The tropical roof: thermal simulations of the ventilated double roof in moist-warm climate

Master Arch. Mariana Guimarães Merçon[1*], Ph.D. Arch. Helena Coch[2*] and Ph.D. Arch. Rafael Serra[3*]

Arquitecture, Energy and Environment Group, School of Architecture of Barcelona, U.P.C.
Diagonal, 649, 7th. 08028 Barcelona - Spain

* Corresponding authors: [1]marimercon@gmail.com, [2]helena.coch@upc.edu and [3]rafael.serra@upc.edu.

Abstract
In warm climate the inside temperature in the living space is largely affected by the roof, which receives more than 50% of the thermal load that acts on the building. The design and materials of the roof are able to minimize the thermal effects caused by the high heat of the tropics. Simulations with physical-mathematical calculations found the necessity of ventilated double roof. These simulations have also found out that the use of local materials in the design has greater significant results in the average inside temperature of the living space than the same design using standard industrial materials used in construction. The differences reaches 5 ºC in average inside temperature. Besides that, it was noticed that the increase of air has no effective cooling capacity of heat, although the flow of air inside the attic is significant because it prevents the heat expanding in this space.

Keywords: single-layer cover, ventilated double-layer cover, ventilated roof, moist-warm climate, tropical climate.

1. Introduction
One of the main functions of the building is to propose a comfortable internal environment to humans beings. Climatic variations and their influence on heat transfer through the walls of the building, are intrinsically related to its envelope where the cover takes on a leading role, that is, it is the main responsible for the gain of heat in a building, specially in hot areas like Brazil.

In these regions, it is necessary to take measures to break the heat flow through the roof, since the solar radiation absorbed by the building envelope has a great influence on the thermal environment inside. Mascaro et al., 1992 [1] show values around 70% of the heat load received by the cover. Vecchia and Nolasco, 2006 [2] show the need of double roof in the tropical climate of Brazil in order to ensure adequate thermal performance of buildings.

Considering these aspects, the aim of this study is to calculate the average value of the indoor temperature of the building for certain outdoor weather conditions (summer), and for certain conditions of the building, taking into account that all actions are constant over time. Based on that, we intend to check the efficiency of the different cover types and cover materials, by comparing the single-layer cover with ventilated double-layer cover designed with different materials used in construction, in Brazil - from local materials to industrial materials. Besides that, we plan to study the thermal performance of wind speed in the interior of the building.

2. Methodology
2.1. Analysis Model
Figure 1 shows the schematic of the cover with a single-layer and with ventilated double-layer.

The dimensions of the model are defined by X (m), Y (m), H (m), d (m), where X = 3.20 m, Y = 2.50 m, H = 2.60 m and d = 0.50 m (Fig. 2).

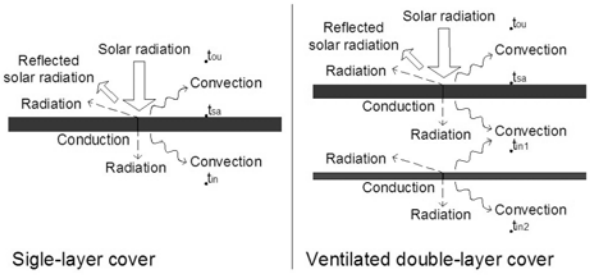

Figure 1 – Heat transfer mechanisms of single-layer cover and ventilated double-layer cover.

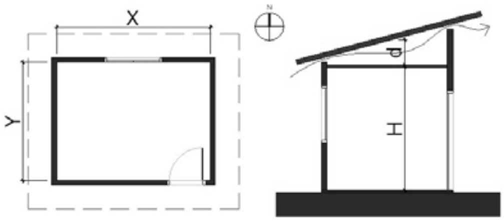

Figure 2 – The dimensions of the model.

2.2 Analysis conditions

The model used in the simulations was designed for the city of Vitória, Brazil, which is 20.6º south latitude and is 40º west longitude, at sea level.

