

Light Guide Collector Prototype: Laboratory Testing

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Abstract

The article reviews the potential of a light guide system equipped by a concentrator device capturing daylight applicable for illumination of building interiors and presents results of experiments on performance of its prototype. The main goal is focused on the comparison of traditional solutions and newly developed prototype of the light guide system and presents examination of its light transmission efficiency based on the laboratory experiments.

Keywords: daylighting, tubular light guide, light transmission efficiency.

1. Introduction

Light guide system is a device that transmits daylight into building interiors. A function of tubular light guides is to capture, collect and transmit daylight into interior spaces which cannot be lit using conventional windows or skylights where daylight is insufficient and/or is missing [1-4]. These systems compared with traditional skylights and windows show several advantages like energy savings (small envelope area relative to the amount of useful light they can admit), lower summer solar heat gains and daylight presence in interiors. The availability and temporal changes of natural light in internal environment can also contribute to the improvement the occupants' well-being [3].

Systems with daylight collectors are usually placed on the building roof or envelope construction. They capture sunlight or skylight to transmit it into the light tube. The collector installation should be designed in buildings that there is a free space for receiving light while any obstruction of solar radiation from adjacent structures should be avoided. The roof collectors suit the deep parts of building, the façade mounted systems are more suitable for the multi-story buildings, but they are recommended to be south oriented.

The collector function is to gather sunlight and skylight from part or whole sky hemisphere. The light guide is usually covered by a transparent dome to seal the pipe against ingress of dust and rain. The dome is designed to meet the fire resistance requirements. It is self-cleaning due to its shape. The material is a single or multiple-layer transparent glass or plastic in various geometric shapes. It may contain optical features (prisms, reflectors or diffusing elements) to enhance the lighting output, especially at low sun altitude angles [5-7].

Many theoretical and experimental works were focused on the construction of light guides and their light transmittance evaluations [2-4 and 8-17]. Special light guide systems have a head in the shape of the collector to concentrate sun rays and direct them into the light guide tube. A prototype of a light guide with a mirrored parabolic head [18] was tested in the laboratory at the Faculty of Civil Engineering of Brno University of Technology (FCE BUT). Results of the daylight measurements on the reference plane in the experimental box are

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summarized in this article.

2. Light Guide Prototype

There are several technologies capturing sun rays on the top of buildings and transport them into interiors. Commonly such devices consist of a dome, hollow tube and diffuser. On the top of the tube a transparent cover can be placed. The cover is provided in various shapes or from materials redirecting incident light rays. The light guide with light collecting mirror parabolic head (CMP) was proposed and tested in its prototype. This system can be assembled as stable or equipped by tracker to set direction towards the sun position. Incoming sun rays are reflected on the parabolic mirror. The reflected rays are concentrated in the focus of the mirrored parabola. The secondary mirror located in the focus reflects the concentrated rays towards the light pipe as is shown in Figure 1. The elevations of the sun rays correspond to situations in Brno on 21st June at 8:00 (Fig. 1a) and 10:00 (Fig. 1b).

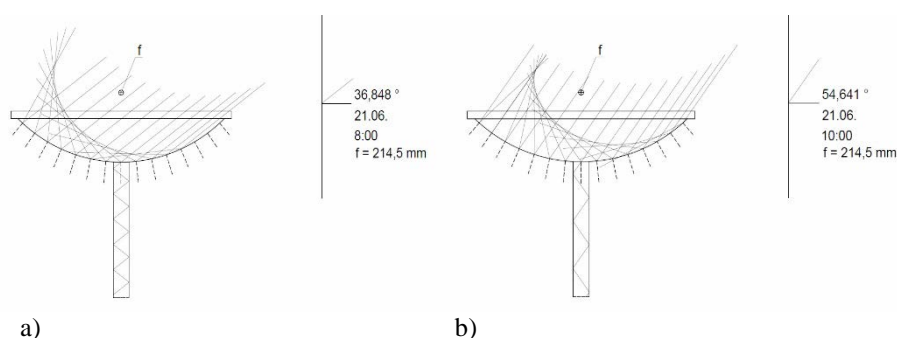


Figure. 1 Scheme of the parabolic head and light rays concentrations on 21st June
a) at 8:00, solar altitude 36.85°; b) at 10:00, solar altitude 54.64°;

