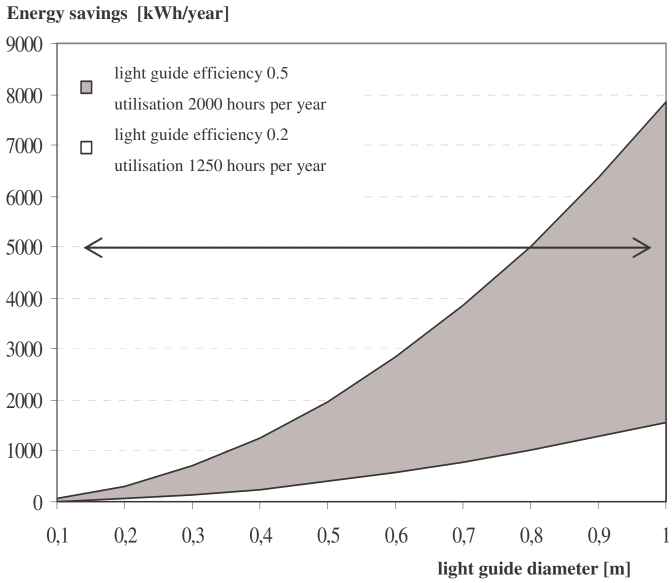


Fig. 4 Possible energy savings per year (calculated for the installation of 100 light guides)

The energy assessment of the selected light guides give results that energy savings from light guides should not be neglected. One hundred tubular light guides installed instead of fluorescent lamp lighting could bring nearly 8 MWh energy savings for the most optimistic variation. It is clear that the light guide systems could play important role in windowless parts in buildings.

Saving of electric energy for artificial lighting has also positive environmental impact. For example an average electric energy savings for artificial lighting 5 000 kWh per year could bring reduction of carbon dioxide emissions about 2.1 t (it was calculated for the value of CO_2 emission for electric energy production 422 g/kWh [13]).

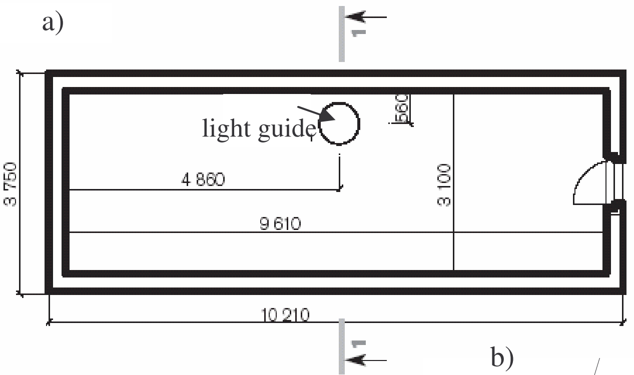
Besides the energy efficiency the tubular light guide main benefit is in the possibility of natural lighting in internal part of building without windows.

4 Daylight Evaluation

Daylighting and visual comfort in buildings is the most important design task and it is superior even energy saving demands and requirements.

The daylighting evaluation of the light guide was completed in a school building, see Fig. 5. The light guide of diameter 0.52 m and length 4.8 m has been installed in a windowless corridor in the building, see Fig. 7. Light measurements and calculations of internal illuminance were completed for the investigation. Internal illuminance was determined on the working plane 850 mm over floor level in the reference room (in the distance 2 m under the light guide ceiling diffuser).

a)



b)

Fig. 5 Building with the investigated tubular light guide
a) photograph of the building with the position of the light guide installation
b) scheme of the plan and section of the corridor illuminated by the tubular light guide

The internal illuminance was measured during the outdoor climatic conditions from overcast cloudy sky with external illuminance between 3800 and 5000 lx to clear sky with average external illuminance about 42 000 lx. Illuminance meter T-10, serial no. 32521004, Konica Minolta, serial no. 51511084 was used for the light measurements.

