OPTICAL SIMULATION OF LIGHTING BY HOLLOW LIGHT PIPES

Oana Dobrre, Gilbert Achard
Design optimization and Environment Engineering Laboratory
Higher Engineering School of Chambery, Savoy University
73376 Le Bourget du Lax Cedex 9, France
oana.dobre@univ-savoie.fr; gilbert.achard@univ-savoie.fr

ABSTRACT

Active diffusing light pipes (such as hollow tubular lighting) are means of directing and diffusion light (daylight or electrical light) into interior spaces.

The two principal objectives of this paper are : 1) to show the development of an advanced new light pipe simulation model and 2) to compare this optical model with another Visual Ergonomics lighting simulation model.

The optical model of a diffusing light pipe was realized for the facility of the simulation using the Apilux software. This optical model is created by reflective mirrors with variable transparence.

The Apilux optical model are designed from the analytical models of efficiency calculation (see section 1).

The Visual Ergonomics lighting model are designed by starting from measurement results (photometrical characterization of a diffusing light pipe).

INTRODUCTION

The first passive light pipe was an internally mirrored pipe (see Figure 1) which transports light, and thus allows the separation of the light source from the location where the light is used. However, such early light pipe plans were impractical because conventional metal-on-glass mirrors are both expensive and inefficient. The expense arises from the complexity of the batch process required for metal deposition and the thickness of material necessary to achieve a robust, good quality mirror.

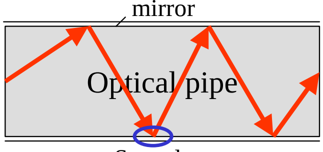

Figure 1 The first mirror light pipe.

The inefficiency is due to light absorption associated with the metallic reflection in ordinary mirrors, which range from 5 to 20%. This is significant because in a typical light pipe the light rays must be reflected numerous times.

These limitations, together with the increasing commercial availability of practical small light sources for general illumination, caused the idea of illumination with very great efficiency prismatic film light pipes (see Figure 2). The polymeric film is rolled up inside the light pipe by the microreplication method.

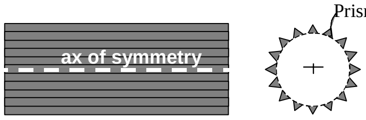

Figure 2 Prismatic passive light pipe.

The prismatic film guides the light entering one end of the light pipe by the total internal reflection inside the prisms. In the case of a passive guidance light pipe, the prismatic film reflects completely the light rays for all angles of incidence.

In the case of an active diffusing light pipe, the prismatic film becomes transparent (translucent) for some angles of incidence. These angles of incidence α are complemental to the beam directional angle θ **(**$\alpha+\theta=90°$**).** The light rays emitted under an angle θ lower than a critical value θ_{max} realize the total internal reflection on the inner surface of the prismatic film :

$$\theta < \theta_{max} = \cos^{-1}\sqrt{\frac{4-n^2\left(2-\sqrt{2}\right)}{2+\sqrt{2}}} \qquad [1]$$

where n is the refractive index of the prismatic film (n=1.5 and θ_{max} = 27.6° for polycarbonate prismatic film).

The light emission outside the light pipe can be accentuated by the presence of an extraction mechanism positioned inside, at the upper section of the light pipe. In particular the extraction system is comprising of a metal cover provided with a number of transversal holes. The extraction holes have the role to change the direction of the light rays, so that they don't realize the total internal condition and so can be diffused outside of light pipe.

Within the framework of this paper we used such a light pipe of 6m length and 10cm in diameter (see Figure 3).

Figure 3 Light pipe used (GeeO laboratory - Grouping of experimental electromagnetism and optoelectronics – Grenoble, France).

The light pipe is supplied with 2 projectors HQI 70W (Metal Hallide). To obtain a uniform diffusion along the light pipe, the spatial distribution of the extraction holes is variable. Thus, the interval between 2 consecutive holes decreases as a function of the distance, starting to the end of the light pipe (where the light is emitted).

The optical model enabled us to determine the light distribution and the efficiency of the light pipe used.

Several different layers constitute the inner structure of the modeled light pipe used (see Figure 4) :

1 - prismatic film positioned on all the cross-section of the light pipe and over all its length;
2 - metal cover placed in the upper section of the light pipe over all its length. This layer have the extraction holes cut out in larger (transversals on the light pipe axis).
3 - white reflective film;
4 - transparent layer of protection;
5 – extraction hole.