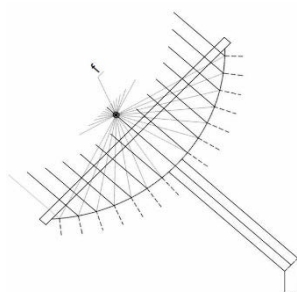


Figure. 2. Scheme of the CMP directed to the sun in elevation 43°

The light pipe with parabolic head is more efficient in hot climate with intensive sun shining when high solar altitudes occur. In temperate climate the system with light concentrator should be tracked to the sun position on the sky. The automatic tracking requires special devices with appropriate software. If tracker is used to direct the CMP towards the sun position than sun rays are parallel to the axis of entry tube as it is shown in Figure 2.

One sample of the CMP prototype was selected for testing of the light transmittance and daylight study. Experiments were carried out with the system consisting of a collector head joined with a tube and diffuser in the static vertical position. It is supposed that the concentrating parabolic mirror located on the building roof can increase light transmittance through the light guide not only due to direct solar radiation but also by diffuse sky light. This will be important finding for the installation of the CMP system in localities with dominant cloudy sky conditions. View into the collecting head is presented in the Figure 3 [18]. The lower part of the collector creates parabolic mirror which reflects sun rays to the upper small metallic concave element with highly reflective surface. The element is used to direct sun rays into the hollow tube with internal surface of the high reflectance.

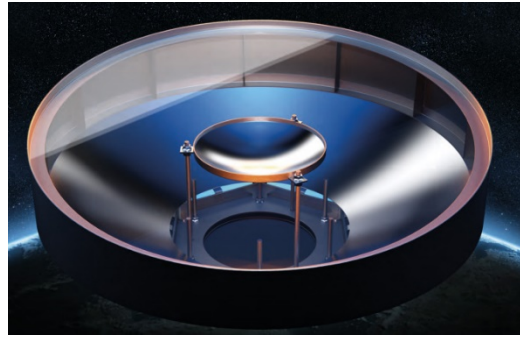


Figure. 3 View onto the CMP head [18]

3. Laboratory Experiment

An experimental box was made for the light guide prototype installation. The box is of dimensions $1.0 \text{ m} \times 1.0 \text{ m} \times 1.0 \text{ m}$, inside of the box – wooden slab surface without painting. The box serves a load-bearing construction. The sample of the special light guiding system consists of 0.520 m diameter and 0.6 m length hollow tube was mounted onto the box. The system includes the CMP collector and a concave element with highly reflective surface, Figure 3. A transparent cover of the collector is made of the clear glass with antireflective coating. The tube end is covered with a translucent diffuser on the indoor side. All joints of the light guide were overlapped by opaque tapes.

Illuminance was measured outside and inside of the box. These measurements give data for specification of light transmission efficiency of the light guiding system. The outside measurements were completed on a horizontal plane at the input of the light pipe concentrator head. The measurements of the horizontal illuminance inside of the box were carried out in the position of the light pipe vertical axis and at the distance of 0.75 m below the diffuser, Figure 4.

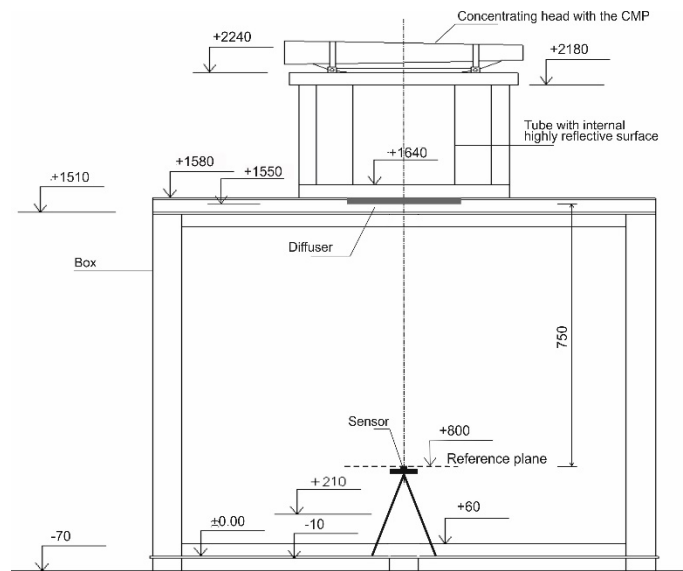


Figure. 4 The experimental setup, location of the light guide with the CMP head and reference plane

The light guide tube was made of hard aluminium sheet coated by high reflective layer on its inner surface. Light transmission efficiency is highest if the tube is short and straight. If tube is longer, bended, or flexible construction, a part of the transmitted light is lost. To minimize light losses, a high reflectivity of the tube lining and glossy inner surface is crucial. This assumption was taken into consideration for the experimental work: light pipe with tube of 0.6 m length was selected for the testing while the light reflectance of the tube internal surface

is $\rho = 0.93$.

