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EXTENSIVE GREEN ROOFS THERMAL EFFECT AND ENERGY SAVING INDOOR BY COOLING

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ABSTRACT

This work analyzes the thermal effect of extensive green roofs (EGR), in different climatic conditions of eight cities in Mexico. A house is simulated and temperature, comfort sensation and air conditioning energy consumption are analyzed. The results show that the extensive green roof helps to decrease the maximum interior temperature, especially in the rooms located on the upper floor, where greater energy saving for air conditioning (cooling) is also observed. In all the cases studied, EGRs contribute to achieve thermal comfort conditions; in fact, their implementation under some climatic conditions avoids the use of air conditioning.

Keywords: extensive green roof; conventional roof; saving energy; air conditioning; comfort; interior temperature.

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1. INTRODUCTION

One strategy for the adaptation of cities to climate change is the implementation of green roofs (Møller Francis and Bergen Jensen, 2017). Green roofs are small ecosystems with shallow substrate depth and low water requirements that can be considered green islands integrated into the urban landscape (Blank *et al.*, 2017). These ecosystems replace conventional roof surfaces with plants, creating a natural environment with environmental and energy benefits (Mohajerani *et al.*, 2017).

Some benefits of green roofs are increase of urban forest surface (Berndtsson *et al.*, 2009), air purification (Suszanowicz, 2018), reduction of the urban heat island effect (Berardi, 2016), biodiversity preservation (Sánchez Dominguez *et al.*, 2020), reduction of runoff (Yao *et al.*, 2020) and energy savings in building for air conditioning (Berardi, 2016; Bevilacqua *et al.*, 2020; Susca, 2019).

Green roofs can play an important role in increasing green space in densely populated urban areas (Berndtsson *et al.*, 2009). Suszanowicz (2018) demonstrated that green roofs have a beneficial effect on the removal of air pollutants, heavy metals, and suspended particles. Berardi (2016) demonstrated that green roofs have an air temperature cooling effect of up to 0.4°C during the day at the pedestrian level, which contributes to the mitigation of the urban heat island. Sánchez Dominguez *et al.* (2020) found that the diversity of arthropods on the green roofs was very rich, with almost 400 species of different feeding groups. Yao *et al.* (2020) demonstrated that greening on effective roof surfaces would provide more effective storm-water regulation benefits, for reductions in both runoff volume and peak flow.

Bevilacqua *et al.* (2020) demonstrated that a green roof provides a significant reduction in cooling energy demand, with annual savings up top 34.9%, for a Mediterranean climate. Susca (2019) concluded that the implementation of green roofs efficiently reduces energy demand between 10% and 75%, depending on the climate zone, type of building and roof composition.

Despite the multiple benefits of green roofs, a barrier to their implementation is their investment cost which is higher than conventional roofs (Liberalesso *et al.*, 2020). According to Saadatian *et al.* (2013) the initial cost is 3–6 times higher. However, a full understanding of their economic value could help to encourage their implementation (Teotónio *et al.*, 2018). To have a broader understanding of their economic value, it is necessary to determine their thermal behavior, so it is essential to know the heat and mass flows involved (Tang and Zheng, 2019). Through simulation a quantitative evaluation of energy-savings could be performed and to obtain different results.

To quantify the energy benefits experimental evaluations or simulations are needed (Kokogiannakis *et al.*, 2014). However, the intermittent environmental conditions complicate experimental evaluations to compare the thermal behavior of a roof before and after implementing a green roof.

In recent years, several studies have been conducted on energy savings due to the implementation of green roofs. However, the existing literature shows a variety of results, so detailed studies are needed in each specific case to predict energy savings (Berardi, 2016).

The objective of this work is to determine the thermal effect of green roofs in the climatic conditions of eight cities in Mexico: Mexicali, Hermosillo, Monterrey, Tampico, Guanajuato, Querétaro, Pachuca and Cancún. EnergyPlus is used to simulate a house with a conventional roof and an identical house with a green roof. Two rooms of the house are analyzed, one located on the first floor and the other on the upper floor. The analyzed variables are: temperature, comfort sensation and energy consumption for air conditioning (cooling).

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2. METHODOLOGY

The methodology used to conduct the study is described follows:

House simulations in EnergyPlus with conventional roof and with extensive green roof (EGR) under different climatic conditions. In this study, the results of two identical rooms are considered, one of them located on the first floor and the other on the top floor. The simulations are performed for the climatic conditions on the 15th of each month of 2022.

The temperature obtained inside the rooms is used to determine the comfort feeling. Comfort is estimated using the methodology proposed by Fanger (1970), which uses the PMV (Predicted Mean Vote) that is a function of the temperature of the place.

If the comfort time is less than 50%, it is considered that the rooms require the use of an air conditioning system for cooling.