A light ray realizing the condition of the total internal reflection (see [1]) and incident upon the inner surface of the prismatic film (in bottom section of the light pipe) will have the way given in Figure 4 (R1).

A light ray incident upon the top section of the light pipe (metal coil 2 - see Figure 4, R2) between two extraction holes 5, undergo a diffuse reflection. A part of the considered rays continue to realize the guidance of the light inside the light pipe (thanks to the total internal reflection, like R1) while the other part will be directed towards the bottom section of the light pipe and diffused by prismatic film (see R2').

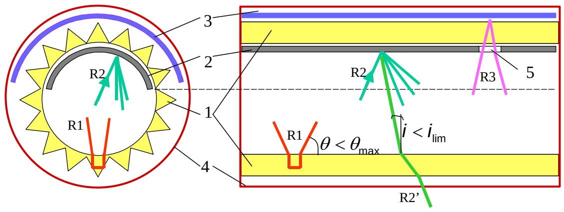

Figure 4 Inner section of the light pipe and the different light ways .

The film becomes transparent for angles of incidence lower than the critical angle $i_{lim} = \pi/2 - \theta_{max}$.

The light rays incident upon an extraction hole 5 (see Figure - R3) will be diffused by the prismatic film 1 upwards and returned by the reflective white layer 3, inside the light pipe, on an almost vertical direction. This direction does not realize the condition of the total internal reflection [1], therefore the rays extracted by a hole will be emitted by the prismatic film (like R2').

1. REALIZATION OF THE "APILUX" OPTICAL SIMULATION MODEL

The inner structure of a diffusing light pipe is very complex. Thus, we realized an optical model which we simulated using software APILUX.

APILUX is a optical and photometrical conception and analysis software. It generates naturally a concept of sequentially propagation and it allows the using of the optical calculation functions in many systems. APILUX uses the optical elements like mirrors, lens, luminous sources…

The optical model that we propose comprises several concave mirrors tilted with 45° and placed at a constant distance (the ones of the others).

The necessary tools used for the realization of the optical model are the following:

- method of calculation of the efficiency of the elements constituting the light pipe (source, coupling, transport, extraction and diffusion elements;
- model of calculation of the laws of recurrence of a light pipe;
- photometrical characterization of the light pipe using a lux-meter.

The calculation of the efficiency of the light pipe that we developed considers that all the phenomena doing inside a light pipe are inter-connected, contrary to the model of calculation, which already exists in the literature (Lorne A. Whitehead).

The efficiency of a diffusing light pipe E_{LP} is given according to:

a) efficiency of the transport of the light inside the light pipe $E_{transport}$;

b) efficiency of the extractor $E_{extractor}$ and

c) efficiency of the exit window of the light pipe $E_{exit-window}$ (transparent and diffusing section of the light pipe):

$$E_{LP} = E_{transport} \cdot E_{exit-window} \cdot E_{extractor} \cdot \qquad [2]$$

The efficiency of the transport of the light is calculated according to :

- the efficiency of the inner walls of the light pipe (given as a function of their reflectance and the average number of reflections inside the light pipe),
- the efficiency of the end mirror (which has the role to return all the remaining light in the light pipe so that it can be extracted and diffused) and,
- the efficiency of the return way of the light inside the light pipe.

The average number of reflections of the light inside a light pipe $\bar{N}$ is given by the relation:

$$\bar{N} = L/d \cdot \tan\theta_m \qquad [3]$$

where L is the length of the light pipe, d is its diameter (or its width), θ_m is the beam directional angle of the electric light source.

The efficiency of the extractor is given according to the average reflectance of the metal coil of extraction provided with holes (see Figure 4 – 2).

The efficiency of the exit window of the light pipe is given according to absorption, reflection or transmittance of the opaque section (top section) and the diffusing section (bottom section) of the light pipe and to the their size. It takes into account the multiple reflections existents in the cavity of the light pipe.

The efficiency of the electrical source of the light pipe was given by the supplier. It can be determined also by the product between the geometrical efficiency (light lost by the cutting of introduction of its lamp, approximately 0,85) and the efficiency of its reflector $E_{reflector}$ (due to the absorption of the walls and calculated by the relation: $E_{reflector} = \rho_R^{\bar{n}}$; where ρ_R represents the reflectance of the reflector and $\bar{n}$ the average number of reflections of the light inside the reflector - approximately 1,2).

