Numerical and experimental analysis of light pipes' performances: comparison of the obtained results

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ABSTRACT: Light-pipes considered in this paper are tubular, linear devices which transmit daylight away from the collector installed on the roof top of the building, through multiple specular reflections which occur in the pipe itself, to a prismatic diffuser located in the room. Two 800 mm long and ϕ = 250 mm light-pipes are installed into a 4,24x3,36 m plant area room, which is the experimental apparatus utilized to effect the experimental analysis of light-pipes' performances. The results have been very useful to test the accuracy of prediction numerical methods, particularly ECOTECT and ENERGYPLUS soft-wares, which are commonly used to evaluate light-pipes' performances and as a design tool of these technological systems.
Due to accidental variables which influence real sky conditions during experimental tests, it's very difficult to compare numerical data with experimental ones, so a parallel analysis has been conducted on a reduced - scale (1:5) model of the room, tested under an artificial sky in order to realize repetitive testing-conditions. Numerical data seem to be comparable with experimental results, particularly reduced-scale ones, but discrepancy increases at great distance from the sources, probably due to internal reflections. Sensibility of both programs to this environmental factor is analysed.

Keywords: light-pipe, daylight

1. INTRODUCTION

In many cases human activities, particularly productive ones, go on in closed environments during seasons in which daylight availability is for a short time, so in a great percentage of working time artificial light must be used, but sometimes it is used instead of natural light, because traditional daylight sources, such as windows, are not able to transmit light at great distances.

Furthermore it is not unusual that artificial light is used even if natural light is available, because a common way of thinking considers it more efficient for human activities because its intensity is not time depending and does not change caused on aleatory factors. On the contrary, several scientific studies showed that natural light, when available, allows to better carry out many human activities.

This paper concerns the obtainable performances by not traditional daylight sources named "light pipes", which give daylight availability in interior spaces where windows are not present, or too small or too distant from the working area.

Light pipes are technological devices that allow the transmission of daylight into hard-to-reach inner spaces. They consist of a top collector which intercepts external luminous rays, the pipe itself which transmits light, through many successive reflections by reflective films applied on its internal surface (3M Visible Mirror for the pipes described in this work), onto a diffuser located in the room. The latter introduces light into the room and gives the desired illuminance value on the work plane.

There are several types of light pipes, varying in length, diameter, aspect ratio and constituting materials. Depending on geometric and structural characteristics, light can be transmitted away from the collector for some meters through the tube and the greater is the tube diameter, the longer is the distance that can be covered by light.

The use of numerical programs to simulate daylight penetration in interior spaces must accurately be tested because many factors influence internal distribution of light, such as external weather conditions, the source type (traditional windows, light pipes or some other technological devices) interactions between light and boundary walls of the room, that can deeply affect the amount of light coming on the work plane and its spectral characteristics. Among these factors, wall reflections are particularly remarkable, because they contribute to the amount of light flux arriving on the work plane, and their effects are difficult to simulate by the most commonly used soft-wares.

For example, ECOTECT, realized by Square One Research Company of Sidney and Welsh School of Architecture at Cardiff University, seems to overrate reflections from the walls, so that when daylight coming from a great window arrives on the work plane, calculated values of illuminace are greater than experimental ones, while, when daylight incomes from a light pipe and illuminance on the work plane is chiefly produced by direct luminous flux, calculated values are underestimated with respect to experimental ones, because reflected contribute is less important than direct one.

Many accidental factors take place during climatic variations and they influence inside penetration of the light. When daylight incomes from light pipes more of these factors are attenuated in their effects and it is possible to obtain comparable data from numerical (Ecotect) and experimental analysis, particularly in positions close to the sources with Overcast sky conditions.

Besides, EnergyPlus too seems to be sensitive to the reflected component, giving illuminance values greater than experimental ones in positions not very close to light pipes.

In order to investigate the accurateness of data obtained both by ECOTECT and ENERGYPLUS softwares the successively described experimental analysis has been conducted.

