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Light pipe prototype testing

***Abstract**. The article reviews the potential of light pipe system as a daylighting approach in buildings and presents results of experiments on performance of tubular light pipe prototype. The main task is focused on an examination of the system light efficiency on the basis of long-term illuminance measurements. The data from the measurement give overview about the potential of the light guiding system for direct solar radiation. For temperate climate with dominant cloudy sky conditions the light guide shouuld be completed with sun tracking system to increase efficiency.*

***Streszczenie.** W artykule zaprezentowano możliwość zastosowania światłowodu do oświetlania pomieszczeń w budynkach. Badano przede wszystkim skuteczność oświetlenia na podstawie długoczaswych pomiarów. W przypadku zachmurzonego nieba system powinien współpracować z układem śledzącym położenie słońca. **Badania możliwości zastosowania światłowodu do oświetlania pomieszczeń**.*

Keywords: Lighting technology, laboratory photometric measurement, light pipe, illuminance.
Słowa kluczowe: świetłowód, oświetlanie pomieszczeń, pomiary fotrometryczne..

Introduction

Light pipes are tubular devices that transmit daylight into interior spaces. Compared to traditional skylights and windows, the light pipes represent advantages of energy savings for artificial lighting in deep plan rooms. On the other hand they cannot substitute windows properly because they do not offer visual contact with outdoors. They are applied as complement and auxiliary daylight systems, mainly for windowless spaces where availability of natural light improves the occupants' well-being and work productivity.

Common light pipes components are a roof dome, reflecting tube and ceiling diffuser. Daylight is transmitted through roof dome into the tube. The light pipes are usually installed in roofs and floor constructions. Also facade mounted light pipes are known. Horizontal light pipes are more convenient for the multi-storey buildings. They are recommended to be installed into unshaded facades exposed to intensive solar radiation.

Tubular light guidance systems and their technical properties were included into tasks of the International Commission on Illumination CIE. The CIE technical report [1] gives conceptual review about technology of daylight guidance systems and their components and is concerned with design methods and recommendations for light guiding systems assessments and instructions for their applications. The light pipes and their daylight performance have been a subject of research investigations [2-5]. Analytic approaches [6-9] and numerical analysis [10-12] as well as daylight simulations [13-15] compared with experimental evaluations [16-18] in field studies [19,20] and laboratory testing [21,22] were completed last decades.

The trend in the light pipes' development is towards innovative light guiding systems [23-26]. Innovative light guides have maximised efficiency to gather both the sunlight and the skylight from whole sky hemisphere. They may contain optical lenses, prisms, reflectors and mirrors or light scattering components. They can use transparent tubes and optical fibres.

This article presents main results of laboratory testing of a new light pipe prototype with head parabolic concentrator [27]. The system was develop for installations in high solar altitude localities. It means in hot climatic conditions with plenty of sunshine during whole year. The main task for this laboratory testing was to investigate whether the system is also applicable for temperate climatic. The study has been involved as a part of the university research project and a sub-task of long-term investigation focused on the light pipes laboratory evaluations and field testing [28,30-32].

Method of the testing

Experiments with the light pipe prototype were performed. The testing was is focused on an examination of the light guide prototype light efficiency determined on basis of illuminance measurements. The purpose of the investigations was to find a way for the best practical installation of the light pipe system in climatic conditions of diffusive daylight of cloudy sky regions. The main goal of the experiment was to investigate whether the system is also applicable for temperate climatic conditions of central Europe regions.

The light pipe prototype was tested in laboratory at Brno University of Technology. A test box of dimensions 1.5 m x 1.5 m x 1.5 m was made to be a supportive construction for the light pipe installation, Figure 1. The top of the box has a circular opening of 0.520 m in diameter for the light pipe fixing. The light pipe was installed including the light concentrator head and antireflective glass cover. The light guiding tube with internal reflective coating has 0.6 m in length. A translucent diffuser was mounted at the end of the tube into the test box ceiling soffit.

