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DESIGN AND USE OF RADIANT BARRIERS AS THERMAL INSULATION FOR HIGH INERTIA HOUSES IN TROPICAL CONDITIONS – A CASE STUDY

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ABSTRACT

This paper deals with the thermal design and performance of a roof-mounted radiant barrier, installed in a high inertia house in tropical and humid conditions. Using dynamic simulations of a mathematical model of a whole house including a radiant barrier installed between the roof slab and the ceiling, the thermal performance of the roof is calculated and the thermal comfort in the house is evaluated using the psychometric chart. The mean method is more particularly used to assess the thermal resistance of the building roof and lead to a value which can be compared to those obtained using mass insulation product such as polyurethane foam or glass wool. The aim of the study is to evaluate the most appropriate technical solution to insulate high inertia roofs of buildings, which can accumulate much energy during the day and create uncomfortable thermal conditions in the late afternoon and during the night in summer tropical conditions.

INTRODUCTION

In tropical and humid climatic conditions, like in La Réunion Island, a French overseas department located in the Indian Ocean, saving energy and assessing thermal comfort conditions in buildings is of great importance. The need for active cooling of buildings, due to extreme climatic solicitations, is indeed growing and on the contrary the means of electricity production are quite limited because of the insularity. More particularly, in case of individual housing, the use of active systems, like split-systems for example, is increasing with the increasing level of household equipment.

Architectural design of houses in La Réunion has greatly evolved with the years and has followed several stages. From the existing range of houses, one can see the general evolution, which can be related to industrial, economical, sociological and environmental reasons [1]. This evolution has led to buildings not always in relation with the climate, such as high inertia houses with flat roofs made of concrete. This type of houses have been promoted for safety reasons associated with the storm risk during summer in tropical and humid climatic conditions. In these old days, roofs were indeed quite unresisting to strong storms and could be destroyed with gusty winds. Although this solution was very effective during storms, its impact in terms of thermal comfort was very negative and has encouraged the use of active cooling. This was in contradiction with thermal design in La Réunion which indeed consists in important efforts to minimize heat gain through buildings, generally with a convenient solar protection of walls and windows.

In this paper, we focus on one of this type of houses with the aim of improving the thermal comfort conditions, using insulation materials for the roof. It is well known that radiation heat transfer is the major source of discomfort of high inertia houses, and that’s the reason why we studied several technical solutions for insulating the roof, including radiant barriers.

NOMENCLATURE

φ	[W.m^{-2}]	Heat flux density through the wall
R	[m^{2}K/W]	Thermal resistance
Tsi	[K]	Surface temperature of the interior side of the wall
Tse	[K]	Surface temperature of the exterior side of the wall

Special characters

α	[-]	Solar Absorptivity
λ	[W.m^{-2}.K^{-1}]	Thermal conductivity
ρ	[kg.m^{-3}]	Density
Cp	[j.kg^{-1}.K^{-1}]	Thermal capacity
a	[m^2.s^{-1}]	Thermal diffusivity

THE CASE STUDY

The house studied here is representative of an old type of building construction, were vertical walls were built with basaltic rocks, linked together with a specific binder called “argamate”. The resulting geometrical characteristic of the wall was its thickness, varying from 0,4 to 0,6m. Thus the thermal inertia of the walls was very important. With the growing use of concrete and in order to be protected from storms, such houses were sometimes renovated and thus equipped with flat roofs made off reinforced concrete. The resulting inertia of the whole house was thus much higher.

A schematic top view of the case house is proposed on figure 1. It is composed of five rooms, including a dining room with kitchen, an entrance hall, a bathroom, a bedroom and a study, with the dimensions indicated on the figure.