2. THE EXPERIMENTAL ANALYSIS

The experimental plant used in this work consists of a 4,24x3,36 m plant area room (Fig. 1), into which two 800 mm long and ϕ = 250 mm tubular light-pipes are installed to introduce daylight in the interior space. They are the unique daylight sources in the room, being the window obscured by an external black sheet of drawing paper (ρ = 5,5 %) and an internal grey one (ρ = 52,5 %) with the aim to simulate an underground area.

Inside the room, illuminance measures on a horizontal work plane 800 mm high on the floor have been carried out by CIE Lux-meters sensors type LSI-BSR001, range 0-25 klux, accuracy 3% of the read value, and contemporaneously external horizontal illuminance has been measured by CIE sensors type LSI-DPA 503, range 0-100 klux, tolerance 1,5 %. Data have been registered by a data-logger type LSI/BABUC-ABC, characterized by 20 inputs.

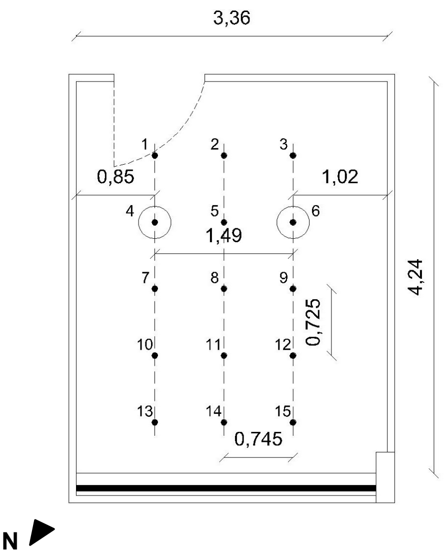

Figure 1: Plant of the room and measure positions.

Fifteen measure positions are placed on the work plane along three axes parallel to the longer side of the room.

Contemporaneously a balsa wood reduced scale model (1:5) of the room has been realized (Fig. 2). It was tested under the artificial sky of CERSIL in POLYTECHNIC University of Torino [2, 3] which is a portioned dome artificial sky able to reproduce all standard CIE sky luminance distributions, based on Tregenza model of sky. [1, 8]

The boundary walls, floor and ceiling of the model were finished off by colour painting with the same reflection factors of real scale room boundary walls. They can be considered perfectly diffusing such as real scale ones.

Table 1 illustrates reflectivity values of all boundary surfaces of the model measured by a spectral-photometer type Minolta CM-508 D.

Table 1: Measured reflectivity values in the model.

	ρ(%)	Surface (m^2)
CEILING	81,7	0,65
FLOOR	55,5	0,65
DOOR	3,5	0,087
BOUNDARY WALLS	64	1,53

Real scale and reduced scale experimental tests were conducted in Winter Overcast conditions with the aim to get data at least affected by accidental factors.

Particularly a CIE OVERCAST sky on December the 21st at twelve o'clock a.m. was used into the artificial sky. In this configuration the measured external horizontal illuminance is 6431 lux. More, real scale experimental measures were carried out in winter climatic conditions between eleven o'clock a.m. and one o'clock p.m., with an external illuminance variable between 6500 and 11500 lux. In Fig. 2 the room reduced scale model tested under the artificial sky is showed.

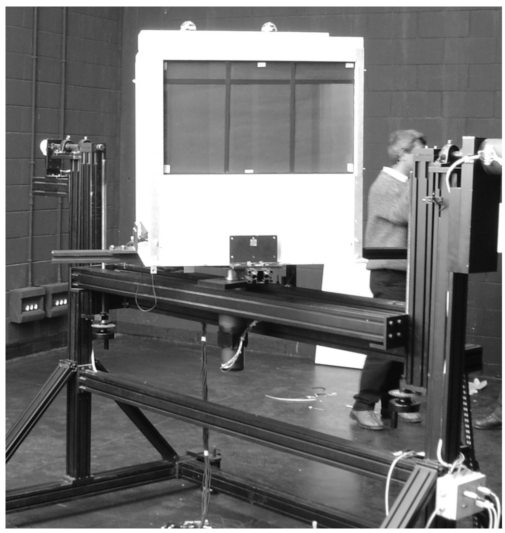

Figure 2: Reduced scale model of the room.

