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Experimental analysis on a 1:2 scale model of the double light pipe, an innovative technological device for daylight transmission

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Abstract

In this paper the authors present the double light pipe, an innovative technological device, designed as an evolution of a traditional light pipe, which distributes daylight to underground areas of a building, illuminating, at the same time, the passage areas thanks to a larger collector and a second transparent pipe attached to the first one. Unlike the traditional light pipe, thanks to this double illuminating function it can be located in the middle of a room, despite its encumbrance.

In this paper the technological design of the double light pipe is presented and the results of an experimental analysis on a reduced scale (1:2) model are shown. Internal illuminance data over horizontal and vertical work-planes were measured in various sky conditions with or without direct solar radiation. Being this innovative device obtained by a light pipe integrated with a second pipe, it performs like a traditional light pipe for the final room and, at the same time, illuminates the intermediate room giving it uniform and high quality light, particularly indicated for wide plant areas, such as show-rooms or museums.

Keywords: Light pipe; Double light pipe; Natural light; Daylight; Experimental analysis

1. Introduction

It is known that every human activity is better carried out in presence of natural light rather than in the absence of it, due to a favourable psychological condition felt by the occupants of the building. This is probably due to the perception of the flowing of time that is unattainable when artificial light is the only light source in the room. In fact electric light sources emanate a time-independent luminous flux and produce steady illuminance on the work plane, that does not allow people to perceive the passing of time. Moreover, the indiscriminate use of electric light has a great impact on energy saving. Indeed buildings use almost 40% of the world's energy (Santamouris, 2007), and a considerable part of this is used for artificial lighting. This problem is sometimes amplified by the inconsiderate behaviour of the building occupants, which use the artificial light when the natural light is available because of a scarce awareness of the energetic matter.

An increasing and more efficient distribution of daylight in interior spaces by windows or skylights, or technological devices, such as light pipes, can reduce the energy demand of buildings.

This paper presents a system which can contribute to achieving this aim by the use of simple but efficient technology which is an evolution of traditional light pipes.

Traditional light pipes are able to transmit natural light from the collection point, commonly on the rooftop of buildings or other external walls freely exposed to the sky, to underground rooms (Oakley et al., 2000).

Some light pipes are equipped with mobile collectors, while the most economic ones adopt fixed collectors, consisting in a transparent dome freely exposed to the sun and the sky. The transport of light is made with the

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pipe which passes through the structures (ceiling or walls) and crosses intermediate areas with the aim of transmitting light to the final room in which a diffuser is located. Many authors have developed prediction methods of the performances of these systems (Jenkins and Muneer, 2003, 2004; Jenkins et al., 2005) and a lot of experimental data are available from many monitored installations (Paroncini et al., 2007; Chella et al., 2006; Zazzini et al., 2006).

If a light pipe is used to transmit light to an underground room and an intermediate area has to be crossed by the system, it is really a problem to position it in the centre of the room, due to its encumbrance. It is often unacceptable to install a large device in the middle of a room if it does not function as a structural or architectonical element.

In these cases a system which is at the same time able to transmit light to the final room and distribute it in the passage areas could be desirable, particularly in wide area rooms destined to be show-rooms, museums, exhibition areas and similar, where a uniform, high quality light is required and a cumbersome illuminating device can be accepted because it can become a piece of furniture or an architectonical element perfectly integrated in the context and it can also be used as an artificial light source.

Regarding this matter the authors propose in this paper the double light pipe (DLP), an innovative technological system, set up with the aim of allowing the natural light transmission in underground rooms, illuminating, at the same time, the passage areas, in which it can be located also in the centre of the room, despite to its encumbrance and unlike the traditional light pipes, since it is an architectonical element with the function to illuminate the room in which is installed.

A reduced scale prototype of the DLP has been recently set up in the Technical Physics Laboratory of the Faculty of Architecture of Pescara, in which an intense experimental activity on reduced scale models of the system has been carried out.

It is an evolution of a traditional light pipe in which a transparent tube is attached to the pipe in order to illuminate the passage room crossed by the system. It is particularly suitable for spacious areas where diffuse light is required, such as museums or any type of exhibition room. Artificial lamps can be added so that the double light pipe can be used as a light source and a piece of furniture perfectly integrated into the surroundings.

The principal objectives of this paper are to illustrate the technological design of the DLP and to present the first results of an experimental analysis carried out with the aim of evaluating the applicability of this system in Architecture and the possibility to improve the performances of a traditional light pipe overcoming some limits that derive from its encumbrance.

2. Technological description of the DLP

The double light pipe is a technological evolution of a traditional light pipe, obtained through a substantial modification of the collection and transport sections. A double light pipe consists of two concentric pipes: the inner one is similar to a traditional light pipe, apart from its external surface which is covered in the same multilayer film used for the internal surface; it is characterized by a very high reflection factor. A cavity is formed between the two pipes. The external pipe is made of transparent material such as polycarbonate and it allows light to be introduced into the intermediate rooms crossed by the system. The double light pipe adopts a larger collector than the traditional light pipe, in order to convey daylight both in the inner pipe and the cavity between the inner and the outer pipe. In order to install the device easily an accurate description of its components is supplied and in Fig. 1 a drawing of the technological design of the DLP is shown.

The DLP consists of the following components:

(1) The internal tube;
(2) The external tube;
(3) The anchorage devices;
(4) The collector;
(5) The diffuser.

1. The internal tube is a modular system. Each module consists of an aluminium sheet internally and externally covered with a multilayer reflective film (3 M Radiant Mirror Film LRF), bent in order to generate a cylindrical shape, that is a tube, $\phi = 0.25$ m in diameter. Three modules are assembled one on top of the other so as to create a 3 m long tube. It can be cut if the room is less high than 3 m.

2. The external tube is a transparent polycarbonate tube, $\phi = 0.5$ m in diameter, 6 mm thick, with a 89% optical transmittance. It consists of three 1 m long mass-produced modules which can be assembled “in situ”, with one piece positioned on top of the other. If the room is less high than 3.0 m, the exceeding portion of the upper module is inserted into the ceiling, and covered internally with the same multilayer reflective film applied on the internal pipe. If the room is 3.0 m high or more, three modules are assembled one on top of the other and a fourth is positioned on top of the upper one. The portion placed in the ceiling is covered by reflective film. In any case, the internal surface of the cylinder hole made in the ceiling must be entirely covered with reflective film.

3. In order to allow for correct placing of the external tube, three types of the aluminium anchorage device are designed, as shown in Fig. 2. The first is placed on the ceiling of both the intermediate and the final rooms, the second is used as a middle device able to connect the central modules of the pipe, and the third allows the first module to be placed on the floor, both in the middle room and on the floor of the upper level, as a basement for the collector.

