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Use of Light Pipe and Electronic Heliostat for Lighting of Underground Areas in Porto Alegre

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Abstract

The use of underground spaces is increasing and light pipes are an alternative to create natural lighting in these areas, but the technique should be tested locally to verify performance and viability. This study was designed to test a specific kind of this technology in the city of Porto Alegre, southern Brazil. A scale model experiment was made in three stages. In the first stage, two different reflective materials were tested. The material that performed better was used for the second stage, where light pipes of different heights were tested. In the third and final stage, an electronic heliostat was added to the system to verify how it would improve its behavior. This specific system can be used in this city to light underground areas under clear sky conditions. However, in cloudy days the performance of the system decreases. Hybrid light systems can be an alternative to deal with this. Heat loading and glare should be controlled to avoid damage and increase in energy consumption.

Keywords: *Daylight, Solar energy, Light pipe, Heliostat, Underground spaces.*

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1. Introduction and background

The use of underground spaces is increasing and making for more sustainable cities, using land more efficiently and concentrating more functions in the same area (Besner, 2002; Durmisevic, 1999; Iscocarp et al., 2015; Kaliampakos et al., 2016). The use of light pipes is an alternative to create natural lighting in environments that don't have windows, such as underground spaces. Despite its growing use, people still relate these areas to bad experiences, such as pollution, claustrophobia, fear of landslides, disorientation, lack of outdoor contact and insecurity, etc. (Durmisevic and Sariyildiz, 2001; Kim and Kim, 2010; Isocarp et al., 2015). Sunlight exposure is a way to improve human experience in these areas because of its important benefits for human well-being (Besner, 2002; Durmisevic, 1999; Soh et al., 2016). The contact with sunlight approximates people to the external world (Boubekri, 2014; Boyce et al., 2003; Hobday, 2006), allows the use of vegetation to make these areas more alive and pleasant (Bringslimark et al., 2007; Dijkstra et al., 2008; Grahn, 1994; Grinde and Patil, 2009; Park and Mattson, 2009), and regulates a lot of physiological processes in the human body (Boubekri, 2014; Harb et al., 2015; Hobday, 2006; Martau, 2009), which is very important to promote good health for users that spend long periods of time in there. The use of vegetation in these areas can also be an important alternative to promote air quality and restore these users stress cycle (Dijkstra et al., 2008; Grahn, 1994; Grinde and Patil, 2009), but plants need a satisfying amount of light per day – 300 lux minimum (Kämpf, 2005).

Light pipes work like a leader that catches the sunlight and guides it into the interior of a building. These systems can be made with lenses, cut laser panels, fiber optics, etc. (Boubekri, 2014). However, the most usual is the hollow duct with reflective internal material, because it's more simple to build than others (Hansen and Edmonds, 2015). Its efficiency depends on how many times the light beam is reflected. Diameter, reflectance of the internal material, height and solar angle incidence must also be considered (Boubekri, 2014). Furthermore, the kind of light sky available should be taken into account. Sunny days and clear skies provide direct sunlight (light beams in the same direction, thus more concentrated) making the systems performance better than on cloudy days, when the diffuse light predominates (light beams in different directions, more disperse) (Boubekri, 2014; Hansen and Edmonds, 2003). Each part of Earth has a different kind of sky, so this kind of technology should be tested in each context to find the best system for it and to evaluate if this system will be able to give the required amount of light.

An example of this is The Low Line Lab in New York, where they were testing the performance of a specific kind of technology for providing sunlight for an underground space with plants. In the near future, it will be the first underground park in the world (The Low Line, 2017). There are several studies about these technologies and examples built in internacional ambit (Akhadov et al., 2014; Boubekri, 2014; Hansen, 2006; Hansen and Edmonds, 2015; Heliobus, 2017; Ji et al.,2016; Peña-García et al., 2016; The Low Line, 2017). But in Brazilian context, a country that has a lot of sun, these technologies don't have much attention yet. The little number of studies on them can be one of the reasons why. The use of underground spaces is increasing in Brazil and there are a lot of spaces that have people working there during long hours. Furthermore, the need to save energy is required in face of the world energy crisis, limited resources and climate changes.