The experiment was focused on the light pipe transmittance evaluation. Simultaneously with the internal illuminance measurements in the box (output) the illuminance data on the horizontal plane at the input to the light pipe were monitored in one minute time intervals.

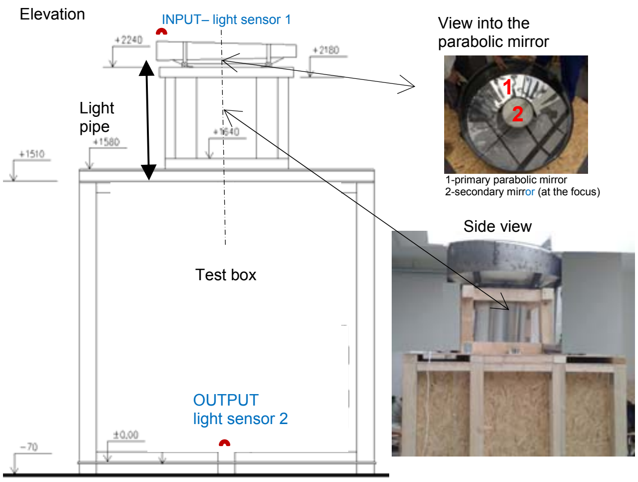

Fig. 1 Elevation of the box (dimensioned in mm) and photographs of the light pipe concentrating head installed in the box

The illuminance daily profiles at input to the light pipe (over the parabolic concentrator head) and at output - inside of the box (Figure 1) were measured from April to July 2015.

A set of two calibrated illuminance meters LX-1128SD were used for measurements. The illuminance meters have continual monitoring of measured data on for memory cards. Daily illuminance profiles were monitored in 30-second intervals for different sky conditions. The measured illuminances give data for the specification of the light pipe prototype efficiency.

Results of the light measurements

The aforementioned light measurements for the monitoring period gave data which are useful for evaluation the prototype daylight transmittance. Profiles of daylight horizontal illuminance were measured at the input (at the entrance to the concentrator head) and output (inside of the box) shown in Figure 1-view to the parabolic mirror.

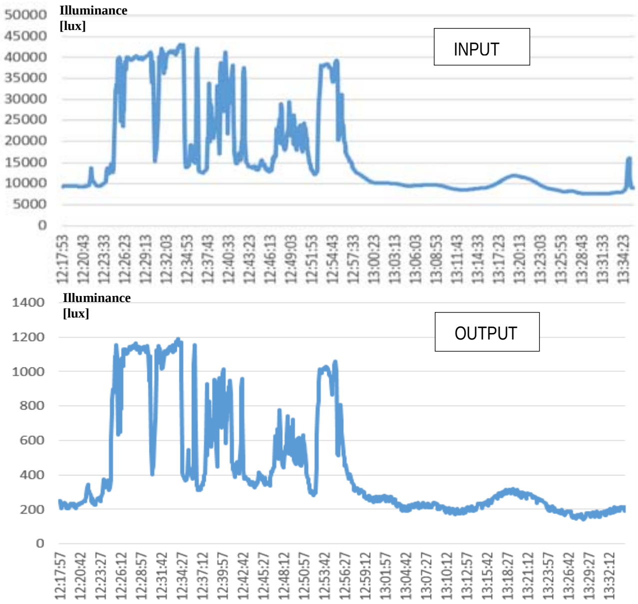

Fig.2 Daylight illuminance at the input (at the entrance the the concentrating head) and output (inside of the box), 25/05/2015