As the authors demonstrated in a previous work [10], there usually is a good agreement between real scale experimental results and corresponding reduced scale ones when daylight sources are light pipes. In this case we note that a good accord is verified everywhere except just under the pipes, where reduced scale data exceed real scale average values of about 20% (Fig. 3).

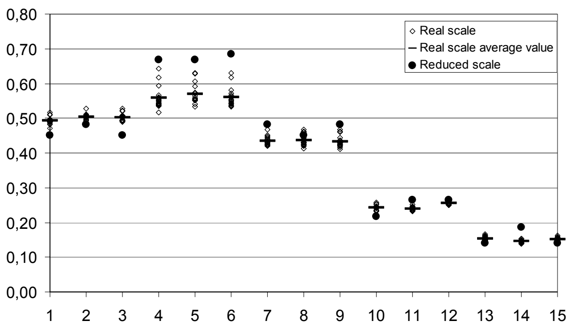

Figure 3: Comparison between experimental data and reduced scale ones in winter overcast sky conditions.

For the feature of repeatability, reduced scale data, which are not affected by accidental climatic events, are chosen for the comparison with numerical results.

3. COMPARISON BETWEEN NUMERICAL AND EXPERIMENTAL DATA

In fig. 4 the comparison between experimental and numerical data obtained by EnergyPlus is shown. The corresponding numerical values are explained in Table 2.

EnergyPlus results seem in good agreement with experimental ones, particularly in positions close to the sources. Discrepancy increases just under the light - pipes and at great distance from them.

Assuming a sky clearness (SC) equal to 0,15, which correspond to a winter overcast sky, the calculated external horizontal illuminance is 6768 lux, very similar to the measured value under the artificial sky in analogue conditions, 6431 lux.

In this configuration a good accord is noted in points 1-2-3 and 7-8-9, which are located 0,725 m from the source axis. In these points an error minus than 20 % occurs, while in positions more than 1,5 m far-away from light pipes, illuminance values by EnergyPlus exceed experimental ones from 23 to 70 %.

At the same time, just under the sources there is a disagreement between numerical and experimental data: EnergyPlus gives rise data about 30-35 % minus than experimental ones. Considering that experimental reduced scale values are overrated with respect to real scale ones under the light pipes' axis (e. g. Fig. 3), the entity of this error is to be considered less relevant and the two series of data are comparable.

Increasing the value of sky clearness from 0,15 to 0,2, which corresponds to a calculated exterior horizontal illuminance equal to 8749 lux, a very light difference is noted in terms of E_{in}/E_{out} values, but generally a better agreement is obtained in correspondence of SC = 0,15.

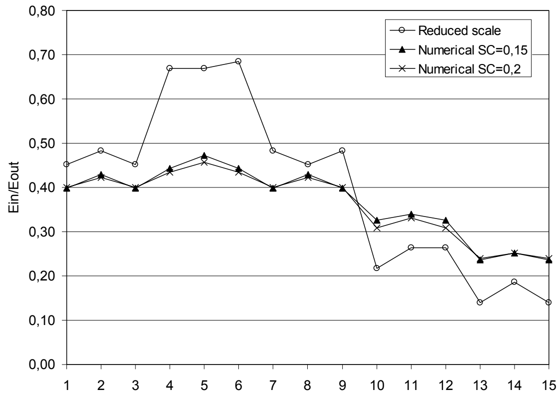

Figure 4: Comparison between reduced scale experimental data and numerical ones (EnergyPlus).

Table 2: Reduced scale experimental and EnergyPlus data.

