Numerical and experimental analysis of the ‘Double Light Pipe’, a new system for daylight distribution in interior spaces

Carlo Baroncini, Fabrizio Chella, and Paolo Zazzini (corresponding author)
D.S.S.A.R.R. Faculty of Architecture, University ‘G. D’Annunzio’, Pescara, Italy
E-mail: zazzini@unich.it

Abstract  An innovative arrangement able to transmit daylight into hypogeal rooms and, simultaneously light the passage spaces, is presented. It is named the ‘Double Light Pipe’. It consists of two coaxial tubes: the inner cylinder is a traditional light pipe, which transmits light from a clear collector, placed on the roof top of the building, downward to a diffuser inside the underground areas, while the outer one allows light to enter into the passage spaces. A numerical analysis has been carried out using ECOTECT and RADIANCE software and the results are compared with a reduced scale experimental analysis.

Keywords  daylight; light pipe; double light pipe

Nomenclature

$E_{in,i}$  internal illuminance in position i [lux]
$E_{ext}$  external illuminance [klux]
$\rho$  reflective coefficient
$\phi$  diameter [mm]

1. Introduction

Daylight plays a more and more significant role in architectural design, since it involves many aspects regarding visual comfort for the occupants of a room and energy saving strategies in order to improve the energetic performances of the building. Traditional daylight sources, such as windows or skylights, allow natural light to go into internal spaces producing visual comfort conditions for people living indoors and not too far from the external walls. Thanks to an efficient integration between artificial and natural light, all the space can become available to the working activity.

Natural light lets people have the perception of time flowing along the day following the lighting effect of the sun over the sky dome. Thanks to these circumstances it is well known that all working activities are better carried out in the presence of daylight rather than in the absence of it, and a more pleasant psychological sensation is felt by people staying in a room lit by natural light.

Furthermore, the availability of natural light in a closed space allows us to limit the use of electric light so as to obtain an efficient energy saving effect and this has led, in the last few decades, to an increasing use of transparent materials, such as glass or polycarbonate in architectonical design of buildings.
On the other hand an excessive use of transparent surfaces, such as windows or skylights, is risky for generating thermal discomfort conditions in internal rooms, owing to a significant increase of thermal losses from boundary walls in winter and of thermal loads in summer, particularly at latitudes typical of Southern Europe.

Moreover, in many cases, daylight is poorly available in the inner spaces of buildings such as in large plant area rooms in which windows are installed over boundary walls, far away from occupied zones, or it is totally absent such as in underground areas without any natural light sources.

An attempt to improve daylight distribution in large plant area interior spaces is to provide the building with a central atrium through which natural light is allowed to enter in zones that are far away from boundary walls and so not illuminated from windows placed over external walls. Naturally the influence of light coming in from the atrium is not significant all over the work-plane. There is in any case a dark zone in the centre of the room [1, 2].

For these reasons numerous architects and civil engineers opt more and more for an increasing use of light pipes which seem to be an efficacy solution to this problem.

In fact, in all the situations in which daylight is absent or poorly present and where it isn’t possible to adopt traditional daylight sources, light pipes play an important part to furnish the necessary amount of daylight inside the core of the building up to the darkest areas, without significantly increasing summer thermal loads and winter thermal losses. By means of light pipes, daylight can be introduced into interior spaces without direct interface with sky or sun, such as hypogeal areas, or large plant area rooms, in which daylight from windows, positioned on boundary walls, doesn’t reach points on the work-plane far away from them [3, 4].

On the other hand, unfortunately, they are characterized by remarkable bulk and they constitute undesirable obstructions in the passage rooms from the collection point, commonly on the roof top of the building, to the diffuser. This is a limit for architects in planning the installation of light pipes in the building.

Starting from these considerations the authors developed the idea, presented in this paper, of proposing an original system, named the Double Light Pipe (DLP). It has been studied at the Laboratory of Technical Physics of the Faculty of Architecture of the University ‘G. D’Annunzio’ of Pescara, in Italy, where a numerical and experimental analysis has been carried out. This innovative technological apparatus consists of two coaxial tubes able to distribute daylight both in the final room, where the diffuser is located, and into the midway zones crossed by the system.

The first internal tube transmits natural light away from the collector to the diffuser, like a traditional light pipe, while the second one, external and coaxial to the first, made of a diffusing material, allows it to illuminate the passage spaces crossed by the system.

