EVALUATION OF RADIATIVE COMFORT IN OFFICE BUILDINGS

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Abstract The research we develop consists of evaluating "radiative comfort" during no heating periods in office buildings.The expression "radiative comfort" is used to characterise the thermal and visual component of the feeling of people set in indoor environments submitted to sky and sun irradiation by bay windows.
Two numerical models, one for the visual behaviour and the other for the thermal aspect, have been adjusted We carried out simulations in the case of offices which is the main scope of our study. Parametric studies offer the opportunity to determine, on the one hand a temporal representation of the discomfort situations, and on the other hand the study of the concomitance of the generated thermal and visual phenomena. The results show that the visual discomfort risks are more frequent than the thermal ones. Visual effects are instantaneous when thermal aspects are delayed in time with regard to the radiative inputs; the delay depending on the thermal inertia of the room.

1. Introduction

Most scientific works have been devoted to the hygrothermal component of human comfort but the visual component has not been examined as well. To our knowledge, both aspects involved in the "radiative comfort" expression have not so far been taken into account at the same time.
First, we collected the main notions enabling the characterization of thermal and visual comfort, then, we chose to model thermal and visual phenomena. Indeed, we did not make the choice of an experimental approach which would have required a very important metrology. Such an approach would not have either allowed to take easily into account the main varying cases of the study.
In the smulation, thermal comfort is evaluated by PMV factor and the visual feelings are obtained from CORNELL index. A parametric analysis has been made for a single oriented office room and for different positions of observer.

2. Chosen parameters to characterize discomfort occurrence

2.1 Visual comfort

Visual comfort is mainly the lack of glare.The glare phenomena is due to luminances higher than the mean value of the adaptation luminance in the visual field. Acoording to the importance of the gap between these luminance values, glare can be shared into two components :

- the disturbing glare which provides from excessive diffusion of light in the eyes and can destroy vision for a moment
- the discomfort glare associated to the heterogeneity of luminances in the visual field and which leads in the end to an eyestrain.

If the discomfort glare do not exist, the disturbing glare cannot intervene. So, the rule to avoid all sort of visual difficulties is to protect the observers against the discomfort glare.

A particular interest has been reserved to discomfort glare by bay windows arising from variable luminance of the sky vault.

Many indexes have been studied to characterize discomfort glare. Most of them have been worked out for small dimensioned light sources and more particularly for artificial light sources. Our bibliographic researches induced us to take a large interest in experimental studies dealt by the Building Research Station in England and Cornell University in U.S.A. [1]. These studies were carried out by observing large illuminated screens in which luminance and size were variable. In consequence of these experiments the followed formula was proposed, and the Cornell index was defined (Table (1)) :

$$G = 10 \log_{10}\left[\frac{1}{L_b + 0{,}07.\Omega_t^{0,5}.Lmoy}.\sum_{i=1}^{m} L_i^{1,6}.\frac{\omega_i^{0,8}}{p_i^{1,6}}\right] \qquad (1)$$

- m : number of sources in the visual field
- L_i : luminance of each source ($cd.m^{-2}$) in the visual field of the observer
- ω_i : solid angle subtended by each source from the eye of the observer
- p_i : GUTH position index of the source which takes into account the variation of the eye reaction in function of the position, on the retina, of the light source image [2]
- L_b: surround luminance
- Ω_t : solid angular subtended by the bay window
- L_{moy} : average luminance of the m sources ($cd.m^{-2}$)

If an excessive localised sunlight occurs in the part of the window, it will be taken into account in the formula (1)

A scale of feelings is associated to Cornell index as shown in Table 1.

Glare perception	Glare index DGI
Just imperceptible	16
Just acceptable	20
Just incomfortable	24
Just intolerable	28

Table 1. Connection between glare perception and the associated index

2.2 - Thermal comfort

Thermal comfort is obtained by balancing the heat gains and losses of the human body, while controlling the environmental conditions (i.e. temperature, humidity,...). The human body adjusts its functions accordingly and responds of the prevailing environmental conditions.
To create thermal comfort for people in indoor environments, it is necessary to have a thorough knowledge of the main parameters influencing thermal comfort : dry bulb temperature, radiant temperature asymmetry, relative humidity, air velocity, barometric pressure, clothing, and activity. Thermal comfort can be evaluated by many different combinations of the above variables. The body's thermal equilibrium is a dynamic balance between heat production due to the human metabolic rate (M), and heat transfer with the environment by convection (C), conduction (K), radiation (R), evaporation (E), and respiration (RE) :