Position	Exp. Results		EnergyPlus SC=0,15		EnergyPlus SC=0,20	
	E_{in} (lux)	E_{in}/E_{out} (%)	E_{in} (lux)	E_{in}/E_{out} (%)	E_{in} (lux)	E_{in}/E_{out} (%)
1	29	0,45	27	0,40	35	0,40
2	31	0,48	29	0,43	37	0,42
3	29	0,45	27	0,40	35	0,40
4	43	0,67	30	0,44	38	0,43
5	43	0,67	32	0,47	40	0,46
6	44	0,68	30	0,44	38	0,43
7	31	0,48	27	0,40	35	0,40
8	29	0,45	29	0,43	37	0,42
9	31	0,48	27	0,40	35	0,40
10	14	0,22	22	0,33	27	0,31
11	17	0,26	23	0,34	29	0,33
12	17	0,26	22	0,33	27	0,31
13	9	0,14	16	0,24	21	0,24
14	12	0,19	17	0,24	22	0,25
15	9	0,14	16	0,24	21	0,24
E_{out} (lux)	6431		6768		8749	

Basing on these results, it's possible to suppose that numerical analysis overestimates reflected contribution to illuminance that is prevalent in positions distant from the sources.

So new tests were effected in which the boundary walls of the room were covered by a black sheet of drawing paper (ρ = 5,5 %) with the aim to reduce the influence of reflected luminous flux on illuminance on the work plane.

From this point on, we shall identify with the term "black walls" the covered walls by black paper, and with "light walls" those uncovered.

In Fig. 5 and Table 3 the results of this analysis are showed, considering EnergyPlus data in the same above mentioned two configurations (sky clearness equal to 0,15 and 0,20) compared with experimental ones, with all boundary walls covered by a black sheet of drawing paper.

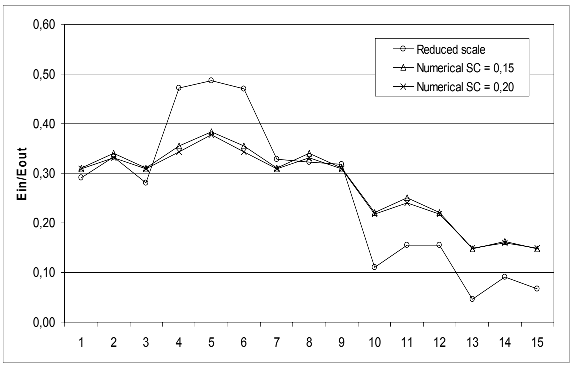

Figure 5: Comparison between reduced scale experimental data and numerical ones (EnergyPlus) - Black drawing paper on the walls.

Table 3: Reduced scale experimental and EnergyPlus data – Black drawing paper on the walls.

Position	Exp. Results		Energy-plus SC=0,15		Energy-plus SC=0,20	
	E_{in} (lux)	E_{in}/E_{out} (%)	E_{in} (lux)	E_{in}/E_{out} (%)	E_{in} (lux)	E_{in}/E_{out} (%)
1	19	0,29	21	0,31	27	0,31
2	21	0,33	23	0,34	39	0,33
3	18	0,28	21	0,31	27	0,31
4	30	0,47	24	0,35	30	0,34
5	31	0,49	26	0,38	33	0,38
6	30	0,47	24	0,35	30	0,34
7	21	0,33	21	0,31	27	0,38
8	21	0,32	23	0,34	29	0,34
9	20	0,32	21	0,31	27	0,31
10	7	0,11	15	0,22	19	0,22
11	10	0,15	17	0,25	21	0,24
12	10	0,15	15	0,22	19	0,22
13	3	0,05	10	0,15	13	0,15
14	6	0,09	11	0,16	14	0,16
15	4	0,07	10	0,15	13	0,15
E_{out} (lux)	6431		6768		8749	

A better agreement is obtained in positions 1, 2, 3 and 7, 8, 9, in which a maximum error of about 10 % occurs, but in positions 10÷15 a discrepancy similar to the previous case takes place.