Until 2017, there were no known studies about this technology related to underground spaces and plants in the country, neither about how this technology would behave in the city of Porto Alegre. Bystronski and Martau (2017) have started a study in this context and tested light pipe models made of different materials, where the polished aluminium had the best performance. Afterwards, they tested a longer light pipe model (1,5 m height and 0,05 m diameter) with this material, but a top heliostat (moved manually) was needed to improve the sunlight transmission. Without it, the system would only work for a short time when the higher sun angles occurred (this experiment was made near the summer solstice). Bystronski et al. (2017) kept this study and tested different positions for the heliostat to focus the light beam, making the amount of sunlight transmitted greater than what was available outside. Besides that, they tested procedures to start building an electronic heliostat. However, this device was tested manually.

In these two experiments, the system can catch enough sunlight to allow plants to live when the direct sunlight is happening. A more in-depth study of light distribution would be necessary in order to make it more uniform and control its intensity, avoiding glaring and heat load conduction. However, Porto Alegre has partially cloudy days predominance and these specific systems wouldn't work well in these conditions. So, how would this system work if it had other height and a more reflective material? And how can this electronic heliostat increase the performance in these systems? Testing other materials and the electronic device is one way to get a better performance of this technology in this specific local context. The results of this investigation can be used in future projects, such as subway stations, underground buildings and also in the existent underground spaces in this city. Furthermore, it can contribute with the work other researches are doing in this same area, helping in the development of a sunnier future for us all.

2. Objective

The purpose of this paper is to continue the studies made in order to verify the behavior of specific light pipes in the city of Porto Alegre, located in the southern region of Brazil. Therefore, this study intends to test other materials, light pipes of different heights and the use of an electronic heliostat to increase the performance of this specific technology.

3. Method and procedures

This work is an experimental study and it was divided into three stages using scale models, which is a good strategy for such studies (Bodart and Deneyer, 2006). In the first one, two light pipes were made (30 cm high and 5 cm diameter) internally coated with different materials to compare their performance. In the second stage, four light pipes of different height (30 cm, 50 cm, 100 cm and 150 cm, respectively) and same diameter (5 cm) were made to compare their behavior under direct and diffuse daylight conditions. These pipes were internally coated with the material that achieved the best results in stage one. In the last stage, one of the light pipes used in the previous stage (30 cm high and 5 cm diameter) was used to test an electronic heliostat with a square mirror (10 cm x 10 cm).

The scale used in this work (1/20) represents a duct of 1 meter in diameter in the real context, and the tallest (150 cm) represents 30 m - approximately the height of a ten-story building. To measure the amount of light, a HOBO UA-002-64 data logger was used and the procedures to built the light pipes were based on the last works by the authors (Bystronski and Martau, 2017; Bystronski et al., 2017). In all stages of this experiment, one data logger was used in the end of each pipe to measure the amount of light transported, and one external to know the percentage of light captured. These devices have an accuracy rate between 60% and 80%, so the amount of light measured is not precise, but it can gives us an idea of which material or duct conducts more light, which is the purpose of this work. Therefore, a more in-depth study with more sensitive measurement devices is necessary to know the exact capacity of these materials in conducting light. Only then it will be possible to compare the behavior between materials that have similar capacity of reflectance, for example.

3.1. Stage 1: procedures to choosing a more reflective material

The material that performed better in the last studies was the polished aluminum (Bystronski and Martau, 2017; Bystronski et al., 2017). However, its reflectance was not specified and, to achieve a better performance, it would be necessary to use an even more reflective material than the one used in the previous studies. So, visual analysis was used to choose a more reflective material. Aluminum Vega 95 was selected because it has 95% reflectance (Almeco, 2017) and it was available in Brazil. There are more reflective types, such as the Vega 98, but it was not possible to find a sample in the country to use in this experiment. A more in-depth study of these materials should be made. The light pipes were tested simultaneously to verify if the aluminum Vega 95 is better to lead the light than the polished aluminum (Figure 1).

