PASSIVE STRATEGIES FOR ENERGY-EFFICIENT BUILDING ENVELOPES FOR HOUSING DEVELOPMENTS IN HOT ARID CLIMATES

KARMINA D. REYES-BARAJAS, RAMONA A. ROMERO-MORENO, CRISTINA SOTELO-SALAS, ANÍBAL LUNA-LEÓN & GONZALO BOJÓRQUEZ-MORALES
Facultad de Arquitectura y Diseño, Universidad Autónoma de Baja California, México

ABSTRACT

Buildings and the construction sector are responsible for 36% of the final energy use as well as 39% of carbon emissions, while the residential sector accounted for 22% of total energy consumption and 17% of carbon emissions. Therefore, housing requires measures which reduce energy consumption and carbon emissions without affecting the living conditions of its occupants. In Mexico, the most commonly used construction systems in mass housing are concrete block walls and concrete slabs, these systems adversely affect comfort conditions and increase energy consumption especially in regions with a hot arid climate, such as Mexicali, in Mexico's northwest region. The objective is to determine the thermal behavior and energy performance of three environmental adaptation strategies applied in the building envelope: thermal insulation, thermal mass, and air cavity walls. A commercial prototype of mass housing was considered as a benchmark case, with concrete block walls and a concrete beam and expanded polystyrene composite roof. The building energy simulation was carried out with the Design Builder® software for the summer period, where building performance was evaluated with passive design strategies (simulation scenarios include variations in thickness and position of materials that make up the layers in the building components) against a benchmark case (without strategies), the corresponding thermal transmittance values (U-value) were also estimated. The results show differences in surface temperature, cooling demand and operative temperature inside the house; energy-saving potential is shown, which contributes to carbon emissions reduction and thus aids in climate change mitigation.

Keywords: passive strategies, energy efficient housing, mass-built houses, hot arid climate, demand of cooling and thermal comfort.

1 INTRODUCTION

Globally, buildings and the construction sector are responsible for 36% of global energy end use and 30% of carbon emissions [1]. While in Mexico the national total energy consumption, at the residential level, accounts for 17.1% [2], that is, more than half of global energy consumption.

These registered percentages are influenced by various factors, such as the climatic region and user's needs, that is, the type of lighting required in the home, the food preparation methods, the heating and cooling systems used to obtain a comfortable indoor climate, among other factors. Mexico's hot arid region (in the states of Baja California, Chihuahua, Coahuila, Nuevo León, Sonora, Sinaloa and Durango) is where high energy consumption is registered, due in large part to the aforementioned factors, however another influencing factor is the lack of use of insulation in the home, INEGI [3] shows that only 22.5% of the homes in this climatic region have wall insulation, while 89.6% of the homes have roof insulation. Cruz [4] states that even economic income, cultural customs, age of the inhabitants, as well as the amount and activity that each member of the family carries out have an effect on the generation of carbon emissions, and therefore, in the total energy consumption in the home.

Accordingly, one of the strategies to reduce high energy consumption and elevated temperatures inside the home is to minimize conductive heat flow, since it is the most

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appropriate measure if there is a significant difference in temperatures between the interior and exterior of the building, as indicated by La Roche [5]. He establishes that there are various techniques within this strategy, among them is thermal insulation and the inclusion of an air space or air cavity, both techniques are applicable to walls, roofs, and floors.

Authors like Barbosa and Ip [6] and Sotelo-Salas et al. [7], show that the technique of ventilated façades in hot arid climates have a considerable thermal impact on the interior environment of a building due to the natural ventilation that takes place in the air cavity, which flows through the building envelope and generates an adequate indoor air quality providing a comfortable thermal environment for the users [8], this translates to a reduced cooling load and energy demand. The depth of the air cavity can vary depending on the design and the thermal performance required.