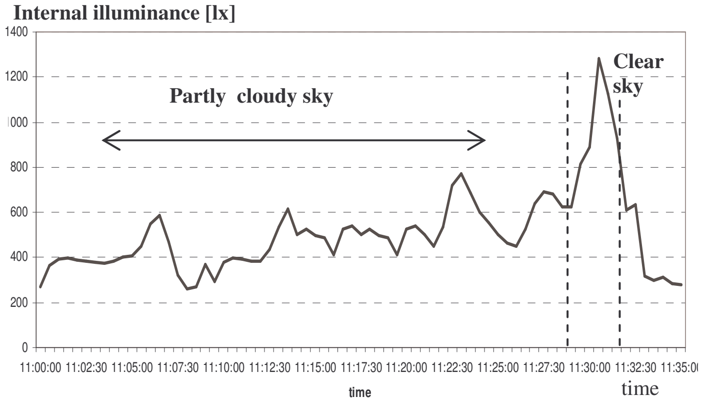


Fig 6 Example of internal illuminance measurements under the light guide

Fig. 7 Photograph of the room with the investigated light guide

Fig. 8 Luminance photograph - luminance distribution inside of the room with the light guide (Luminance camera LMK)

The illuminance in the reference room was also calculated (average luminance of the ceiling diffuser of the light guide is used as an input value for the internal illuminance calculations).

Data from the measurements under the light guide were compared to calculation results which are presented in Table 5 (for under the investigated light guide overcast, partly cloudy and clear sky conditions).

Table 5 Measured and calculated illuminance

Type of sky		Illuminance [lx]	Difference [%]
Overcast cloudy sky	Calculated data	51.9	9.7
	Measured data	57.5	
Partly cloudy sky	Calculated data	185	7.5
	Measured data	200	
Clear sunny sky	Calculated data	732	42.8
	Measured data	1280	

Curves of internal illuminance distribution under the light guides are shown in Fig. 9, determined for overcast sky conditions.

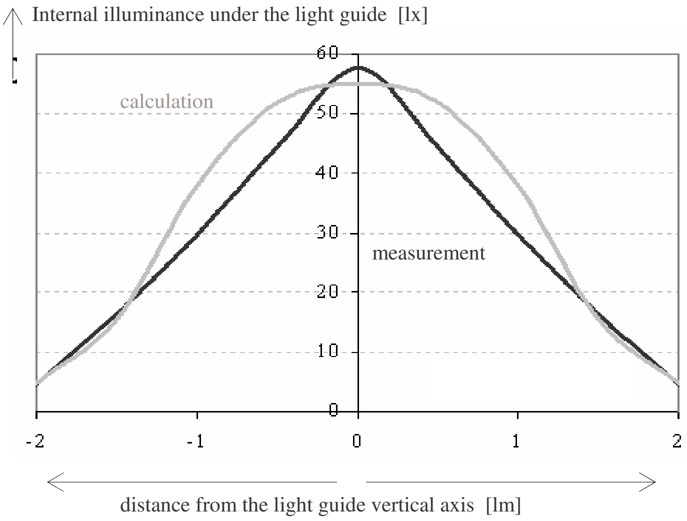


Fig. 9 Internal illuminance under the light guide

The difference between the curve of calculated and measured data presented in Figure 9 is caused by different input characteristics used for calculations. The direct light component transmitted from the light guide was considered for calculations. Results from measurements are influenced by internally reflected component from the floor and wall surfaces. The perfect diffusive e ceiling transparent cover was assumed for the calculations. In real conditions the diffuser transmits a great deal of the propagated light in the direction of the vertical axis of the light guide. For this reason measured illuminances have greater values in the axis of the light guide compared to the value which was calculated. Calculations based on ideal light scattering on the ceiling diffuser give higher illuminances in distant positions from the vertical axis of the light guide compared to data from light measurements in the same places.

It can be expected that the most important effect on daylighting through light guides will be during summer period with the highest sun altitudes. Internal illuminance in rooms with light guides could vary significantly. For example for the light guide of length 5 m and diameter 0.5 m internal illuminance 2 m under the light guide is less than 50 lx for overcast sky and it could increase to about 700 lx and even more in case of clear sky. During sunny days the illuminance distribution on the horizontal work plane is changed in dependence on the sun position. The highest illuminance levels can be expected on the side of the diffuser where the spot with the highest luminance appears.

