Light Pipes Performance Prediction: inter model and experimental confrontation on vertical circular light-guides

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Light pipes performance prediction: inter model and experimental confrontation

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Abstract

The light pipes are innovative devices able to transport and distribute natural light without heat transfer in dark rooms, different from traditional openings, and minimize the loss of light. It is about collecting, concentrating and deflecting sunlight with a dome placed on the roof - called a collector. The latter is then carried through a tube with highly reflective surfaces, which transports the light to where it is needed. A distribution system that includes extractor devices and diffusers extracts the light from the pipe and spreads the light uniformly across the space. This type of device provides significant energy savings by improving the autonomy in artificial lighting. There is a lot of natural lighting applications able to predict the behavior of light in a room through a traditional opening. Only few of them are able to model complex systems such as daylight guidance systems. Added to this, they seem to provide disparate and inconsistent results with respect to the actual performance of light pipes. The purpose of this publication is to present the approach undertaken and the results obtained to highlight the problem. To do this, a survey of the different programs has been carried out internationally to model tubular devices. Then, an inter-software comparative analysis was implemented for some of the applications listed. In order to assess the accuracy of numerical results, the results of an experiment - 1:1 scale and in real weather conditions - were used as references to evaluate the chosen applications. We saw that the various selected programs tend to overestimate or underestimate the real phenomenon. The use of an experimental database permitted to put forward the most efficient applications. These results support the future goal to develop a new model. Future prospects of our study that can emerge are mainly based on the introduction of a new model for predicting the performance of light pipes and its integration in two software products developed within laboratory: CODYRUN (a multi-zone software integrating thermal building simulation, airflow transfers, lighting and pollutants) and HEMERA (a daylighting analysis software).

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1. Introduction

A light pipe refers to an overhead opening that allows daylight to pass through a pipe (often mistakenly called skylight). This system is made of a dome placed on the roof, a highly reflective tube walls (greater than 99%) and a diffuser. The dome should be shockproof and UV resistant. It protects the tube from dust and rain. The device can be coupled with an optical device to capture and redirect the sky radiation inside the tube. Solatube in Australia patented this concept in 1986. The light pipes are often called tubular skylight or lumiduc.

The light pipes are generally required when the area to be illuminated is at a distance of over 10 meters from the wall openings. They permit to overcome problems related to direct illumination (glare, sunspot) by providing a diffused light (in the case of a Lambertian diffuser). Thus, depending on the configuration and requirements in lighting level, several processes of light pipe exist. We can note the best known: for example, pipes using diffusion lenses, prismatic pipes, solid core systems and the Mirrored Light Pipe (MLP) [1]. The tube can be vertical or horizontal, with one or several diffusers. The pipe can be straight or have bends. In the case of our study, we shall focus on one of the most commonly used methods in a standard configuration to be integrated into a building: a straight light pipe - type MLP - with a single diffuser.

The work described in this publication is part of the research related to the study of complex lighting systems. The light pipes are at the center of an issue related to modeling. Many programs permit to model them without providing comparable results. In this context, two objectives can be counted. Firstly, it is to identify all the applications to take into account the tubular lighting systems, and to select some of them according to certain well-defined criteria. Secondly, the selected programs are subject to a comparative analysis on the basis of experimental results obtained by Paroncini in Ancona (Italy) in 2006.

2. Software Inventory

2.1. Methodology

We are conducting an internationally-based inventory on the work of LBNL laboratory in California [2] and on the contribution of Fakra [3] in order to list, in the most comprehensive manner possible, the dynamic simulation software in daylighting by considering the tubular complex systems.

To do so, we can distinguish two types of lighting simulation applications: first, those known as commercial ones, used in engineering offices (most of these programs have not been subject to validation) and second, those regarded as search applications. The first ones are used to quickly evaluate the phenomena, more oriented towards the scientific aspect of the phenomenon, and therefore much closer to the reality that we want to define it. In addition, we can distinguish commercial and free applications. We also tried to draw – except if the information is not given - the list of models used in each program. This inventory is provided in the appendix of this document. Table 1 summarizes the various programs that meet the criteria.

Among the 38 lighting simulation software listed, only 3 are used to model the tubular devices. For our comparative study, we can choose EnergyPlus and HOLIGILM because they are free of charge. In addition, EnergyPlus via Radiance is an internationally recognized program that has already undergone several validation tests. HOLIGILM is dedicated to the modeling of the light pipe software.