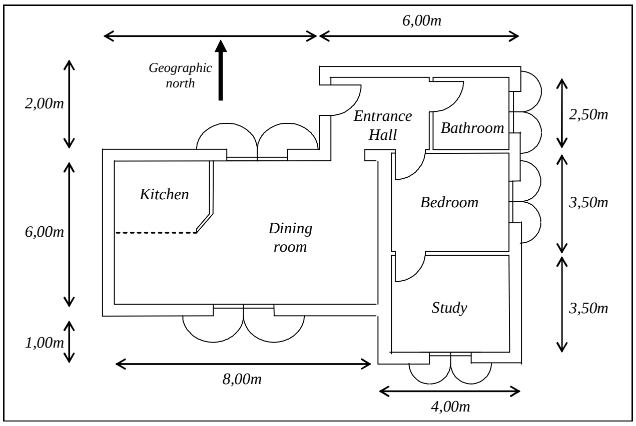

Figure 1: Schematic top view of the case house

In order to have a typical illustration of the whole house, a section view is shown in figure 2, where one can see the flat roof made of concrete.

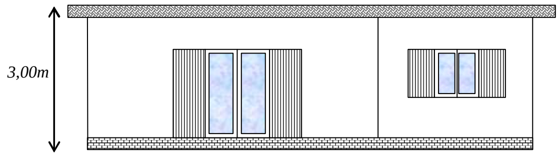

Figure 2: Section view of the case house showing the flat roof

The front side of the house, illustrated above, is facing south, and each of the main rooms is equipped with at least one window with standard dimensions. The floor slab is insulated from the ground and is made of reinforced concrete.

The dimensions and compositions of the several walls of the house can be described as indicated in the following table 1.

Type of wall	Material	Conductivity [W.m^{-1}.K^{-1}]	Density [kg.m^{-3}]	Thermal capacity [j.kg^{-1}.K^{-1}]	Thickness [m]
Exterior walls	*concrete*	*1.75*	*2100*	*653*	*0.5*
Internal walls	*concrete*				*0.1*
Roof	*concrete*				*0.2*
Floor	*concrete*				
Windows	*glass*	*1.4*	*2500*	*750*	*0.008*

Table 3: Physical properties of the walls

The house is located near the island coast (altitude 0) and is supposed to experience a strong summer climate, characterised by a strong solar radiation and low winds. Another important characteristic of the climate influencing the thermal comfort is the relative humidity, which reaches high values under tropical and humid climatic conditions. The climatic data used for the simulations of the houses will be presented further in the paper.

For the insulation of the roof of the case house, several technical solutions are available. Nevertheless, it is important to note that it is rather recommended to insulate flat roofs with an exterior insulating material for higher thermal performances, and that installing the insulating material just below the flat roof is prohibiting because of the structural damages due to the dilatation of the metallic structure.

For our study, we will focus on all possible technical solutions, in order to answer a wide range of situations that can be encountered. The several cases can be summarised as follows:

	Code	Technical insulating solution	Description
1	Ref	*None*	*Reference case without thermal insulation*
2	LDV	*Glass wool*	*Insulation of the roof using glass wool installed under the roof, after an air layer*
3	FPR	*Reflective ceiling*	*The ceiling is equipped with a reflective side facing the roof*
4	PMR	*Reflective insulation material or radiant barrier*	*A radiant barrier is installed between two air layers*
5	Refiso	*Mass insulation*	*Insulation of the roof using mass insulation installed above the roof*

Table 2: The several insulating technical solutions studied

For the LDV, FPR and PMR configurations, a section view of the roof is proposed on figures 3, 4 and 5. It is important to note that an air layer is built in the framework of the insulated roof in case of interior insulation, between the roof slab and the ceiling made of plasterboard (*0.008m thick*). This is the major difference between the cases 2, 3, 4 and the case 5, where there is no air layer between the roof and the thermal insulation.