The simulations are carried out again, but this time an air conditioning system is added, and the energy consumption is determined. Subsequently, the amount of CO_2 equivalent avoided as result of EGR implementation is determined. To do so, the CO_2 emissions factor per kWh of energy produced for México (0.435 $kgCO_2e/kWh$) is used.

3. STUDY CASES

This work evaluates the thermal effect of EGR in climatic conditions of Mexicali, Hermosillo, Monterrey, Tampico, Guanajuato, Querétaro, Pachuca and Cancún. The evaluation compares the interior temperature, comfort sensation and energy consumption for air conditioning of a house with a conventional roof and one with an EGR.

In this section, a description of the house and the climatic conditions of the areas where the evaluation is carried out is made.

3.1 House Description

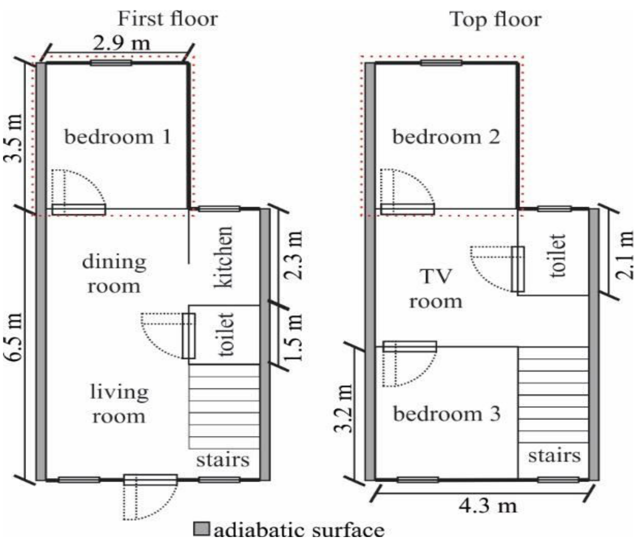

Figure-1. Distribution of the house considered for the study.

For all case studies, the dwelling consists of a building composed of a first floor and a top floor. The study is performed for bedrooms 1 and 2 shown in Figure-1 where the layout and dimensions of the rest of the house can also be observed. The two bedrooms have the same dimensions, but their location in the house is different; bedroom 1 is located on the first floor and bedroom 2 is located on the top floor.

For the study it is considered that the house has lateral abutments, therefore, these walls are considered adiabatic (see Figure-1).

The facade of the house is oriented to the south. Figure-2 shows the dimensions and facade of the house, as well as the dimensions of the EGR.

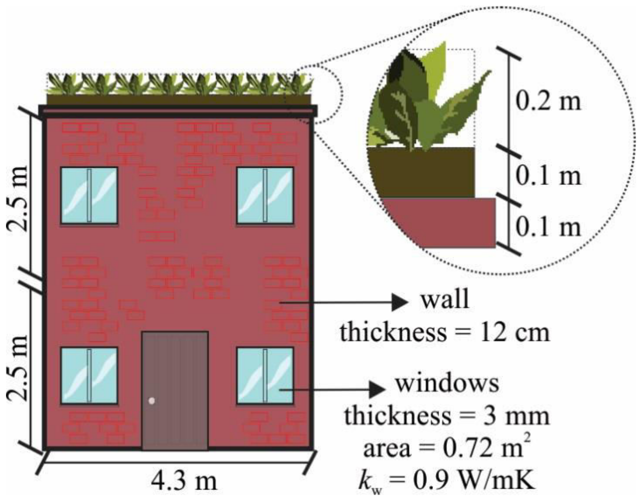

Figure-2. Dimensions of the house envelopes.

Table-1 lists the thermal properties -thermal conductivity (k), density (ρ), and specific heat (Cp)- of the walls and conventional roof.

Table-1. Thermal properties of the materials that make up the housing envelopes.

Envelope	Material	k (W/mK)	ρ (kg/m^3)	Cp (J/kgK)
Wall	brick	0.85	15000	840
roof	concrete	1.95	2240	900

The characteristics of the green layer and the substrate layer are shown in Table-2.

Table-2. Green roof parameters.

Layer	Parameter	Value
Plants	height	0.2 m
	LAI	5 m^2/m^2
	Reflectivity	0.22
	Emissivity	0.95
	minimum stomach resistance	180 s/m
Substrate	depth	0.1 m
	conductivity	0.35 W/(mK)
	density	1100 kg/m^3
	specific heat	1200 J/(kgK)

3.2 Brief Description of Weather Conditions

A brief description of the climatic conditions used for this study is given below.

3.2.1 Mexicali

Mexicali (32.62781, -115.45446) It has a warm-dry climate, the ambient temperature varies from 0.5°C to 48°C, the hottest months are July and August with an average temperature of 33°C. The relative humidity varies from 2% to 100%.