The illuminance meter LX-1128SD was used for light measurements. Illuminances in the investigated points in the interior laboratory and inside of the box were monitored. Daylight conditions were continually registered by the horizontal illuminance meter placed in exterior close the skylight glazing. The measurements were carried out for different daylight levels during a day and under situations from overcast sky to partly cloudy and sunny sky conditions.

4. Daylight Illuminance Measurement

Quality of indoor luminous environment depends on the sufficient daylight. Application of new daylight technologies requires testing not only optical properties but also their performance during typical situations.

The prototype of the light pipe with the CMP was used for experimental study and daylighting measurements before starting of its commercial production. Measurement instruments were installed in April 2015 and data were recorded up to July 2015. Daylight illuminance at the light guide input and output serve for specification of the light guide system efficiency for different sky conditions. The measurements were completed inside of the laboratory at the level of the glass cover of the CMP head and inside of the box. Additional measurements of the outdoor daylight illuminance were also simultaneously carried out.

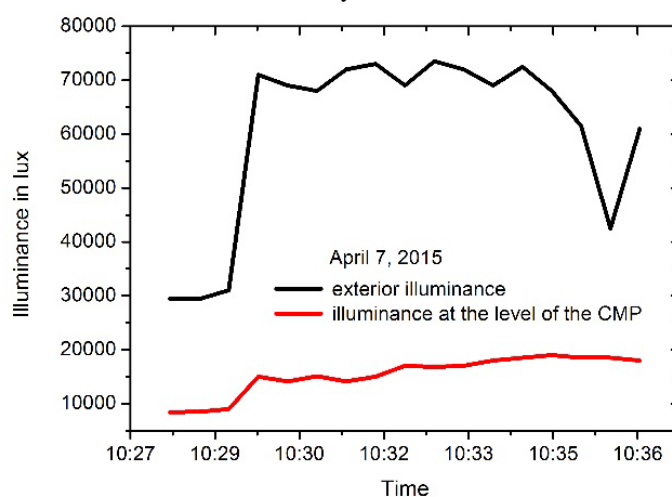


Figure. 5 Fragment of the exterior illuminance and illuminance at the level of the light guide head

Table. 1 Illuminance measured during morning on April 7, 2015 in Brno

Time	Exterior illuminance	Illuminance at the level of the CMP
	[lx]	[lx]
10:28:31	29500	8400
10:29:01	29400	8500
10:29:31	31000	9000
10:30:01	71000	15000
10:30:31	69000	14100
10:31:01	68000	15100
10:31:31	72000	14100
10:32:01	73000	15000
10:32:31	69000	17000
10:33:01	73500	16800
10:33:31	72000	17000
10:34:01	69000	18000
10:34:31	72500	18500
10:35:01	68000	19000
10:35:31	61500	18500
10:36:01	42500	18500
10:36:31	61000	18000

A fragment of a morning illuminance profile of the measurements is shown in Figure 5. The black curve indicates cloudy exterior situation, when illuminance levels change in the range of 29400 to 73000 lx. Horizontal illuminance close the CMP entrance at its level was registered more stable from 8400 to 19000 lx, representing higher diffusivity of incident light, Table 1. These levels as light source can be used in the study of light transmission efficiency of the sample.

5. Daylight Luminous Efficiency Modelling

The luminous flux method applying measured illuminance at the entrance surface area and at the level of the output can be used for the determination of the light transmission efficiency of the light guide systems. Light level - illuminance is the total luminous flux Φ_e [lm] incident on a surface per unit area. If illuminance E_e [lx] at the entrance of the system is known the input luminous flux Φ_e [lm] can be calculated [1]. To determine light transmission efficiency η of the hollow light guide systems the luminous flux Φ_i [lm] leaving diffuser - translucent component in the interior side has to be expressed.