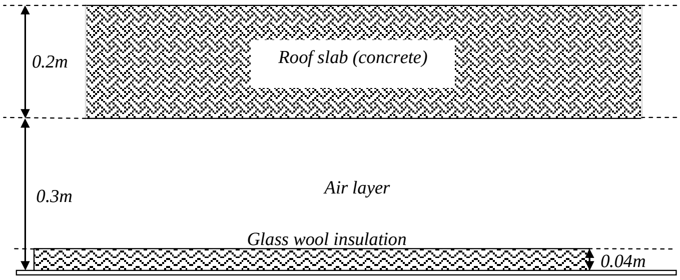

Figure 3: Section view of the roof with glass wool insulation

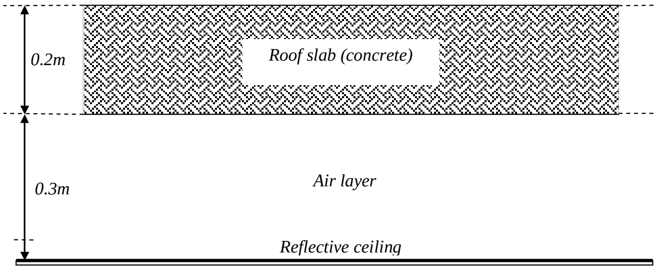

Figure 4: Section view of the roof with a reflective ceiling

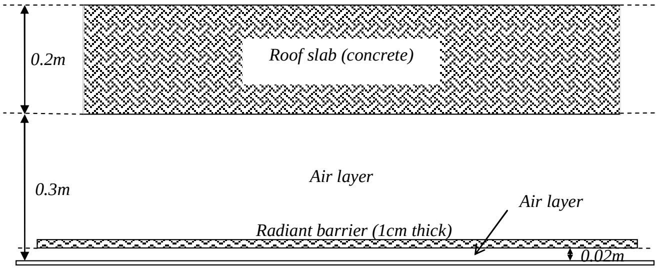

Figure 5: Section view of the roof with a radiant barrier

MATHEMATICAL MODELLING

The models used for the simulations of the several technical insulating solutions were described with the code *ISOLAB*, developed under the *MATLAB* environment at the Building Physics and Systems Laboratory. It is a prototype of building simulation code, which integrates the models for heat and mass transfers in macrovolumes or zones. Specific developments were done to allow the simulation of complex walls and more particularly those containing insulating products such as mass insulation or reflective insulation. They concerned the radiation and convection models, and were implemented according to a multimodel approach (the user can choose between several mathematical models for each physical phenomenon). The method of radiosity is thus used for radiative heat transfers and convective heat transfers in the air layers can be described by means of adimensional correlations or other relations with the generic form $h_{ci} = a.(\Delta T)^n + b$.

For the simulation of the case house, the geometric and thermophysical data included in table 1 are needed as well as the details of the configurations indicated above. Moreover, the choice of heat (conductive, convective and radiative) and mass transfer models has to be made, and in conjunction with the selection of a meteorological file allow the processing of the simulations.

For the general description of the house model, the natural decomposition is the one shown in figure 6. A total of five thermal zones are described, each of them corresponding to a room in the house. As for technical solutions 2, 3 and 4 air layers are needed, the total of zones for each solutions is different, as indicated in table 3.

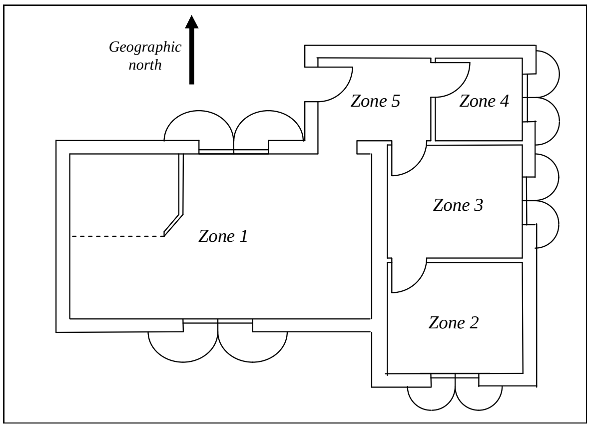

Figure 6: Description of the zones of the model

	Code	Number of zones
1	Ref	*5*
2	LDV	*6 (+ 1 air layer=attic)*
3	FPR	*6 (+ 1 air layer=attic)*
4	PMR	*7(+ 2 air layers=attic + lower air layer)*
5	Refiso	*5*