4. The collector is similar to a traditional pipe collector. A dome transparent polycarbonate collector, $\phi = 0.5$ m in diameter, is used, which allows natural light to enter both

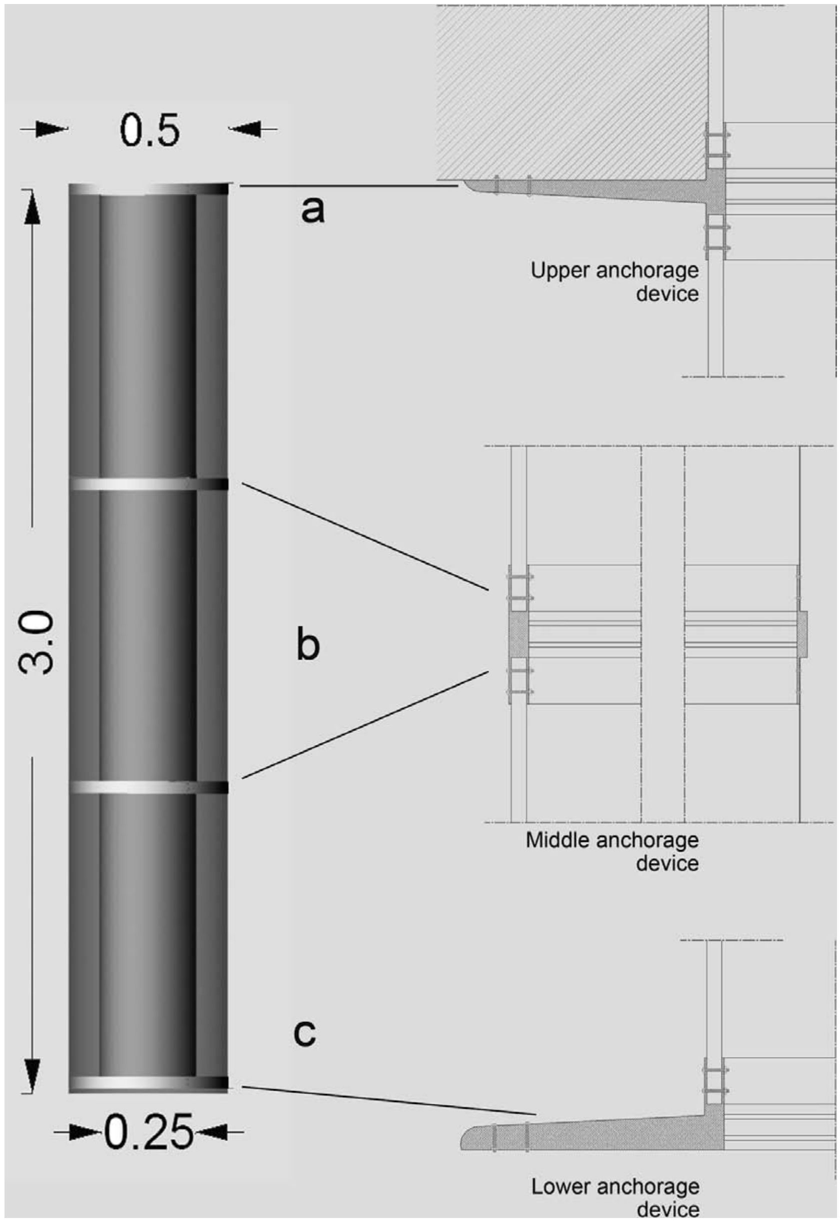

Fig. 1. Constituting elements of a double light pipe.

the internal and the external pipes. In Fig. 3 a picture of the collector is shown.

5. In the final room a diffuser is located as in a traditional light pipe. It allows daylight to enter the final room as a diffusing or concentrated light, depending on its geometric and structural configuration. In Fig. 4 a picture of two types of diffuser is shown.

3. Experimental analysis

The authors have already published the results of an experimental and numerical analysis (Chella et al., 2007; Baroncini et al., 2008) on a reduced scale (1:10) model of a two-level building and they showed how the internal pipe of the DLP behaves as a traditional light pipe, transmitting daylight captured by the collector to the underground area in which the diffuser is installed. Several experimental tests produced illuminance data on a horizontal work plane similar to those obtainable by a traditional light pipe. In this work the authors paid attention to defining the performances of the middle section of the double light pipe which allows light to be distributed to the intermediate room passed through by the system. To attain this purpose they realized a 1:2 scale multilayer wood model of a room passed through by a double light pipe and they experimentally studied the reachable illuminance on a horizontal work plane and on a vertical axis around the pipe.

3.1. Experimental apparatus

The experimental apparatus is a wood model (scale 1:2) of a 3.8x3.8 m plant area room, 3.0 m high. In Fig. 5(a–c)

