Measurements of Light Transmittance of Diffusers Used for Hollow Light Guides

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Abstract:

Currently is the discussion that the daylight is necessary and essential to the human body. One of the way to get daylight to interior spaces in buildings is use of light guide. The daylight can also be transported, where it is not possible to install windows or skylights. Because the price of the light guides is still relatively high, is most often used in offices, warehouses, production halls etc.. The direct sunlight and diffuse skylight are highly variable. Therefore, we cannot set the parameters of the illumination in a room where lighting is solved by using light guide.

This contribution will present results of measurements of light transfer through diffuser and its dependence on the direction of the rays of light.

Keywords: Tubular light pipes, Calculation, Light transmission efficiency, Diffusers

1. Introduction

Due to the general increase of energy prices and also because of the reduction of available stocks of fossil fuels, earth gas and oil, the world-wide energy saving campaign is now in progress. In houses and work spaces there is a trend to satisfy the hygienic requirements on the minimum illuminance levels covering the work plane and directly illuminating only places where visual tasks are expected. Therefore, when for constructional reasons daylight cannot be supplied in deeper spaces the permanent whole day artificial lighting has to be used [1], [2]. However, it consumes electric energy during whole days. To minimise this consumption light guides can be applied in some cases. Light guides transport sunlight and skylight from the building roof into interiors without energy requirements (e.g. [3] - [7]). The light transmission efficiency depends on the optical properties of all light-guide components, i.e. the dome, the pipe and the diffuser [8].

2. Tubular guidance systems

Light guides (Figure 1) offer solutions for transport of natural light into the building core and for the illumination of indoor spaces with insufficient lighting. The advantage of the roof light guide system is the access to sunlight and skylight from the whole hemisphere without necessary additional technical equipment. This passive system consists of the hollow tube, covered with a transparent dome and diffuser (Figure 2) and can be applied as an additional natural light source [1], [5].

The dome must be resistant to external climatic conditions and is generally produced from PMMA plastic material or glass with light transmittance in the range of τ = 0.9 to 0.93 and it is mounted on the building roof or wall. The common shape of the dome is a half sphere but in the case of application on sloped roofs its shape can be adopted to the prevailing sun path changes and sky luminance gradation. The collection of sunlight and skylight is his main function.

The hollow tubes are generally made from the aluminium material with diameters from 50 to 1000 mm and the lengths from 600 to 1000 mm without bends or bends with various angles from 15° to 45°. The desired length of the light guide system is created by joining of standard parts. The inner surface of the tube is special because of its very high light reflectance which is in the range of ρ = 0.9 to 0.98. The transport of daylight for longer distance into interiors is the main function of tubes.

The diffuser is the third part of the light guide system and its shape corresponds with the shape and diameter of the tube. Transparent PMMA plastic or glass are the prevailing materials used in production of this component. Diffusers cover tubes on the interior ceiling side, these can be clear, diffusive or prismatic. Clear diffusers are often applied in the interiors of commercial buildings such as offices, shops, corridors, stores etc. Diffusers in occupied indoor places have to be designed with regard to the exposure of human eyes to glare during sunny days. The diffusion, scattering or redirecting of transported light in the interior space is the main function of diffusers.

a) Dome b) Tube c) Diffuser

Figure 1. Components of a hollow light guide

Light transmission efficiency of the lightpipes depends on the orientation of the dome to the cardinal points, diameter and length of the tube, number of bends and the light reflection factor of their inner surfaces as well as on the optical properties of the diffuser. There are several possibilities for light guide applications. In the case of a horizontal roof and downright directional light propagation the vertical system is used (Figure 2a). In the case of the sloped roof it is useful to design a hollow tube with the minimal number of bends (Figure 2b).

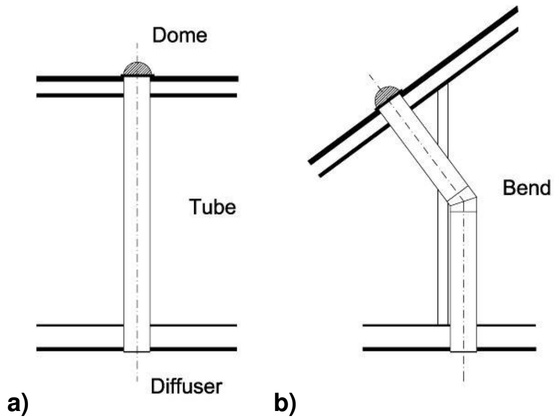

Figure 2. Scheme of hollow light guide,
a) direct light guide, b) light guide with bend

