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Towards Net Zero Energy Buildings in Hot Climate, Part 2: Experimental Feedback

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ABSTRACT

The paper deals with the feedback of the measurements conducted in the first zero energy building "EnerPos" constructed in the French tropical Island of La Reunion. The building was designed to operate as long as possible by using passive techniques (cross natural ventilation, day-lighting). The purpose was to reach an annual energy ratio below 55kWh/m² (which is three times below the mean ratio of standard buildings in La Reunion) by avoiding energy consuming active systems such as air-conditioning and artificial lighting.

The building was inaugurated in January 2009 and since, a post-occupancy evaluation was carried out in terms of thermal, visual and air-speed comfort. First, a comfort survey was conducted on the users : altogether, about 500 students and teachers answered more than 1500 questionnaires, which included questions concerning their personal information (clothing, previous activities) and their comfort at the beginning and at the end of the exposure. The students were asked to express their sensation and judgment for the thermal, hygrometric and air speed comfort. At the same time, the main environment parameters (air temperature, black globe temperature, humidity, air speed and illuminance) were being recorded. The outdoor climatic data were also collected thanks to a meteorological station located on site. The results show that the users feel comfortable when the temperature is below 30°C with an air-speed close to 1m/s. It is then possible to reach a thermal comfort for the users in the classrooms and offices even during the hottest days of the year. Nevertheless, the air-conditioning is needed in the computer rooms during the six hottest weeks of the year (from the end of January to the beginning of March) due to the heat produced by the computers.

Two measurements campaigns were also conducted to assess the visual comfort of the users and to determine the autonomy in day-lighting during summer and austral winter in every rooms of the building. The results show that the autonomy during the hours of occupation is about 80% in the offices, 70% in the most disadvantageous classrooms (on the first floor) and can nearly reach 100% on the second floor. Lastly, the performance of the ceiling fans was measured to evaluate their circles of influence (in which an air-speed of 0,7m/s is reached).

INTRODUCTION

In 2010, the European Commission and Parliament adopted the recast of the Directive on Energy Performance of Building that requires that all new buildings should be "Nearly Zero Energy Buildings" after 2020. Since 2008, the international experts of the IEA SHC Task 40/ECBCS Annex 52 "Towards Net Zero Energy Solar Buildings" are working on several case studies of zero energy buildings under different climates. The EnerPos building constructed in Reunion Island has been chosen as one of those case studies. The purpose of this paper is to give the experimental feedback on this building

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in terms of thermal comfort, ventilation and daylighting measurements as well as the possible improvements that lend to reduce the total energy use of the building.

Concerning the thermal comfort, ISO 7730 that uses the Fanger predicted mean vote (PMV) formula which predicts a numerical value for the mean response to the thermal environment, is still often used to forecast thermal comfort in buildings. However, many field studies of thermal comfort have suggested that design temperatures derived from this standard would require more heating and cooling energy to achieve thermal comfort than was indicated from the survey results (Baker, Heidari). Researchers of thermal comfort field studies have suggested that people are not passive receivers of their thermal environment and that they have a natural tendency to adapt to their environment (Nicol, 2002). When people have more access to building controls such as opening windows, operating on shading devices, there is more "forgiveness" on their thermal environment. Therefore thermal comfort must be studied in real buildings and under regular conditions of occupancy. A thermal comfort survey has been carried out during two hot and humid seasons in the EnerPos building.

Under tropical climate, thermal comfort can be achieved with the use of ceiling fans to increase the air speed on the skin. To describe the thermal environment, it is then important to measure the potential air speed and the distribution in the room that can be obtained by the use of such devices (Arens, 2009). Such measurements were also run at EnerPos.

Always with the aim of reducing the energy consumption of buildings, daylighting measurements were conducted. By choosing a proper spatial distribution of artificial lighting in the rooms, it is possible to optimize the energy consumed. The knowledge of the daylight autonomy percentage is also important to forecast the energy consumption due to lighting.