Table 1. Synthesis software inventory - Criterion: modeling light pipes

Software	Mode of Use	Reference	Models used
ECOTECT	Commercial software	http://usa.autodesk.com/ecotect-analysis (U.S.A.)	(Radiosity, Ray-tracing, Lumen, Split-Flux)
EnergyPlus	Free software	http://www.radiance-online.org (U.S.A)	Legacy Open Studio (using Radiance)
			Radiosity, Ray-tracing
HOLIGILM	Free software	http://www.HOLIGILM.info (Slovaquie)	Monte-Carlo method combined with ray-tracing

2.2. Overview of EnergyPlus

EnergyPlus is a new generation tool developed from the BLAST and DOE-2 tools. It integrates innovative simulation capabilities such as the use of time step under one hour. EnergyPlus has been evaluated in the context of BESTests tests - developed by the International Agency of Energy (IAE). Associated with Legacy OpenStudio, EnergyPlus uses the calculation engine Radiance via Google SketchUp to model the photometric ambiences.

Radiance is a suite of tools - originally written by Greg Ward - to perform lighting simulation. It includes a renderer as well as many other tools to measure the simulated light levels. More precisely, it uses ray tracing to perform all lighting calculations, when it is accelerated by the use of an octree data structure. Radiance pioneered the concept of high dynamic range imaging.

Daylight factors are calculated to determine the levels of illumination at each point of an area. The part of the direct illumination is measured from the ray tracing method. The proportion of diffuse illumination, resulted from the reflections inside the area, is calculated from the split-flux method. EnergyPlus model improves the DOE-2 by using four types of sky [4] against only two in DOE-2. In addition, the DF are calculated on an hourly time [5]. Thanks to its simulation and modeling abilities, Radiance can simulate the light pipes.

2.3. Overview of HOLIGILM

HOLIGILM is a program able to compute the illumination of a rectangular room with light pipe as a light source. The name HOLIGILM is an acronym for HOllow LIght Guide Interior iLlumination Method.

This program does not use a weather file, but offers different types of standardized skies by the CIE (15 different types of sky, with only 10 available in the PRO version HOLIGILM) sky. The maximum number of light pipe is limited to 10. The transparency of the cupola dome forming the collector can be adjusted. Similarly, the properties (diameter, length and reflectance) of the circular tube can be changed. Three types of diffusers can be associated with light pipe: diffuse, transparent or combined with properties that can be adjusted.

The modeling is based on an analytical solution described by its author, Kocifaj in [6]. The downside of HOLIGILM is that it does not take into account the weather files of the place of study, and it is only based on theoretical calculations of the solar position. In addition, it only simulates straight and circular pipe equipped with a Lambertian or transparent diffuser.

3. Description and results of the experimental case study

3.1. Description of the study

In 2007, Paroncini conducted an experimental sequence of the light pipes, and the main objective was to highlight their efficiency. To do so, the study was set up near the campus of Monte Dago (Ancona, Italy). A light pipe was installed in the center of the roof of the experimental cell, measuring 3.2 m by 2.6 m with a height of 3m [7].

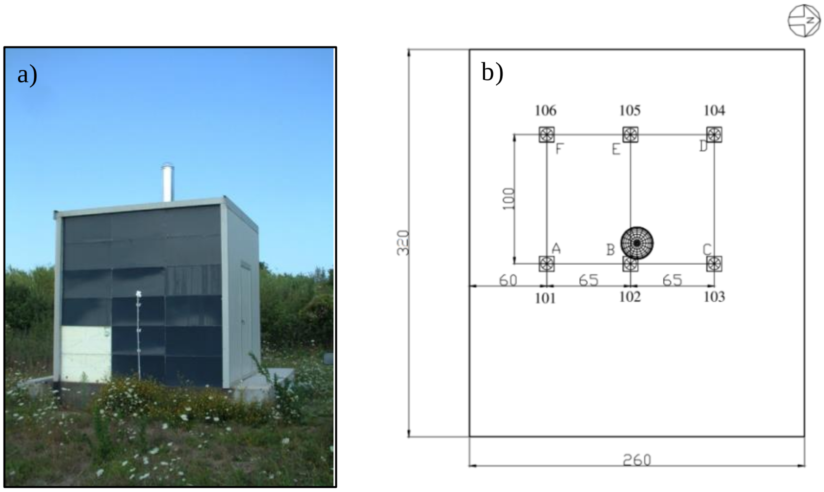

Fig. 1. (a) Test room (b) Sketch of the distribution of the sensors [7]

The walls are oriented North, East and West, and the ceiling panels are prefabricated with a reflection coefficient of 68%. The South wall has a reflectance of about 55%, while the floor is 45.6%.

The room is equipped with six sensors measuring the light levels. These sensors are positioned on tripods with a height of 0.80 m, corresponding to the height of a working plan. A plan is also provided in order to identify the names of these light meters. The sensors are indicated through alphabetic letters and through numerical codes (Figure 1). A sensor located outside is also used to measure the outside illuminance.