The average maximum temperature for a typical day in January (summer) is 31.9 ºC and average relative humidity is 80.4% [3]. The prevailing wind blows within this period with greater intensity in the northeast direction. The average maximum solar radiation intensity is 854 W/m^2 in horizontal plane and 454 W/m^2 in vertical plane [4].

2.3 Cases analysis

For models presented in Figure 1 we defined inner and outer layer materials, presented in Table 1, with their thermophysical characteristics. These materials are divided into two groups: local natural materials and industrialized materials.

Table 1 – Thermophysical characteristics of the cover construction materials.

Material	λ (W / m K)	K (W / ºC m2)	Thickness (m)	ρ (Kg / m2)	Absorptance α
Natural fiber	0,045	1,50	0,03	200	0,50
Wood	0,13	4,33	0,03	430	0,70
Ceramic tile	1,00	50,00	0,02	2000	0,65
Cement tile	0,22	36,67	0,006	1200	0,60
Steel tile	50,00	8333,33	0,006	7800	0,65
Concrete slab	1,316	8,77	0,15	1330	0,60
PVC ceiling	0,17	8,50	0,02	1390	0,05
Plaster ceiling	0,25	12,50	0,02	825	0,08

Based on the roof and ceiling materials we defined the case studies, totaling 21 in all: 5 one single-layer cover cases and the remainder 16 ventilated double-layer cover cases, on Table 2.

Table 2 – Cases analysis.

Cases	Composition Tile	Ceiling	Cases	Composition Tile	Ceiling
Case 1	Natural fiber		Case 3D	Ceramic tile	PVC ceiling
Case 2	Wooden tile		Case 3E	Ceramic tile	Plaster ceiling
Case 3	Ceramic tile		Case 4B	Cement tile	Wooden ceiling
Case 4	Cement tile		Case 4C	Cement tile	Concrete slab
Case 5	Steel tile		Case 4D	Cement tile	PVC ceiling
Case 1A	Natural fiber	Natural fiber ceiling	Case 4E	Cement tile	Plaster ceiling
Case 1B	Natural fiber	Wooden ceiling	Case 5B	Steel tile	Wooden ceiling
Case 2A	Wooden tile	Natural fiber ceiling	Case 5C	Steel tile	Concrete slab
Case 2B	Wooden tile	Wooden ceiling	Case 5D	Steel tile	PVC ceiling
Case 3B	Ceramic tile	Wooden ceiling	Case 5E	Steel tile	Plaster ceiling
Case 3C	Ceramic tile	Concrete slab			

2.4 Physical-mathematical model

From the cases we find the average indoor temperature (t_{in}) given by equation [5,6]:

$$G \,.\, (t_{in} - t_{ou}) = E + D \qquad ①$$

The calculation of the heat transfer coefficient (G), considering the building heat losses through renovation of air and by transmission through the walls - opaque or transparent - is defined by the equation:

$$G = [\sum S \,.\, K \,.\, (t_{in} - t_{ou}) + 0{,}29 \,.\, N\,(t_{in} - t_{ou})]/V \qquad ②$$

The solar heat gain (E) and different indoor heat gain (D) are calculated respectively by the expressions:

$$E = S_v \,.\, R_v \qquad ③$$

$$D = (\sum n \,.\, e \,.\, nh)/24 \,.\, V \qquad ④$$

The indoor heat gains (D) were not considered in this study. $D = 0\ W/m^3$.

The equivalent window area is given by the equation:

$$S_v = (\sum S \,.\, \gamma \,.\, CR)/V \qquad ⑤$$

It was adopted the average solar-air temperature (t_{sa}) rather than the average outdoor temperature (t_{ou}), since the temperature which is very close to the roof is higher than the average outdoor temperature, due to a combination of solar radiation and construction material properties. $t_{ou} = t_{sa}$. This is defined by the equation:

$$t_{sa} = t_{ou} + (I \,.\, \alpha \,.\, R_{so}) \qquad ⑥$$

It was considered the thermal resistance in the attic given by equation ⑦, within it there is an exchange by convection and radiation, which is equivalent to say that in attic thermal resistance is:

$$R = 1 / (h_c/2 + h_r) \qquad ⑦$$

The inverse of $R = 1 / K\ (m^2 {}^oC/W)$.