Furthermore, as previously mentioned, a technique with considerable impact for heat gain reduction is insulation, since the appropriate thermal insulation in the building envelope in extreme climates allows significant savings in energy consumption, as stated by Friess and Rakhshan [9], they report up to 20% in energy savings and 55% in cooling demand in a desert climate. However, despite the fact that the hot arid climatic region has the highest percentage of some type of insulation implementation throughout the country, it also documents that 85.1% of homes do not have thermal insulation [3]. Another important aspect to consider is the low conductivity and high thermal resistance of the material to be used in the envelope, since heat flow is directly proportional to thermal conductivity, if a building material has 50% less conductivity than another, this reduces 50% of the heat flux in the envelope [5].

Considering the factors that influence elevated energy consumption, the climatic conditions of the city of Mexicali, which has registered maximum temperatures of 45°C and up to 54°C historically [10], and the lack of thermal efficiency in low income dwellings, this research focused on providing solutions for this widespread problem, through the study of thermal behaviour and energy performance of an existing housing prototype to determine its deficiencies, and subsequently, propose cooling strategies through an array of passive design measures applied directly to the building envelope.

Therefore, this research was carried out based on the parameters established in the Mexican standards for energy efficiency, while the evaluation of these climatic adaptation techniques were carried out with the Design Builder building energy simulation (BES) software, in which the climatic data of the city were entered, as well as the selected benchmark case and, subsequently, the cases were analyzed with the application of the various techniques, from which favorable results were obtained in the reduction of energy consumption and increase in thermal comfort.

2 METHODS

The research carried out is quantitative in nature since building energy simulations were conducted to evaluate the energy performance of the benchmark case as well as the performance of the applied bioclimatic adaptation techniques.

2.1 Study cases

A benchmark case (BC) was established from the existing housing prototype and its default envelope building materials, case studies were modified with the previously described climatic adaptation techniques.

2.1.1 Benchmark case

For the selection of the benchmark prototype, low income mass housing in Mexicali were identified. The selected prototype has 41.24 m^2 of construction area in a 120.05 m^2 lot. The main façade is south facing, the dwelling has two bedrooms, one bathroom, a living/dining room area and a kitchen (Fig. 1).

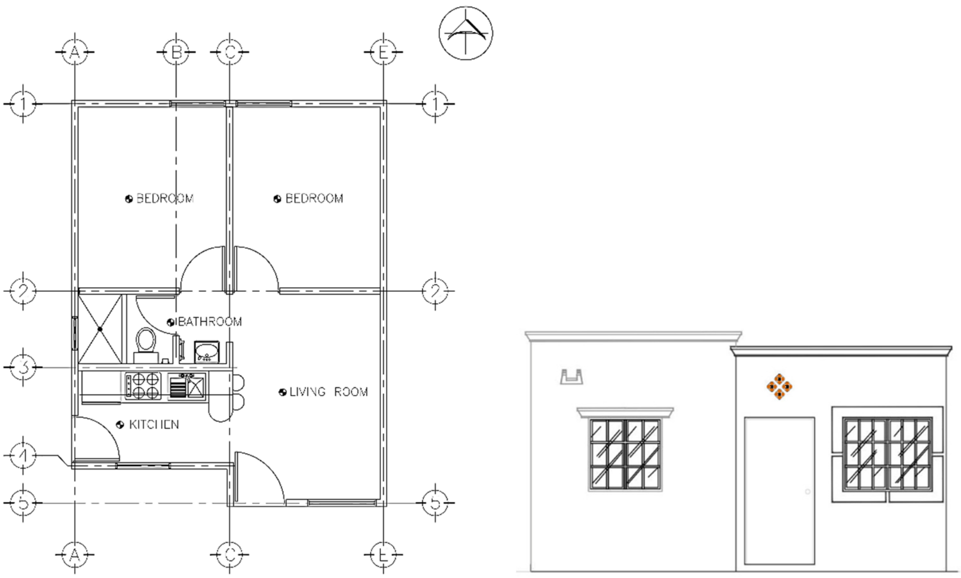

Figure 1: Benchmark case (BC). *(Source: Authors, from the housing prototype plans, 2011.)*