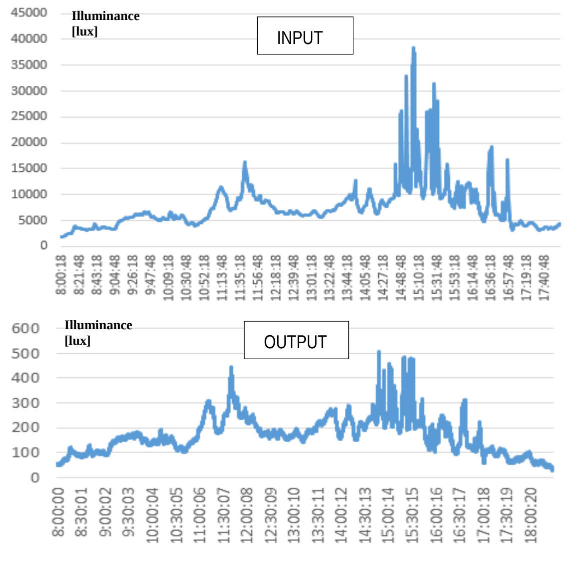

Fig.3 Daily profiles of illuminance on the input and output of the light pipe for cloudy sky daylight illuminance, 02/05/2015

Examples of daylight illuminance measurements were selected for the most characteristic profiles of the locality - for nearly clear sky conditions at noon time, on 25th May (Figure 2) and of cloudy sky measurement with time intervals of low illuminance in the morning changed with higher illuminance level in the afternoon on 2nd May (Figure 3) and also for conditions of dynamic changes in external illuminance 23rd June (Figure 4). The situation is for the sky with dynamic changes of daylight conditions, clear sky with solar shining is changed with overcast sky due to clouds moving.

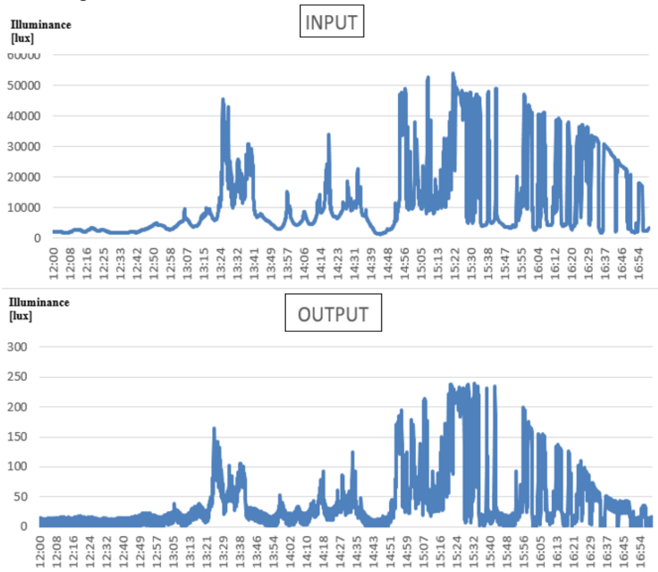

Fig.4 Daily profiles of illuminance on the input and output of the light pipe for dynamic changes of daylight illuminance, 23/06/2015

The region of Brno city belongs to the central Europe region with frequent cloudy sky daylight conditions even in summer seasons. For this reason partly cloudy and cloudy sky conditions were selected for the light guide testing. The question was to find whether the light transmittance for the unfavourable daylight situations of cloudy sky would be acceptable for the system real application in building of this locality. The input and output illuminance measurements are compared in the trend-line in Figure 5 for cloudy and partly cloudy days monitoring in June.

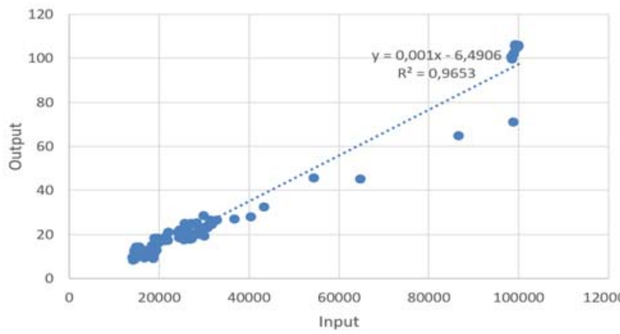

Fig.5 Trend line of the input and output illuminance measurements (cloudy and partly cloudy days in June 2015)

Light measurements were carried out in laboratory conditions. The test box was placed in the laboratory under a big transparent skylight for the reason to be protected against rain and wind so that data of continual daily measurements are available. The input illuminance data were controlled with the external illuminance monitored on unshaded horizontal plane. The external light sensor was located close to the glazed skylight of the laboratory roof. Differences between the external value and illuminance measured in laboratory at the input to the light pipe (above the concentrating head) are shown in Figure 6. The external illuminnace was monitored at the beginning of the measurements on 7th April 2015.