$$S = M - R - C - K - E - RE \qquad (2)$$

When thermal equilibrium equation is satisfied (S = 0), there is no increase or decrease of the body's temperature . However, human comfort is not a simple heat balance, but it needs to take into account complex behaviour and psychological factors. Among the various models and suggestions for the quantitative estimation of thermal comfort, the most widely used is the one suggested by FANGER [3]. Consequently, comfort indexes have been defined, for example the predicted mean vote (PMV) of a large group of subjects according to a thermal psychological scale (-3 cold, -2 cool, -1 slightly cool, 0 neutral comfort, +1 slightly warm, +2 warm, +3 hot) and the predicted percentage of dissatisfied (PPD) of the same group :

$$PMV = [0{,}0303 \exp(-0{,}036\, M) + 0{,}028]\, S \qquad (3)$$

$$PPD = 100 - 95 \exp[-(0{,}03353\, PMV^4 + 0.2179\, PMV^2)] \qquad (4)$$

Although the previously indexes for assessing thermal comfort have been widely used, there are significant discrepancies between predicted thermal comfort and actual comfort sensation. Recently GAGGE [4] proposed a new index PMV* which is more accurate to predict thermal sensation in summer indoor conditions (without cooling system). The formula of PMV* is derived from PMV one. Different terms of Eq. (2) are computed thanks to a two node model of human temperature regulation which introduce the effective temperature concept [3].

3. Modelling of the physical phenomena

3.1 Visual aspects

The modelling of visual aspects was made thanks to the adaptation of Génélux [5] which is the name of the processor developed by the Laboratory "Sciences de l'Habitat" of the "Ecole Nationale des Travaux Publics de l'Etat" in Vaulx en Velin (France), to study the luminous behaviour of buildings. This software permits the simulation of the propagation of radiative energy through a transparent medium using a forward ray-tracking technique. Each ray carries energy in a given wavelength range and can be associated with a number of photon. Rays are generated with a Monte Carlo technique. When the rays hit a surface, they are generated in the appropriate directions for reflection and transmission using the fundamental laws of optics. When the ray falls on a light scattering surface, the primary rays are broken down into secondary ones with appropriate amount of energy

3.1.1 Daylight sources : sky data production

In daylighting, the different possible skies are characterized by their luminance distributions. Correlations have been proposed to establish most typical sky luminance distribution as a function of more spread climatic informations (global and diffuse irradiance, location of sun in the sky, latitude, dry bulb and wet bulb temperature) [6]. We used this algorithm to produce hourly average skies which are divided in two categories :

- for diffuse light, the sky vault is divided into 13 patches which respect the main part of such sky (strip in the horizon, spherical cap on zenith and another strip for the rest of the sky) - Fig. (1);
- for direct sunlight, the model requires 60 sky patches to produce equivalent sky luminances due to the sun alone - Fig. (2).

Meteolux [7], which is the name of the sky data processor, produces for each hour 13 values of luminance of the sky vault and one value of luminance corresponding to the sky patch which includes the sun.

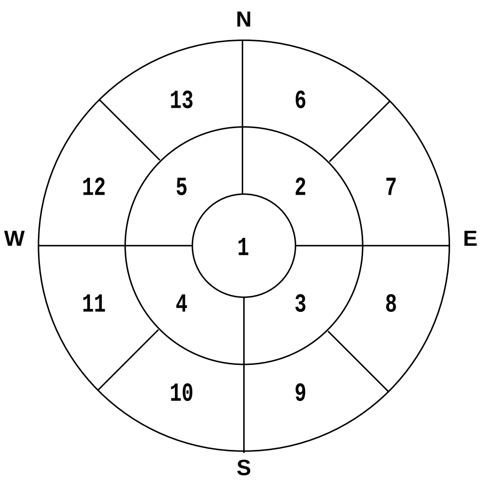


Fig. 1. 13 grids for diffuse sky

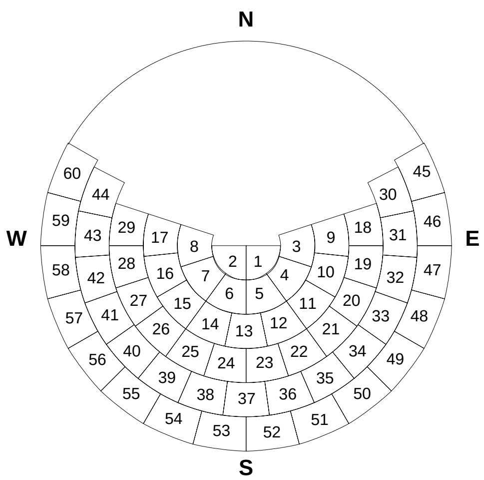


Fig. 2. 60 grids for sunlight

3.1.2 Indoor daylighting computations with Génélux

Two phasis can be mentioned :