Daylight factor DF [%] was determined as the ratio between measured internal illuminance in the selected points on the working plane and external illuminance simultaneously measured on un-shaded horizontal plane in exterior. Light measurements were carried out for outdoor conditions – external illuminance between 3800 to 5000 lx.

The daylight factor DF = 1.15% (2 m under the light guide vertical axis) was determined from measurements under overcast sky. There is the scheme of the light guide installation and the curve of the daylight factor distribution on the working plane under the light guide diffuser in Fig. 10.

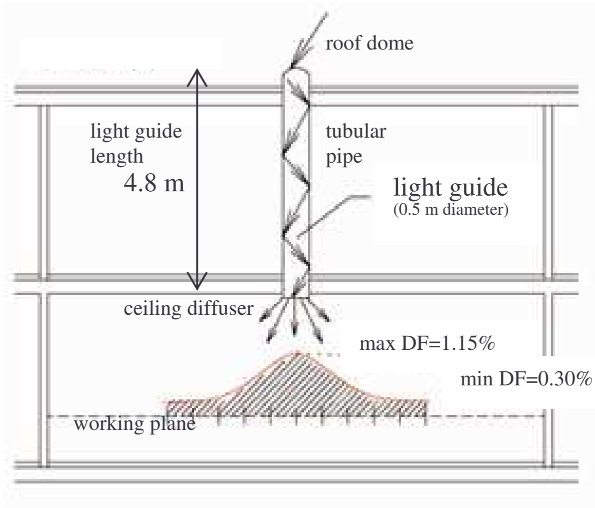


Fig. 10 Daylight factor distribution on the working plane

A calculation module in MS Excel was completed for the evaluation of light guides. The program serves for calculation of internal illuminance in any position on a horizontal plane under investigated light guides of different dimensions. Input data for the program are the light guide radius, luminance of the ceiling diffuser of the light guide, vertical distance of the horizontal working plane under the light guide, horizontal distance of nodal points on the working plane where internal illuminance is supposed to be calculated.

Results of calculations of internal illuminance from the investigated light guide (diameter 520 mm, length 4,8 m) on the working plane determined for overcast sky are presented in Table 6 for average luminance of the ceiling diffuser 1 000 cd.m^{-2} and in Table 7 for the clear sky conditions and average luminance of the ceiling diffuser 14 000 cd.m^{-2}. Similar results were achieved in the computer program Lux-Plot [14].

Table 6 Illuminance E [lx] on the working plane under the light guide (calculated for overcast sky conditions)

E [lx]	2.00	1.50	1.00	0.50	0.00	0.50	1.00	1.50	2.00
2.0	0,76	1,50	2,72	4,10	4,75	4,10	2,72	1,50	0,76
1.5	1,50	3,56	7,64	12,9	15,6	12,9	7,64	3,56	1,50
1.0	2,72	7,64	18,8	32,4	38,0	32,4	18,8	7,64	2,72
0.5	4,10	12,9	32,4	48,5	51,9	48,5	32,4	12,9	4,10
0.0	4,75	15,6	38,0	51,9	53,1	51,9	38,0	15,6	4,75
0.5	4,10	12,9	32,4	48,5	51,9	48,5	32,4	12,9	4,10
1.0	2,72	7,64	18,8	32,4	38,0	32,4	18,8	7,64	2,72
1.5	1,50	3,56	7,64	12,9	15,6	12,9	7,64	3,56	1,50
2.0	0,76	1,50	2,72	4,10	4,75	4,10	2,72	1,50	0,76

Internal illuminance could be more than 15 times greater during clear sunny sky compared to overcast sky outdoor climatic conditions, see Table 7.