Optical properties of the diffuser predetermine the distribution of illuminance on the indoor surfaces. Diffusers with Lambertian diffusion and light transmittance redistribute natural light uniformly to all directions during all overcast and clear days. Diffusers made of clear transparent materials are transmitting incident rays during clear days straight forward. In this case can be created patches with higher luminances (so called hotspots) on the diffusers [9], [10] [11] as well as on the inner surfaces. Light pipes are used during the whole year under various daylight climate conditions and their efficiency can be calculated or measured [12]. The Report [13] recommends to simulate incident light by a fluorescent lamp panel and to measure luminous flux Φ_{ext} produced by the Daylight Guidance System in the integrated sphere. The dome is illuminated by rays from all directions under sunless skies and additionally by momentary sun rays of a specific direction. The analytical solution [11] indicates that recommended measurement method in [13] cannot simulate the real daylight conditions and its redistribution in indoor spaces. It seems that the directional propagation of rays thorough all components still needs to be studied.

3. The CIE calculation method for light efficiency of tubular guidance systems

The technical properties, design and application of tubular daylight guidance systems are described in [13]. The presented method for calculation of light guide efficiency prediction of direct and bent ducts is based on the luminous flux investigation. Determination of the incoming luminous flux Φ_{ext} from the value of exterior illuminance G_v and output luminous flux Φ_{int} are main quantities of the calculation. This method assumes that the levels of exterior illuminance, optical properties and dimensions of the light guide system components are known. The exact exterior illuminance values G_v is one of the major problems because of its permanent changes. Therefore approximate light efficiency calculations are based on the typical outdoor illuminances in various Western and Central Europe locations estimated from the SATEL-LIGHT web server [14].

3.1 Procedure

1. In simple cases the so-called Aspect Ratio $M = L/D$ is calculated from the length of the tube L and its diameter D. When the light guide contains a bend, the value of the Aspect Ratio M for whole system can be determined from the published table in [14]. The light losses effect the lengths $\sum(L/D)$ and bends $\sum M$ and are summed up in the general value of AR.

2. The combined values of the light transmission coefficient of the dome and the diffuser are calculated or estimated. The value of the maintenance factor MF is

set according to the type of the room and the inside and outside air pollution cover. Then the transmission tube efficiency *TTE* can be calculated by the empirical equation:

$$TTE = \frac{e^{\frac{L}{D}\tan\theta\ \ln\rho}}{1-\frac{L}{D}\tan\theta\ln\rho}, \qquad (1)$$

where θ - angle of impact [˚],
ρ - light reflection factor of the internal tube surface [%].

After measuring the effect of pollution the overall guide efficiency *EG* is:

$$EG = TTE\,0{,}63\ MF. \qquad (2)$$

The constant 0.63 in the equation (2) represents the overall value of the light transmission coefficient of the dome and the diffuser. This value is recommended when are unknown the light transmission coefficients of both components.

3. The luminous flux entering the tubular guide Φ_{ext} is calculated after determining the area of the tube section $A = \pi\ r^2$ and value of the global outdoor illuminance G_V:

$$\Phi_{ext} = G_V\ A. \qquad \text{[lm]} \qquad (3)$$

Considering the light loss within the light guide components the output luminous flux Φ_{int} into interior from the diffuser can be expected as:

$$\Phi_{\text{int}} = \Phi_{ext}\ EG. \qquad \text{[lm]} \qquad (4)$$

4. After the CIE method it is assumed that the indicatrix curve of diffuser is similar to the cosine function and the output luminous flux illuminates the work plane, wall and ceiling surfaces. Therefore it is important to consider the room dimensions, which can be expressed by the room *k* index:

$$k = \frac{a_r\ b_r}{V\left(a_r + b_r\right)}, \qquad (5)$$

where a_r - the room depth [m],
b_r - the length of the room [m],
V - the distance between the diffuser and the work plane [m].

5. The work plane is also illuminated indirectly by multiple reflections from the room walls. This effect takes into account the Utilisation Factor *UF* for diffuser output devices. Its value is tabled in [13] and determined when values of wall, floor and ceiling reflection factors as well as the room index *k* are known. Then the value of the daylight penetration factor *DPF* (which represents the average usable luminous flux on the work plane from the *N* number of light guides compared to exterior flux) can be calculated as:

$$DPF = \frac{N\,\Phi_{\mathrm{int}}\,UF}{A\,G_v} \quad [\%] \tag{6}$$

6. Finally, the light guide efficiency η is expressed by the ratio of the luminous flux Φ_{int} leaving the light guide into the interior to the luminous flux Φ_{ext} entering the light guide in the exterior:

$$\eta = \frac{\Phi_{\mathrm{int}}}{\Phi_{ext}} \quad [\%] \tag{7}$$

4. Directional light transmittance of the light-guide diffuser

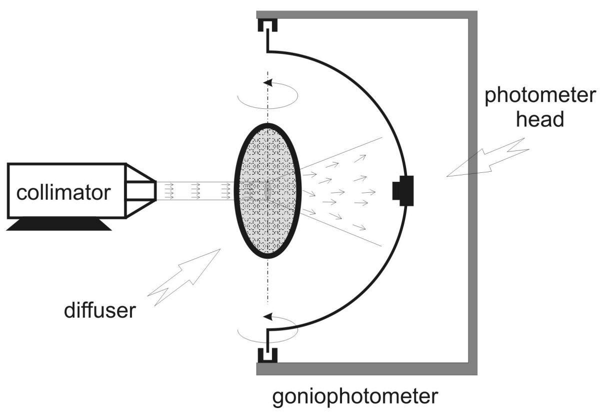

Figure 3. Scheme of the experimental set-up


Figure 4. A sample of the diffuser

The main function of the diffusers is to scatter light from the light guide (similar to luminaries) into the indoor space. Therefore, the material and structure of their surfaces are designed in accordance with user requirements. When the diffuse light is required in the interior the diffusive material is applied. In case of the requirement to supply daylight in a specific direction the transparent or structured surfaces of materials with high light transmission are applied. Therefore it is necessary to quantify the amount and direction of light transmitted by the diffuser [15].

That is also the reason why the materials and technology used for the manufacturing of diffusers provide their inner structure regarding the current needs. The surface of the diffuser usually is not homogenous and therefore the light transmitting is not uniform. Because of this, it is necessary to quantify the size and direction of the light going trough the diffuser. It is also necessary to establish the conditions according to which it is possible to characterize the light scatter on the downward surface of the diffuser.

The standard test method for determination luminous transmittance of transparent plastics published in [16] is based on the investigation of diffuse light influence on the luminous transmittance. The sample is mounted on the integration sphere while the light is supplied into this sphere by a tube collimator. Kocifaj in [11] has shown that the propagation of light through the hollow tube corresponds to the conditions of integration sphere only during foggy days. Daylight situations under overcast, cloudy and clear skies are characterised by various sky luminance distributions which result in very different intensities and directions of rays entering hollow guide lights.

In these cases applying the measured method after [16] can lead to results valid only under scarce and specific daylight situation. Better results can be expected when possible rays (sun beams and sky luminance elemental influences) received by the dome and diffused will be tested.

A luminous intensity distribution of light sources as well as light transmittance of transparent materials is investigated using a goniophotometer. For practical measurements the illuminance-meter head can be applied in the case of a larger distance between sample and sensor. In other cases when this distance is smaller than the limit of the photometric value, luminance-meter is applied for the determination of the directional light transmittance. The laser or collimator is the light source part of the goniophotometer.

To determine this transmittance the values of the spatial distribution of luminous intensity have to be measured. The applied methodology is based on the measurements of illuminance values E [lx] of the light transmitted diffuser which is rotated to the incident ray. Then the obtained data can be tabling and used for calculating of the diffuser luminous intensity indicatrix. For practical application the sample rotation of 5° from normal direction is sufficient. When the distance between the sample and the illuminance-meter is constant then values of luminous intensity I [cd] can be calculated as:

$$E = \frac{I}{r^2}, \qquad \text{[lx]} \qquad (8)$$

$$I = E\, r^2. \qquad \text{[cd]} \qquad (9)$$

4.1 Test measurement of the directional light transmittance

The directional light transmittance of the PMMA diffuser with the radius 0.32 m was tested at the goniophotometer, Figure 3. The sample used for measurements had a plane surface on the tube side while on the interior side its surface was structured by irregular spread bulleted inprints. This sample was mounted in the rotating head and its smooth surface orientated towards the collimator and its structured surface to the photometer head, Figure 4.