The entrance surface area of the tube is calculated as:

$$S = \pi \times r^2 \quad [\text{m}^2] \quad (1)$$

The sensor of illuminance meter was fixed on the horizontal plane in the point of the tube axis. Then solid angle ω of the translucent part of the diffuser can be calculated as:

$$\omega = 4\pi \sin^2\left(\frac{\alpha}{2}\right) \quad [\text{sr}] \quad (2)$$

$$\text{where } \alpha = \arctan\left(\frac{r}{h}\right) \quad [\text{deg}] \quad (3)$$

r is the radius of the translucent part of the diffuser [m]

h – distance between diffuser and sensor on the horizontal plane [m].

The total light transmission efficiency of the guide system depends on the light transmittance of its components. The above mentioned experiments were focus on the study of the daylight transmission throughout the complete system. In this case the measured data of illuminance at the level of the system input and at the level of the system output can be used for calculation of the light transmission efficiency η of the sample. Then, value of the incoming luminous flux Φ_e , i.e. flux entering the guidance system is:

$$\Phi_e = E_e \times S \quad [\text{lm}] \quad (4)$$

where

E_e is measured horizontal illuminance at the level of the CMP [lx].

The luminous flux Φ_i leaving the guide output at the level of the diffuser can be calculated applying equations (5) and (6). Then value of the luminous intensity I is:

$$I = \frac{E_i}{h^2} \quad [\text{cd}] \quad (5)$$

where

E_i is measured illuminance on the reference plane in the box [lx]

and the luminous flux Φ_i will be:

$$\Phi_i = I \times \omega \quad [\text{lm}] \quad (6)$$

Finally, the light transmission efficiency η of the complete guidance system is determined as a ratio of the output to input luminous flux:

$$\eta = 100 \frac{\Phi_i}{\Phi_e} \quad [\%] \quad (7)$$

6. Daylight Luminous Efficiency on the Investigated Light Guide System with the CMP

The light transmission efficiency as example was expressed for selected fragments of the daily illuminance courses. Data were recorded on 25th May, 2015 at the level of the CMP, Figure 6, and simultaneously on the reference plane in the box, Figure 7. Using radius of the tube $r = 0.26$ m, distance between diffuser and reference plane $h = 0.75$ m and formulae (1) – (7) the light transmission efficiencies η of the guidance system consisting of the CMP head, 0.6 m length hollow tube and translucent diffuser were calculated. Results with average values of η are summarised in Table 2. Results indicate that light transmission efficiency of the guidance system with the CMP head is very sensitive for angle of incident rays. It was found value $\eta = 2.49\%$.

If incident direct solar beams are not concentrated in the focus of the parabolic mirror, it can occur situation that high quantity of incident luminous flux can be reflected back to the space as it is shown in the Figure 1. The input of the hollow tube is in the axis shaded by the small metallic concave element which results into reduction of the system efficiency under sunless skies when only diffuse light is transmitted.

Light guidance systems equipped with the CMP head require tracing facilities to direct parabolic mirror towards the sun position and then as much as direct sunlight can be collected.

