# DETERMINATION OF ANGULAR TRANSMITTANCE OF GLASSES FOR LIGHT GUIDES

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**Abstract:** Tubular light guides transport daylight into internal windowless parts in buildings via multi-reflections on highly reflective surface. They consist of roof dome of glass or transparent plastics, metal hollow core light pipe with mirrored internal surfaces and ceiling cover from diffusive glass which scatters daylight into interior. The investigation of light efficiency of these new systems of tubular light guides needs correct data of transmittance of transparent roof domes and ceiling covers of these systems. Angular transmittance of curved glasses and glasses with pattern are not available. A method for determination of angular transmittance of transparent components of light guides was set up. The method is based illuminance measurements within an experimental box with glass samples.

## 1. INTRODUCTION

Visual comfort in buildings is one of main demands for quality of indoor environment in buildings. Dayligting of internal parts of buildings is a technical problem. Tubular light guides represent possibility of natural lighting and also energy saving alternative in a comparison with artificial lighting. Light guides are special tubular systems, which optically connect outdoors with indoors. Their function is based on the principle of light transport for distant places due to multi reflections on highly reflective surfaces. A tubular light guide consists of a roof transparent dome of glass or transparent plastics, metal hollow core light pipe with mirrored internal surfaces and ceiling cover from diffusive glass which scatters daylight into interior (Bracale et al., 2001; Yohannes, 2003).

Values of angular transmittance of glass represent important input data for daylight and solar systems evaluations. Data of angular transmittance are determined for clear flat glass and for clear glass with steel wires (Kittler and Kittlerová, 1968; Rybár, 1987; Hopkinson et al., 1966). The relative angular transmittance of the flat clear glass is defined as the ratio between transmittance $\tau_\theta$ in the incident angle $\theta$ and normal transmittance $\tau_n$

– according to Kittler ((Kittler and Kittlerová, 1968)

$$\frac{\tau_\theta}{\tau_n} = \cos\theta\left(1+\frac{1}{2}\sin^2\theta\right) \tag{1}$$

– according to ČSN 730580 (Rybár, 1987)

$$\frac{\tau_\theta}{\tau_n} = \cos\theta\left(1+\sin^3\theta\right) + e^{-\frac{\theta}{27}} - e^{-\frac{\theta}{26}} \tag{2}$$

– according to Rivera (Hopkinson et al., 1966)

$$\frac{\tau_\theta}{\tau_n} = 1,018.\cos\theta\left(1+\sin 3\theta\right) \tag{3}$$

Angular transmittance of curved glasses or plastics which are used for roof domes and flat diffusive glasses with patterns which are convenient for ceiling diffusers are not available. The investigation of light efficiency of tubular light guides needs correct data of angular transmittance of their transparent parts. A method for determination of light transmittance of the transparent components of light guides was set up. The method is based on angular transmittance determination on basis of data from illuminance measurements.

## 2. MEASUREMENT METHOD

The method for determination of angular transmittance of transparent components of light guides requires data of light measurements within an experimental box with glass samples. Dimensions of the box are 0.6 m x 0.6 m x 0.95 m. There is a circular opening of diameter 0.16 m in the middle of the front side of the box for a glass sample placing. Source of light – four fluorescent lamps 4 x 18 W covered by a frosted glass cover of dimensions 0.5 m x 0.5 m was used. The cover serves for diffusion of the lamps light. The distance of the light source from the front side of the box is 2.5m=5*ds*, where *ds* is the dimension of the light source (0.5m). This distance is in compliance with „*oft-quoted five-times rule*“ which is required for photometric measurements (the measurement error is minimized for this distance) [6]. The box with the glass sample on its front side was revolved at defined angles with respect the light source position. There were two light sensors of luxmeter Minolta T10 fixed in side walls of the box – see Fig. 1 (c1 – the upper sensor fixed in the distance 0.15 m x 0.15 m from the upper left hand side corner of the box, c2 – the lower sensor fixed in the distance 0.15 m x 0.15 m from the lower right hand side corner of the box). Values of illuminance monitored inside of the box give data for the mean internal illuminance which was compared to the reference value (illuminance inside the box without a glass sample). These values served for determination of angular transmittance of selected glass samples.

Results of illuminance measurements have given data for determination of curves of angular transmittance in angles from 0° to 90° (with 10° interval) for the following samples of light guide elements: roof glass dome, plastic dome (PMMA), flat ceiling covers of clear float glass and antireflection glass, flat glass diffusers with patterned surface for light scattering – smooth and rough patterned diffusers. All samples have diameters 0.17 m and thickness 3 mm. Luminance measurements for the selected samples at given angles were 5 times repeated.