The efficiency of the coupling between the light pipe and the source is approximately 0,833. It was determined by the product between the geometrical efficiency of the coupling (which depends on the quantity of light, which escapes from the air space) and the transmission efficiency from the coupling.

The optical properties of the mirrors of the model were given using the laws of recurrence, which we developed. They are the mathematics relations between the flows transported inside the light pipe, or the relation between a flow extracted from a section and flow entering this section. We divided, in a fictitious way, a diffusing light pipe in n sections of equal length, and we noted the flow injected into the light pipe by F_0; the flows extracted by the k section is noted by Fe_k and the flows transported inside the light pipe, between 2 consecutive sections $Ft_{k-1,k}$.

The analytical form of the recurrence laws is according to the light pipe efficiency E_{LP}, the number n of sections, the index k of the section where the law is applied, and the flow lost P_k:

$$Fe_k = \frac{E_{LP}}{n} F_0;\; Fe_k = \frac{E_{LP}}{n-(k-1)} Ft_{k-1,k};$$
$$P_k = \frac{1}{n}(1-E_{LP})F_0 = \frac{1-E_{LP}}{n-(k-1)} Ft_{k-1,k}; \qquad [4]$$
$$Ft_{k,k+1} = \frac{n-k}{n-(k-1)} \cdot Ft_{k-1,k}.$$

With the extracted flows known (measured by a photometrical characterization using a lux-meter) we determined transported flows. The mirrors of the optical model are characterized by :

- a reflectance equal to each extracted flow and;
- a transmittance equal to each transported flow.

To prevent the light from going to the top of the model, we placed a reflective half-cylinder in the top section of the model (see Figures 5 and 6).

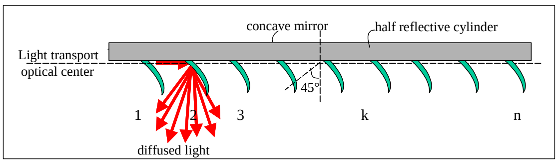

Figure 5 Diagram of optical model of the light pipe.

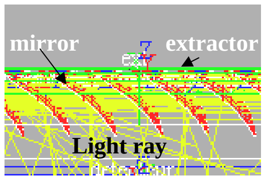

Figure 6 Detail of the APILUX optical model.

The losses of light were simulated by different transparent and absorbent optical elements (see Figure 7).

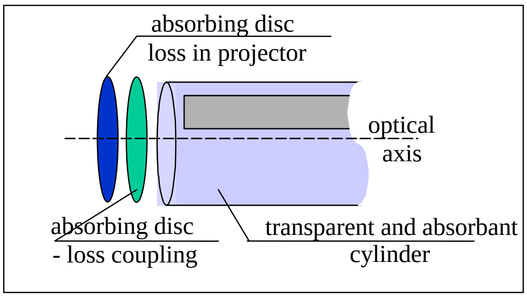

Figure 7 Detail of the model simulated by APILUX.

The losses of light of the source (projector) and the coupling were simulated by two discs placed at front of the model and characterized by a transmittance equal to their efficiency.

The losses of light due to the transport, the extraction and the diffusion of the light were simulated by a cylinder, which surrounds the model and is characterized by a transmittance equal to each corresponding efficiency. For this reason the mirrors of the model are not absorbent.

2. REALIZATION OF THE "VISUAL ERGONOMICS" LIGHTING SIMULATION MODEL

In order to compare the distribution of the light emitted by the optical model of the light pipe we have realized another simulation of the luminous behavior of the same light pipe using Visual Ergonomics software. This software, invented by SPEOS OPTIS is a natural extension to mechanical CAD software for total virtual prototyping.

The necessary tool used for the realization of this model is a photometrical characterization of the light pipe using a lux-meter (see Figure 8).

In absence of a gogniophotometer we have used a lux-meter to determine the illumination distribution on a horizontal level. The light distribution of the light pipe was useful to us.

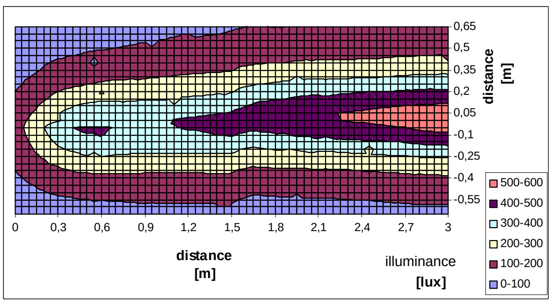

Figure 8 Isolux Curves – lux-meter photometrical characterization (half light pipe).