The constructive system of the benchmark case is predominant in the affordable housing market, it consists of concrete masonry unit blocks (CMU) of 0.12 m x 0.2 m x 0.4 m with hollow cores, cores are cast every 0.61 m with concrete f'c = 140 kg/cm^2. The roof is made of a composite concrete joist and vault which is 0.17 m thick, the concrete is f'c = 200 kg/cm^2 and with reinforcing steel bars (Ø0.0071 m); covered with fiberglass reinforcement mesh and two layers of plaster, finished with elastomeric paint. Table 1 shows the layout of the benchmark case and its south facing façade.

Table 1: Surface areas of the benchmark case envelope. *(Source: Authors, from the housing prototype construction plans, 2020.)*

Orientation	Surface area (m^2)			
	Walls	Windows	Doors	Total
North	15.47	2.20	–	17.67
South	14.02	2.38	1.85	18.25
East	22.04	N/A	–	22.04
West	20.25	0.37	1.78	22.40
Total	72.15	4.95	3.63	80.73
Roof				41.24

2.1.2 Modified benchmark case

The benchmark case was modified with the application of thermal insulation techniques (A) and the air cavity technique on the opaque ventilated façade (B), with thickness variations (Table 2). The evaluated cases in technique A were simulated with 0.0254 m (1") of expanded polystyrene, while in technique B, in addition to the different thickness in the air cavity for the construction system of the ventilated façade, the inner wall is a plasterboard wall with a steel frame structure of 0.0762 m (3") rectangular steel tube at every 0.6 m (vertically and horizontally), the interior face is a 0.0127 m plasterboard, the hollow interior of the wall is filled with fiberglass, the outside face is 0.0127 m fiber-cement board and grills were proposed to allow natural ventilation in the air cavity. Finally, technique C was simulated with the combination of techniques A and B.

Table 2: Case studies modified with passive design techniques. *(Source: Authors, 2020.)*

Name	Description
BC	Benchmark case
A	Benchmark case with expanded polystyrene insulation
A1	Benchmark case with 0.0254 insulation in south façade
A2	Benchmark case with 0.0254 insulation in west façade
A3	Benchmark case with 0.0254 insulation in north façade
A4	Benchmark case with 0.0254 insulation in east façade
B	Benchmark case with air cavity
B1	Benchmark case with 0.1 m air cavity
B2	Benchmark case with 0.15 m air cavity
B3	Benchmark case with 0.2 m air cavity
B4	Benchmark case with 0.25 m air cavity
B5	Benchmark case with 0.3 m air cavity
B6	Benchmark case with 0.35 m air cavity
C	Benchmark case with combined A and B
C1	Benchmark case with A1 and B6
C2	Benchmark case with A4 and B6

Table 3 shows the thermal transmittance values (U value) of the construction systems evaluated in the different case studies.

Table 3: Thermal transmittance of constructive systems. *(Source: Authors, from data obtained in Design Builder®, 2020.)*

	Constructive system	Valor "U" (W/m^2 °C)[1]
BC	Concrete masonry unit blocks, cast cores, 0.12 m	2.932
	Concrete joist and beam roof 0.17 m	0.860
A	Concrete masonry unit blocks, cast cores, 0.12 m with a layer of expanded polystyrene 0.0254 m (1")	0.988
B	Fiber cement board wall 0.12 m, with fiberglass insulation	0.439

[1]U value obtained from Design Builder®.

For the simulated scenarios, in addition to the envelope constructive systems, the internal loads of the house were considered, such as the electrical appliances (televisions, refrigerator, coffee maker, microwave, chargers, laptop, gas burner, internet modem, hair dryer), air conditioning (HVAC), lighting (six bulbs) and the activities and of four users.

2.2 Building energy simulation setup

To achieve these results, as already mentioned, the Design Builder® version 5.4.0.021 software was used. The city of Mexicali is located at 32° 39’ 54” N latitude, 115° 27’ 21” W longitude and 4 m above sea level [10]. The weather file from the California climate zone CZ15RV2 was used, as well as the specifications of the construction systems that were used in the simulation scenarios, the benchmark case was also modeled with its corresponding thermal zones.