PRESENTATION OF THE ZERO ENERGY BUILDING "ENERPOS" IN LA REUNION

La Reunion is a small French island located in the Indian Ocean near Mauritius Island (55.5°E, 21°S). The energy context of the island is extremely complicated because the energy demand is increasing regularly with an annual growth percentage of 4%. Because of its insularity, La Reunion has to provide its full electricity production. Mainly produced by fossil fuels, it is one of the most polluting in the world. An electrical kilowatt-hour generates about 820g of $CO2$ (ADEME, 2010). Housing and tertiary buildings energy demand represents 30% of the total energy consumption of the island. In the context of global warming and fossil fuels decline, the energy consumed by the building sector must decrease and renewable sources of energy need to be found.

The climate of La Reunion is humid tropical all along the coastline. Table 1 gives the main characteristics of the climate in Saint-Pierre. There is a dry season occurring from May to October, mainly cool and dry and predominated by Southeastern prevailing winds. The hot and humid season occurs from November to April and most of the time only thermal breezes blow.

Table 1. Climate conditions in Saint-Pierre, La Reunion

	Air temp. (°C)			RH	Mean air speed	Mean global solar radiation
	Mean	Min	Max	(%)	(m/s)	(kWh/m²/day)
SUMMER	25.6	17.8	32.5	73	2.4	6.1
WINTER	21.3	14.3	29	73	3.2	4.7

In January 2009, the first zero energy building of La Reunion was inaugurated in the campus of Saint-Pierre (in the south of the island). It is a two-floors university building (split into two parallels parts separated by a vegetated patio) composed of an administration zone (7 offices and an assembly room), 2 computer rooms and 5 classrooms for a total net floor area of 625 m². The main feature of the building is to use passive means to achieve thermal and visual comfort in the building. Air-conditioning and artificial lighting should be used as a last resort (Garde, 2006). The methodology used to design the building is explained in the part 1 of this paper (Garde, 2011).

The building is surrounded (3m band) by vegetation in order to prevent heated air from penetrating the building when used in natural ventilation mode. The main facades are north-south orientated (to exploit thermal breezes during summer) and their porosity is 30% thanks to glass louvers which have the advantage of allowing regulation of the airflow, while also providing protection against cyclones and break-ins. The porosity is defined as the percentage of opening in a facade. The

PERENE tool, a specific design standard in La Reunion gives the minimum value for the porosity as 20% (Garde, 2005) to ensure a sufficient natural ventilation of the spaces. In the administration zone, the central corridor around which the offices are located was cutting off the ventilation. The original feature of the project was to install indoor louvers which enhance the interior airflow, providing an interior porosity of 30% (Figure 1). Another innovation was to install large ceiling fans (Figure 4) in all spaces, including those with air-conditioning. The use of ceiling fans guarantees an additional air speed during the windless days and allows a transitional period before the use of active air-conditioning systems.

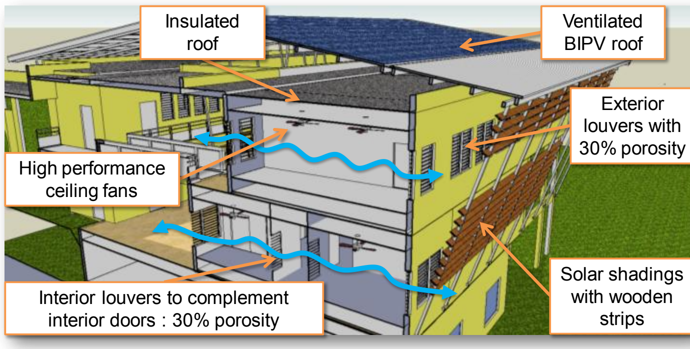

Figure 1 *Main features of the Enerpos building: passive design such as cross natural ventilation, solar shadings and insulated roof.*

Concerning the envelope, the roofing is insulated with a 10 cm-layer of polystyrene and a ventilated BIPV (building integrating photovoltaic) over-roof; the walls are made of concrete; the north and south facades are solar protected with shadings made of wooden strips; the east and west gables are insulated with mineral wood and a wooden siding.