The light pipe has a diameter of 25 cm, with a 1m-length tube to achieve a ratio aspect of 4 (length / diameter).

The tube is finished by an aluminum multi-layer film with high reflectance (over 99% as reported in the specifications of the producer [8]).

The surface of the diffuser has a convex shape enabling the light to spread in the room in an isotropic way (figure 2).

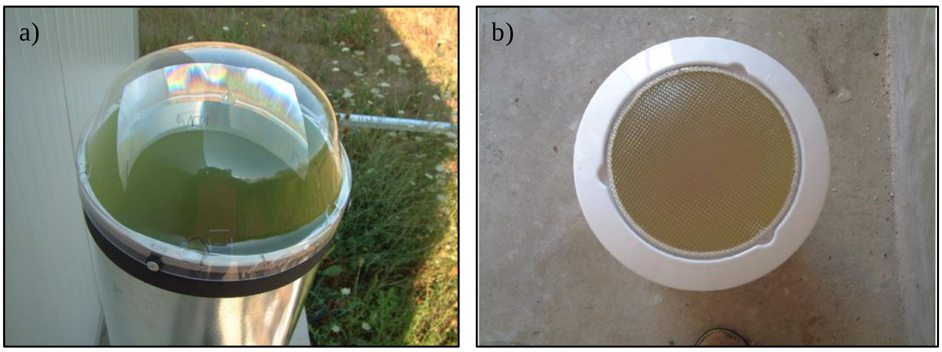

Fig. 2. The external dome with the optical device and Diffuser device [7]

3.2. Results of the study

Special fonts, such as fonts used in the Far East (Japanese, Chinese, Korean, etc.) may cause problems during processing.

The results of Paroncini's experimentation are presented in different forms. He show curves presenting the evolution of the exterior and the interior lighting during the day. Paroncini also presents the ratios of internal average illumination on the outside global illumination, and the light distribution inside.

The first presentation mode gradually provides effective control on the evolution of the illumination. However, to make a comparison with the software results, the external conditions (i.e. external illumination) must be the same. Indeed, in EnergyPlus, a downloadable weather file on the database of the DOE (*http://apps1.eere.energy.gov*) must also be provided. Unfortunately, the weather files were not necessarily measured during the same year of Paroncini's experimentation. Thus, we are not sure we have the same weather conditions. For HOLIGILM, the problem is that this software does not use measured weather data, but it is based on the skies as defined by the CIE with a calculated sun path.

All these distinctions can make experimental results and software differ from one another. To overcome this problem, we use the concept of DPF (Daylight Penetration Factor), developed by Zhang in 2002 [9]. This factor is a dimensionless ratio of the interior illuminance situated at a given point on the outdoor global illumination.

The DPF is a factor that is similar to daylight factor because it determines the illumination inside the room through a common concept:

$$DPF_{(x,y,z)} = \frac{E_{\mathrm{int}(x,y,z)}}{E_{ext}} \tag{1}$$

Like the DF, this model is functional in any type of sky.

By using this concept, we can compare similar results, as they should not vary compared to climatic conditions (the level of external illumination is proportional to the level of interior illumination, which leads us to obtain the same ratio).

Given that HOLIGILM is limited to the use of sky type, we selected three days' measurement on Paroncini's study. These days are in clear sky condition.

4. Simulation parameters

4.1. EnergyPlus

In EnergyPlus, the dome, the tube and the diffuser must be of the same size (within ± 2%) to ensure the smooth running of the simulation [10].

EnergyPlus simplifies the procedure by treating the dome and the diffuser as special glazed surfaces. Together, the dome and the diffuser become "receiver" and "transmitter", i.e. the radiation entering the dome eventually leave the diffuser. The tube is simulated by a different calculation module.

The general methodology is to create a transition zone containing the light pipe.

For our case study, we are presenting in Table 2, the parameters of our simulation as well as a view of the model created in Legacy OpenStudio (Figure 5).

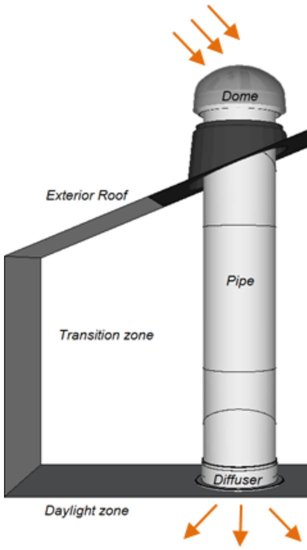

Fig. 3. Modeling light pipes in EnergyPlus

Table 2. Simulation parameters in EnergyPlus

Localization	*Ancona* *Latitude : 43,62 N* *Longitude : 13,52 E* *Time zone : +1* *Altitude : 105 m*	Weather file	*ITA_Ancona.161910_IGDG.epw*
Building	*Length : 3,2 m* *Wide : 2,6 m* *Height : 3 m* *Reflectance :* • *North/East/West walls : 68%* • *Ceiling : 68%* • *South wall : 55%* • *Floor : 45,6%*	Dome and diffuser	*Rectangular (25x25cm)* *Transmittance of the dome : 92%* *Transmittance of the diffuser : 75% (Lambertien)*
Working-plane	*Height : 0,80 m*	Pipe	*Reflectance : 99,5%* [8] *Length : 1m* *Diameter : 0,25m* *Position : center of the room*