Simulations were evaluated in the summer period (May to October), this period is introduced in the simulation program, considering the effect of the internal loads mentioned above. Certain simulations were evaluated with natural ventilation, in order to show the impact that each technique had on comfort conditions inside the dwelling, and others were carried out considering air conditioning use.

Technique A was evaluated in each of the basic cardinal orientations while technique B was only evaluated in the critical orientation (obtained from the scenarios in technique A), and finally, technique C was analyzed by combining the critical orientation in the technique A and the most favorable scenario in technique B, in order to achieve a comparison of the three techniques to visualize the best option in energy savings and comfort conditions in the dwelling.

Therefore, the evaluation will obtain results of energy performance and comfort conditions based con cooling load (sensitive zone cooling), heat gains per wall surface area (kWh/m^2) and comfort based on the predicted mean vote (PMV) model. For the analysis of the data, especially those of thermal comfort, the data obtained by the BES software had to be entered into a spreadsheet [11], in order to present data on the scale established by the PMV model in the ISO 7730 standard [12] (Fig. 2).

COMFORT SCALE ISO-7730	
< -3	Very cold
-3 a - 2	Cold
-2 a -1	Slightly cold
-1 a -0.5	Comfortable cold
-0.5 a 0.5	Comfort
0.5 - 1	Comfortable warm
1 a 2	Slightly warm
2 a 3	Hot
> 3	Very hot

Figure 2: Comfort scale. *(Source: Luna from ISO-7730, 2019.)*

3 RESULTS

The energy consumption results of each case study are presented, as well as the required cooling load and the thermal comfort performance.

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3.1 Energy performance

The results of heat gains were presented only in walls, this because, as shown in Table 1, the walls represent more surface area than any other envelope component. Table 4 shows the results obtained in kWh from the simulations of technique A, there it can be observed that in the BC total gain through walls was close to 10,000 kWh and in addition, the critical case is A1, that is, if the insulation is implemented in this orientation it results in the minimum heat gain reduction compared to the other case studies.

Table 4: Results of the case studies in the summer period. *(Source: Authors, 2020.)*

Case study	Heat gains through wall (kWh)	m^2	Heat gains through wall (m^2)
BC	9,988.56	72.15	–
A1	8,716.27	14.02	621.52
A2	7,889.90	20.25	389.57
A3	8,908.25	15.47	575.84
A4	7,444.92	22.04	332.30

Table 5 shows the energy to be removed or sensible cooling of the thermal zone considering the external and internal loads of the benchmark case.

Table 5: Cooling load for selected case studies. *(Source: Authors, 2020.)*

Name	Cooling loads (kWh)
BC	–17,337.63
A1	–16,113.77
A2	–15,339.30
A3	–16,285.66
A4	–14,870.49

Table 6 shows the results that were obtained, both for heat gains and cooling loads, for technique B. It is observed that in heat gains per wall, with respect to BC, case B6 showed a slightly over than 2,000 kWh reduction, this was considered the best case scenario, while the B1 case showed the lowest energy reduction with 1,962 kWh. While the best case for cooling load reduction was B1 and the worst (or critical) case was B6. However when comparing the BC with the most favorable case, the difference is not as significant since only 1,330.53 kWh were saved.

Table 6: Results of case studies in the summer period. *(Source: Authors, 2020.)*

Name	Heat gains through wall (kWh)	Cooling loads (kWh)
B1	8,025.68	–16,007.1
B2	8,0001.74	–16,411.7
B3	7,977.8	–16,480.3
B4	7,956.3	–16,483.8
B5	7,934.36	–16,496.1
B6	7,911.76	–16,502.7

Table 7 shows the results of the evaluating technique C, it is shown that based on the results of BC with technique C2 it reduces more than 4,000 kWh of heat gains per wall, and 3,322 kWh less than the BC of cooling loads.