The BIPV roof allows the production of 70 000 kWh/y. The building is fully monitored with energy meters by type of use to evaluate the real consumption of the building during occupancy. The first results give an energy index of $30kWh_{FE}/m^2_{NFA}/y$; the building produces almost four times as much energy as it consumes.

THERMAL COMFORT EXPERIMENTAL FEEDBACK

Methodology

The thermal comfort study consisted in a survey based on ISO 10551 (1995). The evaluation was carried on the students during the classrooms hours of occupancy. Students were asked to fill a questionnaire at the same time as the environment variables were being recorded. The study was carried out during 2009 and 2010 hot seasons (October - April), overall a total of 1749 questionnaires were filled in by 594 students and their teachers during 108 2-hours sessions. The average age was 23 years old; the mean value for the clothing was 0.4clo.

The survey. The survey was based on four sections:

1. Personal information (age, gender, size, weight, details of clothing and activities before the exposure);
2. Thermal comfort at the beginning of the exposure (when the occupants enter the classroom);
3. Possibly thermal comfort before and after the break (only for 4-hours sessions);
4. Thermal comfort at the end of the exposure (when they leave the room).

The three scales defined by ISO 10551 (1995) were used: perceptive, evaluative and preferential judgment. The perceptive judgment scale (Table 2) was used to express thermal sensation; the thermal judgment was stated by the evaluative judgment scale (Table 3).

The answers given at the beginning of the exposure depend a lot on the previous activity of the respondents. Moreover it is not characteristic of the interior environment indeed according to Nicol (2004) the human body needs time to respond to a change in the heat balance. That is why the following results will only include the mean answer at the end of the exposure (or possibly the mean answer before the break and the mean answer at the end of the class).

Table 2. Perceptive judgment scale – thermal sensation. "How do you feel at this moment?"

Cool	Slightly cool	Neutral	Slightly warm	Warm	Hot	Very hot
-2	-1	0	1	2	3	4

Table 3. Evaluative judgment scale – thermal judgment. "How do you judge this environment?"

Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable	Extremely uncomfortable
0	1	2	3	4

Thermal comfort parameters. The environment variables are air temperature (T_a in [°C]), globe temperature (T_g in [°C]), air velocity (v_a in [m/s]) and air humidity (*RH* in [%]). Specific equipment in accordance to ISO 7726-1998 was placed at the center of the classroom; the parameters were recorded every minute throughout the session. In the following results, the measures taken into account are averaged over the last hour of exposure except for the air velocity which is averaged over 15 minutes. Those measurement periods are defined by ASHRAE Standard 55-1992.

Results

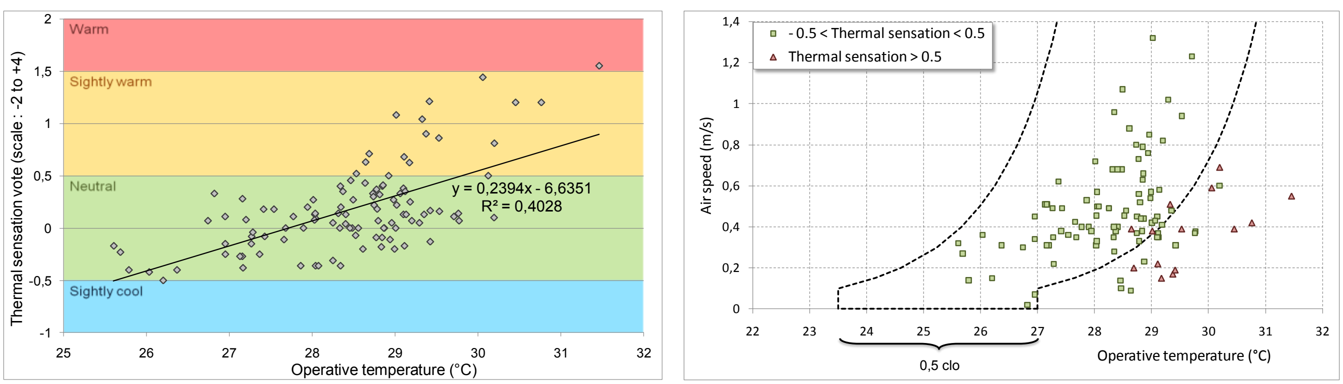

Figure 2 *(a) Thermal sensation as a function of the operative temperature and (b) air speed as a function of operative temperature.*