Nomenclature:

G	heat transfer coefficient ($W/m^3 {}^oC$)	α	surface absorptance
E	solar heat gain (W/m^3)	γ	solar gain coefficient
D	indoor heat gain (W/m^3)	λ	thermal conductivity (W/mK)
t_{in}	average indoor temperature (ºC)	R_{se}	outdoor surface resistance ($m^2 {}^oC/W$)
t_{ou}	average outdoor temperature (ºC)	S_v	equivalent window area (m^2/m^3)
t_{sa}	solar-air temperature (ºC)	R_v	average solar radiation intensity on vertical plane (W/m^2)
K	thermal conductance ($W/m^2 {}^oC$)		
R	superficial thermal resistance ($m^2 {}^oC/W$)	h_c	convective heat transfer coefficient ($W/m^2 {}^oC$)
S	area for heat transfer (m^2)		
V	indoor volume (m^3)	h_r	radiation heat transfer coefficient ($W/m^2 {}^oC$)
CR	coefficient as window guidance	n	number of radiating heat elements
N	number of air changes per hour (m^3/m^3h)	e	energy radiated by element (W)
I	solar radiation intensity (W/m^2)	nh	operating daily hours

3. Results

First it was made a comparison between cases with a single-layer cover. Then we compared cases with ventilated double-layer covers. It was finally compared the cases presenting the same outer layer material with different inner layer materials. This last comparison allowed us to analyze the extent in which the inner layer material interferes in the overall cover thermal efficiency.

For each case was made a comparison of different rates of air in order to verify if the amount of air changes per hour has the ability to minimize thermal effects on the cover - when it has an attic - and of the interior living space.

3.1 Single-layer cover (Fig. 3)

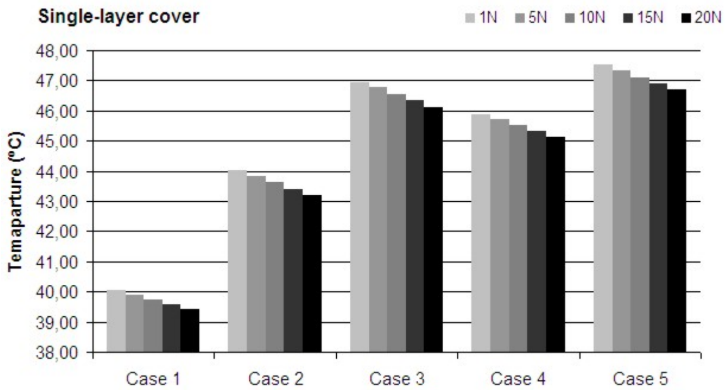

Figure 3 – Average indoor temperature (t_{in}) for different construction materials and different numbers of air changes per hour in single-layer cover.

In the case of a single-layer cover (Cases 1-5), t_{in} values reach far above t_{ou}, surpassing a 15 ºC difference between t_{in} and t_{ou} (Case 5). The choice for certain materials (Case 1) makes t_{in} more enjoyable. Depending on the values of λ and α, t_{sa} can increase a lot and consequently t_{in} increases.

With the increase of more air in the building, t_{in} decreases although the air flow inside the attic is insignificant to cooling the interior space.