- on one hand, luminance distribution in visual field and several characteristic illuminances are computed inside and outside the test cell. This spatial distribution is made thanks to directional daylight factors that allow to access to the reference contribution of each patch of an uniform sky separately. Then these directional daylight factors are multiplied by the real distribution luminance of the sky calculated from meteorological data with Perez model [8]. The final results are obtained by the sum of the contribution of each.patch of the sky.

- on the other hand, parameters must be determined to compute glare indexes (solid angles, Guth position index, incidence angles, size of grids...). They mainly depend on the configuration of the test cell, on the position of the observer and finally on the characteristics of bay windows.

3.2 Thermal aspects

A lot of software tools exist to compute thermal phenomena. Our investigations are developed with TRNSYS [9], because of its polyvalence and its easy use. Its modular conception allow us to develop specific applications and to modify existing ones; for instance a comfort model has been developed and the detailed zone model used to compute thermal phenomena in the test cell has been changed in two main points :

- On one hand, we have improved the radiative exchange using Gebhart method to take into account the long wave radiation exchanges between grey surfaces.
- On the other hand, we enhanced the modelisation of the windows taking into account the photometry of the glasses.

4. Parametric exploitations

Using the numerical models described above, parametric exploitations have been carried out for the test cell fitted out with a large bay window [10]. The chosen meteorological data correspond to a Test - Reference - Year from Mâcon station in France (Fig. (3)). To compute visual comfort index, six reference positions in the test cell have been kept (Fig. (4)). Each observer is supposed to remain seated.

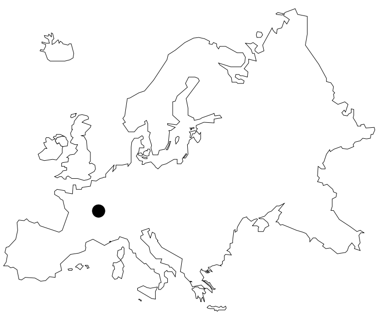


Fig. 3. location of meteorological station of Mâcon in Europe

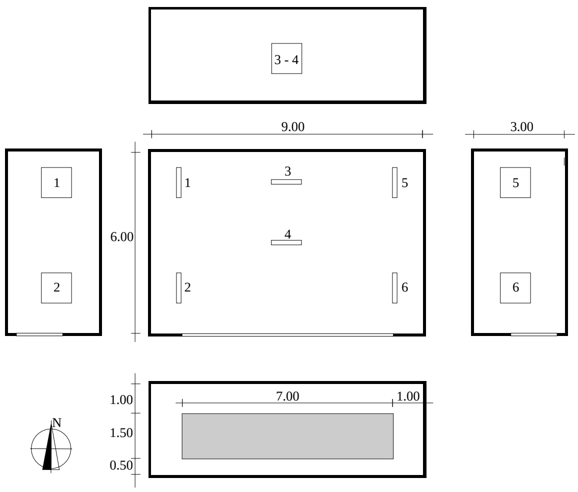


Fig. 4. description of the test cell with a large bay window and six observers

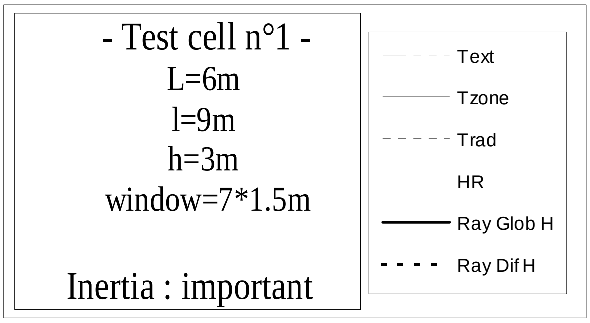
Simulations realised concurrently with Génélux and TRNSYS gave a temporal representation of comfort indexes. Several physical values have been hourly computed as mentioned in Table (2). The three parts of Fig. (5) to (7) here under give an example of a temporal representation of the physical values computed for Mâcon in a day of June.