To represent the comfort survey results, we used the operative temperature (T_{op}), defined in ISO 7730-1995, which take into account not only the air temperature but also the walls temperature responsible for the radiant exchanges with the human body. The measurement of the globe temperature (T_g) enables the calculation of the mean radiant temperature T_{mrt} (ISO 7726-1998).

$$|T_a - T_{mrt}| \leq 4°C \quad \rightarrow \quad T_{op} = \frac{T_a + T_{mrt}}{2} \qquad (1)$$

$$T_{mrt} = \left\{\left(T_g + 273\right)^4 + 2.5 \times 10^8 \times {v_a}^{0.6}\left(T_g - T_a\right)\right\}^{1/4} - 273 \quad (2)$$

Thermal sensation. The thermal sensation is plotted on Figure 2(a) as a function of the operative temperature. It shows that the EnerPos building is rather comfortable for its occupants because most dots are included in the "neutral" zone. The dots above correspond to the hottest days of the year in the computer rooms (with 20 computers turned-on). During a few days per year, the air-conditioning is preferable to achieve thermal comfort in computer rooms and offices. But compared to a classical building in La Reunion (wherein air-conditioning would be used at least 6 months per year), the air-conditioning period is drastically reduced.

Below 29°C, the majority of the respondents feel "neutral" which means that they can't say if they are cool or warm. Above this temperature, they express a sensation of light warmth. The tendency is an increasing linear straight line but the correlation coefficient (R^2) stays low.

Arens (2009) defines a comfort zone extended from -0.5 PMV (the thermal sensation midway between "neutral" and "slightly cool") and + 0.5 (between "neutral" and "slightly warm") that depends on operative temperature and air speed. A comfort zone of the same kind is drawn on Figure 2(b). ASHRAE Standard 55 (1992) indicates a still-air range for operative temperature of 23.5°C – 27°C (for 0.5 clo). Starting with this range, comfort envelopes are defined using the work of Nicol (2004) on air movement: when the air velocity is above 0.1m/s, the comfort temperature can be raised according to Eq. (3).

$$T = T_{op} - 7 + \frac{50}{4 + 10v^{0.5}} \quad (3)$$

The same dots as in Figure 2(a) are drawn, differentiating the thermal sensations inferior to 0.5 (green squares, corresponding to a comfort situation) and superior to 0.5 (red triangles, corresponding to discomfort). Most green dots (indicating comfort) are inside the comfort envelope whereas most red dots are outside. This comfort zone seems to represent well the thermal sensations of the occupants. But thermal comfort is not only about the sensation, but also about the judgment of a specific ambiance.

Thermal judgment. While the thermal sensation depends mainly on the heat balance of the human body, the thermal judgment is more difficult to forecast because it depends also on psychological factors and thermal experiences. According to Humpreys (2007), people in hot climates might prefer a sensation slightly cooler than neutral. On Figure 3, the mean thermal judgments votes are represented as a function of the mean thermal sensation votes at the same time. A parabolic tendency emerges on this graph, the regression factor of which is R^2 = 0.64. The minimum is situated around -0.15, which means that people do not necessarily feel comfortable when their sensation is neutral. It seems that some people prefer to feel "slightly cool". This could be explained by high air humidity which provokes an increase in the comfort temperature.