It’s clear that there is no possibility to adjust or turn off the amount of daylight introduced in the in-between areas, since the technology used doesn’t allow this.

A model of the DLP was created in a reduced scale (1:10) and it was experimentally tested under real sky conditions. The results were compared with numerical
ones obtained through some of the more commonly used software for simulation of daylight effects.

2. Evolution from traditional light pipes to double light pipes

2.1 Traditional light pipes

A light pipe is a technological device designed with the aim of distributing daylight into occupied spaces where naturally it is absent. Therefore it’s most common application is in those rooms in which there is no traditional daylight source, such as windows or skylights, or where the natural light entering the room is inadequate. It consists of three sections, each destined to achieve a particular function.

The first one, the collector, is the section in direct interface with daylight sources, sun or sky, and it captures solar radiations and redirects them into the pipe itself. The pipe is the second section of the system and it works as a transducer of light, which channels daylight captured from the collector, thanks to multiple very efficient reflections, towards the diffuser. A multilayer reflective film coats its internal surface in order to transmit light more efficaciously from the captation surface to the output device.

The diffuser is the third and last section of the system, commonly made by polycarbonate material, that introduces light into the room in which it is positioned and protects the pipe from the dirt. At the present time many types of diffusers are in commerce, each one gives a particular distribution of light, more concentrated or with narrow beam (spot), or diffused or with large beam (flood), depending on its structural or geometric configuration [5]. The diffuser, usually with faceted design, provides both to reduce direct-glare effects and to achieve a better distribution of the light.

The collecting function is the most delicate phase, because it allows to have a major or minus availability of natural light, depending on its acceptance capability of sun radiations. Active or passive collectors can be used to this aim. Active collectors are more efficient but more expensive systems and they need technological devices, mechanically moved, so as to follow the position of the sun over the sky hemisphere, varying in time depending on day hour, month or season of the year.

Passive zenithal fixed collectors, commonly made by polycarbonate domes with the same diameter of the pipe, are cheaper but less efficient captation devices, so many attempts were carried out with the aim to improve performances obtainable by such collecting devices [6].

The rapid development of technology in the adoption of very efficient materials for daylight transport [7, 8] has not been in line with a corresponding enhancement of standard design methods such as in electric lighting plant, even if many prediction methods, ranging from theoretical, empirical, or semi-empirical methods up to fully developed numerical codes, have been developed by various authors in order to predict illuminance on the work plane in a room equipped by one or more light pipes [9, 10].

The problem is very difficult to solve due to variations in weather that commonly occur in every season of the year, in every day of each season, and in every hour of
the day. Sky conditions are not characterized by repeatability and data obtained by experimental tests are not reproducible. As a consequence light pipes’ performances are not fully predictable because they perform in real climatic conditions, with all possible sky configurations, and sun positions, and better or worse internal illuminances can be obtained depending on temporary weather variations, with partially cloudy or clear sky configuration, or steady state conditions such as under an overcast sky. The attempt to standardize the experimental data obtainable in a proof, testing reduced scale models of a building under an artificial sky in standard overcast sky conditions is partially suitable, because it gives a general idea of the capacity and the efficiency of the system, and it does not take into account that the passage from overcast to clear sky conditions with the presence of sun implies not only an increase of illuminance due to a growing luminance of the sky, but also the incidence of a particularly intense direct component of solar radiation which involves unpredictable and non uniform distribution of light on the work plane.

Another problem associated with light pipes’ design and installation procedure is related to their considerable dimensions, which make them impossible to be installed in the centre of a room, because it involves unacceptable problems, being very bulky systems. This is a restraint for architects because they are forced to abandon the idea or to plan solutions that take into account this hypothesis and solve the difficulty.

2.2 The idea

This last question has originated the idea that the authors developed in this paper, following the aim to realize a system capable of illuminating both the crossed spaces and the room where the diffuser is installed, so transforming an obstructive bulky system into an architectonical component integrated with the surrounding environment in which it is inserted and besides useful to distribute light in the midway space between the collector and the diffuser.

When a traditional light pipe is installed, light is captured on the rooftop of the building and transmitted to underground areas, passing through rooms not illuminated by the system and occupied by a very voluminous device, as explained in Fig. 1(a). Its size makes it impossible to be installed in the centre of the room because it constitutes an undesirable stumbling block in the passage room.

The proposal of a double light pipe arises from these considerations and in order to resolve this problem. If a double light pipe is used instead of a traditional one, the system becomes an architectonical component, in good harmony with the architectonic context, which is able to furnish light both into the final and the crossed rooms, as in Fig. 1(b).