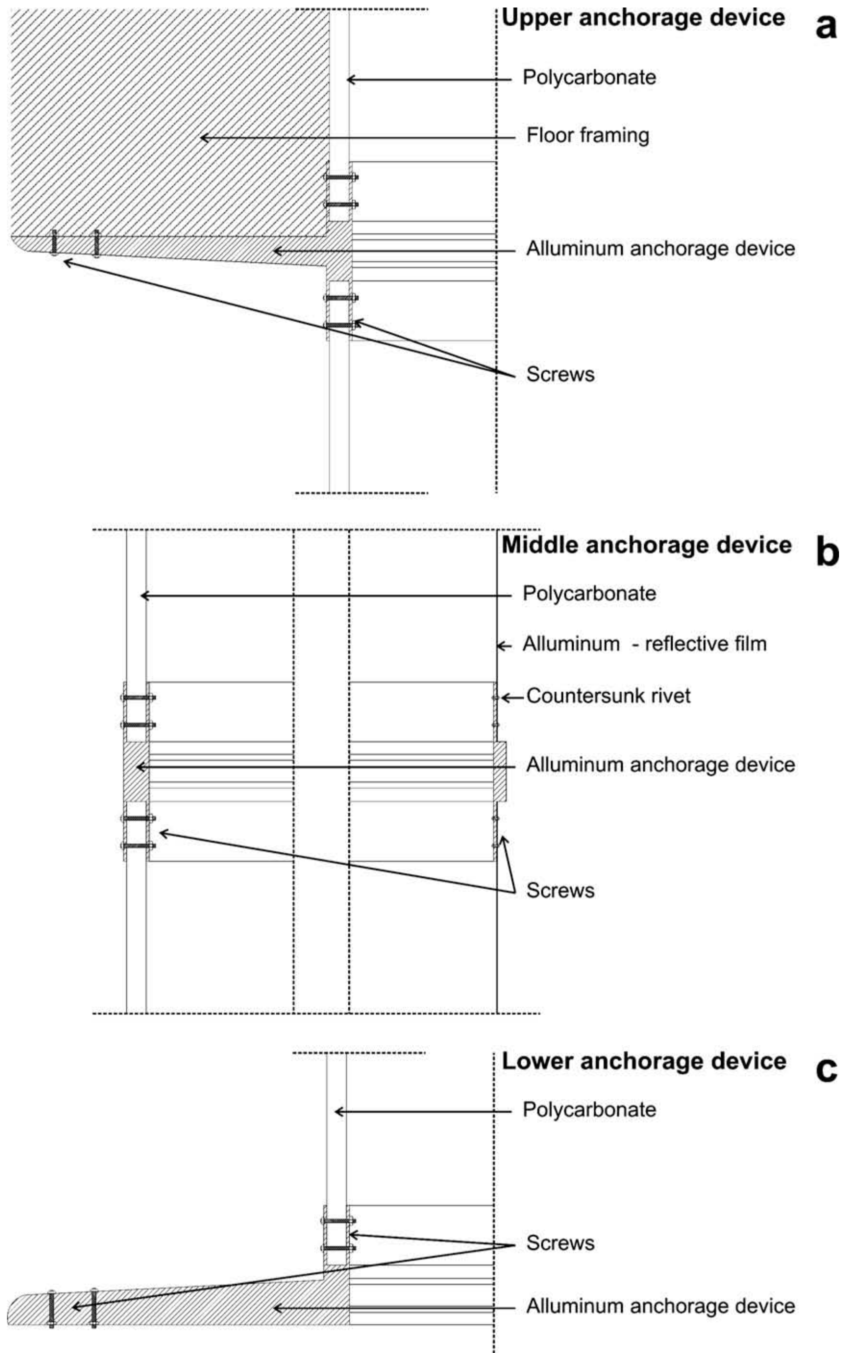

Fig. 2. Anchorage devices.

Fig. 3. A picture of the collector.

Fig. 4. A picture of two types of diffuser.

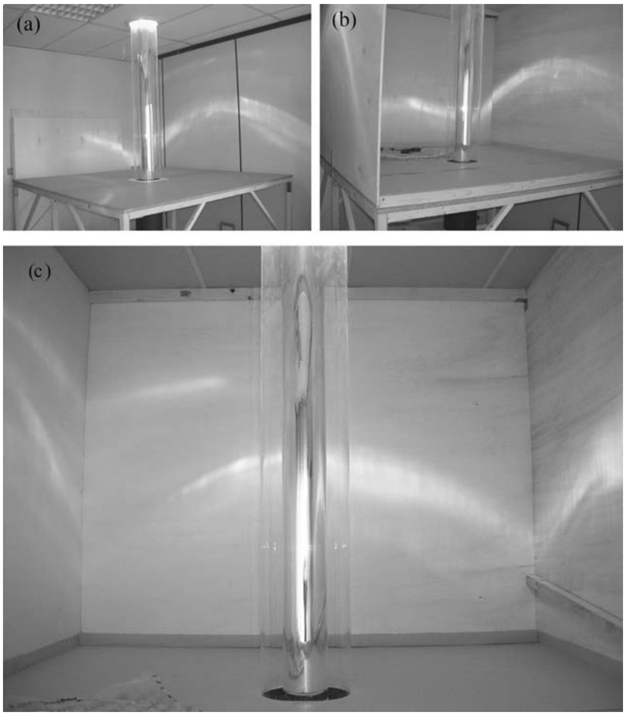

Fig. 5. Construction phases of the experimental apparatus.

some steps of the building of the apparatus are illustrated, while in Fig. 6, a drawing (elevation and section) of the complete system is shown. The vertical walls are made of unpainted multilayer wood, characterized by a reflection factor of about 50%, while the floor and the ceiling are covered in grey painted sheets of drawing paper ($\rho = 49.1\%$). The reflection factors were measured by a spectro-photometer type MINOLTA CM-508 D. In the room no window or skylight is present, so the DLP is the only daylight source. In this way the model simulates the passage room of a two-level hypogeal construction in which daylight is introduced by the double light pipe, both in the final room (ground level) and in the passage room (first level).

The double light pipe consists of two concentric pipes, the internal one is made of plastic material externally covered by a reflective film (3 M Radiant Mirror Film LRF) with $\rho = 99.5\%$, while the external one is a transparent polycarbonate tube. Twelve CIE Lux-meters sensors type LSI-BSR001, range 0–25 klux, accuracy 3% of the reading value for illuminance, are located in the room, based on two different configurations: in the first one (configuration a) all the luxmeters are positioned on a horizontal work plane 0.4 m high on the floor as illustrated in Fig. 7, while in the second (configuration b) four luxmeters (5, 6, 15, 16) are in the same positions on the horizontal work plane and the remaining eight are located on four vertical axes around the pipe (Fig. 8). In both configurations external horizontal illuminance (E_{ext}) is measured by a CIE sensor type LSI-DPA 503, range 0–100 klux, tolerance 1.5%. The data were registered and elaborated by a data-logger type LSI/BABUC-ABC, characterized by 20 inputs. In Fig. 9 a photographic representation of both configurations is shown.

3.2. Results

In Fig. 10 the results of a 6-h test are shown. It was carried out in the configuration (a) with Overcast Sky conditions, the external horizontal illuminance (E_{ext}) ranging between 6 and 44 klux, with an average value of 23 klux.

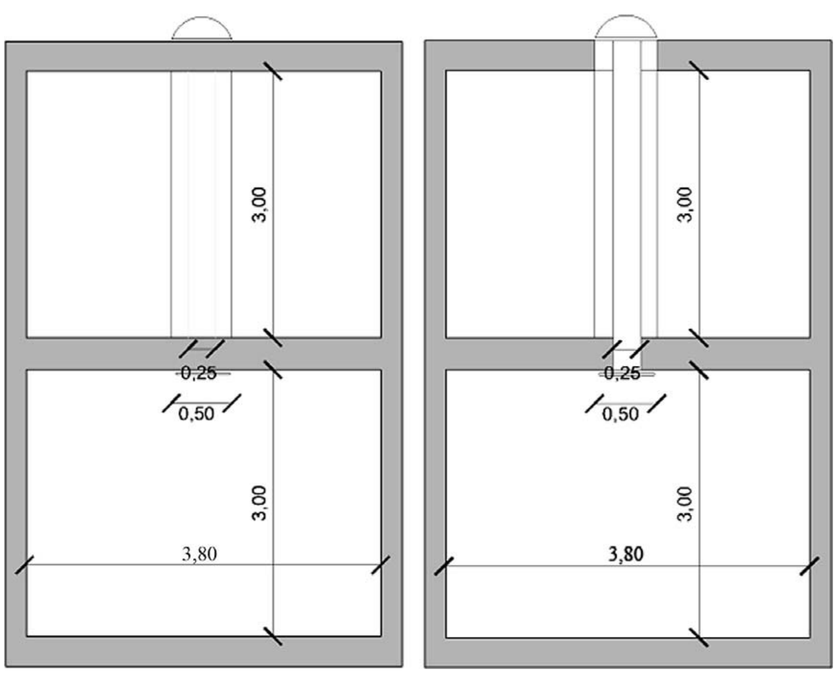

Fig. 6. Elevation and section of the complete system.

