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Abstract. This paper presents the Post Occupancy Evaluation of the first naturally ventilated lecture theatre built in a tropical region. The challenge was to design a bioclimatic amphitheatre of 550 seats, which does not use air conditioning and remains comfortable at the same time. A post-occupancy evaluation has been carried out based on, in parallel, indoor and outdoor measurements, and a user's survey. Airflow measurement is used to check the good performance in terms of natural ventilation. A follow-up of the building's actual consumption has been carried out as well, which showed overall positive results. 92% of the users feel comfortable or slightly comfortable during the hottest days. Nevertheless, 50% of them would prefer to get more air movements. In terms of energy consumption, the lecture theatre consumes four times less than a standard one.

1. Introduction

Bioclimatic buildings allow the control and the limitation of energy consumptions, particularly impacting the building sector. However, to be properly used, occupants must be in a comfortable situation inside the building, which will prevent the addition of active consumer equipments. Because of the number of variables influencing thermal comfort inside the buildings, the occupants' opinions are very important in order to understand the interrelationships between these different variables.[1]

In tropical climates, many studies have demonstrated that users are acclimatizing to their natural environment and can tolerate warmer indoor temperatures [2], particularly in naturally ventilated buildings, which has led to the adoption of new standards of adaptive comfort [3,4]

Post occupancy evaluations (POE) evaluate buildings performances with respect to energy consumption, environmental impact, and occupant sensation and thermal judgment. POE allow identifying problems in the buildings and to check the performance that the building promised [5]. Khalil highlighted the importance of POE by providing feedback to the building owner, using physical measurements and self-administered 5-point questionnaire surveys over a specific slot. [6]

Nevertheless, the measurement periods are not necessarily representative of all climatic conditions. In this context, we have tried to extend occupants' sensation over a long period, by finding correlations between the indoor temperature, the black globe temperature over a time slot, and users' thermal sensation mark.

Very few studies have been carried out on naturally ventilated lecture theatres in tropical climates. Kavgic explained the complexity of this kind of environmentally friendly building, because thermal loads are often high and must be distributed over large areas. In addition, the thermal characteristics must be in accordance with the acoustic principles [7]. Researches about lecture theatres in tropical climates mainly focused on air-conditioned buildings [8–10]

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This paper presents the POE and the results obtained of the first naturally ventilated lecture theatre in tropical climates between 2014 and 2017.

2. Research methodology

As the building is innovative, we do not have a similar building reference. We wondered if the building was comfortable for the users. The problem with high-performing buildings is that they are often delivered regardless the actual performance or user satisfaction.

2.1. Presentation of the first naturally ventilated Lecture Theatre in Reunion Island

The building designed by the architect Olivier Brabant is located on Saint-Denis university campus, in Reunion Island, a French overseas department in the Indian Ocean (55.5°E, 21°S).

The construction of this 550 seat bioclimatic lecture theatre is part of the sustainable policy of the University of La Reunion, which aims to be an active green stakeholder by constructing sustainable buildings in order to reduce its environmental impact. Unfortunately, because of the insularity of Reunion island, the electricity production is mainly based on fossil fuels. Standard academic buildings (including lecture theatres) are fully air-conditioned and consume more than 100 kWh/m²/year.

The lecture theatre does not use air conditioning and operates by using innovative passive design principles of natural ventilation. It was delivered in September 2014.

The goal was to create inflows and outflows, using natural ventilation according to the climatic conditions, even when the intensity of the outside wind is low. The principle is to reach -4°C in perceived temperature relative to the indoor temperature, creating an air movement about 1m/s in the thermal zone occupied by students or spectators. The architect Olivier Brabant, with the help of the French expert in building aerodynamics Jacques Gandemer, has defined several design principles. The main innovating idea was to create an opened U shaped-roof at the top to accelerate the trade winds and create a low pressure by the venture effect. Thanks to this natural pump, airflows can come from the sides of the building and underneath the seats, as represented by Figure 2. Those principles have been validated by wind tunnel tests conducted in the Eiffel Laboratory in Paris. Combined with natural ventilation, solar gains are avoided with large overhangs that protect the glass louvers and the main facades, and an efficient insulation for the roof.