In a traditional light pipe a very reflective film is applied only over the internal surface of the pipe and the collector is a transparent surface with the same diameter of the pipe. On the contrary, in a double light pipe, the same reflective film is applied on both the internal and external surfaces of the inner pipe and a second larger pipe, concentric to the first one, is made of a transparent polycarbonate tube and it is internally coated by a diffusing film, as shown in Fig. 2. In this case the collector, on the rooftop of the building, is larger than the traditional, with the same diameter.
Figure 1. Comparison between a traditional light pipe and a double light pipe.

Figure 2. Evolution from a traditional light pipe to the innovative DLP.
of the external tube, in order to partially introduce light into the inner tube and the remaining part into the outer one. The larger dimensions of the technological apparatus with respect to a traditional light pipe are balanced by the advantages consisting in the possibility to have the passage room be illuminated by it.

2.3 The components of the new system

A double light pipe, such as a traditional one, consists of three components:

1. The light input device, called the collector;
2. The transport module;
3. The light output device, called the diffuser.

In this first stage of the work the authors concentrated on the transport phase, investigating the best way to convey daylight from the collector to the diffuser, and simultaneously distribute light in the passage rooms. So a traditional polycarbonate diffuser with a regular prismatic geometry was adopted in order to not modify the performances got by a corresponding traditional light pipe.

Besides, regarding the collection section, a clear glass (or polycarbonate) plate collector was planned instead of a traditional top dome one, in order to do the captation function in the simplest way and to refer all the obtainable improvements of performances by the systems to the transport phase in which the fundamental idea is developed. In this way the authors try to improve the performance of the system due only to the transport phase, reserving to a second stage the optimization of the collection phase, which is the most delicate function particularly in a double light pipe.

At this moment the diffuser is a traditional one, since no improvement can be obtained at this phase in which daylight exits from the pipe.

2.4 Description of the used materials for the transmission module

The inner pipe of the transmission module is made by an aluminium sheet covered by a multilayer highly reflective film both over its internal surface and the external one. This film is characterized by a very high reflective coefficient ($\rho = 99.5\%$) and it permits, thanks to multiple reflections, to channel direct and diffuse light coming from the sun and the sky, downward to the diffuser.

On the contrary, the outer pipe consists of a transparent polycarbonate tube internally covered by a diffusing material, called OLF (Optical Lighting Film) which distributes light into the room passed through by the system. OLF is a thin flexible polycarbonate film with $90^\circ$ micro-prisms applied on one side and smooth on the other side. OLF is commonly used to uniformly distribute natural or artificial light on a surface. In some applications, light from a point or linear source is spread by OLF, creating a perfectly diffusing surface light source.

It has good optical properties since it can simultaneously reflect or transmit depending on the angle at which a light ray strikes the film. If this angle is less than about $27^\circ$ with respect to the axis of the prisms it is reflected, while if it is greater than this value, it is transmitted.
3. Experimental Analysis

3.1 Description of the model
A reduced scale (1 : 10) balsa wood model of a two-level building was created in order to experimentally analyse the performances of a DLP. Each level consists of a $5 \times 5$ m plant area room, $h = 2.7$ m, and the DLP is realized by a $\phi = 30$ mm internal tube and a $\phi = 60$ mm external one, so that an interspace between the two pipes is originated by the geometric configuration. The external pipe is 3.0 m long and the internal one is 3.3 m long since it passes through the intermediate ceiling between the two levels. (e. g. Fig. 3)

The floor, boundary walls and ceiling are all made of unpainted balsa wood characterized by a reflection factor of about 50 %.

In both rooms no window is present, so the DLP is the only daylight source. This configuration allows the model to be similar to a two-level hypogean construction in which daylight is only introduced by the double light pipe, both in the final room (ground level) and in the passage room (first level).

3.2 Experimental apparatus
The experimental analysis was carried out by measuring internal luminance in two positions on the ground level (1, 2), the first just under the pipe and the second 1.5 m distant from it, while four positions were selected in the first level (3, 4, 5, 6), 0.5 m apart from each other, on a horizontal work plane 0.8 m high on the floor, as illustrated in Fig. 4 and Fig. 5.
Measurements were carried out by CIE Lux-meters sensors type LSI-BSR001, range 0–25 klux, accuracy 3% of the reading value for illuminance. Simultaneously external horizontal illuminance was measured by CIE sensors type LSI-DPA 503, range 0–100 klux, tolerance 1.5%. The data was registered and elaborated by a data-logger type LSI/BABUC-ABC, characterized by 20 inputs.