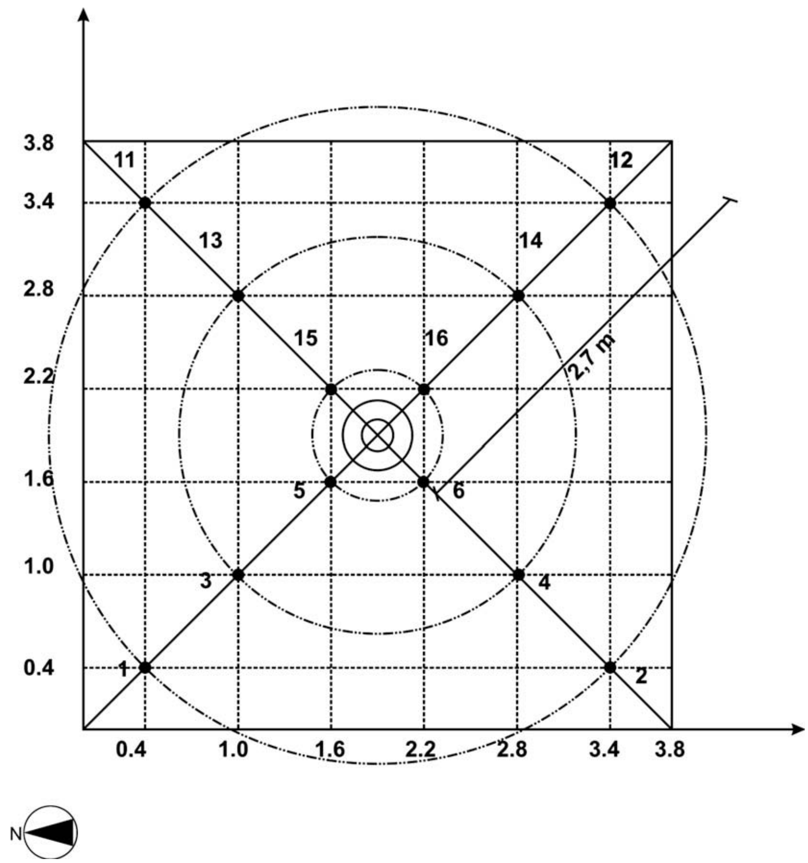

Fig. 7. Measure positions in configuration (a).

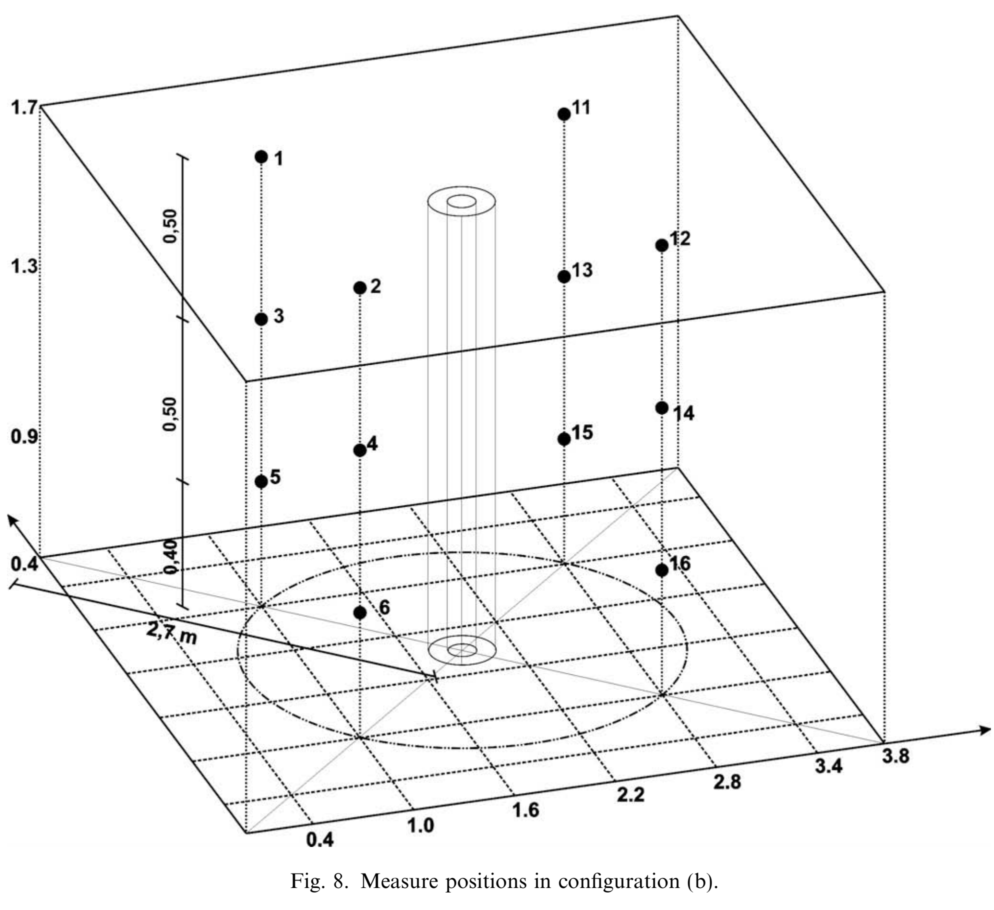

Fig. 8. Measure positions in configuration (b).

Fig. 9. Measure positions in configuration (a) and (b).

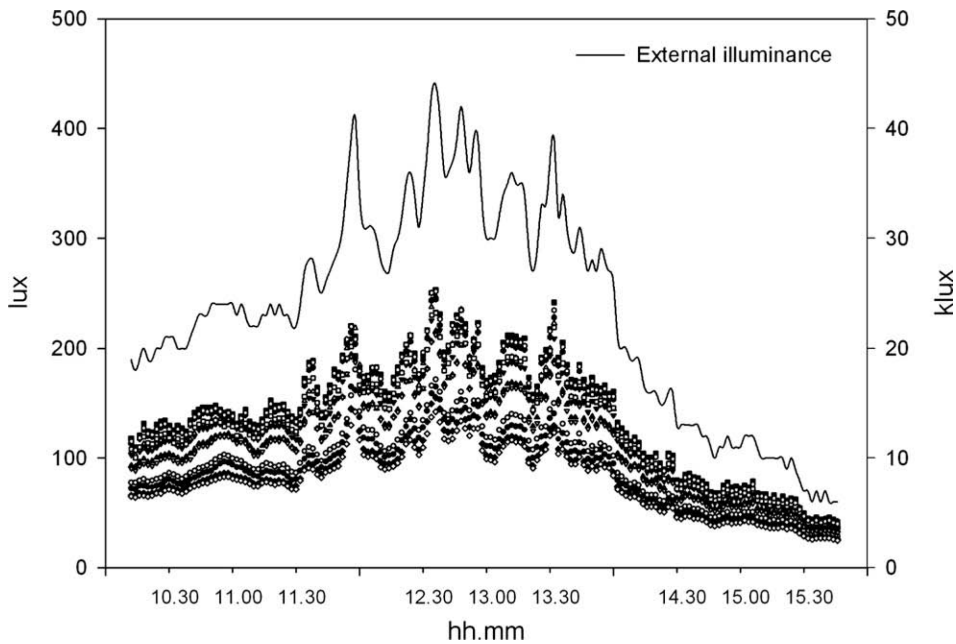

Fig. 10. Internal and external illuminance – Overcast Sky conditions.