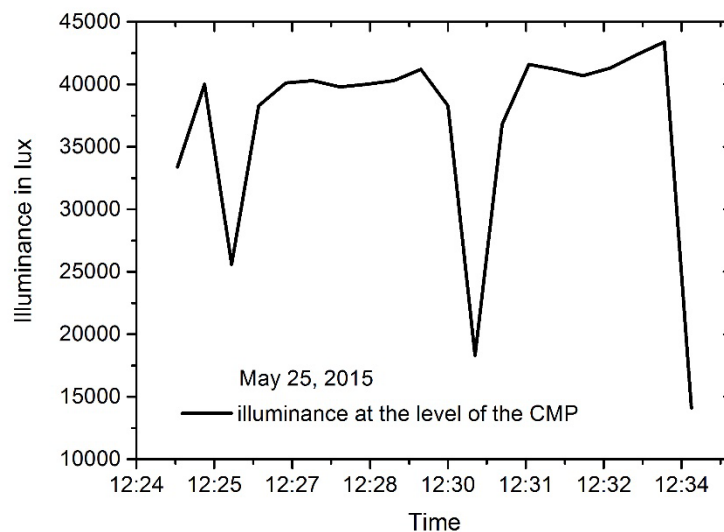


Figure. 6 The daylight illuminance at the level of the CMP, May 25, 2015

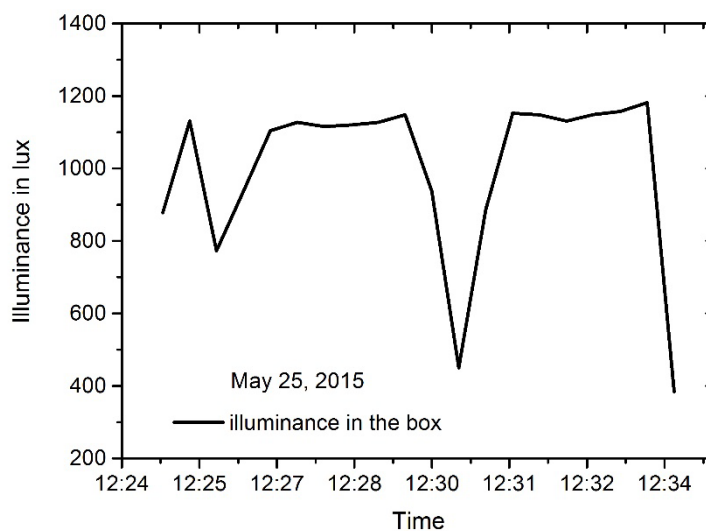


Figure. 7 The daylight illuminance in the box, May 25, 2015

Table. 2 Light transmission efficiency of the guidance system with the CMP, May 24, 2015

Time	Horizontal illuminance		Luminous flux		Luminous efficiency
	E_i	E_e	In the output	In the input	
hour	[lx]	[lx]	Φ	Φ_e	η
			[lm]	[lm]	[%]
12:25:00	878	33400	171.18	7093.21	2.413
12:25:30	1131	40000	220.51	8494.87	2.596
12:26:00	773	25600	150.71	5436.71	2.772
12:26:30	937	38300	182.68	8133.83	2.246
12:27:00	1104	40100	215.24	8516.10	2.527
12:27:30	1127	40300	219.73	8558.58	2.567
12:28:00	1116	39800	217.58	8452.39	2.574
12:28:30	1120	40000	218.36	8494.87	2.571
12:29:00	1127	40300	219.73	8558.58	2.567
12:29:30	1148	41200	223.82	8749.71	2.558
12:30:00	937	38300	182.68	8133.83	2.246
12:30:30	450	18300	87.73	3886.40	2.257
12:31:00	886	36800	172.74	7815.28	2.210
12:31:30	1152	41600	224.60	8834.66	2.542
12:32:00	1148	41200	223.82	8749.71	2.558
12:32:30	1131	40700	220.51	8643.53	2.551
12:33:00	1149	41300	224.01	8770.95	2.554
12:33:30	1157	42400	225.57	9004.56	2.505
12:34:00	1182	43400	230.45	9216.93	2.500
12:34:30	384	14100	74.87	2994.44	2.500
Average					2.491

7. Conclusion

The light transmission efficiency of the sample of the hollow light guide prototype with the CMP head was experimentally investigated in the laboratory conditions. This system was installed in the stable position with

orientation of the parabolic mirror towards zenith. Two sources of daylight occur in the nature: sun producing direct sun beams with very high intensity and sky producing diffuse light of the lower intensity.

The idea of the CMP head construction is to focus direct beams by parabolic mirror and redirect them towards the highly reflective tube of the light guide. Experiments prove that if parabolic mirror is not tracking to the sun position only a limited part of sun rays affecting the light guide head is redirected into the tube. When the CMP head is illuminated by the diffuse light the light transmission efficiency can be expected in the level of 2.5%. The value of the light transmission efficiency was determined from recorded illuminance data.

The light transmission efficiency is very low which indicates the fact that without the tracking system the advantage of this light guiding system is not used properly in the conditions of temperate climatic region. The passive installation of the light guide prototype in the static position could be applied only in regions with hot climate and with high solar altitudes. The light transmission efficiency of the system is increased significantly in the case of the tracking of the parabolic mirror to the intensive solar radiation position. An automatic operation of the tracking is recommended for the practical installations in buildings.

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