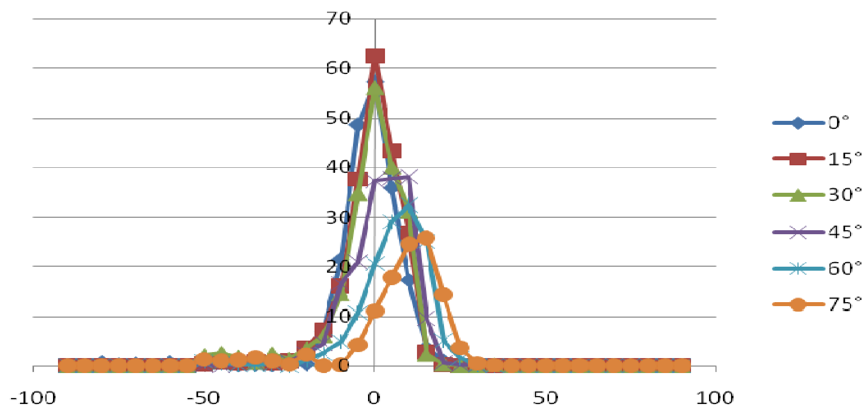

Figure 6. Luminous intensity in dependence on the angle of incident rays

Table 1. The measured illuminance values for multiple C-planes

Angle	C-planes					
	C0 – C180	C15 – C195	C30 – C210	C45 – C225	C60 – C240	C75 – C255
	E [lx]					
90° - 45°	**)*					
40°	0	0	0	0	0	0
35°	0,072	0,053	0,217	0	0,094	0,132
30°	0,041	0,066	0,038	0,027	0,114	0,564
25°	0,098	0,070	0,001	0,148	1,472	3,613
20°	0,973	0,209	0,464	0,675	5,062	14,280
15°	3,750	2,791	2,328	9,603	25,090	25,800
10°	17,250	26,850	31,230	38,120	32,460	24,610
5°	35,830	43,400	40,020	37,760	29,080	17,730
0°	57,210	62,550	56,030	37,300	20,590	11,050
-5°	48,640	37,600	34,650	20,930	10,700	4,250
-10°	21,460	16,040	14,480	16,540	4,957	0,233
-15°	6,983	7,259	6,140	4,542	2,521	0,043
-20°	0,413	3,507	3,522	2,389	1,099	2,316
-25°	0,520	1,003	1,330	0,936	0,072	0,357
-30°	0,198	0,594	2,437	0,434	0,479	1,028
-35°	0,336	0,832	0,760	0,519	0,167	1,733
-40°	0,184	0,516	1,744	0,183	0,261	1,179
-45°	1,003	0,695	2,586	0	0,534	1,053
-50°	0	0	0	0	0	0
-55° – -90°	**)*					
Note:	**) measured values are equal zero*					

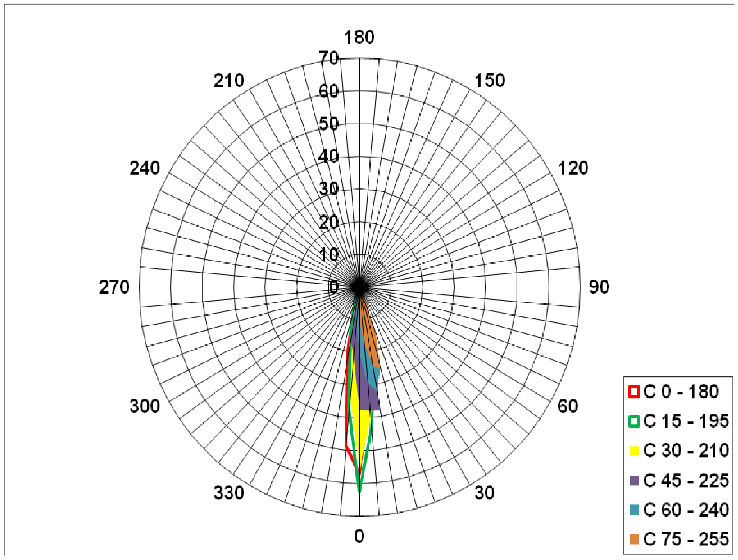

Figure 7. Measured luminous intensity curves

Because the sample can be considered as a rotary symmetric, the measurement positions can be applied in the range of 0°-90° in two perpendicular directions. During measurements the sample was rotated in angular steps from 5° to 45° deviations from the normal direction. The illuminance of the transmitted light was measured for these positions in C-planes.

The surface of diffuser was illuminated within a 37 mm circle patch in normal direction by the collimator. The distance between photometer head and the sample was r = 457 mm. The received illuminance 1619 lux on the diffuser was constant during all measurements.

Results of measurements are documented in Table 1. The luminous intensities were calculated for each C-plane after (9) and sequentially their indicatrix curves were plotted in the rectangular diagram, Figure 6, and polar diagram, Figure 7.

5. Conclusions

The sample of a diffuser used in measurements was produced from the PMMA plastic material with a specific inhomogeneous diffusing profile. The test of the directional light transmittance has shown that incident rays on the smooth diffuser surface facing the tube are refracted and due to the inhomogeneous bottom profile are redirected to various directions, thus the effect of a diffuse light source in the interior is created.

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