We could realize the luminous intensity diagrams (see Figure 9), transformed into IES format, starting from measurements of illumination (photometrical characterization method), for all the sections of the light pipe (43 sections for a 6m length light pipe).

The IES curves were positioned the ones after the others, for obtain the whole light pipe. This set were placed in a room being the same dimensions as the room used for the optical model.

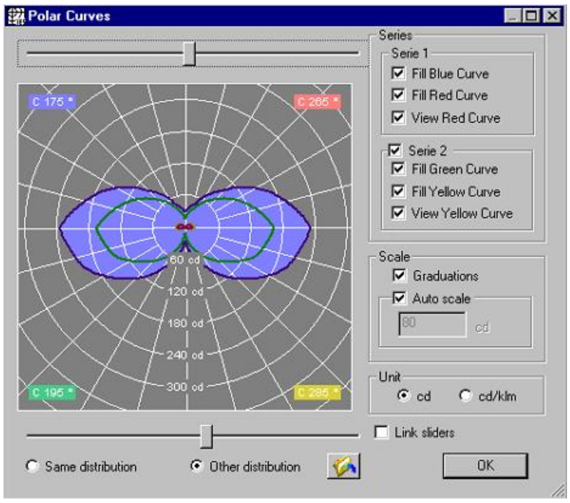

Figure 9 Distribution of light on a lateral wall.

3. RESULT ANALYSIS

The model of the light pipe was placed inside a voluminal absorbent detector, which is able to count all the light rays incident upon its surface in order to evaluate the flow received by each wall of the detector. Figure 10 and Figure 11 show a front view and a side view of the model with the detector and the light rays.

As we can observe, the distribution of the light emitted by the model is accentuated in the first end of the light pipe (see Figure 11, on the right). That is due to the injection of the light inside the optical model.

This phenomenon can be also met in reality. To prevent it, in the first part of the light pipe there will be less extraction holes.

The light distribution on the ground (see Figure 12) has the same form as that resulted from measurement during a photometrical characterization carried out using a lux-meter. The first end of the model is placed in top of the graph.

The light distribution on the inner walls of the detector can be seen in Figure 13 (distribution on a fictive wall placed at the middle of the detector) and in Figure 14 (distribution on a lateral wall).