Table 7: Results of case studies in the summer period. *(Source: Authors, 2020.)*

Name	Heat gains through wall (kWh)	Cooling loads (kWh)
BC	9,988.56	–17,337.63
C1	7,927.10	–16,542.26
C2	5,371.79	–14,005.41

In Fig. 3 each evaluated technique is compared, and it is observed that the best option to reduce energy consumption in the dwelling is C2. Finally, Fig. 4 shows the results of heat gains per wall that were obtained from the evaluated case studies.

3.2 Thermal comfort performance

The evaluation of the benchmark case showed that the dwelling maintains 100% of the summer period in comfort conditions, this considering that most Mexicali dwellings keep air conditioning systems constantly activated (Table 8). However if only the use of natural ventilation is considered, this condition was implemented to better illustrate the effect of each technique, a 17.8% of hours in thermal comfort is obtained for the summer period for the BC. Technique A shows A2 and A4 as best cases with 23.4% of hours in thermal comfort, as shown in Table 9.

Table 10 shows the results of technique B, where the best case was B6 with 30.2% hours in thermal comfort, so it was concluded that technique B performs better than technique A because it provides more hours in thermal comfort.

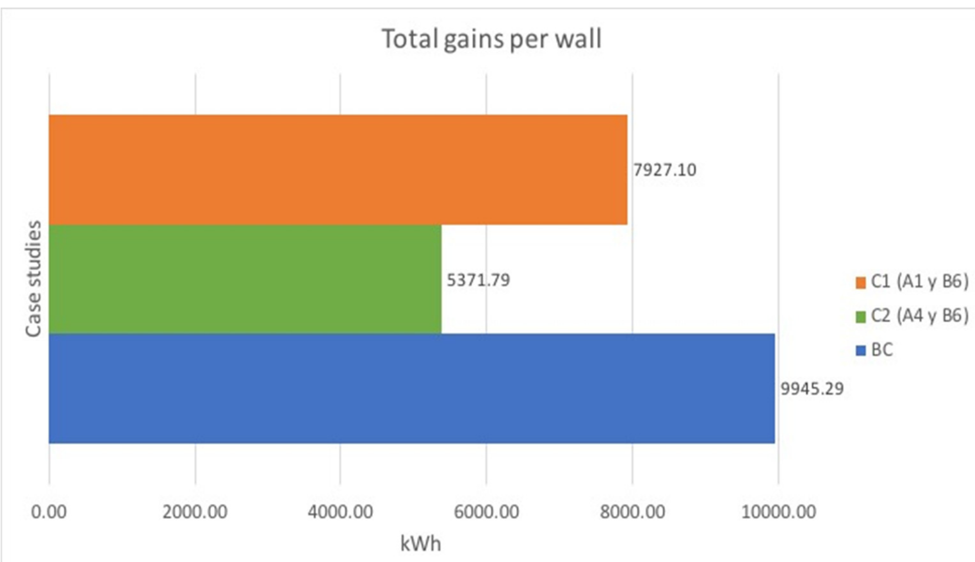

Figure 3: Performance of technique C case studies. *(Source: Authors, 2020.)*