The internal illuminance in positions 1 ÷ 6 and 11 ÷ 16 follows the trend of external illuminance. A very regular trend is observed in all measure positions, following the external illuminance trend.

The illuminance ratio E_{in}/E_{ext} ranges between 0.32% and 0.76% as shown in Table 1.

Fig. 11 shows the range in which all data are included at any time. There is an average difference of about 60 lux between minimum and maximum illuminance at any time, with instantaneous values ranging between 17 and 118 lux. The minimum difference (17 lux) is registered at about 16.00 close to sunset, while the maximum difference (118 lux) is verified at about 13.30, but generally in the central time of the day the highest differences are verified and they decrease close to sunrise or sunset.

Dealing with uniformity, the illuminance values in all the measure positions oscillate between −30% and +25% of the average value at any time. Pick values of −38% and +31% take place in the middle of the day, with the maximum in position 5 close to the DLP and the minimum in position 12 close to one corner of the room.

Besides, in absence of direct solar radiation, quite a symmetrical distribution is verified over the horizontal work

Table 1
Illuminance ratio E_{in}/E_{ext} (%) in a 6-h test, Overcast Sky conditions, $E_{ext} = 6 \div 44$ klux.

	Minimum	Medium	Maximum
Pos 1	0.36	0.38	0.50
Pos 2	0.38	0.41	0.52
Pos 3	0.50	0.54	0.65
Pos 4	0.53	0.56	0.66
Pos 5	0.51	0.62	0.76
Pos 6	0.47	0.56	0.69
Pos 11	0.33	0.35	0.45
Pos 12	0.32	0.34	0.45
Pos 13	0.45	0.50	0.60
Pos 14	0.45	0.48	0.57
Pos 15	0.50	0.60	0.76
Pos 16	0.51	0.60	0.72

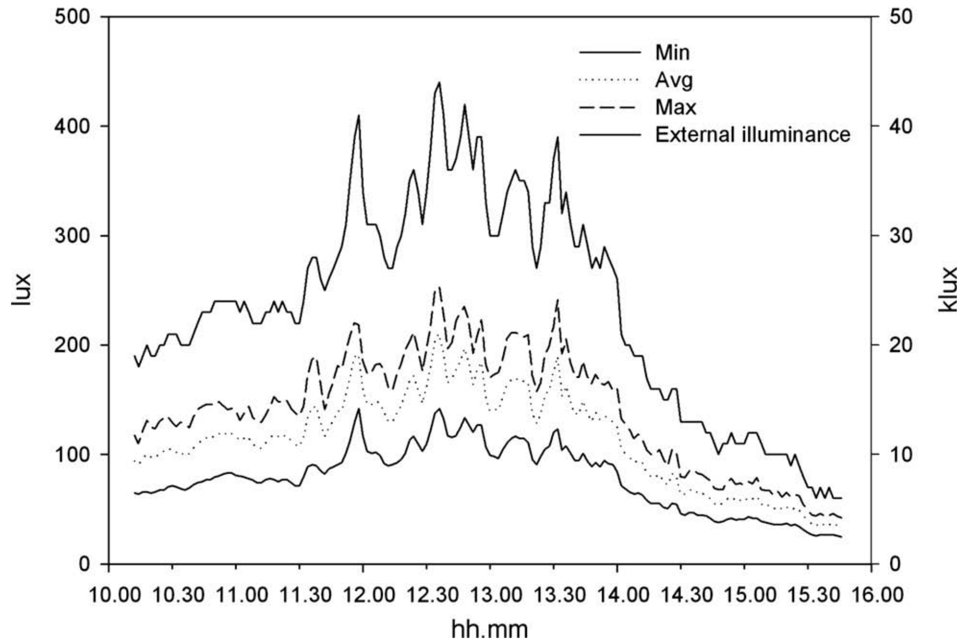

Fig. 11. Minimum, average and maximum illuminance data – Overcast Sky conditions.

plane as shown in Fig. 12, in which a two-dimensional grey intensity representation of internal illuminance data at 12.00 is shown.

In absence of direct solar radiation the internal illuminance follows the trend of the external one in all positions over the work-plane, but that is not the case in the presence of direct solar radiation. As an example we can consider the results of a 6-h test with Intermediate Sky, E_{ext} ranging between 11 and 74 klux. As shown in Fig. 13 the external illuminance is characterized by a very irregular trend significatively conditioned by the variations of direct solar radiation. In this case the illuminance in all the measure positions follows the trend of external illuminance except for positions 1, 2 and 11, near the three corners of the room, in which pick values of illuminance are verified, probably due to particularly intense reflective radiation. In particular the picks in position 2 are verified in the morning (between 10.30 and 11.00) and in the afternoon (between 14.00 and 15.30), in position 1 between 11.00 and 12.00 and between 13.00 and 14.00, finally in position 11 between 12.30 and 13.30. They are probably due to mirror reflections from the interior tube. So the authors propose covering the upper portion (0.4–0.5 m high) of the internal surface of the transparent tube with a diffusive film (3 M Optical Lighting Film), that they tested in (Chella et al., 2007; Baroncini et al., 2008). It would be useful to reduce the risk of glare that may occur in presence of direct solar radiation and contribute to producing a diffuse light distribution. Table 2 shows minimum, maximum and average values of the illuminance ratio $E_{in}/E_{ext}\%$. In this case data range between 0.28% and 0.89%.