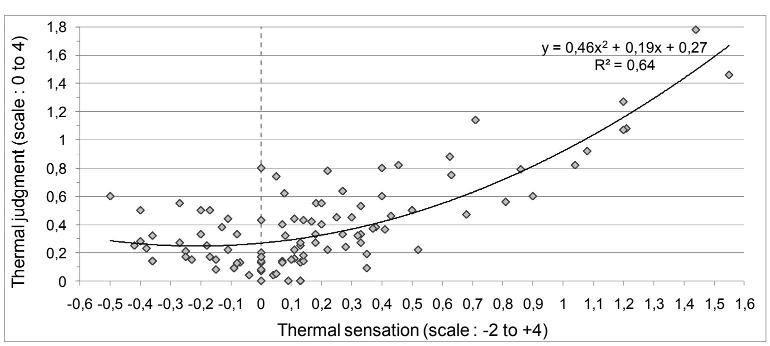

Figure 3. *Thermal sensation votes as a function of thermal judgment votes.*

MECHANICAL AND NATURAL VENTILATION EXPERIMENTAL FEEDBACK

Description of the ventilation system

Ceiling fans are used in the EnerPos building to complete natural ventilation and to create an air speed on the skin of the occupants and thus to increase the comfort temperature. A total of 55 ceiling fans with 132 cm blade diameter are provided in offices, assembly hall and classrooms. Figure 4 shows the type of 3-blades ceiling fan used in the building. For the offices whose area is less than 15 m², one ceiling fan was installed and two were placed for offices whose area is more than 15 m² (but less than 20 m²). In the classrooms six ceiling fans are arrayed in 50 to 60 m². Fans are controlled individually (in the offices) or in groups of two or four (in the classrooms) from wall-mounted switches and have three speed levels. The maximum power used is 80 W (given by the manufacturer). The measurements conducted in the building gave a power of about 70W when the ceiling fan is running at the higher speed. The aim of this paragraph is to study the potential ventilation of the spaces provided by natural ventilation and by the ceiling fans.

Methodology

The air speed measurements were conducted in a classroom on the second floor with a height of 0.9 m that represents the chest of a seated person. The aim was to establish the range area of the ceiling fans (functioning at the maximum speed level) in which 0.7 m/s air velocity is supplied. Two measurement series were carried out, the first one with closed louvers and the second one with the louvers opened. The day of measurements was during summer season and was not very windy, with a mean air speed of 0.9 m/s (the averaged outside air velocity during summer in Saint-Pierre is 2.4 m/s given in table 1).

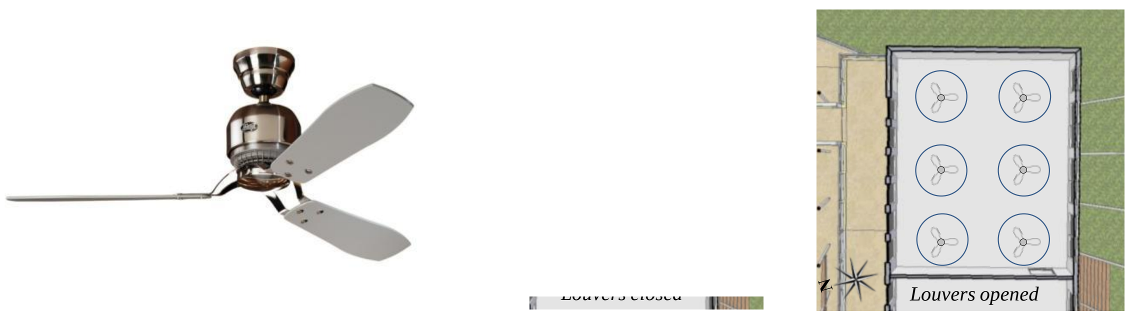

Figure 4 (a) High performance ceiling fan. (b) Results of the air speed measurements conducted with the louvers closed: ceiling fans are represented and the blue circles are the areas in which 0.7 m/s air velocity is supplied. (c) The same results with the louvers opened (natural and mechanical ventilation combined).

Results

The results on Figure 4 (b) show the circles in which 0.7 m/s air velocity is supplied. When the louvers are closed the circles are small, with a diameter barely bigger than the blades. This small radius can be explained by the fact that the switches control a group of ceiling fans whereas they are originally sold with individual controls. For convenience reasons, the fans are controlled in groups of two (ahead of the blackboard) and four (the rest of the classrooms) but it seems that the intensity provided by the potentiometers do not correspond to the one provided by an individual switch. The current switches should be soon replaced by individual ones; it should then increase the range of the ceiling fans. On Figure 4 (c), the same results are presented with the louvers opened during the measurements. The circles drawn are the average diameter in which 0.7 m/s air velocity is supplied. The average diameter is 1 m and a major part of the classrooms has then an average air velocity of 0.7 m/s.