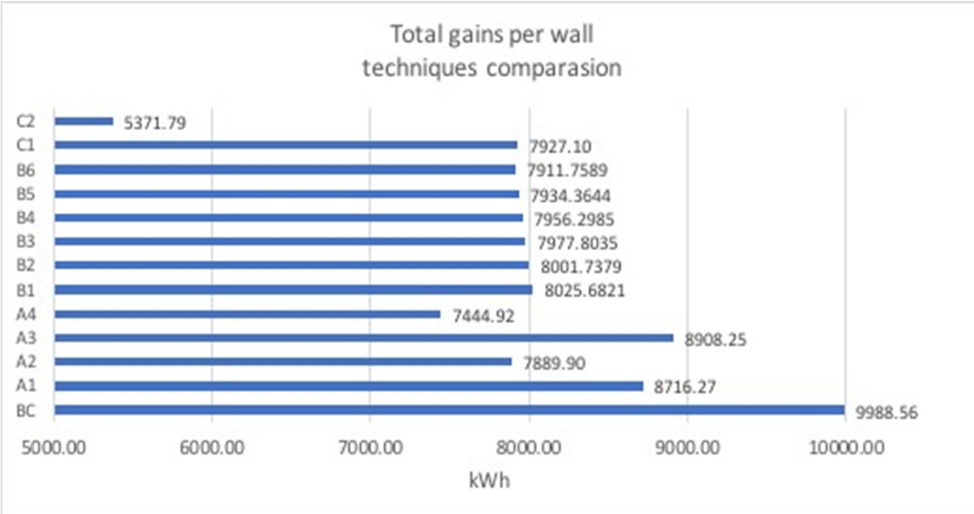

Figure 4: Energy performance of case studies. *(Source: Authors, 2020.)*

Table 8: BC thermal comfort. *(Source: Authors, 2020.)*

Case studies	Thermal comfort hours in summer	Thermal comfort (%)
BC with HVAC	4399	100
BC with natural ventilation	269	17.8

Table 9: Thermal comfort results of case studies. *(Source: Authors, 2020.)*

Name	Thermal comfort hours in summer	Thermal comfort (%)
BC	269	17.8
A1	360	22.5
A2	385	23.4
A3	358	22.3
A4	394	23.4

Table 10: Thermal comfort results of case studies. *(Source: Authors, 2020.)*

Name	Thermal comfort hours in summer	Thermal comfort (%)
B1	368	23.3
B2	350	22.6
B3	556	29.6
B4	565	29.9
B5	563	30
B6	575	30.2

Lastly, the results of technique C are shown in Table 11, these are the best options of all the techniques evaluated, with 30.5 to 31.4% of thermal comfort obtained for the summer period (Fig. 5).

Table 11: Thermal comfort results of case studies. *(Source: Authors, 2020).*

Name	Thermal comfort hours in summer	Thermal comfort (%)
BC	269	17.8
C1	572	30.5
C2	574	31.4

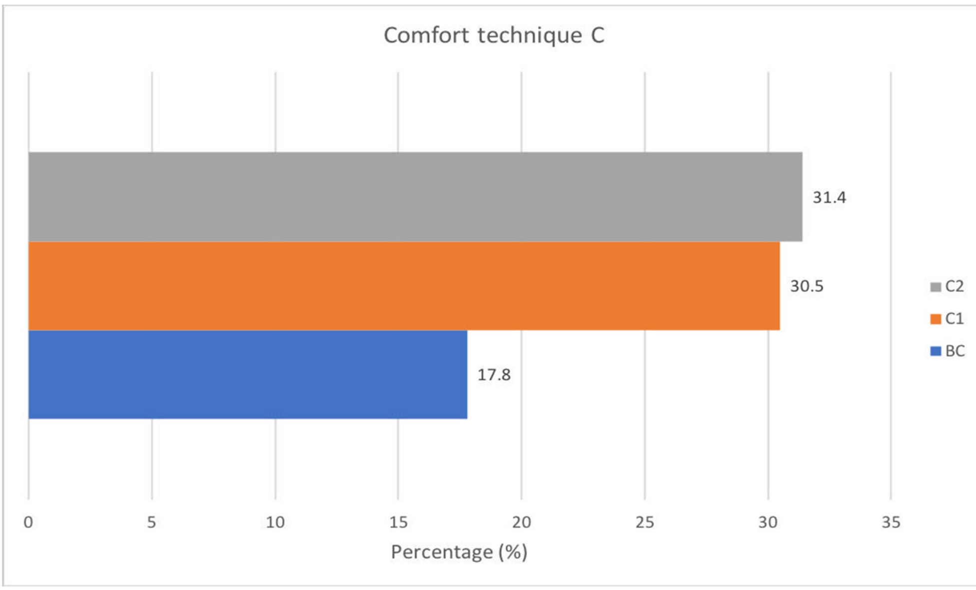

Figure 5: Thermal comfort of technique C case studies. *(Source: Authors, 2020.)*

Therefore, it was determined that to obtain greater thermal comfort conditions, the best option is to use technique A, since it provides higher percentages of comfort for the summer period (Fig. 6).