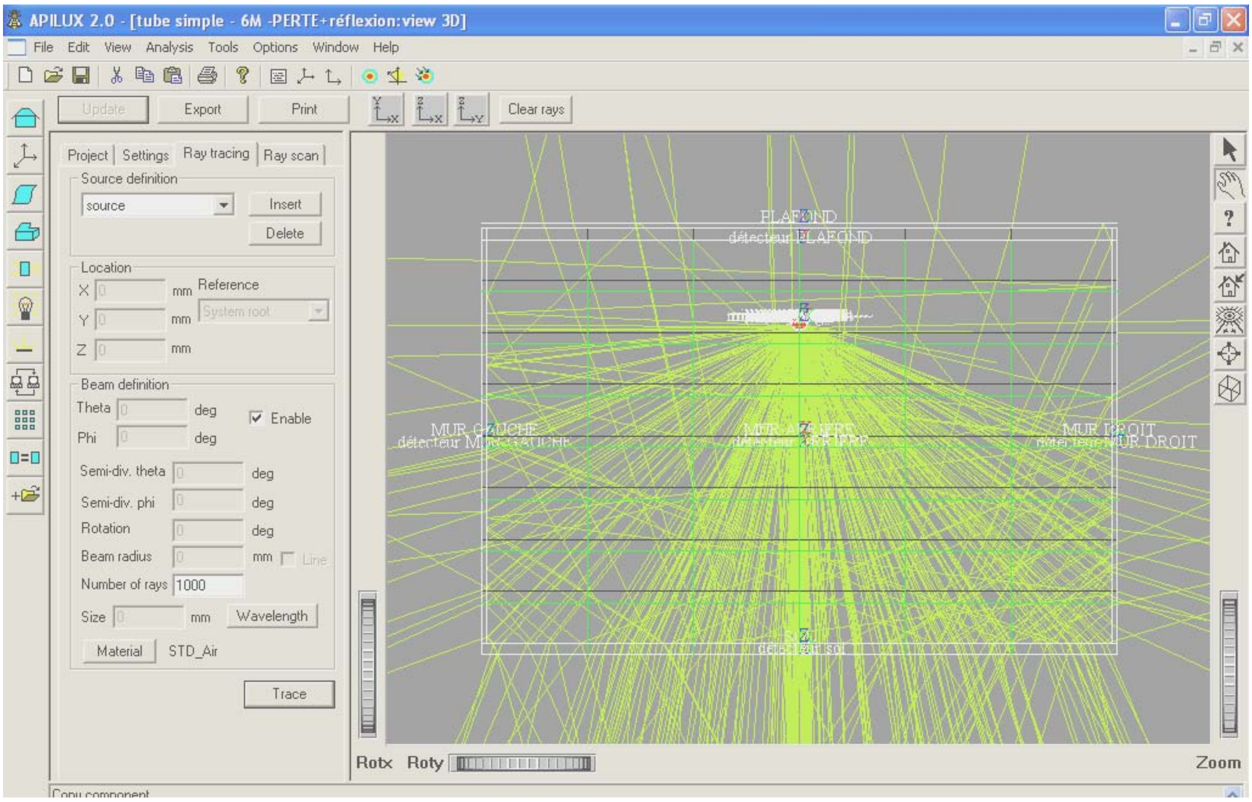

Figure 10 Detail of light ray tracing - front view.

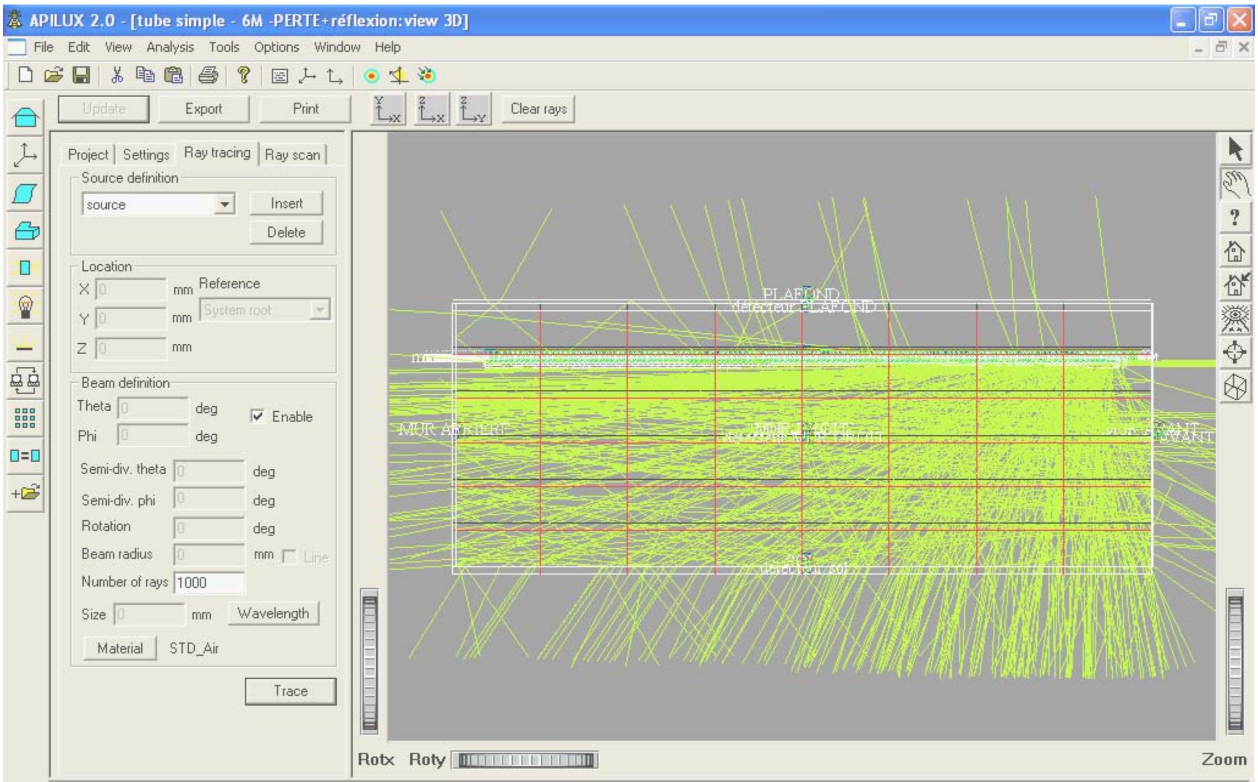

Figure 11 Detail of light ray tracing - side view.