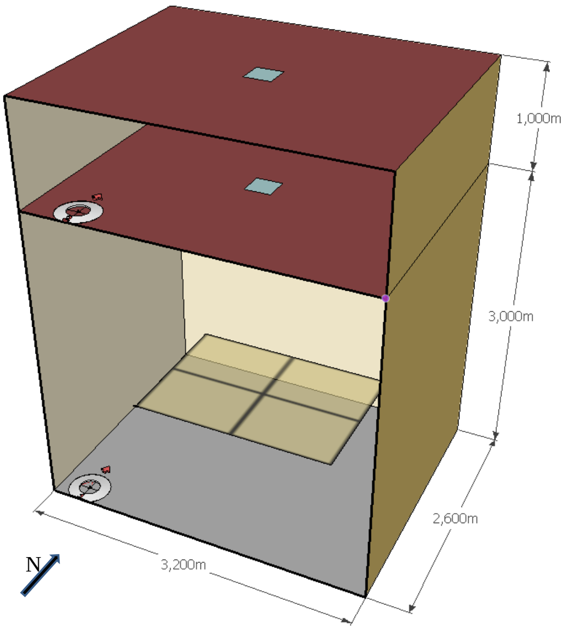

Fig. 4. Case study modeled in EnergyPlus-Legacy Open Studio

4.2. HOLIGILM

In HOLIGILM, the simulation is easier thanks to its user-friendly interface. The weather conditions are fixed. They depend on the type of sky chosen for the simulation, as well as on the location of the study.

For our case study, we are presenting in Table 3 the parameters of the simulation.

Table 3. Simulation parameters in Holigilm

Localization	*Ancona* *Latitude : 43,62 N* *Longitude : 13,52 E* *Time zone : +1*	Type of sky	*CIE Clear Countryside*
Building	*Length : 3,2 m* *Wide : 2,6 m* *Height : 3 m*	Dome and diffuser	*Transmittance of the dome : 92%* *Transmittance of the diffuser : 75% (Lambertien)*
	Reflectance : • *North/East/West walls : 68%* • *Ceiling : 68%* • *South wall : 55%* • *Floor : 45,6%*	Pipe	*Reflectance : 99,5%* [8] *Length : 1m* *Diameter : 0,25m* *Position : center of the room*

5. Results and discussion

5.1. Comparison of the illumination

The comparative study using the "indoor illuminance" parameter cannot be considered as being objective if the physical models - specific to each software - are studied.

If we are a simple user (without specific knowledge), we use only the capabilities of software to simulate the same building. Thus, the weather data will not be exactly the same from one program to another, but remain comparable with respect to the standard use.

Indeed, EnergyPlus uses the weather data collected / calculated by ASHRAE (Climate Design Data 2009 ASHRAE Handbook) in a different year from the year of Paroncini’s measurement. This element will not cause any difference in the sun path, but on the outside light level, varies depending on the position of the measurement (depending on the albedo of the ground, the presence or absence of clouds, and the presence of masks).

HOLIGILM uses sky types, which does not take into account the particular area.

We are performing this analysis in an attempt to get closer to the external experimental data using weather data and a type of sky close to reality.