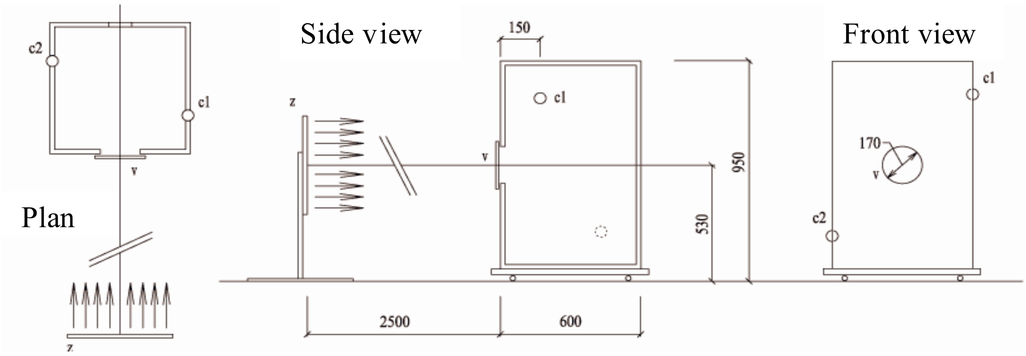


**Fig. 1.** The experimental box for illuminance measurements (dimensioned in mm)
z – light source, v – glass sample, c1, c2 – luminance meter sensors (dimensioned in mm)


**Fig. 2.** Photographs of the box for illuminance measurements, a) box with a glass sample, b) light source - lamp, c) angular scale, d) lower sensor of the luxmeter

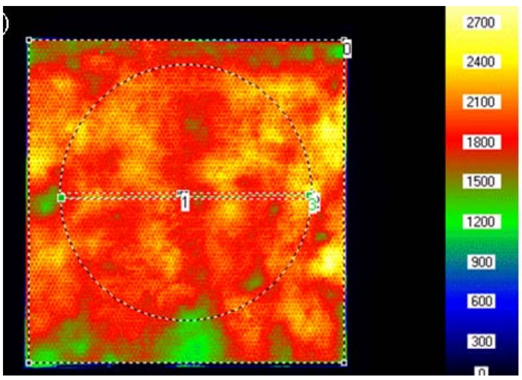


**Fig. 3.** Luminance distribution of the light source transparent cover (monitored by LMK Vario)

Luminance of the transparent frosted glass cover of the used lamps was monitored by luminance camera LMK Vario, see Fig. 3. Minimal, maximal and average luminance is presented in Table 1. The luminance distribution was monitored for determination of light conditions. Average luminance from the measurements is L = 1947 $cd.m^{-2}$ luminous emittance H = π.L = 6 116 lx, which is adequate to outdoor conditions of uniformly overcast sky with diffusive light in accordance with the CIE overcast sky model (CIE S 011/E, 2003) with sky luminance gradation from horizon to zenith 1:3 – average luminance is 1592 $cd.m^{-2}$). For this light conditions measurements of angular transmittance of the light guide components was carried out.

**Tab. 1.** Luminances L of the cover of the used light source (luminance camera LMK)

| Measurement | L[$cd.m^{-2}$] | | | |
|---|---|---|---|---|
| | Mean value | Minimal value | Maximal value | deviation |
| 0 | 1920 | 27.7 | 3030 | 276.8 |
| 1 | 1895 | 1758 | 1983 | 58.65 |
| 2 | 1983 | 1192 | 2642 | 173 |
| 3 | 1990 | 1545 | 2309 | 158.8 |
| Average luminance 1947,0 $cd.m^{-2}$ | | | | |

## 3. RESULTS FROM MEASUREMENTS

Results from the light measurements give average illuminance for particular angles of incidence which are used for calculation of transmittance and specification of curves of relative angular transmittance. Normal light transmittance $\tau_n$ for light rays affecting the glass sample in angle 0° (light rays are normal to the glass sample) is calculated from illuminance data

$$\tau_n = \frac{E_{n-z}}{E_{n-b}} \qquad (4)$$

where: $E_{n-z}$ is illuminance inside of the box with the glass sample [lx] (for normal incidence, angle $\theta=0°$), $E_{n-b}$ is illuminance inside of the box without the glass sample [lx] (for normal incidence $\theta=0°$)

Curves of angular transmittance of glass samples were determined for relative values calculated from the following formula

$$\frac{\tau_\theta}{\tau_n} = \frac{E_{\theta-z} / E_{\theta-b}}{E_{n-z} / E_{n-b}} \quad (5)$$

where: $\tau_\theta$ is light transmittance for light affecting the sample at the angle of incidence $\theta$, $\tau_n$ is normal light transmittance ($\theta$=0°), $E_{\theta\text{-}b}$ is illuminance [lx] inside of the box without the glass sample for light rays at the angle of incidence $\theta$ [lx], $E_{n\text{-}b}$ is illuminance [lx] inside of the box with the glass sample for light rays at normal incidence $\theta$=0° .