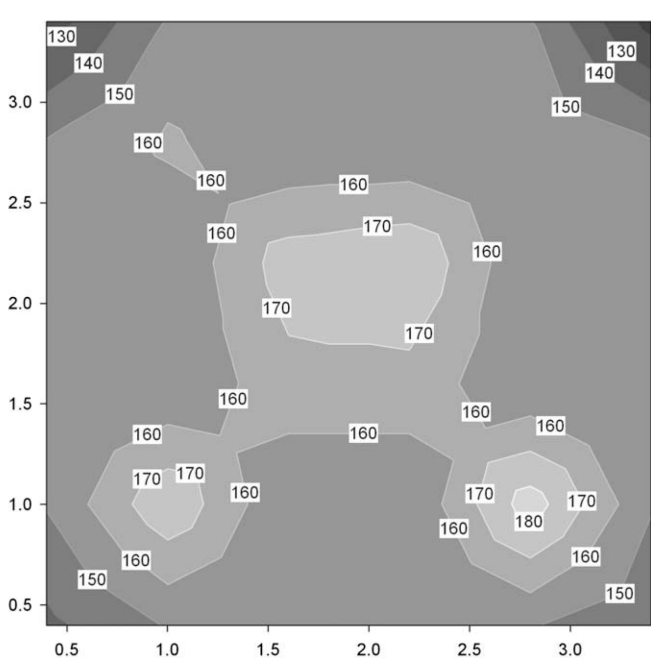

Fig. 12. Two-dimensional grey scale representation of internal illuminance – Overcast Sky conditions.

In Figs. 14–16 the results of a two-day test carried out in configuration b are shown in which the performances during sunrise and sunset are evident. During the first day Clear Sky conditions are verified with E_{ext} ranging between 11 and 87 klux and an average value of 65 klux, while the second day is characterized by Overcast Sky conditions, E_{ext} ranging between 4 and 47 klux with an average value of 18 klux.

During the first day a very regular trend is verified in which external illuminance increases before 12.00 and decreases after 12.00. A maximum value of 87 klux is verified at 12.00 o'clock. Coinciding with this maximum value, in the four measure positions on the horizontal work plane

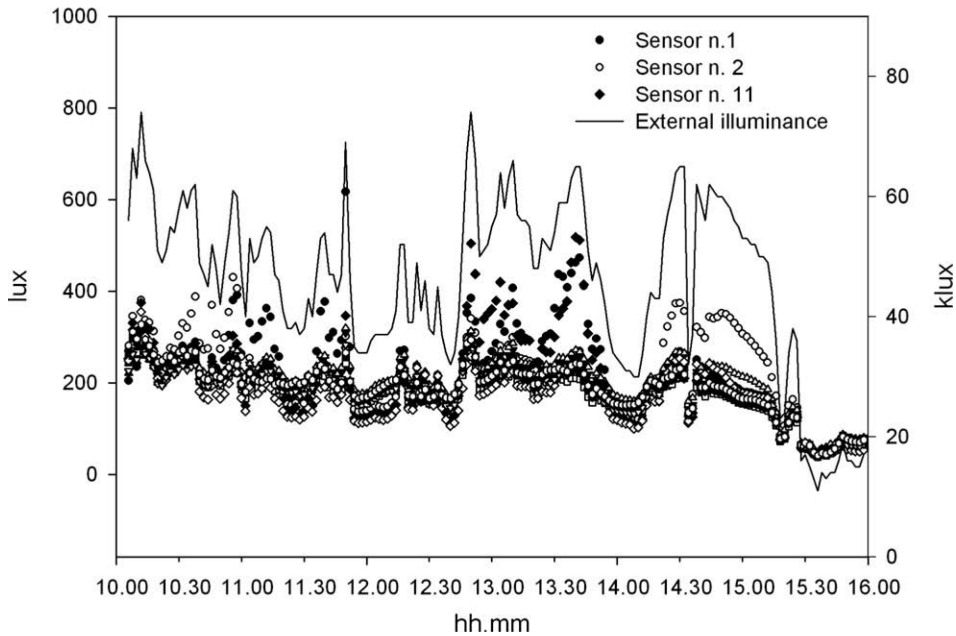

Fig. 13. Internal and external illuminance – Intermediate Sky conditions, in presence of variable direct solar radiation.

Table 2
Illuminance ratio E_{in}/E_{ext} (%) in a 6-h test, Intermediate Sky conditions in presence of direct solar radiation, E_{out} ranging between 11 and 74 klux.

	Minimum	Medium	Maximum
Pos 1	0.34	0.47	0.89
Pos 2	0.36	0.46	0.71
Pos 3	0.33	0.44	0.52
Pos 4	0.37	0.46	0.55
Pos 5	0.30	0.41	0.54
Pos 6	0.28	0.38	0.50
Pos 11	0.31	0.43	0.80
Pos 12	0.31	0.36	0.48
Pos 13	0.30	0.40	0.49
Pos 14	0.30	0.40	0.49
Pos 15	0.29	0.41	0.53
Pos 16	0.31	0.42	0.54

400 mm high on the floor, maximum values are verified particularly in position 5 close to the north–north west face of the room, as shown in Fig. 14. This is probably due to a very high direct component coming from the sun which is located in the south position at that time (Azimuth 0°, Elevation about 60°). If we consider the results in positions 3, 4, 13 and 14 on a vertical work plane 900 mm high on the floor, we notice that in this case a higher value of illuminance is obtained at 12.00 o'clock in position 4 and 14 diametrically opposite to position 5, probably due to a mirror reflection coming from the internal tube. On the contrary, in position 3 and 13, the maximum values are lower than in positions 4 and 14 and out of phase in time. It is clear that reflections from the walls and direct components of solar radiation significantly influence the illuminance data and they are not easily predictable. A particular situation is verified in positions 1, 2, 11 and 12 on a vertical work plane 1400 mm high from the floor. In this case we notice that very high values of illuminance data are verified but maximum values occur in the afternoon close to sunset, while at twelve o'clock minimum values are verified. This is probably due to the low elevation of the sun in the sky and the influence of direct components in positions 11 and 12 and reflections from the internal tube in positions 1 and 2.

On the second test day, with Overcast Sky conditions, a more regular trend of illuminance is verified in all the measure positions except for position 5 in which pick values occur at twelve o'clock in correspondence with the higher values of direct solar radiation.

4. Luminance distribution from the double light pipe

In order to characterize the DLP from the point of view of the visual comfort of the occupants of the passage room, a detailed analysis regarding the risk of glare from the DLP is necessary, since the luminance of the upper section of the device is overcoming that of its lower portion and of the surroundings. This risk is particularly high in condition of Clear Sky with sun, due to the solar reflections coming from the external surface of the inner tube.