Table 7 Illuminance E [lx] on the working plane under the light guide (calculated for clear sky conditions)

E [lx]	2.00	1.50	1.00	0.50	0.00	0.50	1.00	1.50	2.00
2.0	14	28	51	76	88	76	51	28	14
1.5	28	66	142	241	290	241	142	66	28
1.0	50	143	350	603	708	603	350	143	50
0.5	76	241	603	903	966	903	603	241	76
0.0	88	290	708	966	989	966	708	290	88
0.5	76	241	603	903	966	903	603	241	76
1.0	50	143	350	603	708	603	350	143	50
1.5	28	66	142	241	290	241	142	66	28
2.0	14	28	51	76	88	76	51	28	14

The internal illuminance on the working plane 2 m under the light guide diffuser can vary in the range from minimal value 50 lx (determined for overcast sky conditions) to maximal value 1000 lx (determined for clear sky conditions with direct solar radiation) in accordance with results from calculations and measurements. These results are in compliance with published presentations of tubular light guide investigations [15], [16], [17], [18].

The following table 8 presents results of calculations of internal illuminance of light guides of diameters 0.25, 0.50 an d 0.75 m in the position 0, 1, 2 and 3 m from the vertical axis of the light guide on the plane 2 m under the light guide (θ-angle between vertical axis and line connecting the centre of the ceiling diffuser and the investigated point on the horizontal working plane).

Table 8 Illuminance from light guides of different diameters under clear, partly cloudy and overcast sky

Distance, angle	Sky conditions	Light guide diameter [m]		
		0.25	0.50	0.75
0 m, θ_0=0°	overcast	12.3	49.1	110.4
	partly cloudy	49.2	196.4	441.6
	clear	172.2	687.4	1545.6
1 m, θ_1=26.57°	overcast	8.8	35.1	79.0
	partly cloudy	35.2	140.5	316.0
	clear	123.2	491.4	1106.0
2 m, θ_2=45°	overcast	4.3	17.4	39.0
	partly cloudy	17.4	69.4	156.1
	clear	60.2	243.6	546.0
3 m, θ_3=56.31°	overcast	2.1	8.4	18.8
	partly cloudy	8.4	33.5	75.4
	clear	29.4	117.6	263.2

Graphs in Figure 11 compare curves of internal illuminance 2 m under the light guides of different radii from 0,1 to 1,0 m, determined for the light guide of efficiency 0.32 and for overcast sky conditions. Illuminance under the light guide directly in its axis is increased from 8 lx (for r=0.1 m) to illuminance 416 lx in case of the light guide of radius r=1.0 m.

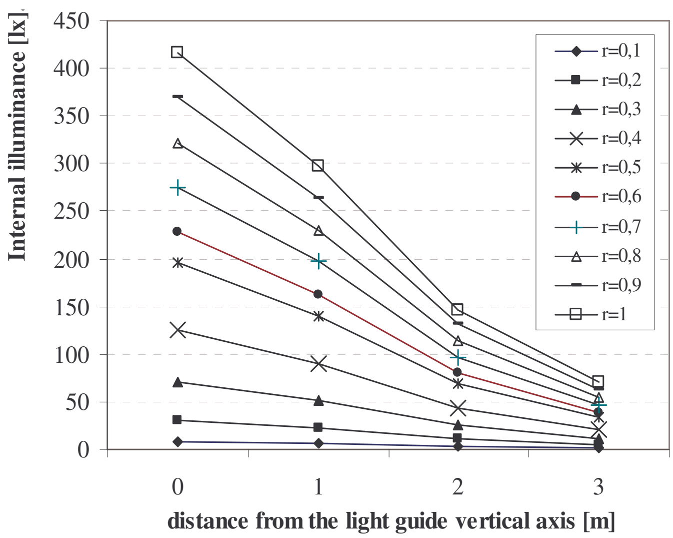


Fig. 11 Curves of internal illuminance under light guides of different radii (between 0.1 and 1.0 m)

5 Tubular Light Guides Compared to Windows and Skylights

The evaluation of energy savings and daylighting assessment of the investigated tubular light guides has shown that these systems play quite positive role in buildings. They could not permanently substitute traditional daylight systems as windows and skylights but they can be used as additional daylight complements and systems of lighting of windowless internal parts of building interiors.