Table 3: Number of zones for each configuration

Once this general description is stated, it is necessary to choose the convenient models for each physical phenomenon. For heat transfer by conduction in the several walls, the Fourier equation is solved numerically by finite difference approximations, which is the common method in building simulation codes. For the radiation heat transfer in each zone, the radiosity method is used and allows taking into account the radiation characteristics of the walls; this approach is necessary when dealing with heat transfer with radiant barriers for example, whose emissivity is very low, of the order of 0.1. For the convection heat transfer in the house, it is important to have accurate relations in order to correctly translate the general behaviour of the zones. Thus, for each of the zones 1 to 5, that is, the dining room, the study, the bedroom, the bathroom and the hall, the convection coefficient is calculated according to the relations given by awbi [2] for vertical walls, floors and lower side of ceilings. These relations are interesting in the sens that they are based on experimental results and have been well compared with the other existing relations. For the convection heat transfer coefficient in the air layers (attic and lower air layer), the relation given by Elsherbiny [3] was used. This relation is indeed interesting because it is based on experimental results of natural convection within differentially heated cavities and has also been well compared with other existing relations.

Finally, to account for air infiltration in the building, a mechanical ventilation system is described in the model and allows the evacuation of three volumes of air per hour.

SIMULATIONS AND RESULTS

The five models described previously have been run with *Isolab* on a climatic sequence corresponding to a strong summer in La Réunion. The main characteristics of the climate conditions are shown on figure 7, for solar radiation, and 8, for outdoor air temperature and relative air humidity.

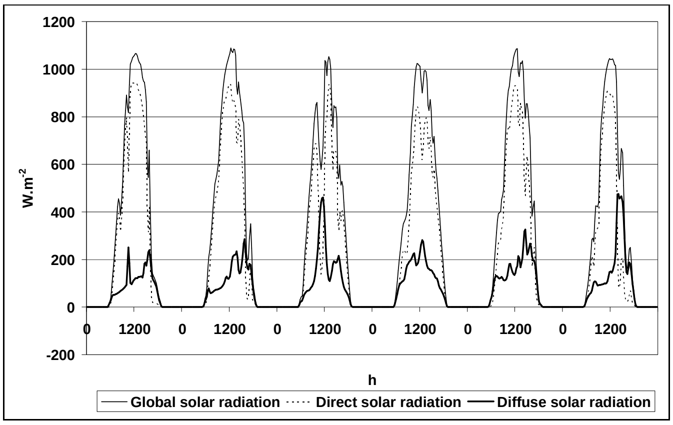

Figure 7: Solar radiation during the climatic sequence

As seen on the figures, the tropical and humid summer is characterised by a strong solar radiation coupled with a high level of relative humidity.

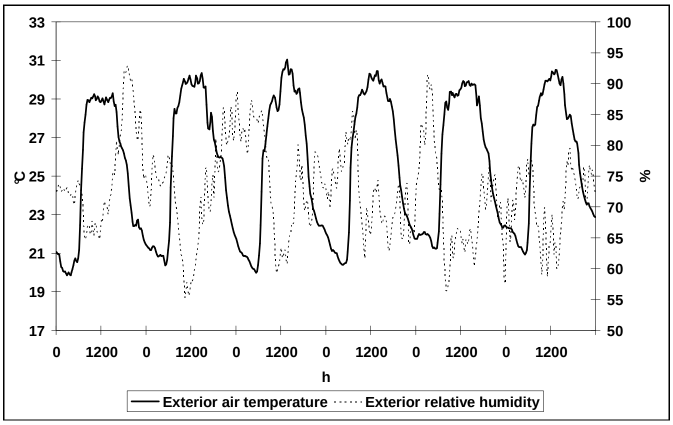

Figure 8: Exterior temperature and relative humidity during the climatic sequence

Moreover, to better understand the general behaviour of the building, a sensitivity analysis has been run in a first stage.

Results of the sensitivity analysis

The sensitivity analysis procedure is based on the works of Mara [4]. The method consists in affecting at each parameter of a model a specific frequency (its signature) and in running several simulations (N+1, where N is the number of parameters of the model). For each simulation, the parameters are varied according to a given percentage, the general form along the whole procedure being a sinusoid, thus allowing a specific sampling of the values of the parameters; this procedure is used to allow a wide scanning of the parameters space and thus put in evidence the influence of the parameters on a chosen output. For this, it is possible to identify the influent parameters from a spectral analysis of the results of the multiple simulations.