Figure 1 Cross-ventilation in user's living space. One can see glass louvers on each side for cross natural ventilation and the opened "U shape" at the top of the ceiling, which creates a low pressure that allows airflows to come from the sides. Photo credit (René Carayol)

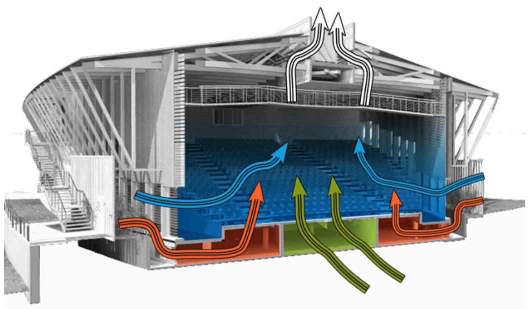


Figure 2 Principles of natural ventilation. The opened « U shape » at the top of the roof creates a low pressure which allows air flows to come from the sides (blue arrows) or underneath the seats (orange and green arrows). Image courtesy of Olivier Brabant

2.2. Field measurements

Different sensors have been set up in strategic areas of the building. Some measurements were made over the whole period, and others over specific slots.

Nine air temperature and relative humidity sensors, collecting data every 10 minutes, have been allocated throughout the amphitheatre.

In the same time, on the roof, a weather station was measuring wind speed and direction, air temperature, and relative humidity under a ventilated shelter, rainfall, and solar radiation.

During the distribution period of the comfort surveys, a thermal Data Logger, measuring air temperature, black globe temperature, humidity, luminosity, CO2 concentration and wind speed, has been placed in the bleachers in the central area of the amphitheatre.,1m10 high, in the user's living-space.

The first measurements have been conducted for 7 months, from December 2014 to June 2015. Additional measures have been carried out in 2016 and 2017.

Table 1 Measured parameter

Instrument and measured parameters	Quantity	Location	Measurement period	Accurancy
Air temperature and relative humidity sensors	9	Throughout the amphitheatre	Continuous measurements between January and June 2015 + 2016/2017 Time interval: 10 minutes	Temperature : +/- 2% Relative humidity : +/- 2%
Weather station (wind speed and direction, air temperature and relative humidity under a ventilated shelter, rainfall, and solar radiation)	1	On the roof	Continuous measurements between January and June 2015 + 2016/2017	
Thermal Data Logger (air temperature, black globe temperature, relative humidity, luminosity, and air speed)	1	In the bleachers (central area of the amphitheatre ,1m10 high, in the user's living-space)	During the time slots of surveys between January and June 2015 + 2016/2017 Time interval: 15 seconds	Wind speed : 0,02 m/s for 0,05m/s < v < 1m/ or 0,1 m/s for 1m/s < v < 5 m/s

2.3. Subjective surveys

Besides the measurements, we have tried to assess the users' thermal perception of the building. A total of 1144 questionnaires have been completed, over about twenty time slots. The users were mostly students from the university or people who come to attend conferences or performances.

The survey includes open or closed questions about user's comfort, air movement, humidity, but also questions concerning their personal information (clothing), acoustics, space, furniture, and visual aspect. Each person must indicate his or her position in the bleachers. This makes it easier to identify problematic areas. Some questions need to be completed at the beginning of the slot and others at the end of it. We consider that the first impression depends on the previous activity and not on the real atmosphere of the building.

Survey questions should be easy to understand, the context needs to be presented in a convenient form, and data must be easily recorded and processed. Survey gives us occupants' sensation and judgment for the thermal, hygrometric and air speed comfort, over this period, using the three scales defined by ISO 10551 (1995). The thermal sensation is given by the perceptive judgment scale. It represents user's feeling at the moment. The evaluative judgment scale gives the thermal judgment of the environment. The last part of the survey aims to identify all the comments and ideas that will be used to analyze the comfort profile according to the location, and to make various improvements in the building. At the same time, physical measurements allow to provide objective quantitative data and to locate problems.