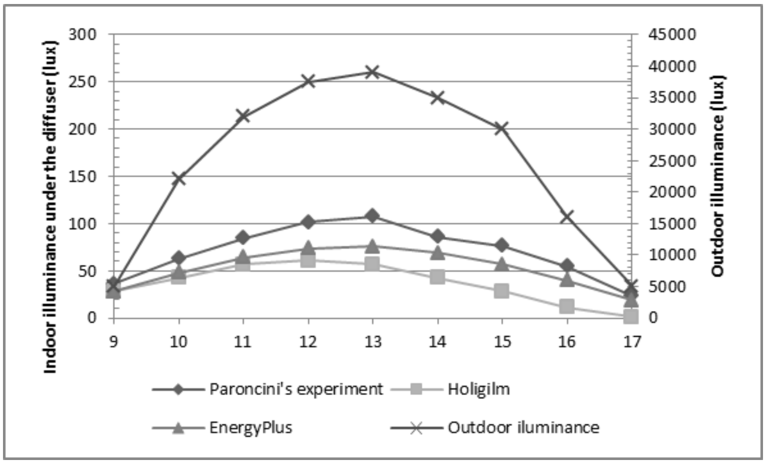

Fig. 5. External and internal illuminance at sensor B during 19 February 2006

The simulations on the winter day of February19, clear sky, are offering disparate results (figure 5). The time that we get the maximum illumination under the diffuser is the same as for the experimentation and EnergyPlus (13:00). HOLIGILM has an offset of one hour (12:00). In addition, the values reached by the two programs - on the measurement interval - show that the illumination under the diffuser is significantly lower than the values measured by Paroncini. Thus, we can note a maximum indoor illuminance of 76 lux for EnergyPlus, compared to 61 lux HOLIGILM while Paroncini detects a value of 107 lux. EnergyPlus seems to follow the trend of the experimental curve. The all day long average illuminance of the working plane obtained by experimentation amounts to 63.3 lux. EnergyPlus accounts for an average of 43.8 lux compared to 30.8 lux for HOLIGILM.

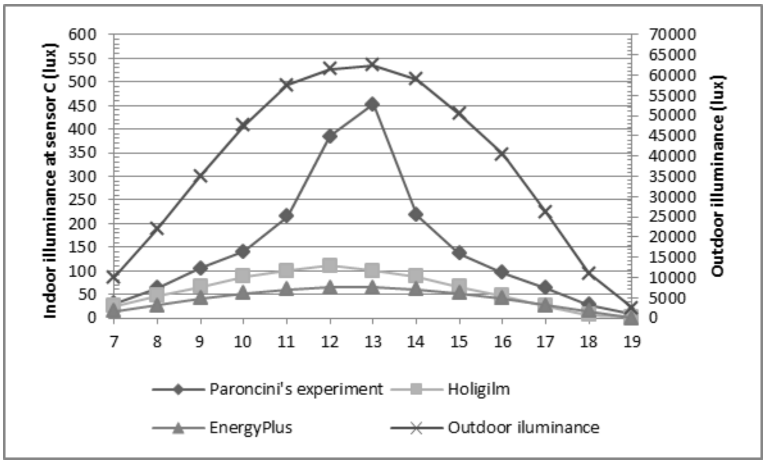

Fig. 6. External and internal illuminance at sensor C during 27 April 2006

During springtime, the results between the experimentation and the simulation are growing (see figure 6). We are choosing to make our comparative analysis on the values measured by sensor C where the maximum illumination reached is of 455 lux.

The simulation performed on the day of April 27, shows a gap on the maximum illumination reached: it is nearly 273 lux for HOLIGILM and 320 lux for EnergyPlus. A particular increase of the illumination is carried out according to the experimental data for the 11:00-02:00 interval, which is not transcribed by software simulations.

The average illumination measured on the working-plane throughout the day amounts to 147 lux while we get 56 lux for HOLIGILM and 38 lux for EnergyPlus.

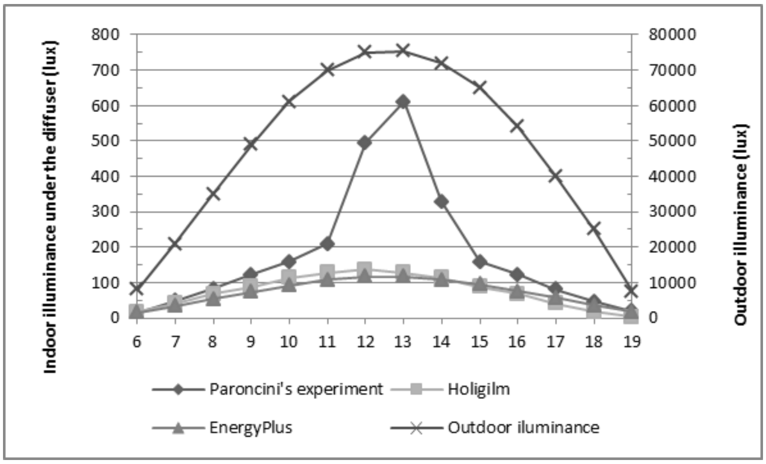

Fig. 7. External and internal illuminance at sensor B during June 27, 2006

In summer time, the simulation results are completely different from the experimental data (figure 7). Paroncini notes a maximum illumination of 617 lux at sensor B while EnergyPlus announces 116 lux, and HOLIGILM, 136 lux. The evolution of the illumination during the day is not the same as transcribed by the results of the two programs. The average illuminance on the working plane, measured throughout the day, reaches 152 lux. In the simulation, we obtained an average of 64 lux for HOLIGILM and of 59 lux for EnergyPlus.