About the risk of glare, it is not so clear what the most suitable index to quantify the phenomenon. In fact the DLP is a daylight source but it does not allow the direct interface with the external surroundings, sky vault or external buildings and obstructions, so the commonly used daylight glare indexes such as DGI, DGP (Wienold and Christoffersen, 2006) or DGI_N (Nazzal, 2005) do not seem so appropriate to characterize the system from this point of view. On the other hand, it is not an artificial light source, so the glare indexes commonly used for artificial light sources, as CGI or UGR (Wienold and Christoffersen, 2006) are not suitable at all. Finally, a specific glare index

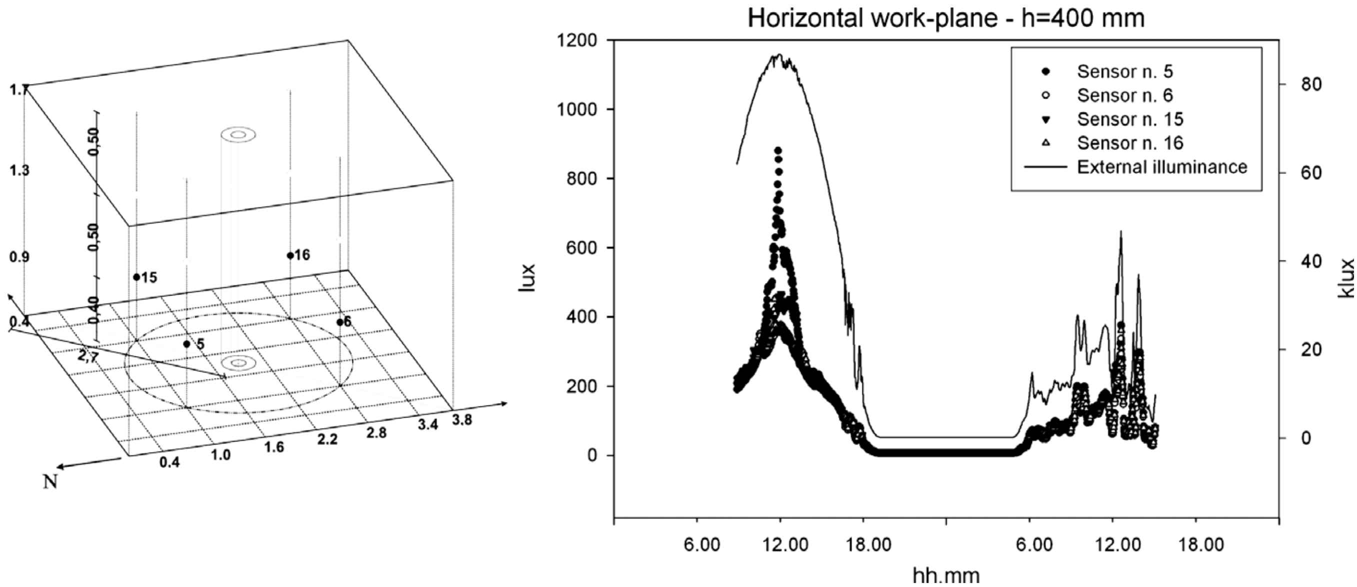

Fig. 14. Internal and external illuminance – Two-day test, Clear Sky and Overcast Sky conditions, positions 5, 6, 15, 16.

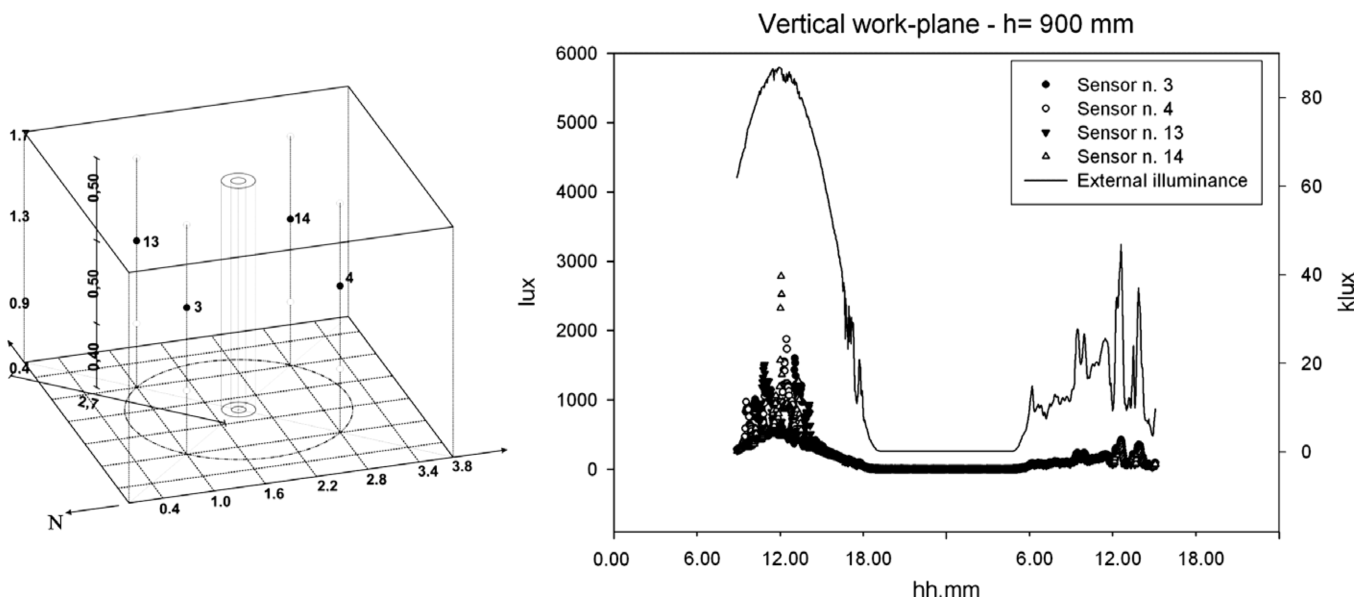

Fig. 15. Internal and external illuminance – Two-day test, Clear Sky and Overcast Sky conditions, positions 3, 4, 13, 14.

for light pipes or similar not traditional daylight sources has not been formulated yet.

Moving from these considerations, in this first phase, the authors decided to carry out a numerical analysis by the soft-ware Radiance with the aim to define the luminance distribution in the intermediate room illuminated by the DLP in standard conditions of sky (CIE Clear Sky with sun) and to verify what degree of contrast of luminance takes place in the field of view of the occupants.

As an example, in Figs. 17 and 18, the distribution of luminance in the field of view of an occupant in position 2 on the horizontal work plane is shown. The simulation has been done on February the 28th at 11.00, under CIE Clear Sky with sun, $E_{ext} = 83700$ lux. In the same position the highest values of illuminance took place during the experimental analysis under real sky with sun, therefore it could be considered the situation at higher risk of glare.