Table 2 Thermal sensation and thermal judgment

Thermal sensation scale - Perceptive judgment at the moment	Very cold	Cold	Slightly cold	Neither hot nor cold	Slightly hot	Hot	Very hot
	-3	2	1	0	1	2	3

Thermal judgment scale of the environment	Comfortable	Slightly uncomfortable	Uncomfortable	Very uncomfortable
	0	1	2	3

2.4. Extension of results over a longer period of time
From the results of the post-occupancy evaluation over specific slots, we aimed to expand the occupants' feelings over a longer time-period, by finding correlations between the indoor temperature, the temperature of the black globe over a slot, and the thermal sensation score given by the users. In order to obtain the results over an extended period, the following steps were necessary:

Step 1 Correlation between black globe temperature and thermal sensation mark over specific slots
Step 2 Correlation between inside temperature and black globe temperature over specific slots
Step 3 Inside temperature measurement over 6 months
Step 4 Interpolation and determination of the thermal sensation mark over the whole period

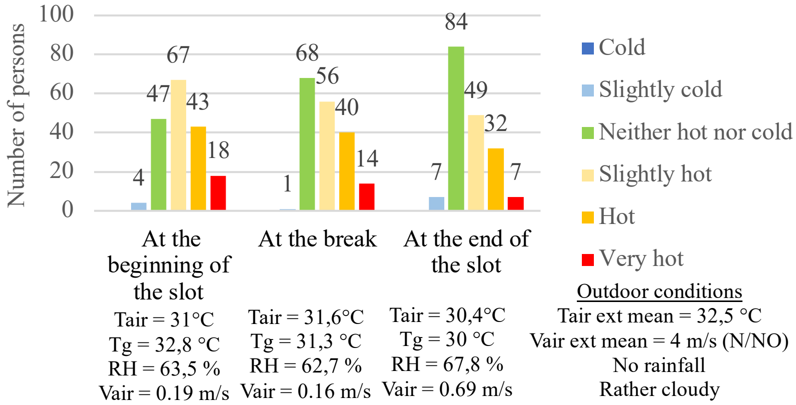
2.5. Additional monitoring
This is the first building in Reunion Island to be tested in a wind tunnel in the Eiffel laboratory in Paris. In order to validate the proper building operation, we used an experimental protocol, developed by Jacques Gandemer, with airflow meters allowed to verify the airflow efficiency inside the lecture theatre, especially on stage and in the different rows where users are seated, during different periods and intensity of wind. Finally, the last step of the feedback consisted in analyzing the energy performance of the building, thanks to energy meters, installed by end-uses. The complete results of these studies will be reported in a subsequent paper.

3. Results and discussion
From the building's instrumentation and comfort surveys, we can analyse different outcomes: analysis of the overall comfort, comfort analysis by area, building functioning.
Analyzing the indoor temperature measurements, we can see that the hottest months extend from December to March, for the year 2015, with some temperatures exceeding 30°.

The overall thermal sensation is "neither hot nor cold", and the thermal judgment is "slightly uncomfortable", which may correspond to a lack of ventilation inside the lecture theatre during the hottest months. However, the given marks are more in line with a comfortable zone. The highest thermal judgment ratings are reached for the areas at the bottom of the amphitheatre, close to the stage. This can be explained by the fact that the lower areas are slightly less exposed to lateral windows. We have found that the more general concept of thermal judgment is not always well-understood by users, contrary to the concept of thermal sensation, which better describes the user's feeling according to a very specific factor.

Results of the evaluation form give a linear regression between black globe temperature and the global thermal sensation mark. Up to 28.5°C, users feel " Neither hot nor cold ". Beyond 28.5°C, users start to feel "Slightly Hot"; it is here that the proper management of the opening of the windows must be carried out, in order to increase the air velocity.

Figure 3 Thermal sensation evolution_ Example of January 20, 2015_2pm to 4pm. (Tair = Air temperature [°C], Tg = Black globe temperature [°C], RH = Relative humidity [%] and Vair = Air velocity)



Over the 6 months surveyed in 2015, 78% of occupants felt that they were in a neutral situation. 14% felt slightly hot between December and March, the warmest months of 2015. Over this period, the lecture theatre is not busy because of school holidays, therefore the high temperatures are not necessary disturbing for users. 22% were slightly cold after May, at the beginning of the winter season. In summer, the most uncomfortable period is between noon and 4 p.m. In winter, it's the opposite.