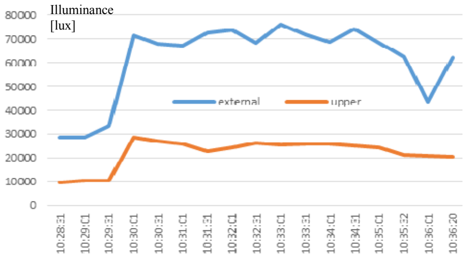

Fig.6 Horizontal illuminance - external and upper (input) data

Measured illuminance data at the input of the light pipe is shown for selected days over the monitoring period in Figure 7 for minimal and maximal and mean as well as median daily values. Maximal values do not extend 50 000 lux, mean illuminance values are in interval between 5 klux and 20 klux. These values are in compliance with standards daylight data for the CZ climatic locality [29].

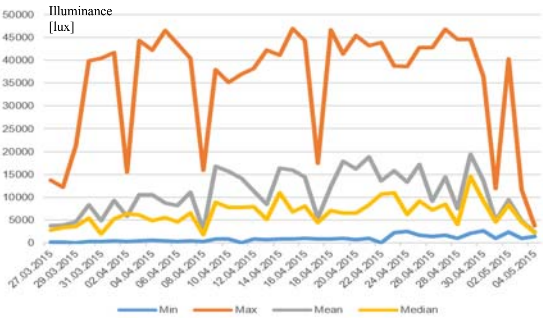

Fig.7 Minimal, maximal, mean and median input illuminance

The illuminance data processing gives information about the light pipe system efficiency. The efficiency η [%] was determined as a ratio of luminous flux at the output affecting the internal space of the test box Φ_2 [lm] and at the input into the light pipe head Φ_1 [lm] flux as following: $\eta = 100 \times \Phi_2/\Phi_1$ [%]. The luminous flux Φ_1 depends on the illuminance E_1 [lux] monitored above the parabolic concentrator head and cross sectional area of the light pipe. Luminous flux Φ_2 in the solid angle ω depends on illuminance E_2 [lux] monitored in the distance *l* of 1.5 m from the light pipe diffuser, Figure 8.

The box was completed of wooden chip boards. The boards have uneven surface which cause light scattering, surface reflectance is ρ=0.25. It means internal reflective component inside of the wooden box is very small. Only direct light component of the light transmitted through the light pipe was taken into the consideration. The concentrator consists of the primary parabolic mirror and secondary mirror [27], see Figure 1. Reflectance of the parabolic mirror surface as well as internal surface of the light pipe is ρ=0.95. Light transmittance of the glass cover is τ=0.95 and light transmittance of the light scattering translucent plastic diffuser is τ=0.45.

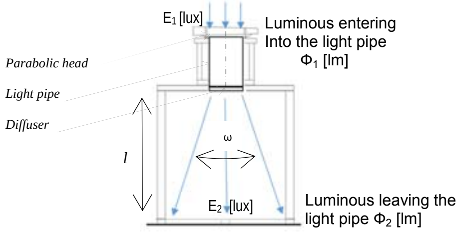

Fig.8 Luminous flux distribution through the light pipe

The light pipe prototype efficiency specification for selected days is shown in Table 1. It is obvious that the efficiency is rather low – mean efficiency is 3.4 percent and maximal value is less than 5 percent. The efficiency it is lower than efficiencies of common light pipes without light concentrating heads determined from laboratory measurements under artificial sky for the CIE overcast sky model [30]. Also luminance camera monitoring of straight light pipes shown higher values of their light efficiency [31,32]. The tested light pipe system low efficiency is because of the static position of the parabolic concentrator in the horizontal position. This installation seems to be less convenient position for cloudy sky regions.