3.2 Ventilated double-layer cover (Fig. 4)

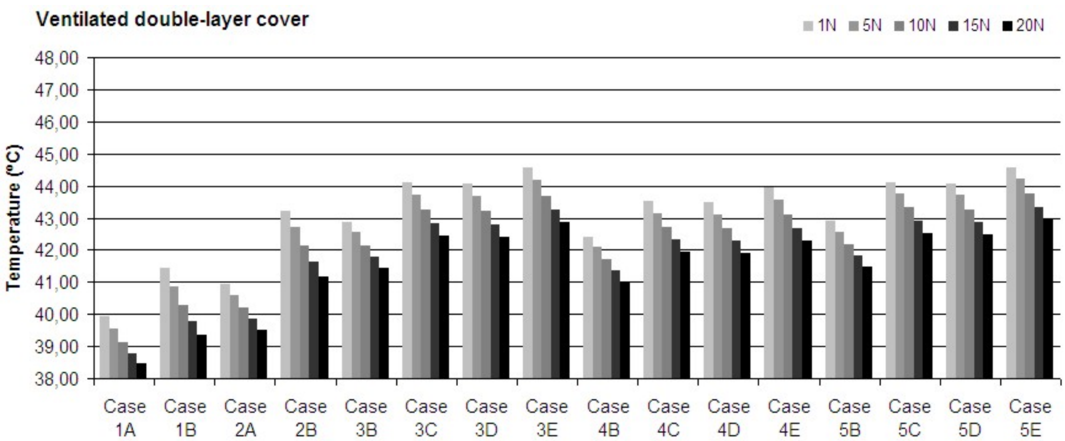

Figure 4 – Average indoor temperature (t_{in}) for different construction materials and different numbers of air changes per hour in ventilated double-layer cover.

The choice of inner layer material makes the t_{in} difference clear in living space. Comparing the different materials of the inner layer with the same outer layer material, we notice that the material which has a smaller *K* presents also lower t_{in} (materials A and B).

The fact of introducing air into the cover, this way creating a ventilated cavity, helps minimize t_{in}, reaching a maximum of 2 ºC on the cover with better performance (Cases 1B and 2B) - covers that use local materials. In industrialized materials covers, the difference achieved is about 1.5 ºC by comparing the solutions with 1N and 20N. There is a considerable increase in the number of air changes per hour to obtain any satisfactory result.

3.3 Single-layer cover X Ventilated double-layer cover (Fig. 3 and 4)

In cases of ventilated double-layer cover, some cases present substantial results if compared to the single-layer cover. The temperature difference between the two types can reach 5 °C.

It can be noticed that the best results for t_{in} are covers made of local materials, either single-layer or ventilated double-layer.

The cases that use natural fiber (Cases 1A, 1B and 2A) have the most pleasant temperatures for all the possibilities of study. The cases that use wood in the inner layer (Case 3B, 4B and 5B) show the best performance of t_{in} per group of outer layer, between the covers made of industrial materials.

Among cases of covers made of industrial materials, the cases of group 4 (Cases 4B, 4C, 4D and 4E) are those that have the best t_{in} in living space for the same number of air changes per hour. This happens because cement tile (4) presents a K and α lower than ceramic tile (3) and metal tile (5). On the other hand, metal tile (5) presents the worst results for t_{in} as it shows the highest K among all solutions studied.

4. Conclusions

The analysis shows that the design of ventilated double-layer cover is adequate in reducing t_{in}, concluding that:

- The t_{in} decreasing is appreciable in virtually all cases studied by comparing the single-layer cover and ventilated double-layer cover with the same materials of roof and under the same analysis conditions. The temperature difference reaches 5 °C.
- The selection of materials with low K combined with low α for both layers (inner and outer layers) always presents better results. The combination above increases overall efficiency.
- The introduction of a ventilated cavity contributes for t_{in} reduction, although the increase of air does not have an effective heat cooling capacity. This is why it is necessary to considerably increase the number of air changes per hour to obtain any satisfactory result. However, the airflow inside the attic is significant because it prevents the heat expanding in this space.
- The solutions which use local materials (non-industrialized), in the outer layer as well as in the inner layer, present lower t_{in} compared with other solutions, under the same analysis conditions.

5. References

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