Daylight studies based on computer simulations in programs Ecotect [19] and Radiance [20] were completed to compare internal illuminance from light guides with vertical windows and roof skylight of the same glazed area, see Fig. 12, Fig. 13 and Fig. 14. The tubular light guide was evaluated in the design variation with clear glass ceiling cover. This simulation gives information about direct transport of daylight through the light guide.

The comparison of advantages and disadvantages of daylighting by tubular light guides, vertical windows and skylights are summarized as follows:

Tubular light guides

Advantages: Daylight transport into distant internal rooms inside of buildings without windows, zenith daylighting systems which collect daylight of the whole sky hemisphere, in many cases they are not shaded by obstacles and barriers. Tubular light guides dive uniformly distributed light in case if they are completed with the ceiling diffuser.

Disadvantages: Tubular light guides are systems without visual contact with outdoors, common light guides have no possibility for opening and natural ventilation. High investment price of the system.

Windows

Advantages: Visual contact with outdoors, possibility of natural ventilation.

Disadvantages: Higher light losses, high light reflectance on vertical glazing, light is collected from only ½ of the sky hemisphere (lower sky luminance to compare zenith luminance), dependence on the orientation towards to the North -South. In many cases windows are shaded by neighbouring obstacles and barriers, non-uniform daylight distribution.

Skylights

Advantages: High light intensity, possibility of natural ventilation, uniformity of daylighting can be achieved by convenient position and dimensions of the skylights.

Disadvantages: No visual contact with outdoors, unwanted glare effect in time of intensive sun shine, excessive solar gains and overheating of rooms, daylight system without possibility to transport of light into distant places in buildings.

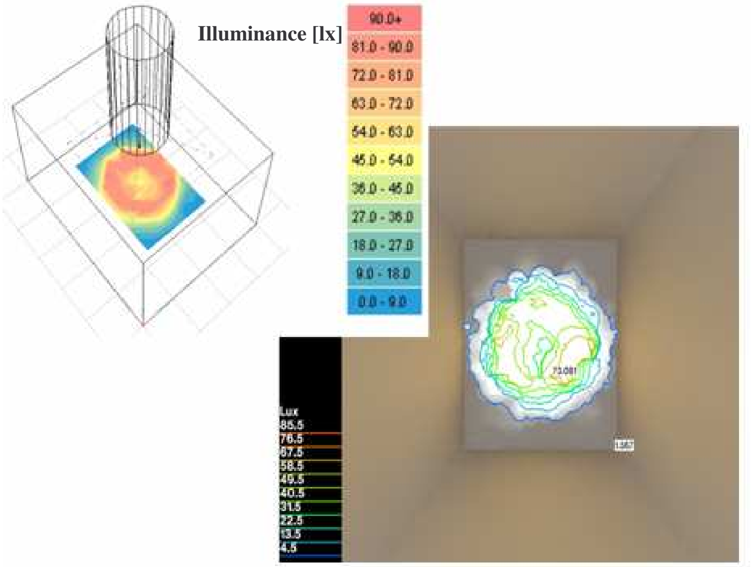


Fig. 12 Illuminance [lx] from the tubular light guide (with clear glass ceiling cover)