The Fig. 17 shows the luminance distribution on the surfaces of the room and on the DLP. All the values are smaller than 65 nits, except for the higher portion of the DLP and the base of it on the floor. As shown in Figs. 5 and 9, the luminance of the base of the DLP is not so high as in the Radiance simulation, so, probably, the reflections from this surface are overestimated by the numerical analysis. A wider range of the false colour scale, as that adopted in Fig. 18, shows that only the upper surface of

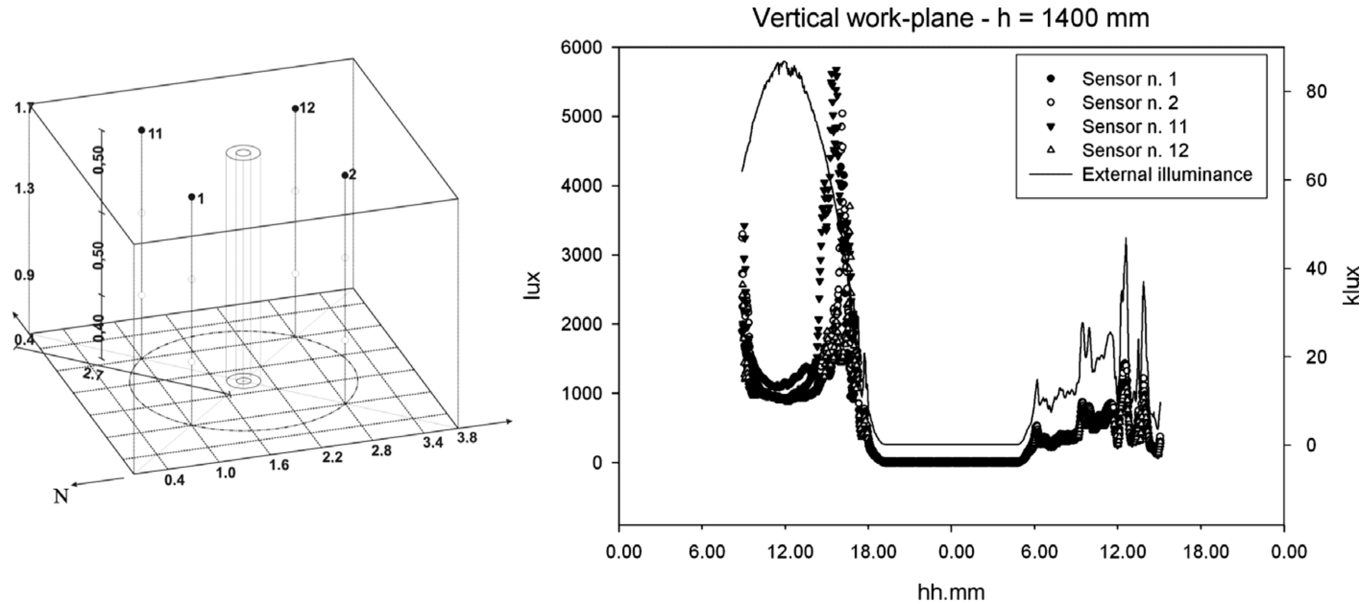

Fig. 16. Internal and external illuminance – Two-day test, Clear Sky and Overcast Sky conditions, positions 1, 2, 11, 12.

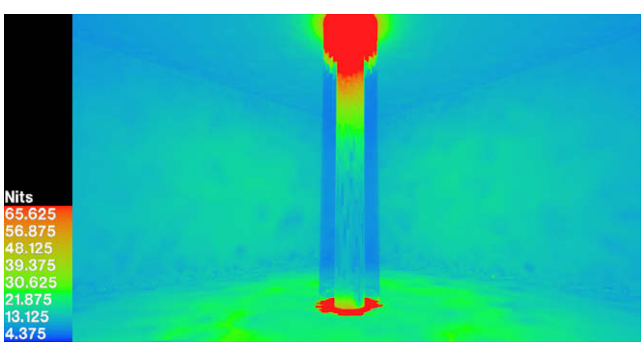

Fig. 17. Luminance distribution – Clear Sky with sun.

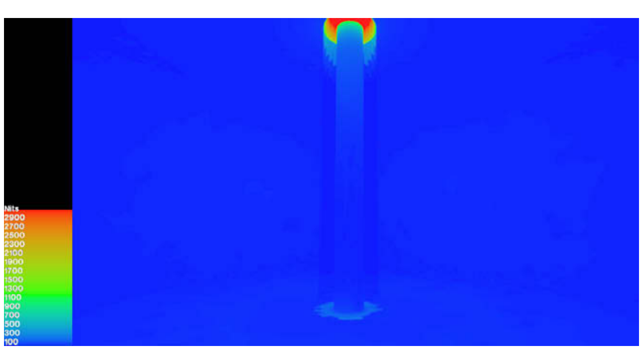

Fig. 18. Luminance distribution with a wider false colour scale– Clear Sky with sun.

the DLP presents luminance that overcomes 2000 nits up to 3000 nits.

Only the upper portion of the DLP is therefore characterized by high values of luminance in great contrast with the other surfaces of the room. For this reason we can consider this part at risk of glare in presence of direct solar radiations.

These results underline that a deeper analysis is necessary, so the authors are coming to set up an experimental apparatus able to examine experimentally the luminance distribution in various climatic conditions during the year.

As already said in Section 2.2, the authors propose covering only the upper portion (0.4–0.5 m high) of the inner surface of the external tube, with a diffusive film (3 M Optical Lighting Film), so to reduce its luminance without decreasing too much the illuminance on the work plane. In fact, if the whole internal surface of the external tube would be covered with OLF, an excessive depreciation of illuminance would take place, ranging between 15% and 50% in various sky conditions, as the authors verified in previous experimental tests on 1:10 scale model of the system.

5. Conclusions

The results obtained in an experimental analysis on a 1:2 model of the double light pipe are shown in this paper, in order to describe the performances of the system in many different sky conditions. Particularly with Overcast Sky conditions a more predictable trend of internal illuminance is verified very similar to the external one, while in the presence of direct solar radiation, it is very difficult to predict internal illuminance in all the positions because a particularly intense direct component or the reflections from the walls or from the tube significantly influence the illuminance on a horizontal or vertical work plane.

In addition, the first results of a numerical analysis of the distribution of luminance in the passage room, carried out by Radiance, are shown. They allow to underline that a real risk of glare is present, so a more detailed analysis will be carried out in the future about this matter, since it is very important for the spread of the DLP in Architecture.

At this first phase the authors propose to cover the upper portion of the inner tube of the DLP with a highly diffusive material, named 3 M Optical Lighting Film, able to realize a more uniform distribution of light all over the work-plane, and to contribute to decrease the risk of glare.

Finally, the illuminance ratio E_{in}/E_{ext} is always less than 1% and the maximum values are obtained with direct solar radiation. It is evident that this ratio is not always a reliable reference index for the evaluation of daylight performances of the system particularly in the presence of direct solar radiation.

From this first analysis of the system, the authors can conclude that the double light pipe can be used as an efficacy device to transport daylight in underground areas particularly in wide plant area rooms, such as show-rooms, museums, and similar locations, in which it can be fully integrated as a piece of furniture or as an architectural structure.

Moreover, at night time, traditional or innovative lamps, such as OLED film applied on the external surface of the interior tube, could be added to the system. In this case, it becomes a useful natural and artificial light source.

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