VISUAL COMFORT EXPERIMENTAL FEEDBACK

Methodology

Always with the goal of reducing the energy use, daylighting measurements were conducted in the offices and classrooms in order to evaluate the daylight autonomy of the building. The illuminance was measured in 12 points of the room (on the desks), every hour from 8 am to 6 pm in a classroom on the second floor. The measurements were carried out on a cloudy summer day (global solar energy on horizontal plane: 4.4 kWh/m²).

Results

Three zones were defined functions of the illuminance level (Figure 5). The graphic presents the average illuminance in each zone for every hour. The recommended level of illuminance (300 Lux) is reached in all zones during the day except at 8 am and after 5 pm. The daylight autonomy for this classroom is 90% on a cloudy summer day.

This daylight study was carried out with the aim of optimizing the artificial lighting distribution. As for daylighting, three zones should be defined for artificial lighting with three individual switches so that the occupants could turn on only the essentials lightings.

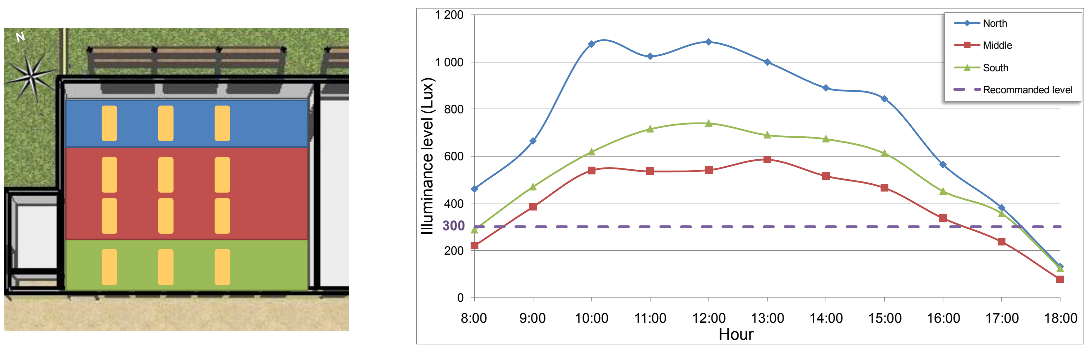

Figure 5 (a) Distribution of the three daylighting zones and location of the 12 desks on the classroom. (b) Graphic representing the average illuminance level for each zones during every hours from 8 am to 6 pm on a cloudy summer day.

CONCLUSION

This paper presents the experimental feedback of the "EnerPos" building in terms of thermal comfort, daylighting and ventilation. All measurements were conducted with the aim of reducing the energy use of the building and to maximize the bioclimatic solutions such as cross natural ventilation and daylighting to avoid energy consuming active systems such as air-conditioning and artificial lighting.

The first part concerning thermal comfort feedback based on a survey conducted in the building during two summer seasons shows the difficulty of assessing thermal comfort in tropical climates. The thermal sensation can be linked with the globe temperature and air velocity, but it is particularly difficult to forecast the responses for the thermal judgment that not only depends on the environment but also on psychological factors and behavioural adaptations. The study should be continued especially to include the problematic influence of humidity which is very high under tropical climate.

The second and the third parts about ventilation and daylighting measurements show that these measurements can give the opportunity for optimizing the systems, such as ceiling fans and artificial lighting, and lead to a decrease in energy consumption of these systems.

NOMENCLATURE

RH = Relative humidity [%]

T = Temperature [°C]

v = Velocity [m/s]

Subscripts

a = Air

g = Globe

op = Operative

mrt = Mean radiant temperature

fe = Final Energy

nfa = Net Floor Area

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