3.2. Stage 2: procedures to test the behavior of four light pipes of different heights

The four light pipes were internally coated with aluminum Vega 95 and also tested simultaneously in order to compare their performance (Figure 2). This test was also made to compare the behavior of intermediate heights (50 cm and 100 cm) compared to the others (30 cm and 150 cm) that were tested in the previous studies. Testing these other height possibilities may help us find an approximate depth in which the duct is able to conduct the required amount of light without the need for a heliostat.

Fig. 1: stage 1

Fig. 2: stage 2

Fig. 3: stage 3

3.3. Stage 3: procedures to test the behavior of an electronic heliostat

Bystronski et al. (2017) started the procedure by using 3D modeling software to test the operation system. Afterwards, they used a 3D printer to make the parts, assembled the set and tested the operation manually. An Arduino-type microcontroller was added to manage the electronic components (servomotor and step motor) and the squared mirror (10 cm x 10 cm) (Figure 3). After the complete assembly of the system, they tested it and made some more adjustments to improve it.

4. Results and discussion

4.1. Stage 1: behaviour of two different reflective materials

This stage was tested on July 23, 2017, under partially cloudy sky conditions. The results are on Table 1 and they show that the aluminum Vega 95 is a better light conductor. It conducts almost twice as much light as the polished aluminum. The performance is reduced as the sun goes down, while the relation between the amount of light absorbed and transmitted through the duct increases. This light pipe can catch a significant amount of light until 5 PM, which points to the possibility of vegetation in areas with this specific type of light pipe. The duct internally coated with polished aluminum can conduct less amount of light, but it can be used for lighting general areas. It also provides the minimum amount of light needed to perform basic tasks for a period of time during the day according to NBR ISO/CIE 8995-1 (ABNT, 2013).

Tab. 1: Materials performace

Line	Hour	Polished aluminum (lux)	Aluminum Vega 95 (lux)	External sensor (lux)	Transmission of the most efficient material
1	3:05 pm	1.980	3.444	93.689	3,67%
2	3:35 pm	1.894	3.272	79.911	4,09%
3	4:05 pm	484	947	10.677	8,87%
4	4:10 pm	462	914	10.333	8,84%
5	4:40 pm	312	710	4.650	15,27%
6	5:00 pm	226	549	2.497	21,98%
7	5:30 pm	107	269	1.205	22,32%
8	6:00 pm	0	0	64	-

4.2. Stage 2: behaviour of four light pipes of different heights

This stage of the experiment was done on July 22 under clear sky conditions. The shortest duct can guide a greater amount of light than the others and the ability to carry the light decreases as the duct height increases. Table 2 shows the results - some of the data on the 50 cm duct were excluded because they are the same or a little higher than what was measured in the shortest duct. Maybe there was some interference at the measuring moment, but it may also have been a consequence of the dataloggers precision, as previously mentioned. This happened during higher solar angles, when the light is brighter and any interference may be stronger than in other moments. The collected data is sufficient for this study, nevertheless the use of more accurate devices is required to compare the behavior between ducts with little height difference.

The direct sunlight acted in the beginning of this experiment, but after 4:00 pm all the ducts were probably in the shadow absorbing diffuse light. Previous studies showed that the tallest light pipe needed a heliostat during most of the time to catch sunlight, but the light pipe improved its behavior with this more reflective material (Table 2). The amount of light guided through the duct decreases as the sun goes down. Nevertheless, it can be used for lighting deep buildings during a part of daytime. As previously stated, plants need 300 lux minimum to survive and this amount of light is not provided by the tallest pipe during the whole period of the day. Therefore, the heliostat can be a strategy to improve the system performance and even more reflective materials should be investigated. The intermediate height light pipes can also be used for lighting deep areas, but it depends on the amount of light required.