Table 1 The light pipe efficiency [%]

Date	E_1 [lux]	E_2 [lux]	Efficiency	Date	E_1 [lux]	E_2 [lux]	Efficiency
27.03.2015	3123	73	3.83	04.04.2015	7803	140	2.95
28.03.2015	3203	76	3.92	05.04.2015	6799	149	3.61
29.03.2015	3791	92	3.98	06.04.2015	6231	122	3.23
30.03.2015	6664	113	2.79	07.04.2015	8693	172	3.25
31.03.2015	3933	74	3.10	08.04.2015	2151	60	4.59
01.04.2015	7535	149	3.24	09.04.2015	13200	241	3.00
02.04.2015	4612	119	4.24	10.04.2015	12230	221	2.97
03.04.2015	8845	166	3.08	11.04.2015	11430	191	2.74
Efficiency: Mean 3.41, Maximal 4.6, Minimal 2.72							

The light pipe efficiency was also determined for clear sky conditions of selected day from the monitoring period, on 25th May for time interval between 12:26 and 12:34, Figure 9.

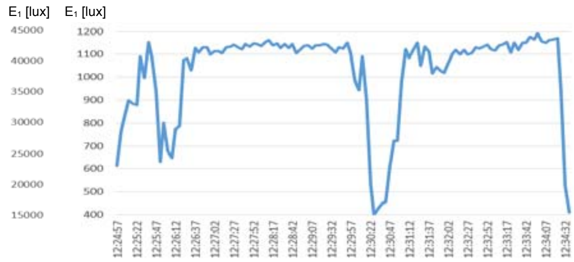

Fig.9 Horizontal illuminance at the input E_1[lux] and output E_2[lux]

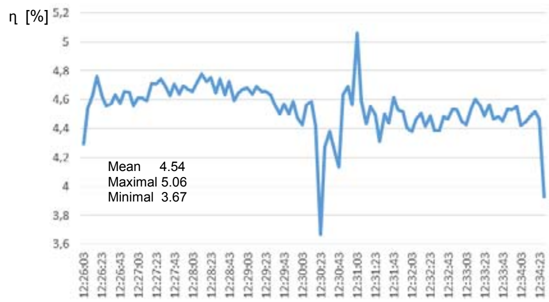

Fig.10 Light pipe efficiency η [%], clear sky, 25th May

The light efficiency is increased about 1 percent for the clear sky (mean 4.54 %) compared to cloudy sky conditions (mean 3.41 %). It appears that the light concentrating head with the parabolic mirror in the given position acts as an obstruction for daylight transmission into the light pipe.

Efficiency Improvement Opportunities

The light pipe location and orientation was studied for reflection of direct solar rays. Day of summer solstice - 21st June was selected for the study. Solar altitude for locality of latitude 50° [34] is determined for morning time between 7:00 and 12:00, Table 2. Direct solar rays affecting the light pipe head (red lines) are reflected (blue lines) on mirroring surface of the parabolic concentrator are shown in Fig. 10.

Table 3 Solar altitude, 21st June

Time	7:00	8:00	9:00	10:00	11:00	12:00
Solar altitude	27.224°	36.848°	46.205°	54.641°	60.98°	63.45°