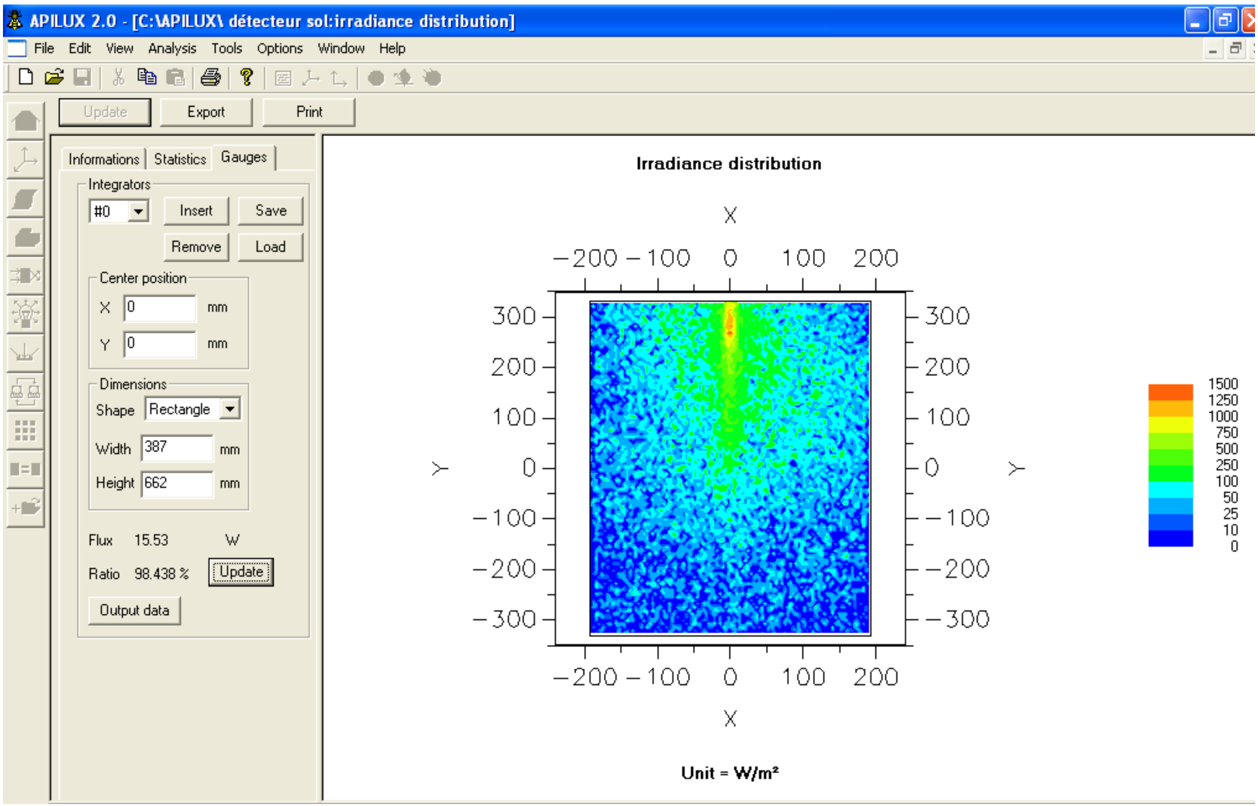

Figure 12 Distribution of light on the ground.