The authors verified that a similar trend is obtained too by Energy plus soft-ware in other configurations, such as Winter and Summer Clear sky.

If we estimate the difference between data in the above cited two configurations: light walls and black walls, we note that a smaller divergence takes place if values are calculated by soft-ware, rather than measured into the scale model.

So we deduce that reflectivity is less influent in numerical analysis than in experimental one and probably it is not the cause of data overestimation at great distances from light pipes.

Most likely the used algorithm is responsible of this divergence. This is strengthened by the fact that the same trend is realized in various configurations of sky, as already underlined, even if the more concentrated light distribution just under the pipes, obtained with reduced scale model, is partially due to a parallax error which occurs in the artificial sky.

In fact an overestimation of reduced scale data is obtained with respect to experimental real scale ones. (e. g. Fig. 3)

Finally, we can say that Energy – plus algorithms furnish sufficiently precise results in light pipes simulation in points close to the source axis, while significant errors take place far-away from them (more than 1,5 m).

The same analysis has been conducted through the soft-ware ECOTECT in the two above considered configurations.

In Figs. 6 and 7 a grey scale picture of the estimated illuminances is shown.

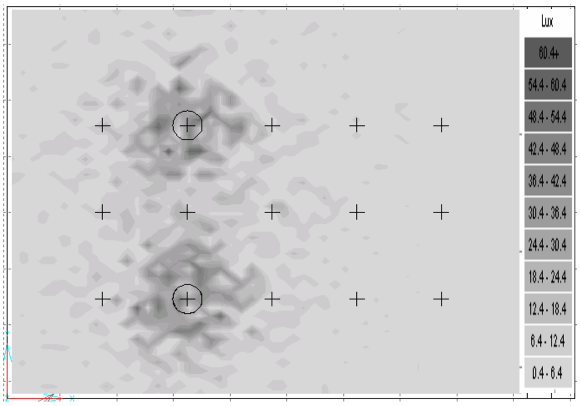

Figure 6: Numerical analysis (ECOTECT) – Overcast sky, E_{ext} = 6431 lux – light walls.

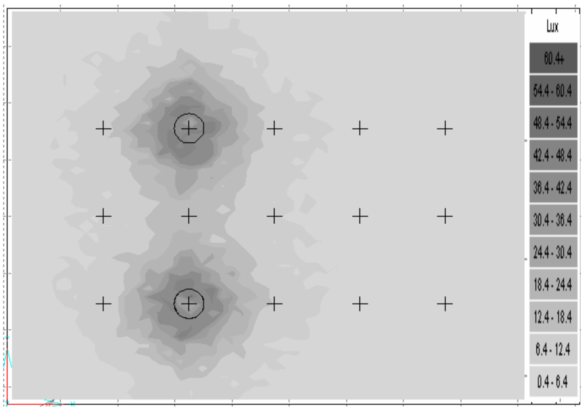

Figure 7: Numerical analysis (ECOTECT) – Overcast sky, E_{ext} = 6431 lux – black walls.

Table 4: Ecotect data with light and black walls.

Position	Ecotect light walls		Ecotect black walls		Error %
	E_{in} (lux)	E_{in}/E_{out} (%)	E_{in} (lux)	E_{in}/E_{out} (%)	
1	21	0,33	14	0,21	33,3
2	23	0,36	12	0,19	47,8
3	23	0,35	17	0,26	26,1
4	36	0,56	37	0,58	2,8
5	36	0,56	26	0,40	27,8
6	39	0,60	36	0,56	7,7
7	19	0,30	14	0,22	26,3
8	21	0,33	11	0,17	47,6
9	19	0,30	15	0,23	21,0
10	10	0,15	7	0,11	30,0
11	8	0,12	6	0,09	25,0
12	8	0,12	9	0,14	12,5
13	5	0,08	3	0,04	-
14	3	0,05	3	0,04	-
15	3	0,05	2	0,03	-

In Table 4 the numerical values are reported, in which the difference is calculated between illuminances in the two above mentioned configurations. The percentage error respect to “light walls” illuminances is determined in order to evaluate the influence of reflected contribute to light distribution. For $E_{in} \leq 5$ lux it’s omitted since it seems not representative, for too small illuminance is realized in both cases.