We also want to show the results for the measurement points close to the walls of the room. We are choosing sensor D located near the corner of the room. We are making a comparison on April 27, 2006.

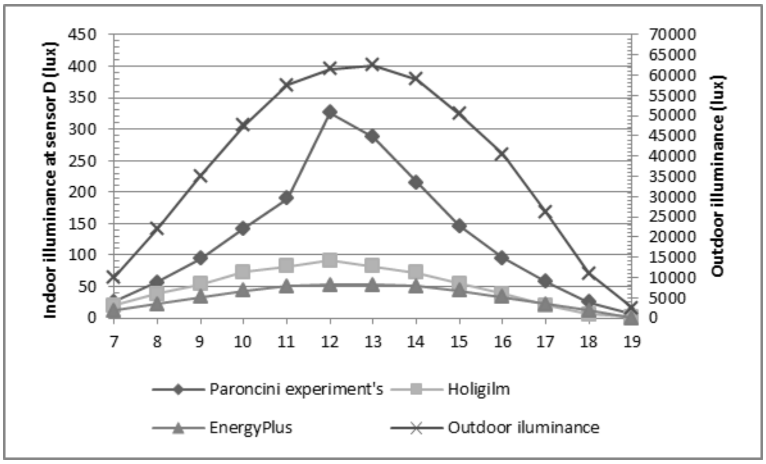

Fig. 8. External and internal illuminance at sensor D during April 27, 2006

The conclusion remains the same: the applications offer results in total disagreement with the experimental results (figure 8). We can note a maximum deviation of 235 lux at noon for HOLIGILM compared to 274 lux for EnergyPlus. The results obtained for the comparison, with the illumination in the room at different positions, show that HOLIGILM and EnergyPlus do not reach the values obtained by Paroncini's measurements. As a simple user, that is to say, by using the input provided by these two software settings (EPW files for EnergyPlus; Type of sky for HOLIGILM), we will never be able to achieve and transcribe the real phenomenon of light transmission through a light pipe.

5.2. Comparison of DPFs

As mentioned previously, the DPF being a dimensionless ratio, we can get more objectivity in the results from external weather data. We are making a new series of comparison considering the DPF achieved under the diffuser and a point near the walls (sensor D).

The simulation results show very low amplitude of variation compared to the DPF reached in the experimentation (figure 9). The maximum DPF reached in wintertime stands at 0.73% in the morning, which is due, according to Paroncini, to the presence of a lens in the dome - aiming to improve the capture of light when the sun altitude is low. We can obtain an average DPF on the working plane throughout the day of 0.31% for the experimentation, compared to 0.09% for HOLIGILM and 0.28% for EnergyPlus.

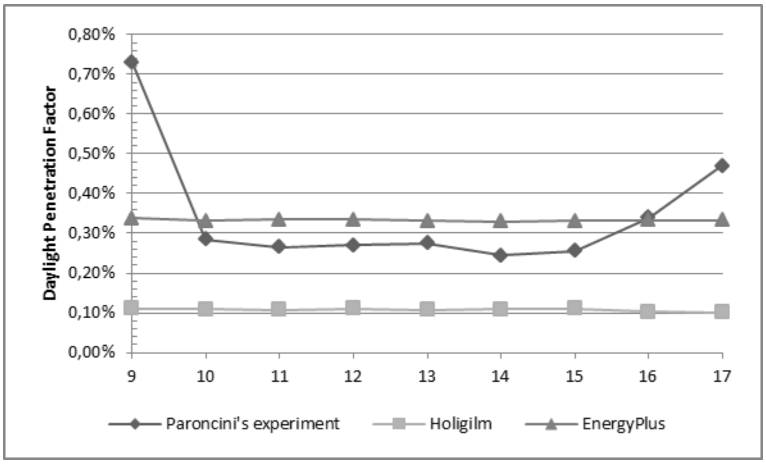

Fig. 9. Daylight Penetration Factor under the diffuser (sensor B) during February 19, 2006

In springtime, the data from simulations with EnergyPlus tend to follow the values measured experimentally in the early morning and afternoon (figure 10). From 11:00 AM to 02:00 PM, the difference between the results grows, because EnergyPlus not transcribed the phenomenon observed in the experiments. HOLIGILM remains still far from the values reported by Paroncini. The maximum DPF reached at sensor B equals to 0.72% for the experimentation. EnergyPlus achieved a maximum of 0.30% and HOLIGILM, 0.11%.