Results from illuminance measurements within the box and the above mentioned calculations of angular transmittance of selected samples are presented in curves of relative transmittance $\tau_n/\tau_\theta$ in dependence on the angle of incidence $\theta$ in Fig. 4.

Another light source (see Fig. 5) was used for the control measurement – metal-halide lamp HQL (power 250 W, luminous flux 22 500 lm), with light characteristics similar to real daylight conditions of direct light of the clear sky - similar like the daylight simulator used in experimental investigations of light guides (Yohannes, 2003) and above mentioned measurements were repeated for the control light source.

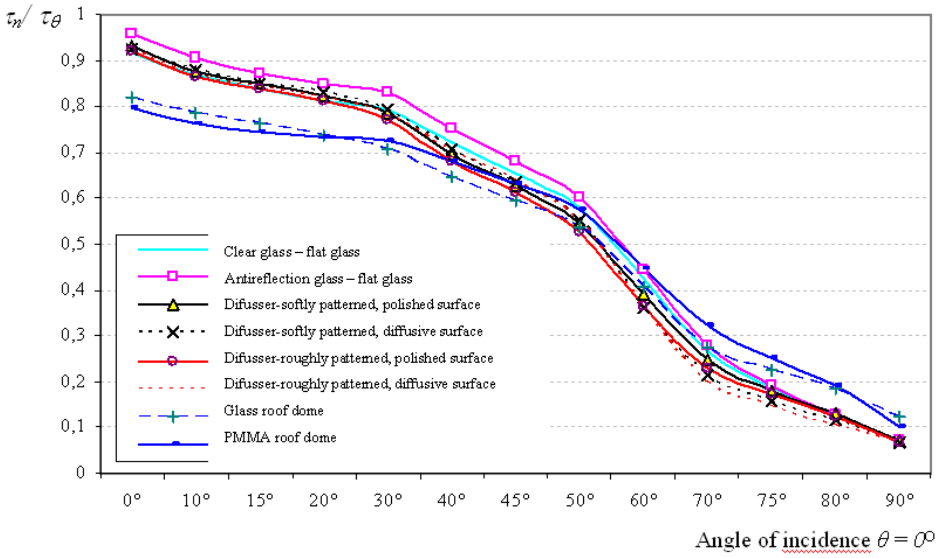


**Fig. 4.** Curves of relative angular transmittance of selected transparent elements (roof domes and flat ceiling covers) of the tubular light guide

Values of relative angular transmittances of the flat clear glass determined on the basis of illuminance measurements were compared with the curves of the clear flat glass transmittance determined from calculation results in accordance with equations (1) and (2), see Fig. 6.