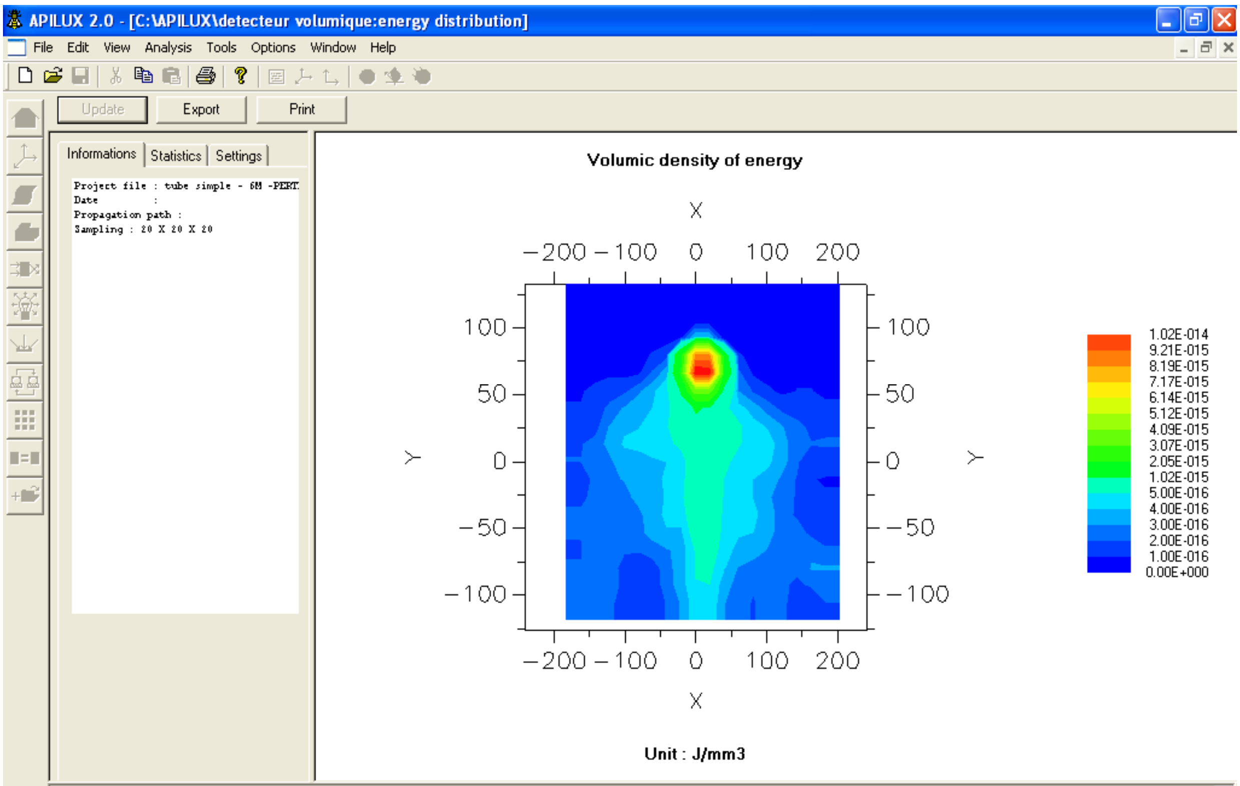

Figure 13 Distribution of light on a fictive wall placed at the middle of the detector.

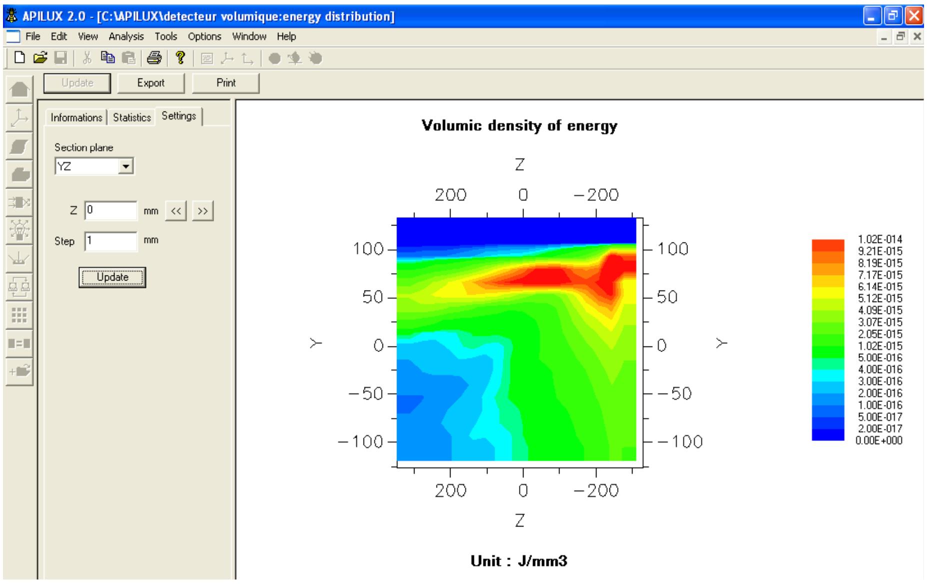

Figure 14 Distribution of light on a lateral wall.