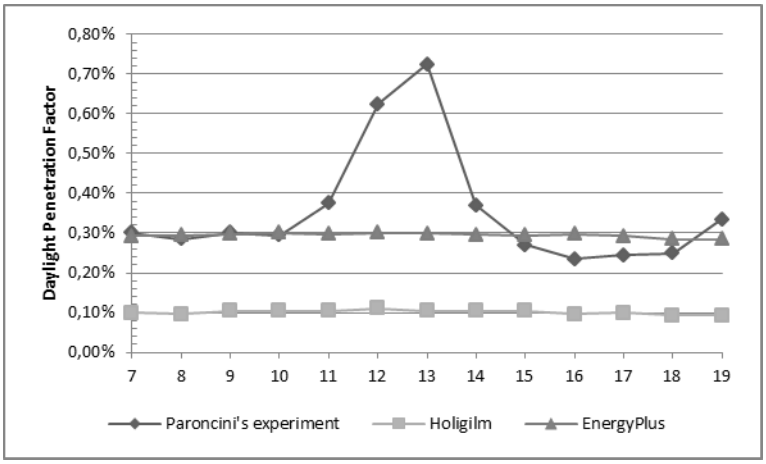

Fig. 10. Daylight Penetration Factor at sensor C (April 27, 2006)

Throughout the day, on the working plane, the average DPF from the experiment is 0.36%, compared to 0.09% for HOLIGILM, and 0.28% for EnergyPlus.

At last, in summer time, June 27, 2006, the maximum DPF obtained by simulation is 0.34% for EnergyPlus, and 0.12% for HOLIGILM (figure 11). The experimental maximum DPF is 0.81%, i.e. a 0.46% difference with the results of EnergyPlus, and 0.69% for those of HOLIGILM. The two programs do not follow the evolution of the experimental DPF. On the whole working plane, the average DPF obtained by simulation reaches 0.28% for EnergyPlus, 0.10% for HOLIGILM compared to 0.29% for Paroncini's results.

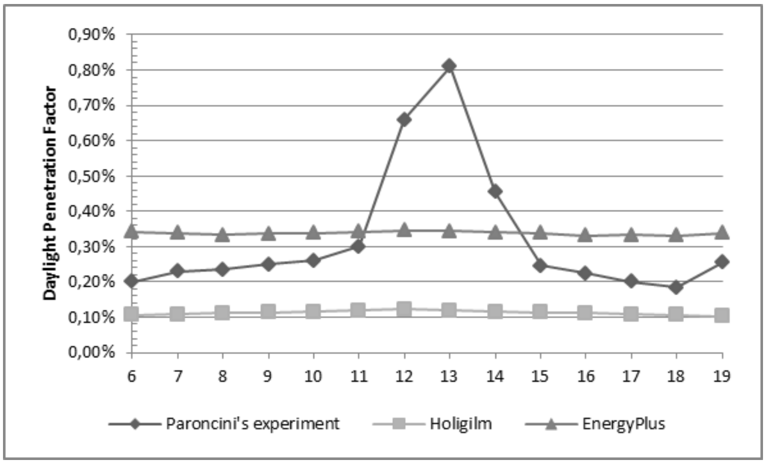

Fig. 11. Daylight Penetration Factor under the diffuser (June 27, 2006)

The results concerning HOLIGILM do not change from one season to another, remaining approximately the same.

EnergyPlus offers a bit more conclusive results in springtime by approaching the experimental values in the early morning and in the afternoon. On the average data DPF results, EnergyPlus offers results close to the experimental values.

The parameters that can justify these important differences are:

- Holigilm: This software only takes into account the types of sky, and not the weather file, which let it away from the real weather conditions. In addition, it does not provide for the parameters related to the study such as the reflectance of the indoor area or the height of the working-plane.
- EnergyPlus: it does not take into account the specific parameters of the dome and the diffuser, which can be simplified by considering them as a single horizontal glazing.

Note that, in 2008, Paroncini used approximately the same methodology to compare results from experimentation and simulation [11].

6. Conclusion and Perspectives

In this paper, we were able to identify all the applications able to simulate the tubular devices such as light pipes. In this work, we were also able to select two programs that we have submitted to a comparative analysis. HOLIGILM is a software dedicated to the simulation of light pipes. EnergyPlus is a software that provides high possibility of simulation and it is internationally recognized. To carry out this comparison, we selected a case of experimental studies in literature. The experiment conducted by Paroncini in 2006 allowed us to see the consistencies of these programs' results confronted to experimental data. This work allowed us to see the limitations of existing applications and to highlight the following problem: is it possible to find an inside lighting numerical simulation software (natural and artificial), which can be at the same time user-friendly and accurate in the calculations and, which will satisfy both the research area and the professionals from the field?

The observation of this study supports the objective of the research initiated in the laboratory PIMENT. An experimentation is in progress, the data can be used to confirm the results of this study - based on a light pipe with an aspect ratio of 6.