The procedure has been used to identify the most influent parameters on the dry air temperature of the first zone (dining room) and on the surface temperature of the lower side of the roof for the reference model. From the spectral analysis of the results, the following parameters were obtained for both outputs:

1. α, solar absorptivity of the roof
2. ρ, density of the roof
3. C_p, thermal capacity of the roof
4. λ, thermal conductivity of the roof

The identified parameters were expected; the first one plays a major role on the heat flux transferred through the roof and the three other can be combined to form the diffusivity *a* of the roof:

$$a = \frac{\lambda}{\rho.C_p}$$

Hence the sensitivity analysis confirms the great importance of the thermal diffusivity *a* for high inertia walls of buildings.

Results of the simulations

From the various models presented previously, it was possible to run simulations and to appreciate the thermal behaviour of the different technical solutions.

Figure 9 shows the evolution of the surface temperature of the lower side of the ceiling for each of the five configurations studied.

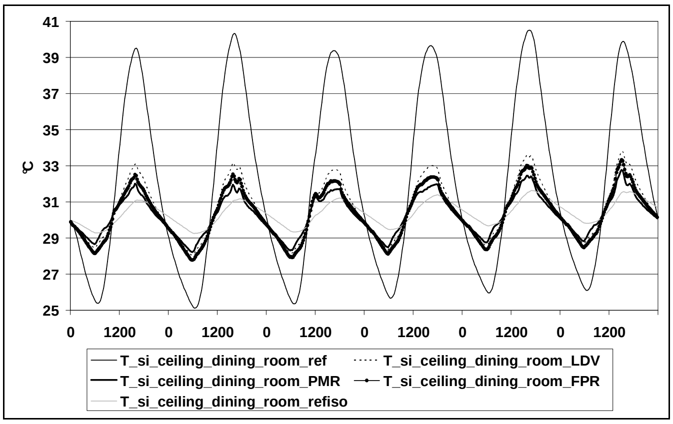

Figure 9: Surface temperature of the lower side of the ceilings as a function of time (six days of simulation)

The temperature for the reference model reaches high values, with a maximum near 40°C and shows the most important amplitude. Moreover, the evolutions of the temperatures for the interior technical insulating solutions are quite similar, with a lower amplitude compared with the reference case and a maximum difference between the three curves of 1.5°C. The roof with an exterior insulation reaches the lowest temperature, 32°C at the maximum, and also shows the lowest amplitude.

Figure 10 shows the evolution of the dry-air temperature for the dining room in each configuration. The main comment is that the values are quite high, with a range of variation between 27°C and 34°C, well above the thermal conditions of thermal comfort. The results here confirm what is often observed with high inertia houses and show that even with insulating products, whether interior or exterior, the air temperature remains quite high, the difference being 2°C at the maximum. Each technical solution in this case leads to a quite similar result, notably because of the impact of the mechanical ventilation system, which tend to balance the impact of the insulation materials. Moreover, the resulting delay due to the thermal inertia is lower in the case of the insulated roof.

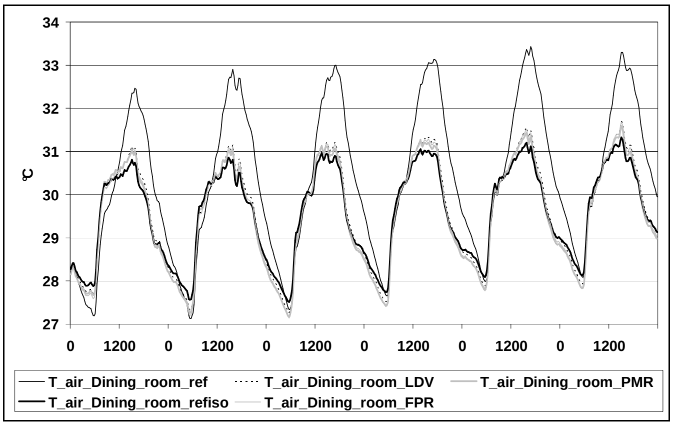

Figure 10: dry air temperature of the dining room as a function of time (six days of simulation)

In order to identify the effect of the radiation of the flat roof, the radiant temperature of the room is proposed on figure 11.