4 CONCLUSIONS

In the results presented, it is observed that the implementation of any of the evaluated techniques in the dwelling results in favorable performance, both in thermal comfort and for energy consumption reduction, however not all the passive design measures present significant differences with respect to the benchmark case, that is, in some cases there are minimum savings of just over 1,000 kWh in energy consumption and a difference of only 4.5% in thermal comfort in the worst-case scenario. The other case studies had similar results, that is, only in one of the output variables (cooling loads, wall gains or thermal comfort) had better results than in the other ones.

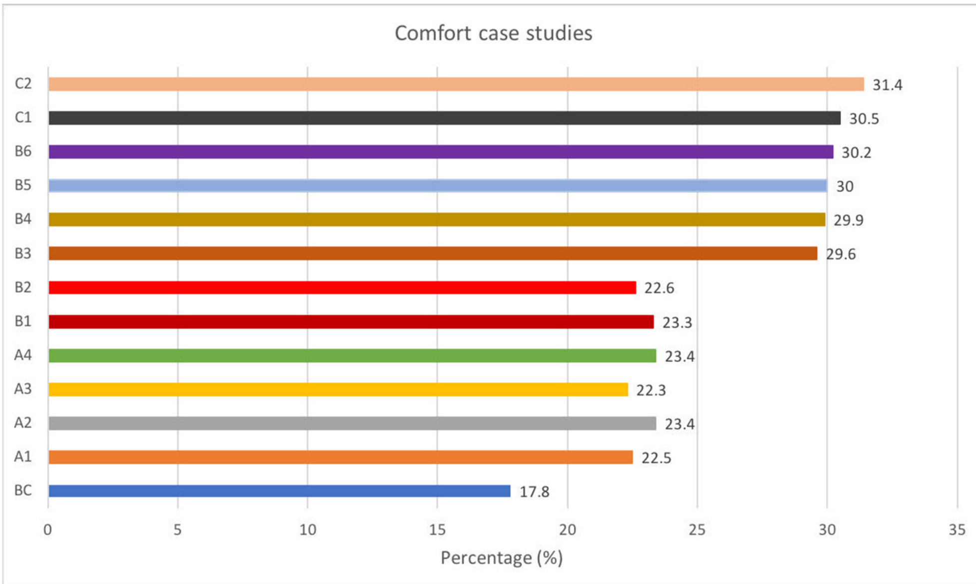

Figure 6: Thermal comfort performance in case studies. *(Source: Authors, 2020.)*

Such is the case of evaluations carried out with technique B, they all represent a minimum difference in gains per wall only between 1,900 and 2,055 kWh, in cooling loads just with 800 to 1,330 kWh and in thermal comfort the differences are 4.3% to 12% more comfort than in the benchmark case. Another favorable case was the A2, with more than 2,000 kWh less than in the benchmark case but only in cooling loads, however, in terms of thermal comfort is one of the least favorable cases.

Therefore, it was determined that the best option is to implement the C2 technique, because this case study presents better conditions in both thermal comfort and energy consumption, it is the combination of the air cavity with a thickness of 0.35 m and the thermal insulation applied to the east-facing wall, since this case reduced more than 4,000 kWh compared to the BC in wall heat gains and just over 3,000 kWh in the cooling load. It is also the best case to promote comfortable indoor conditions for the dwelling, as 31.4% of thermal comfort was achieved in the summer period with natural ventilation, that is, 13.6% more than in the BC. This clearly demonstrates that the implementation of bioclimatic adaptation techniques such as thermal insulation and opaque ventilated façades have a favorable impact in hot arid climates.

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