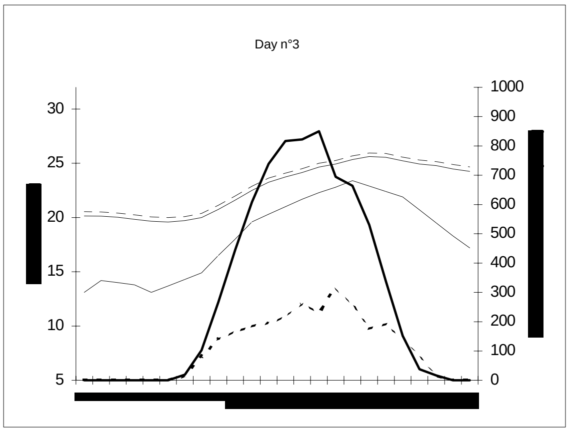
Thermal indexes	Visual indexes
- Energetic irradiances - Operative temperature - Mean radiant temperature - Dry bulb temperature	- Bay window grid luminances - Horizontal and vertical characteristic illuminances inside and outside the test cell

Table 2. Computed physical values with TRNSYS and Génélux

4.1 Thermal parameters

Fig. 5. Time evolution of thermal parameters

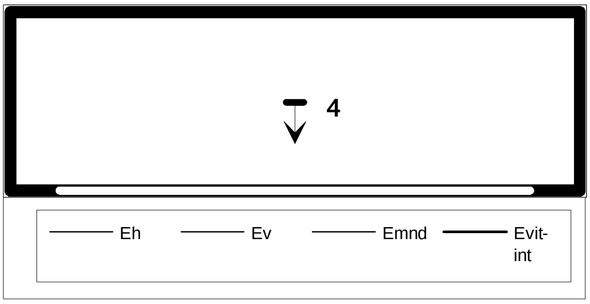




We notice on the Figure (5) that the delay between inside air temperature and global horizontal irradiance is around for hours, when it is only around one hour between inside and outside air temperature. The first delay come from internal thermal inertia provided by the envelope elements located on the inside part of the walls and floors which act on radiative inputs going through the windows. In our case this internal inertia is important and the energy coming from the sky and the sun is well stored before to be restitute slowly by covection to the inside air. The second delay is lower because the thermal inertia which have an effect on the thermal response is not the same. In this case all the envelope contributes to this global inertia but the ventilation rate leads to reduce the amount of its effects and even the global inertia is important, the final result corresponds to a low inertia.
The main radiant temperature is just upper the air temperature and follows practically the same time variation. This behaviour is due to the important internal thermal inertia which is rather a good solution to avoid passive overheatings of large amplitude.

4.2 Visual Parameters

Fig. 6. Time evolution of visual parameters



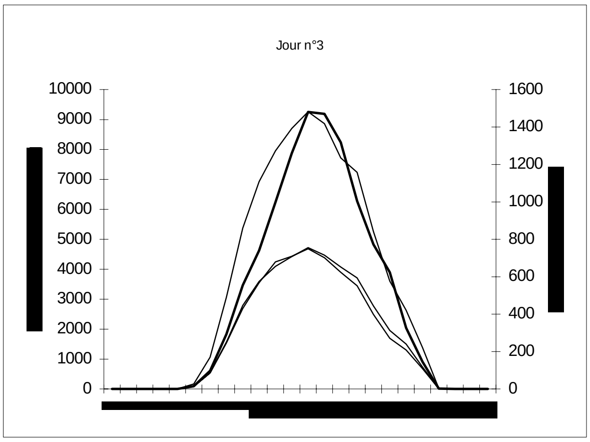


Figure 6 shows the variation of 4 different illuminances in function of time for a characteristic day. Each illuminance results from the both influence of the direct luminous radiation of the sky and the sun through the window and of the interreflexions inside the room :

- Eh is the horizontal illuminance at the point 4 and at a height of 0,85 m

- Ev is the vertical illuminance at the level of the eyes of the observer 4 (1,20 m)

- Emnd is the vertical illuminance on the wall in the opposite from the window(1,20 m)

- Evit-int is the vertical illuminance on the inside surface of the window. It is produced only by the interreflexions inside the room because the receiving surface cannot "see" the sky .