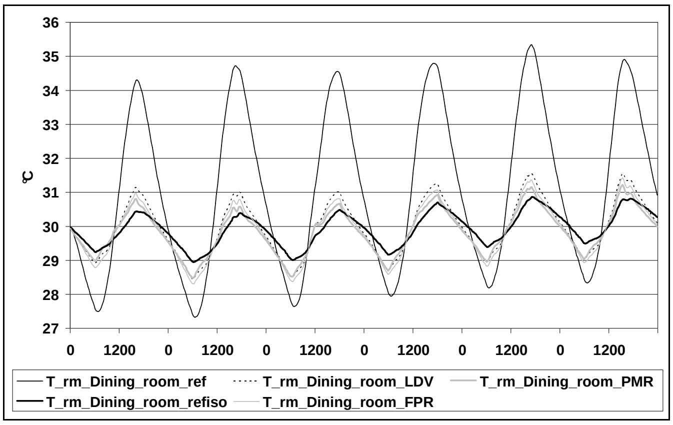

Figure 11: radiant temperature of the dining room as a function of time (six days of simulation)

These curves are interesting because the radiative impact of the flat roof is clearly identified; for the reference case, the radiant temperature is higher than the dry air temperature and reaches a maximum near 36°C. Moreover, the difference between the curves for the reference case and the insulated cases is much more important, approximately two times more than in the case of the dry air temperature. This clearly shows that the technical insulating solutions play a great role on the radiation from the roof. Except the reference roof and in terms of lower radiant temperature, the most effective solution is the exterior insulation, then the radiant barrier, then the reflective ceiling and finally the glass wool. These results are confirmed by the plot of the heat flux through the ceiling (figure 12) where, in terms of lower values, the same order is observed.

In order to determine the thermal performance of each technical solution, the mean method [5] was used to calculate the thermal resistance of the roofs. The method is based on the following formulae, applied on series of dynamic data:

$$R=\frac{\sum_{i=1}^{n}\left(T_{se,i}-T_{si,i}\right)}{\sum_{i=1}^{n}\varphi_i}\quad\text{where}\quad\begin{cases}R\text{ is the thermal resistance of the wall}\\T_{si,i}\text{ is the interior surface temperature}\\T_{se,i}\text{ is the exterior surface temperature}\end{cases}$$

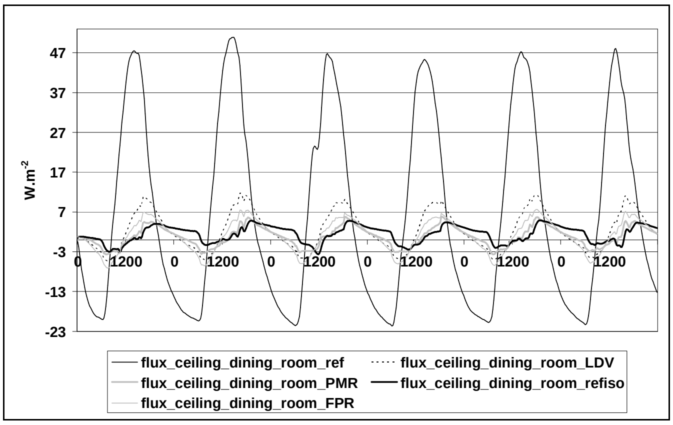

Figure 12: Heat flux through the ceilings of the dining room as a function of time (six days of simulation)

The following results were obtained using the simulation results for the six days of the sequence:

	Code	Thermal resistance R (calculated) [m².K.W^{-1}]	Thermal resistance R (theoretical) [m².K.W^{-1}]
1	Ref	*0.11*	*0.11*
2	LDV	*1.09*	-
3	FPR	*2.87*	-
4	PMR	*3.45*	-
5	Refiso	*1.49*	*1.22*

Table 4: Thermal resistances of each technical solution

The results tend to confirm the preceding comment for the thermal performance of the roofs, except for the exterior insulation, for which the thermal resistance is found to be less than that of the reflective ceiling. This can be explain by the fact that even if the heat flux through the ceiling is the lowest for the exterior insulation (figure 12), it remains positive (it enters the room) for a longer period of time. The preceding formulae being based on a cumulated sum of flux, the result for the exterior insulation is thus expected. The other values tend to confirm that for such flat roofs, it is important to block the radiation heat transfer, as done by reflective insulation products [6].