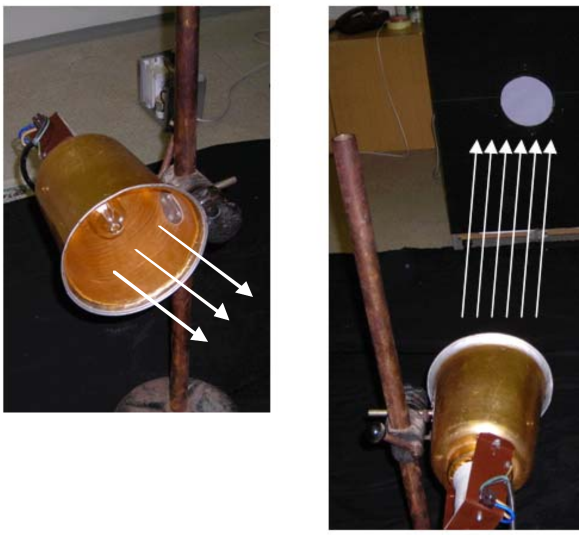

**Fig. 5.** Control measurements with Metal-halide lamp HQL

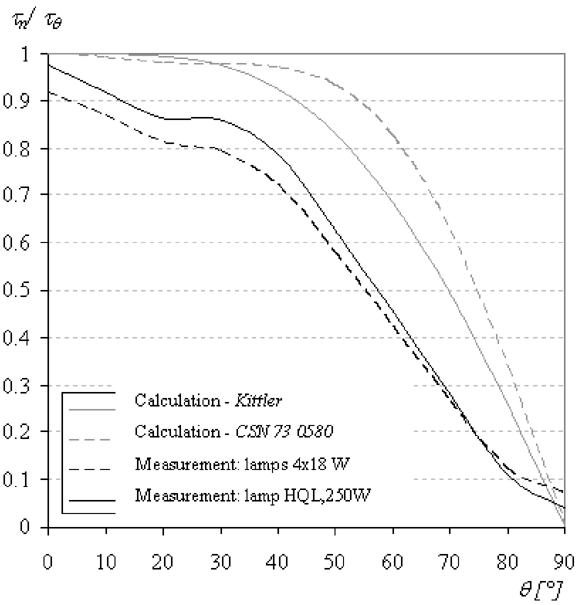


**Fig. 6.** Curves of angular transmittance of flat clear glass (determined from measurements and from calculations)

Results of angular transmittance of the flat clear glass sample determined from measured illuminances vary about 2 to 20 % compared to calculated values. The difference is caused by different methods of evaluations. The equations (1), (2) were derived from results of laboratory illuminance measurements and for a light source with parallel light rays affecting the glass sample. Results from the above described method in the box are close to real service conditions. The box is the model of a room of dimensions 3 m x 4.75 m, clearance height 3 m; used light source with four fluorescent lamps with frozen glass cover simulates diffusive light of sky.

Determination of the angular transmittance of the selected samples gives information that the glass and plastic domes have higher transmittance for angle of incidence between 50° and 90° but lower transmittance for angles 0° (normal incidence) to 50° compared to flat glass samples. It is caused by the roof dome rounded shape, which for higher incident angles (angle of incidence is measured from the normal to the surface) - lower elevation angles (elevation angle is measured from a horizontal plane) gives higher transmittance but light rays of the same elevation are reflected on the surface of the flat glass pane, see Fig. 7. Light rays of lower angle of incidence - higher elevation angle are reflected more on curved parts of the roof dome and they have high transmittance through the flat glass cover.

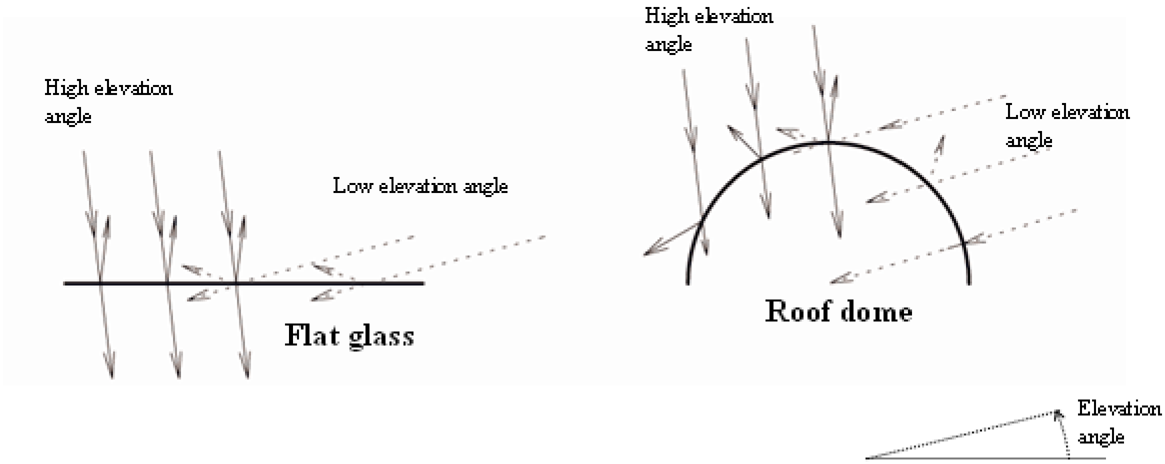


**Fig. 7.** Scheme of reflection and transmission of light rays of different elevation angle on the surface of the flat and rounded glass sample

## 4. SUMMARY

Light transmittance of a roof dome and ceiling diffuser influence light efficiency of the whole light guide system. The curves of angular transmittance serve as input data for light efficiency evaluations of tubular light guides. Angular transmittance of the flat glass cover determined on the basis of the illuminance measurements are in agreement with results from calculations according to theoretically and experimentally derived formulae. For this reason it can be assumed that the curves of angular transmittance of transparent roof domes and patterned glass ceiling diffusers are determined in sufficient accuracy to be useful as input data for the following evaluations of the tubular light guide efficiency.

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