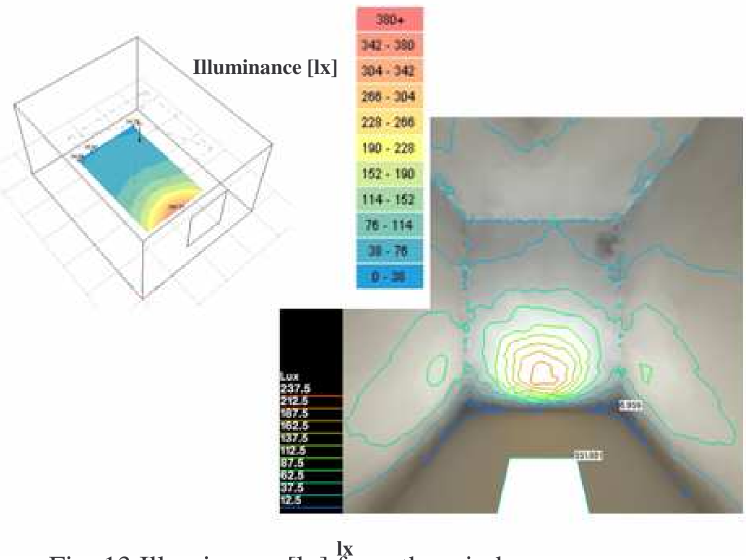


Fig. 13 Illuminance [lx] from the window

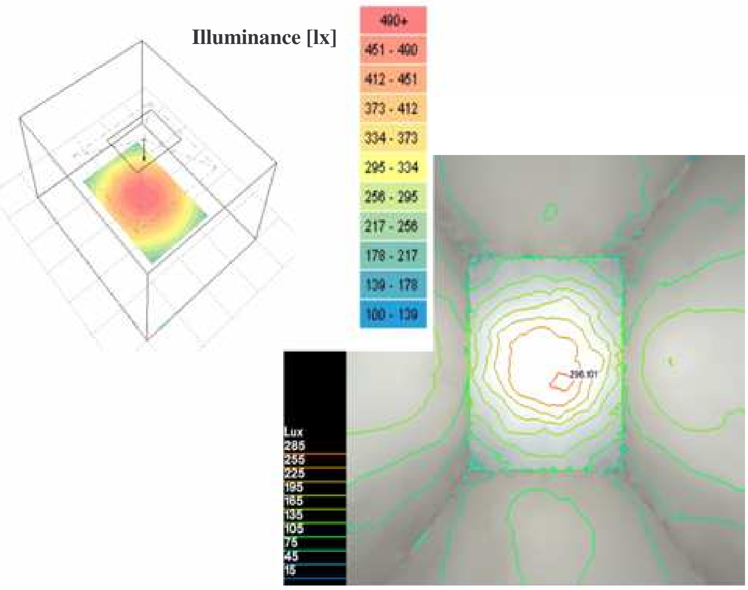


Fig. 14 Illuminance [lx] from the skylight

6 Conclusion

The tubular light guides represent modern way of illumination of internal parts in buildings.

The investigation of tubular light guide light efficiency and electric energy savings was carried out. Light efficiency of light guides is the ratio between luminous flux leaving the light guide and entering light guide and it also could be determined from luminance of the ceiling diffuser and sky luminance. The light efficiency of common light guides varies in the dependence on their dimensions and optical properties between 0.5 and 0.2.

Efficient use of the tubular light guides in buildings depends on many factors. Optical properties as high light transmittance of the roof dome and the ceiling diffuser and high reflectance of internal surface of the light guide tube and its dimensions play important role in the design of the light guide. It is recommended to design light guides to geometry length/diameter less than 20.

The practical installation of the light guide of standard dimensions and optical properties was selected for the daylight study and compared with computer calculations. The presented calculation method was used for the evaluation of internal illuminance from tubular light guides.

It can be expected that the greatest effect of light supply will occur during summer period with the highest sun heights. During clear days the illuminance distribution on the working plane will be changed in dependence on the sun position. The highest illuminance levels can be expected on the side of the diffuser where the spot with the highest luminance appears.

Results from illuminance measurements indicate that this technology could be considered as the subsidiary daylight system in the deeper parts of room or could substitute artificial lighting in the windowless spaces without requirements for visual tasks such as corridors, halls, vestibules, stores or public spaces with needs of natural lighting.

The advantage of the tubular light guide systems is in energy savings and reduction of energy cost for artificial lighting compare to permanent electric lighting operation. Wider application of light guides in buildings could also bring positive environmental impact in reduction of carbon dioxide emissions. On the other hand the pay back period of these systems is very high to compare the investment price.