Figure 4 The extended thermal sensation between December and June 2015. Yellow = Slightly hot, Green = Neither hot nor cold, Blue = Slightly cold

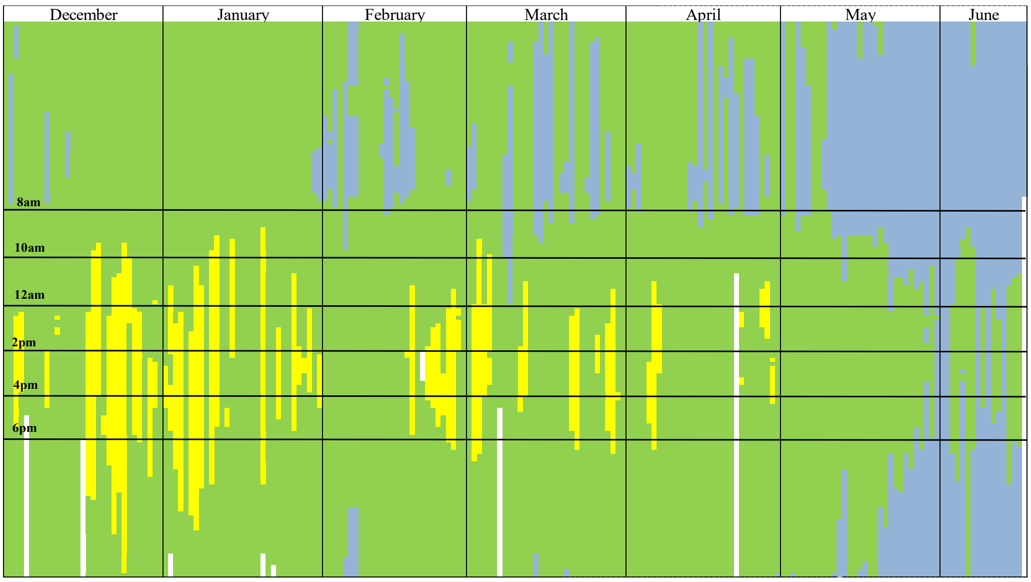
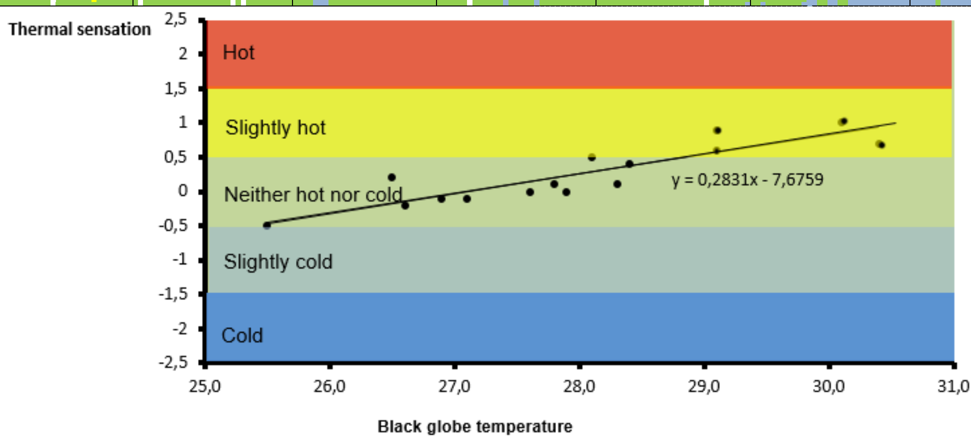


Figure 5 Linear regression between black globe temperature and thermal sensation in 2015



A lack of air movement is felt by the majority of users in hot periods, even if thermal comfort is reached. The central part of the theatre is less efficient in terms of air movements whereas the sides of the theatre are more comfortable. With reference to energy performances, this innovative lecture theatre consumes only 23 kWh/m²/year, which is four times less than a standard lecture theatre.

4. Conclusion

Results show that the POE of the first naturally ventilated lecture theatre in the Tropics is overall positive. The lecture theatre of La Reunion gives a comfortable work environment without using air conditioning, which is very reassuring for the staff of the University and the designers of this new kind of building. It should allow the University to adapt the occupation schedule, avoiding conference and lectures between midday and 4 pm in the summer, in order to optimize users' comfort.
Optimizing natural ventilation is an important key in tropical climates and helps to avoid the use of air conditioning. The ventilation principles used on tertiary buildings, such as offices, are more easily repeatable, because they are generally more compact and more suitable for natural cross-ventilation.
This study has shown it is possible to bypass air conditioning for an amphitheatre with a larger structure, by optimizing air flows using a depressurisation well system.

5. Acknowledgments

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