We notice that all these illuminance are all nearly concomitant with the global solar radiation. The evolution of Eh and Ev are almost identical because, at the point 4 :

- the parts of the sky seen from an horizontal surface element at 0,85 m and from a vertical surface element at 1,20 m are similar

- and the corresponding solid angles projected on the receiving surface are almost the same.
However, the vertical illuminance has an evolution more smoothly because it is less influenced by the direct radiation from the sun

4.3 Discomfort Indexes

As we have remarked on all the cases we have studied, the visual discomfort appears always before the thermal discomfort (Fig 7), when it takes place during the occupation period, that is not systematic

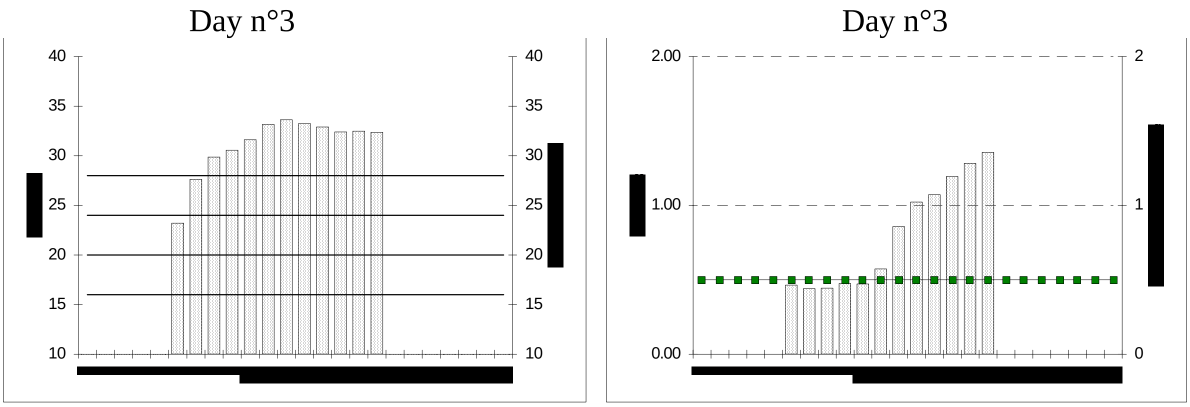


Fig. 7. Comfort indexes

The results allow us to say that visual discomfort situations are more frequent than thermal discomfort.situations It has been check that visual phenomena always anticipate thermal ones as it is again shown in the time evolution of discomfort indexes on Figure (8).
Consequently, it is possible to prevent overheating by modyfiing the transparency of the window bay to avoid disconfort glare, some hours before thermal disconfort appears. This advance period depends on the amount of internal thermal inertia.
In other words, visual indexes are connected directly with the radiation inputs and it must be possible to use them not only to control an occultation system of bay windows to cancel disconfort glare but also to prevent future overheatings

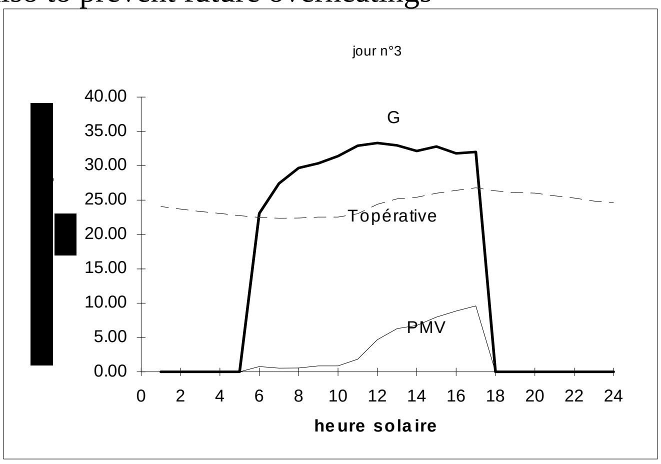


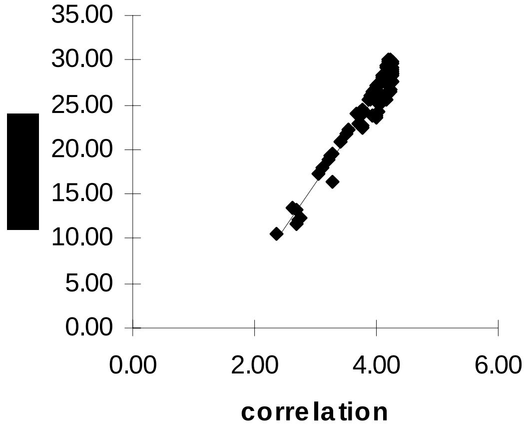
Fig. 8 : Delay time between Cornell index G and PMV