3.3 Results
In Fig. 6 and Fig. 7 experimental data obtained under Clear Sky conditions, from 10am. to about 6pm, respectively on the first level and ground level, are shown.
In a previous experimental analysis carried out in Overcast and Intermediate sky conditions a good uniformity in illuminance values on the work-plane was obtained, probably due to the axial symmetric configuration of the device and the geometrical symmetry of the model. There would be expected to be an analogous spatial uniformity in the distribution of illuminance all over the work plane under clear sky conditions too, due to the presence of diffusing film OLF on the external pipe. So, measuring positions were chosen in a way that takes into account symmetrical characteristics of the building and the system, as shown in Figs 4 and 5. The experimental results under the clear sky didn’t validate this hypothesis. In fact, referring to Fig. 6, three different ranges can be considered:

1. The first one, from 10am. to 1pm., during which a regular increasing trend of external illuminance is verified, ranging from about 70 to 90 klux;
Figure 6. Experimental results – Clear sky, 1st floor.

Figure 7. Experimental results – Clear sky, ground floor.
2 The second one, from 1 to 2pm., in which a very irregular behaviour of external illuminance occurred, varying between 35 and 95 klux, due to momentary climatic changes;

3 The last one, from 2 to 6pm., during which a regular decreasing trend of external illuminance is verified, from about 80 to 40 klux.

During the first period a regular trend of internal illuminance in positions 3 to 6 is verified, decreasing from about 600 lux in position 3 to 250–300 lux in position 6, apart from two peaks, in position 5 at about 10.30 and position 3 at about 10.45.

In the second time range it is very difficult to compare data in measuring positions in the first level each to the other, due to the very irregular trend of external illuminance, on the basis of which analogous variations of internal illuminance occur.

In the third period three maxima were verified in measuring points, at regular intervals, 25–30 minutes one from the other: the first one at 2.30pm in position 3, the second at 3pm in position 4, the third at half past 3 in position 5 and the last at about 4pm in position 6. This is probably due to a particularly powerful direct component of solar radiation refracted by OLF that produces a more intense illuminance in all measuring positions in turn depending on time variation of azimuth and elevation of sun. Maxima verified in positions 3 and 5 in the morning, as already said, are probably due to the same reason.

In order to more deeply examine the influence of the optical properties of OLF on DLP performances, an experimental analysis has been carried out on the same reduced scale model of the building with a DLP without OLF over the internal surface of the exterior polycarbonate pipe. In this case the external pipe is a simple transparent tube coaxial to the internal one.

In Fig. 8 the results of a test with DLP without OLF are reported. The data is relative to the time ranging between 1.30pm and 3.30pm, that is the period in which peaks at equal intervals are verified in measuring positions with the DLP in the configuration with OLF. When OLF is absent, internal illuminances are very similar to external ones and maxima are verified in correspondence with external illuminance trend. They are probably caused by the direct component of sun radiation that is not refracted but transmitted by the transparent polycarbonate and simultaneously generates maxima in all measuring positions. The presence of OLF, on the contrary, produces not simultaneous maxima in measuring points, due to the refraction effect which is different at every time depending on the incidence angle of the direct component of sun radiation.

In Fig. 7 data in positions 1 and 2 on ground floor level are explained, in Clear Sky conditions, in which illuminance trend is strictly depending on external data, particularly in position 1, just under the pipe. It is interesting to underline as data in position 1 is more speedily increasing than external illuminance values due to a more and more significant presence of direct component of light while sun altitude is rising. On the other hand, the results in position 2 are not influenced by the sun altitude. In fact the illuminance is affected more by the reflective component than by the direct one. Data in positions 1 and 2 are typical results obtainable by a traditional light pipe.
4. Numerical Analysis

Numerical analysis was affected by ECOTECT and RADIANCE, two of the most reliable soft-wares commonly used in daylighting analysis. ECOTECT uses the BRE method for the calculation of the Daylight Factor, while the Point-to-Point method is adopted for electric lighting calculations. Alternatively, RADIANCE gives the possibility to allow a more detailed analysis of daylight distribution by means of the ray tracing algorithm so as to obtain photorealistic representations of lighted internal spaces.