In figure 12 on the left, we can observe that the APILUX software posts the percentage of flow received by each wall of detector compared to the total flow emitted by the point source. In function of this information we can determine the efficiency of the model, which is very close to that found in measurements or by calculation. Thus the light pipe efficiency is 32% from measurements, 35,6% from calculation and 34% from APILUX optical model.

One of the great differences between the two softwares used is that the Apilux software can plot curves of intensity distribution starting from a simulation, while Visual Ergonomics software needs these curves to generate a simulation.

The distribution of light generated by Visual Ergonomics software is very similar to that found in the measurements (see Figure 15).

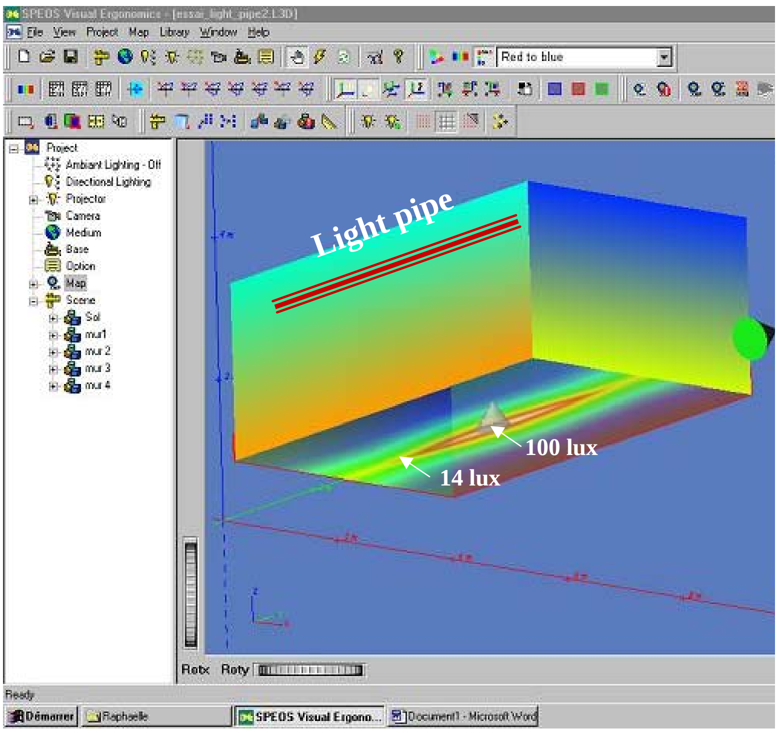

Figure 15 Distribution of light on the ground.

The two distributions given by the two models are comparable if we add the second symmetrical half representation, which is done by the bilateral light source.

CONCLUSIONS

The part played by the daylight or mixed light in the building construction is fundamental for the improvement of quality and comfort like for the control of the costs and the power consumption. To answer these criteria the light pipes are very adaptable. However, we note that the lighting designers often miss technical information on the structure and the capacities of the diffusing light pipes (like efficiency, emitted flow...). Moreover current lighting software does not bring suitable simulation models for these systems of light pipes.

Consequently, our work mainly relates to the study and the photometrical and numerical characterization of these systems of diffusing light pipes, which led us to the realization of an optical modeling that we could simulate using Apilux software.

The two models used results is similarly with the measurement results (see Figure 16). In this picture we are situate in the transversal plane to 50 cm distance of the light pipe. The average error between the APILUX model and measurement results is from 7 to 15%.

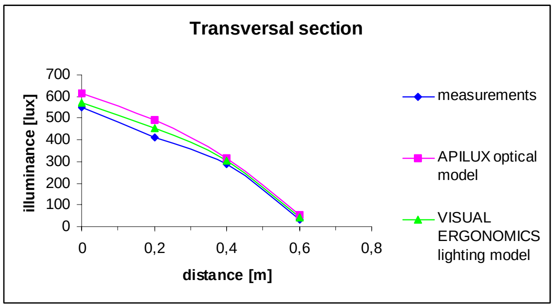

Figure 16 Results comparison.

The results obtained will be able to constitute technical answers for the designers of light pipes of light as well as a "toolbox" for the various actors concerned by the projects of lighting.

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