The main objective of the research paper is to create a new model to predict the behavior of the light pipe based on additional parameters than to those used in current models. Then, this model will be integrated into two numerical simulations programs: CODYRUN and HEMERA. CODYRUN is a multi-zone software integrating thermal building simulation, airflow transfers, pollutants and lighting, and has been developed in the laboratory since 1993 [3], [12], [13], [14], [15], [16], [17], [18]. HEMERA is a numerical simulation tool that is under development; it is dedicated to the photometric phenomena in a building (artificial and natural lighting).

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Appendix A. Software Inventory

Software	Modeling light pipes?	Mode of Use	Reference	Models used
ADELINE	No longer available			
AGI 32	No	Commercial software	http://www.agi32.com (U.S.A)	Radiosity, Ray-tracing
BSim 2002	No	Commercial software	http://www.bsim.dk (Denmark)	Radiosity
Building Design Advisor	No	Free software	http://gaia.lbl.gov/bda/bda31.htm (U.S.A)	No data
Daylight	No	Free software	http://www.archiphysics.com (U.S.A)	No data
Daysim	No	Free software	http://daysim.ning.com/ (Canada)	No data
Deci	No	Free software	http://www.cstb.fr (France)	No data
DesignBuilder	No data	Commercial software	http://www.designbuilder.co.uk (England)	Radiance, DF
Dial+ lighting	No	Commercial software	http://www.estia.ch/index.php (Switzerland)	No data
DIALUX	No	Free software	http://www.dialux.com (Germany)	No data
Ecasys	No	Commercial software	http://www.fundamentalenergy.com (U.S.A)	No data
EcoAdvisor	No	Free software	http://www.ecoadvisor.com (U.S.A)	No data
Eco Lumen	No	Free software	http://www.ecolumen.com (India)	No data
ECOTECT	**Yes**	Commercial software	http://usa.autodesk.com/ecotect-analysis (U.S.A.)	Radiosity, Ray-tracing, Lumen method, Split-flux)
EnergyPlus via Openstudio (with Radiance)	**Yes**	Free software	http://apps1.eere.energy.gov/buildings/energyplus/index.cfm (U.S.A.) http://www.radiance-online.org/ (U.S.A)	Used Radiance via Legacy Openstudio (Radiosity, Ray-tracing)
Energy Profil Tool	No	Commercial software	http://www.energyprofiletool.com (Canada)	No data
ENVSTD and LTGSTD	No data	Free software	http://www.energycodes.gov (U.S.A)	No data
FlucsDL	No	Commercial software	http://www.iesve.com (England)	DF
FlucsPro	No	Commercial software	http://www.iesve.com (England)	Radiosity, DF

HELIOS	No data	Free software	http://www.helios32.com (Canada)	Radiosity, ray-tracing
HiLight	No	Free software	http://www.eley.com (U.S.A)	No data
HOLIGIM	**Yes**	Free software	http://www.holigilm.info/index.php?selected=news (Slovakia)	Monte-Carlo method combined with ray-tracing
LESODIAL	No	Commercial software	http://madd.epfl.ch/f/transfer_software_lesodial_f.html (Switzerland)	Radiosity, DF
Light R	No	Free software	Designer : Bernard Kwok [Kwok, 1992] (Canada)	Radiosity, ray-tracing
Lightscape	No	Commercial software	http://www.except.nl/lightwave/lslwtute/lightscapelightwave-4.htm (Netherlands)	No data
Lightworks	No	Commercial software	http://www.lightworkdesign.com/ (England)	No data
OptiMizer	No	Free software	http://www.fdlabs.com/ (U.S.A)	No data
Photopia	No	Commercial software	http://www.ltioptics.com/Photopia/overview.html (U.S.A)	No data
Quick Calc	No	Free software	http://www.ExceLine.com (U.S.A)	No data
Quick Est	No	Free software	http://www.genlytesupplydivision.com (U.S.A)	No data
RadVis	No	Commercial software	http://www.cs.cmu.edu/~radiosity/radvis.html (USA)	Radiosity
Relux	No	Free software	www.relux.biz (Switzerland)	Ray-tracing
Render Park	No	Free software	http://graphics.cs.kuleuven.be/renderpark/ / (Belgium)	Radiosity, ray-tracing
SkyVision	No longer available			
Solene	No	Commercial software	https://groupes.renater.fr/wiki/solenetb/ (France)	No data
Sombrero 3.01	No	Commercial software	http://nesa1.uni-siegen.de/ (Germany)	No data
SPOT	No	Free software	http://www.archenergy.com/SPOT/index.html (U.S.A)	No data
Visual	No	Free software	http://www.VisualLightingSoftware.com (England)	Lumen method