In terms of thermal comfort, the psychrometric chart is a well used tool to have visual results. Figure 13 and 14 show the results for the reference case and the radiant barrier roof.

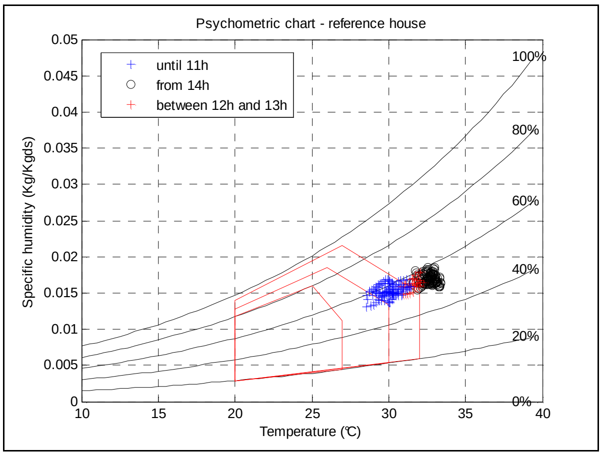

Figure 13: Psychometric chart for the reference case

The main comment is that from 12am, all the points are out of the last comfort zone, indicating the impossibility to achieve thermal comfort conditions event with an air velocity of 1 m.s^{-1}. It is also quite obvious that without ventilation, assessing thermal comfort conditions is impossible.

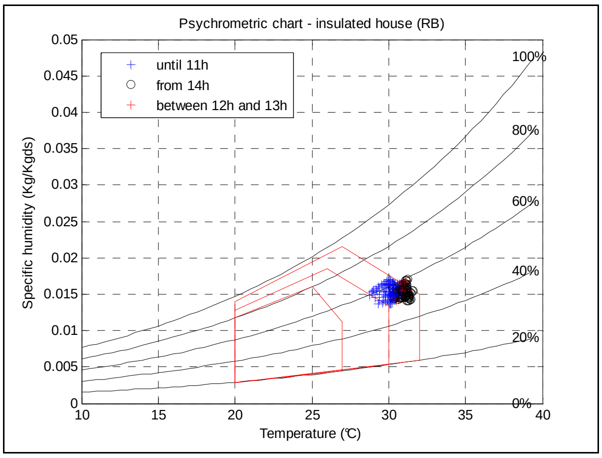

Figure 14: Psychometric chart for the radiant barrier case

From figure 13, we can see that with the radiant barrier, the points for the afternoon are all in the last comfort zone, thus indicating that in this case, thermal comfort conditions can be obtained with ventilation. This result is quite interesting and shows that for houses with flat roofs, the use of an appropriate insulation product can lead to better thermal conditions.

CONCLUSION

This case study was intended to show the impact of several technical insulating solutions for high inertia houses under tropical and humid climatic conditions. Five solutions have been identified, with exterior insulation which is said to be the best, and with interior solutions, for which care has to be taken to avoid structural damage of the flat roof.

A first stage of sensitivity analysis has confirmed the great impact of the thermal diffusivity on the thermal conditions in the building. Then, based on simulations, the several technical solutions have been analysed in relation with the surface temperature of the lower side of the ceiling, the dry air temperature of the room, the radiant temperature of the room and finally the heat flux through the ceiling. The main conclusions are that the discomfort due to flat roof is confirmed, but that when using an appropriate insulation product, such as a radiant barrier whose action is to block thermal radiation, thermal comfort conditions can be achieved, with the help of ventilation.

In terms of thermal performances of the technical solutions, the results illustrate that the most effective technical solution is the radiant barrier, with an ability to considerably and durably reduce the radiation heat transfer through the roof.

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