4.4 Secondary parameters

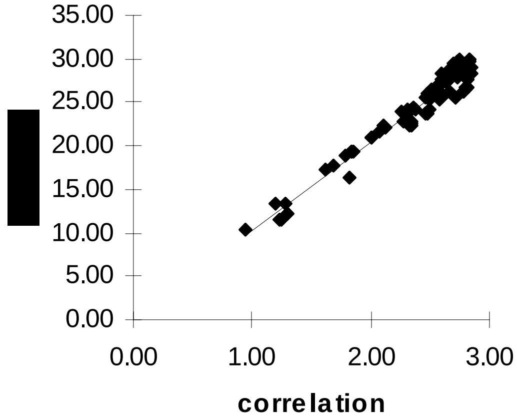
Some investigations have been made with the aim of creating an expression of the discomfort glare index. more simple than the formula (1).

The general form of this new expression is : $$G \cong a \cdot \ln\left[\frac{(En)^x}{Ed}\right] + b$$ (5)

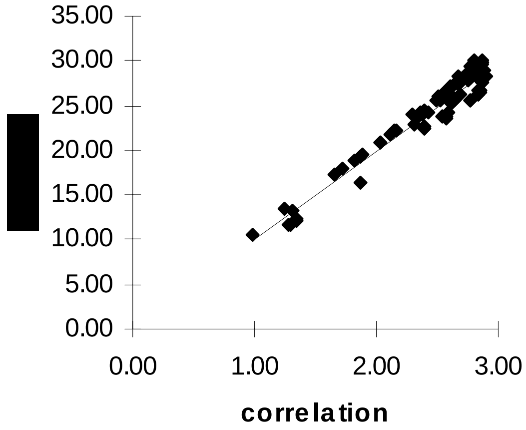
The numerator En and the denominator Ed in the argument of the logarithm of the previous expression are two particular illuminances which are easier to measure than luminances as those of the formula (1). These two particular illuminances could be the illuminances studied in the paragraph 4.2 or others. In fact, we have to analyse the quality of different correlations between glare index G and secondary parameters as illuminances or ratio of illuminances.
At the present time, the best correlations is shown on the Figure 9



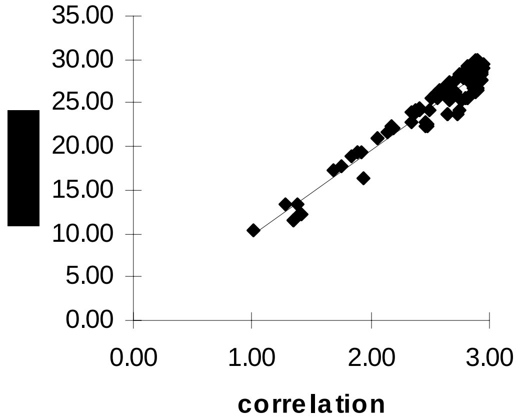
a. **Corrélation n°8** (E_N = Evit_ext, E_D = Evit_int)



Corrélation n°1 (E_N = EvNoir, E_D = Eh)



Corrélation n°2 (E_N = Ev, E_D = Eh)



Corrélation n°3 (E_N = Ev, E_D = Emob)

Figure 9 : Comparaison of the correlations n°8,1,2 et 3
- *logarithm scale on the horizontal axis*
- *Evit-ext : illuminace on the external surface of the window*
- *Evnoir : illuminance Ev without the influence ofinside interreflexions*
- *Emob : illuminance of the opposite wall from the window*
- *others symbols : see Figure 6 and paragraph 4.2*

5. Conclusion

Our final objective is to design a simple and cheap metrological system that could be subsequently industrialized.
Such a sensor will be derived from the choice of the better correlation where the secondary parameters are not only representative of the phenomena but also easy to measure.
The result will be a compromise and it must be integrated into a control chain of an occultation system of bay windows in order to avoid hoverheatings and glare in office buiding.
To value "radiative comfort", our results induce us to design a metrological system using only luminous values which are more suitable to be implemented than a system based on energetic ones.
The following stages of the work consists in :
- detailed study of frequencies and interactions between thermal and daylight phenomena;
- reseach of secondary parameters able to characterize visual and thermal discomfort and more easier to measure than primary ones which take place in the formula (1) to (4)

Parametric exploitations must be extended to others test cells in which the orientation of the bay window and its size will be changed.

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