The main contribution of light guides is in the improvement of visual comfort in buildings and possibility of dynamic daylighting in internal parts of buildings. Daylighting is natural source of energy which could not be substituted by any artificial source of light.

Acknowledgement

This presentation has been completed with the support of the project: the project MSMT CZ-102 and SK-CZ-11006 "Research of real annual conditions of illuminance for effective use of light guides in climatic conditions of the Slovak and Czech Republic".
The author thanks to Assoc. Prof. Jiri Plch, PhD for his help with light measurements and Frantisek Vajkay, MSc for computer simulations.

References:

[1] Baker, N., Franchiotti, A., Steemers, K., *Daylighting in Architecture*. James & James Science Publishing, Brussels, 1993, pp. 2.11-2.15.

[2] Bracale, G., Mingozzi, A., Bottiglioni, S., Performances and Daylighting applications of Solatube. The Tubular skylight. Proc. Conf. *Lux Europa, 2001*, Reykjavik, 2001, pp. 360 – 384.

[3] Carter, D.J., The measured and predicted performance of passive solar light pipe systems. *Lighting Research and Technology*, vol .34, no. 1, 2002, pp. 39-52.

[4] Jenkins, D., Muneer, T., Modelling light pipe performances – a natural daylighting solution. *Building and Environment* 38, 2003, pp. 965-972.

[5] Swift, P.D., Smith, G.B., Cylindrical mirror light pipes. *Solar Energy Materials and Solar Cells*, 36, 1995, pp. 159-167.

[6] Yohannes, I. Characterising the performance of light-pipes in UK climate PhD Thesis, Nottingham University, 2003.

[7] Callow, J.M. *Daylighting Using Tubular Light Guide Systems*. PhD thesis, University of Nottingham, 2003.

[8] Gall, D. (2004) *Grundlagen der Lichttechnik*, Licht und Beleuchtung, Pflaum Verlag, GmbH, p. 127-131.

[9] Robbins C. L. Daylighting - Design and Analysis, Van Nostrand Reinhold, New York & Wokingham, US, 1986

[10] Darula, S., Kittler R. Predetermination of exterior radiation and illumination conditions: the unification of their characteristics. CD Proc. Conf. Lumen V4, Ba latonfured, 2006

[11] Darula, S. et al., *Determination of light guide light efficiency under the artificial sky*. Report from experimental measurement. Slovak Academy of Sciences, Bratislava 2006

[12] Plch, J., Mohelnikova, J., Light Guides – Daylight and energy saving possibility. *Proc. of the International conference Lux Europa 2005*, Berlin, Germany, September 2005, pp. 259-261.

[13] http://projects.bre.co.uk/sap2005/

[14] Jenkins, D., Muneer, T. Light-pipe prediction method. *Applied Energy*, 2004, vol. 79, no. 1, p. 77-86,
[15] Shao, L., Riffat, S.B., et al. A Study of Performance of Light Pipes Under Cloudy and Sunny Conditions in the UK. *Right Light,*1997, vol. 1, no.4.
[16] Shao, L., Mirror light-pipes: Daylighting performance in real buildings. *Lighting Research & Technology*, 1998, vol 30, no 1, pp. 37-44.
[17] Marwaee, A., Carter, D.J. A field study of tubular daylight guidance installations. *Lighting Research & Technology,* 2006, vol. 38, no. 3, pp. 241-258.
[18] Carter, D.J. The Measured and Predicted Performance of Passive Solar Light Pipe Systems, *Lighting Research & Technology*, 2002, vol. 33, no. 1, p. 39-52.
[19] http://www.squ1.com
[20] http://www.artifice.com/cgibin/alk?http://radsite.lbl.gov/radiance
[21] Darula, S., Kittler, R., Kambezidis, H., Bartzokas, A. Dynamics of Radiation and Daylight Climate Linked with Standard Skies. *Proceedings of CIE/ARUP Symposium on Visual Environment Symposium*, London, CIE Publication x 024:2002, p. 43-48
[22] *The IESNA Lighting Handbook*. Reference & Application, IESNA New York, 2000.