A more uniform daylight distribution is obtained with light boundary walls, so in positions 1-2-3 and 7-8-9 a significant increase of illuminance is realised. More, in positions 4 and 6, just under the light pipes, a quite perfect correspondence of values is obtained, while in position 5, in the middle between the pipes, a great difference is noted.

Being this point equally influenced by both the sources, we should have expected the effect of superposition of the two direct contributions being prevalent with respect to the reflected component. On the contrary a relevant difference is noted in the two configurations (light and black walls) so a significant reflected contribution takes place.

These results confirm the idea that ECOTECT overestimates reflected contribution to illuminance.

In fact, if we compare numerical data by Ecotect with experimental ones in the configuration with light boundary walls (Fig. 8), we note quite a uniform underestimation of numerical illuminance values in all measure positions, while the arrangement with black walls, in which reflected component is at least influent (Fig. 9), an underrate of numerical data is obtained with respect to experimental ones, even though, in some positions, a very good correspondence between numerical and experimental results is obtained.

Finally, it is possible to say that numerical analysis by Ecotect gives rise better results if the reflected component is less relevant than direct one.

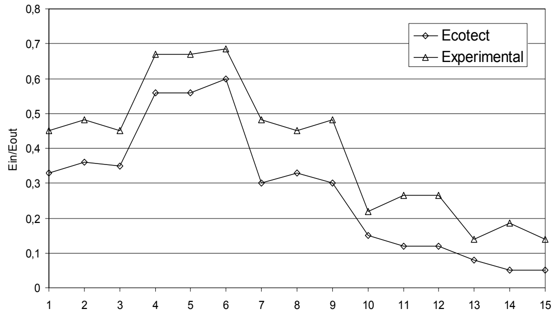

Figure 8: Comparison between reduced scale experimental data and numerical ones (Ecotect) – Light walls.

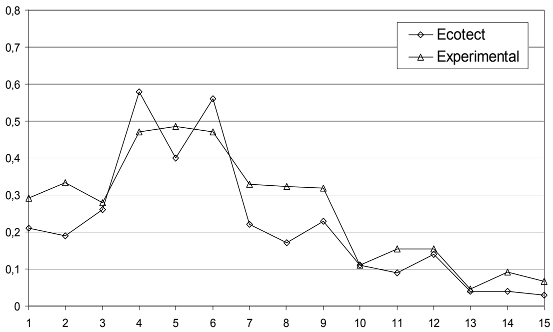

Figure 9: Comparison between reduced scale experimental data and numerical ones (Ecotect) - Black walls.

4. CONCLUSION

This paper presents the results of a numerical and experimental analysis carried out on technological devices called “light-pipes” able to introduce daylight captured by a collector on the roof top of the building into hard to reach internal rooms.

The experimental analysis has been conducted on a reduced scale model (1:5) tested under an artificial sky and in the corresponding real scale room in overcast sky conditions. Reduced scale data have been used for the comparison with numerical ones for their feature of repeatability.

Numerical analysis has been conducted by two of the most commonly used prediction numerical soft-wares, Ecotect and EnergyPlus.

The comparison of data allows to underline that both soft-wares gives results comparable to experimental ones, but EnergyPlus data are underrated close to the pipes and overrated away from them, while numerical values obtained by Ecotect are underestimated in all measure positions.

The reflected contribution seems to be relevant in affecting these discrepancies particularly with Ecotect, while, probably the algorithms used by EnergyPlus are mainly responsible of the differences.

In general we judge acceptable the results by both the considered soft-wares in order to evaluate the obtainable performances by light-pipes.

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