Tab. 2: Light pipes performance

Line	Hour	30 cm (lux)	50 cm (lux)	100 cm (lux)	150 cm (lux)	External sensor (lux)	Transmission of the most efficient material
1	11:00 am	2.411	2.325	1.377	796	115.734	2,08%
2	11:30 am	2.669	-	1.636	990	126.756	2,10%
3	12:00 pm	3.272	-	2.066	1.324	132.267	2,47%
4	12:30 pm	3.616	-	2.066	1.377	132.267	2,73%
5	1:00 pm	2.755	-	1.808	1.151	126.756	2,17%
6	2:00 pm	2.497	-	1.377	796	99.200	2,52%
7	2:30 pm	2.152	2.066	1.162	602	88.178	2,44%
8	3:30 pm	1.550	1.377	592	236	9.644	16,07%
9	4:00 pm	839	796	344	96	6.200	13,53%
10	4:30 pm	645	592	258	64	4.822	13,38%
11	5:00 pm	333	301	129	32	2.497	13,34%
12	5:30 pm	204	183	64	10	1.550	13,16%
13	6:00 pm	10	0	0	0	140	7,14%

4.3. Stage 3: behavior of electronic heliostat in this specific context

The third stage was tested on July 7, 2017, under partially cloudy sky conditions. The light measurements were collected at the same time as the first stage of this study and the sky was clear at this moment. The system performance improves with the electronic heliostat. The capacity to guide sunlight increases considerably. Table 2 shows the same duct guiding approximately 1.550 lux when the amount of external light is around 10.000 lux and that number reaches 24.800 lux when using heliostat (Table 3). The light pipe used in this stage is 30 cm high and next studies should test the behavior of this electronic system in the tallest duct (150 cm) to check its ability to provide the required amount of light for plants to survive in deeper areas.

Tab. 3: Electronic heliostat performance (positioned at the top of the 30 cm light pipe)

Line	Hour	Internal sensor (lux)	External sensor (lux)	Transmission through the ligh pipe
1	3:05 pm	22.044	93.689	23,53%
2	3:35 pm	42.711	79.911	53,45%
3	4:05 pm	24.800	10.677	232,27%
4	4:40 pm	15.155	4.650	325,91%
5	5:00 pm	613	2.497	24,55%

The transmission percentage is variable and it increases considerably comparing the results on lines 1 and 2, for example. While the amount of external light is greater at 3:05 pm, the light pipe absorbed less than at 3:35 pm. And at 4:40 pm (line 4) the internal sensor absorbed more sunlight than the external one as the beams were concentrated. The system accuracy is probably responsible for this, because the angles may not be changing according to the sun’s movement. A more in-depth study about the electronic heliostat is necessary. The amount of light absorbed can involve glare and heat loading and strategies should be adopted to deal with them. Furthermore, the sunlight transported through the light pipes is not uniform causing variability in its distribution. The use of diffuse device is an alternative to face it and should be tested in next studies.

5. Conclusions

The use of underground spaces is increasing and light pipes are an alternative to create natural lighting in these areas. This technology has to be tested in local context to find the suitable system and test its viability.

This study intended to verify strategies to increase the behavior of a specific kind of this technology in the city of Porto Alegre. Scale models are used to test the system performance in three stages. First, a performance comparison was conducted between polish aluminum and aluminum Vega 95, the latter proving to be more effective. Afterwards, four light pipes of different heights were tested and the shortest one had the best performance. The tallest light pipe could also absorb light, but not enough to guarantee the survival of plants. An electronic heliostat can improve these systems, as shown in the third stage. The use of these technologies can provide natural light for deep buildings, but under cloudy sky conditions the tall ducts were not able to conduct enough light. The use of hybrid systems (with electric light) may be an alternative to this limitation. More in-depth studies are needed on reflective materials, techniques to increase the accuracy of the electronic heliostat model built in this study and to dissipate the light that reaches the end of the duct, as well as controlling the heat load conduction and the glare transmitted by direct sunlight. The preliminary results will be part of another research to test the behavior of specific plants in deep environment illuminated by the light pipes described in this paper. The behavior of this technology under cloudy sky conditions will also be tested. This study may be used for existing deep buildings or to project new underground spaces, such as the future subway of this city.

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