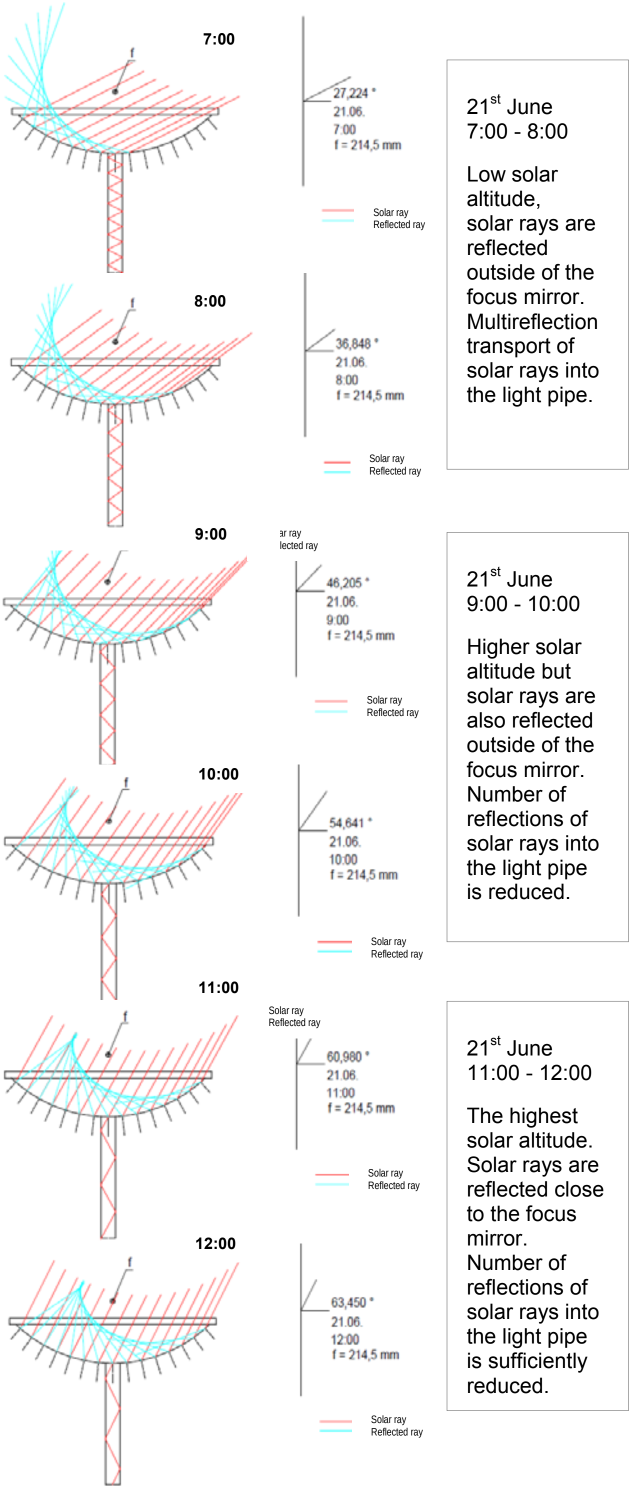

Fig.10 Solar rays reflections on the light pipe parabolic concentrator
(f - focus of the parabolic concentrator, position of the secondary mirror)

The optimal design is in case that solar rays affecting the concentrator vertically which is adequate to solar altitude of 90°, Figure 11. But it is not available in the central European region at latitude about 50° - maximal solar altitude is 63.45° for 21st July, noon time. That means it is necessary to move the concentrator position towards to daylight rays for enhancement of the light pipe efficiency, Figure 12. Completion of the concentrator head with additional mirror would increase efficiency of the light pipe system, Figure 13.