The authors recently published two works in which the most relevant differences in data obtained by each of the two soft-wares for daylight calculations are evidenced. Besides they were compared with those obtained by ENERGY PLUS [11, 12].

The numerical results obtained by ECOTECT are in good agreement with experimental data. As an example, numerical results by ECOTECT are shown in Fig. 9 and Fig. 10, in which numerical simulation is carried out at the beginning and near the end of the test. Illuminance values in lux are explained in a grey scale representation. A symmetrical distribution is obtained both at the first level and at the ground level. The tests are carried out during the daytime when the diffusing effect of OLF in the first level and the prevailing contribution of reflections on the ground level are more significant than the direct component of illuminance.

The comparison between experimental and numerical data by ECOTECT underlines that, also in presence of the direct component, a good agreement is obtained in all measuring positions, as shown in Table I, in which reported data refers to the
third time range in which peaks in illuminance values are verified. In fact the percentage error is up to 10% in all measuring points.

Finally a photorealistic rendering of the second level of the building affected by RADIANCE, lighted up by the DLP, under clear sky conditions is shown in Fig. 11. The image evidences how the reflective component by boundary walls is significant

Table 1. Comparison between experimental and numerical data from Ecotect

<table>
<thead>
<tr>
<th>h</th>
<th>2</th>
<th>3</th>
<th>4 p.m.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pos 3-exp</td>
<td>678</td>
<td>687</td>
<td>516</td>
</tr>
<tr>
<td>Pos 3-num</td>
<td>638</td>
<td>619</td>
<td>496</td>
</tr>
<tr>
<td>Pos 4-exp</td>
<td>502</td>
<td>682</td>
<td>402</td>
</tr>
<tr>
<td>Pos 4-num</td>
<td>505</td>
<td>627</td>
<td>421</td>
</tr>
<tr>
<td>Pos 5-exp</td>
<td>350</td>
<td>532</td>
<td>384</td>
</tr>
<tr>
<td>Pos 5-num</td>
<td>380</td>
<td>510</td>
<td>415</td>
</tr>
<tr>
<td>Pos 6-exp</td>
<td>288</td>
<td>329</td>
<td>467</td>
</tr>
<tr>
<td>Pos 6-num</td>
<td>310</td>
<td>301</td>
<td>448</td>
</tr>
</tbody>
</table>
Figure 10. Numerical results by Ecotect first level, at 5pm.

Figure 11. Numerical results by Radiance: qualitative image of the system in Clear sky condition.
on illuminance data on the work plane. OLF creates a good uniformity in light distribution and avoids the glaring effect which could generate a visual discomfort condition in rooms where DLP without OLF are installed.

5. Conclusions

In this work an innovative technological device capable of channelling daylight from a captation point in direct interface with the sun or sky into the core of the building far away from it, is presented.

It is named the Double Light Pipe, thanks to its particular configuration made of two concentric tubes, and it is able to distribute daylight both in the final room, where the diffuser is installed, like a traditional light pipe, and in the crossed rooms where traditional light pipes are characterized by significant encumbrances.

As already said, the DLP consists of two concentric pipes, the first one able to illuminate the final room as a traditional light pipe, and the second, external to the first, which allows light to enter the room traversed by the system. In these intermediate rooms it becomes an architectonical element in good agreement with the environment, capable to transmit quite a diffused light all around it.

The experimental and numerical results of the analysis carried out by the authors show that good performances are obtained in the passage room, maintaining the same performances of traditional light pipes in the final room. Particularly, upstairs (in the passage room), in summer climatic conditions, with clear sky configuration, maxima are verified in all measuring positions, at equal intervals, probably due to the refraction effect of Optical Lighting Film (OLF), a thin flexible diffusive material with special optical properties, applied over the internal surface of the exterior transparent polycarbonate tube, with the aim to diffuse into the in-between room light captured by the collector. On the contrary, the application of OLF allows us to achieve a good uniformity of illuminance on the work plane with overcast and intermediate sky conditions.

Downstairs (in the final room) experimental results, confirmed by numerical data, show that the performances of the DLP are similar to those obtainable by a traditional light pipe with the same structural and geometrical features of the internal pipe.

Further analysis will be centred on OLF capacity to uniformly distribute daylight in all climatic conditions, since it seems very efficient with overcast and intermediate sky, but not with clear sky conditions too. Besides, a particular care will be devoted to the analysis of the captation function, which will be improved, even if only light pipes with a passive zenithal collector are considered, that are less efficient but cheaper than ones with mobile captation.

6. References