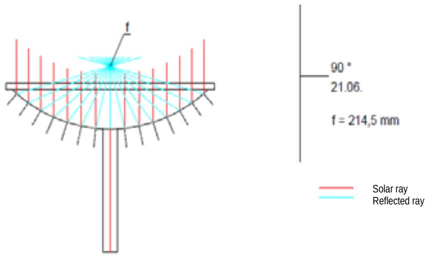

Fig.11 Direct daylight rays reflections on the light pipe head

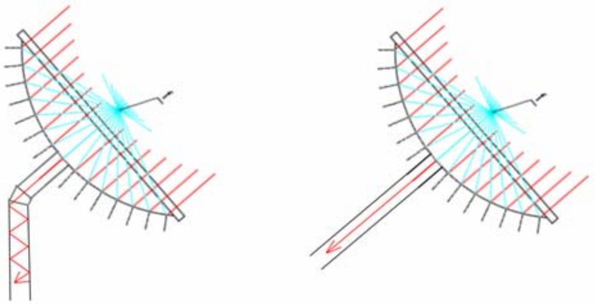

Fig.12 Direct daylight rays reflections on the light pipe head

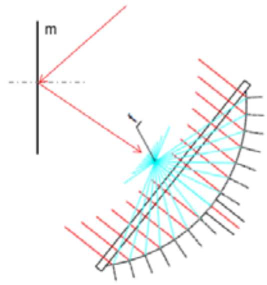

Fig.13 Direct daylight reflections on a mirror towards to the light pipe concentrator head, (m – mirror)

Conclusion

The prototype of the light pipe tested in the laboratory conditions represent a new light guiding system with a daylight concentrator device. The objective of the experiment was to solve the following tasks:

- test the new light guide prototype for light transmittance,
- compare results with light efficiency of the common light pipe of comparable dimensions and geometry,
- analyse the function of the system a give some recommendations for its possible improvement,
- find potentials for applications of the light guiding system in temperate climatic conditions.

The continual illuminance measurements gave data for light transmittance through the light pipe. The system light efficiency was determined as a ratio of luminous flux entering the light pipe and luminous flux inside of the test box. The measurements gave data for the light efficiency of the light pipe. The efficiency varies between 3 percent for cloudy sky and 4 percent for sunny sky conditions.

The light pipe efficiency is not very high and it is even lower than traditional light pipes with roof transparent domes with the declared efficiencies [30,31]. Lower efficiency of the light pipe prototype shows on the fact that the light pipe with the concentrator head in static horizontal position could be an obstruction for diffuse daylight. It is clear that the light pipe in real external conditions and for time with clear sky and direct solar radiation will increase its efficiency. But for temperate climate regions the light pipe system should be design for dominant cloudy sky conditions.

The tested light pipe has been used for a newly constructed residential building. It is mounted in a saddle roof with south orientation. This installation could be convenient in case of the passive light guiding system. The light pipe system could be also useful in cases that daylighting through façade windows is impossible because of massive shading and colourful obstructions [32]. On the other hand high reflectance of surfaces could considerably influence daylight level [35,36] and visual sensation in buildings. It means that the light pipe system should be designed with regard to the whole internal space in rooms for indoor visual comfort.

Some improvements of the light pipe are recommended for its application temperate climates. Movable concentrator heads [37] and/or system of mirrors and heliostats [38] or prismatic shells [39] directing solar radiation inside of the light pipe during daytime would be positive for the efficiency of the light pipe. These improvements would be very efficient but they increase investment price of the light guiding system. Positioning of the light concentrating head to the direction of the dominant solar irradiation, i.e. towards the south and west orientation is recommended. A fixing of the concentrating parabola in an inclination to the prevailing solar rays seems to be less expensive variation acceptable for example for common residential buildings.

Also direction of the light transmitting tube to the position of the concentrator is possible but for buildings with rigid floor structures it would be rather complicated installation. This type of light pipe appears to be convenient for wooden lattice girder roofs. In these roofs the light pipe with oblique tube can be relatively easy mounted. The light pipe should be carefully designed for the installation in wooden constructions. It should be covered by non-flammable envelope and its connection with roof and floor constructions must be fire-resistant. Mainly the roof concentrating mirror represent the place of potential overheating problems due to concentration of solar radiation energy.

The light pipe prototype testing was completed within the frame of the doctoral candidate dissertation research. The further investigations of the light pipe system with the concentrator head is aimed at its installation in real buildings with different roof structures, slopes and orientations towards cardinal points. The transformation of the tested light pipe prototype into active solar system with concentrator directed solar radiation and evaluation daylight availability and pay back ratio for investment and energy savings on artificial lighting are tasks for the prototype final completion into the new type of the light guiding system applicable for temperate climatic conditions.

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