3.2.2 Hermosillo

Hermosillo (29.1026, -110.97732) has a warm-dry climate. The hottest months are June, July and August with average temperatures of 32°C, 33°C and 32°C, respectively.

3.2.3 Monterrey

Monterrey (25.67507, -100.31847) has a warm semi-arid climate; its months with the highest average temperatures are July and August with 28°C, while the coldest month is January with 14°C on average.

3.2.4 Tampico

Tampico (22.28519, -97.87777) has a humid subtropical climate with an average annual temperature of 25°C. The highest temperature month is June with 29°C, while January has the lowest temperature at 19°C.

3.2.5 Guanajuato

Guanajuato (21.07784, -101.25289) has a temperate climate, with an average annual temperature of 18°C, the hottest month is May with an average temperature of 22°C, while the coldest month is December with 14°C.

3.2.6 Querétaro

Querétaro (20.58806, -100.38806) has a semi-arid climate, an average temperature of 17°C, the warmest month is May with an average temperature of 21°C and the coldest month is January with an average temperature of 13°C.

3.2.7 Pachuca

Pachuca (20.11697, -98.73329) has a dry-cold climate, its average annual temperature is 14°C, May is the hottest month with an average temperature of 17°C, while the coldest month is January with an average temperature of 11°C.

3.2.8 Cancún

Cancún (21.17429, -86.84656) has a warm-humid climate; its average annual temperature is 23°C and an average annual relative humidity of 79%. July and August are the hottest months with an average temperature of 28°C, while the coldest months are December and January with an average temperature of 23°C.

The meteorological data, corresponding to the eight cities in Mexico, are taken directly from the Energy Plus data base.

4. RESULTS AND DISCUSSIONS

The results of the simulations performed in EnergyPlus for the climatic conditions of Mexicali, Hermosillo, Monterrey, Tampico, Guanajuato, Querétaro, Pachuca and Cancún are presented below. Subsequently, the results are discussed.

4.1 Results

Figure-3 shows the maximum temperature (T_{max}), the minimum temperature (T_{min}) and the average temperature ($T_{average}$) during one year in bedroom 1 in a house with a conventional roof and an EGR. As it can be observed, the green roof has practically no impact on the minimum temperature. However, the EGR has a significant impact on the maximum temperature, reducing it by up to 2.5°C.

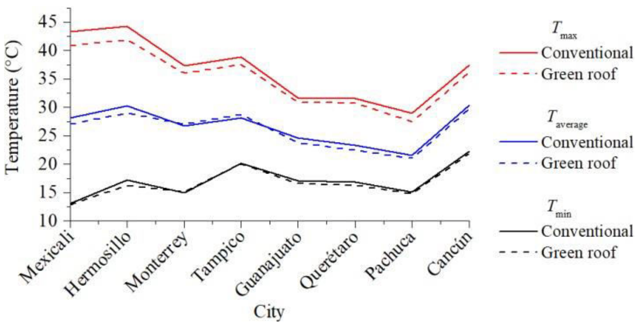

Figure-3. Maximum, average and minimum temperature in bedroom 1 for the different climatic conditions.

Figure-4 shows the temperature results for bedroom 2. In contrast to the results for bedroom 1, in bedroom 2 there is a noticeable change in the minimum temperature, the EGR can increase it by up to 4°C. The EGR also reduces the average temperature up to 12°C and the maximum temperature by almost 11°C.

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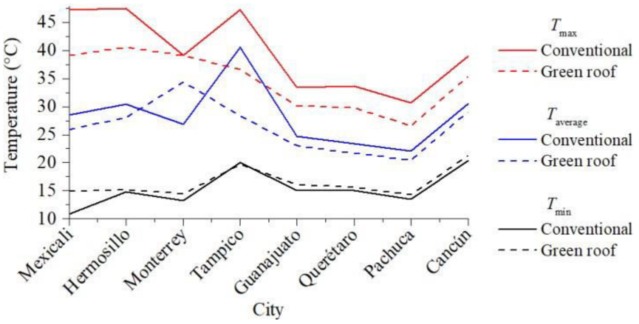

Figure-4. Maximum, average and minimum temperature in bedroom 2 for the different climatic conditions.

With the interior temperature of the house, obtained with EnergyPlus, the percentage of time per year with a feeling of comfort inside the house is determined. For Mexicali, Monterrey, Tampico, Guanajuato, Querétaro and Cancún, the comfort time increases with the implementation of the EGR (see Figure-5). However, the EGR for Hermosillo decreases the comfort time in bedroom 2; for Pachuca it decreases the comfort time in both bedrooms, according to the PMV there is a cold sensation for a longer time with the EGR.

In Guanajuato and Querétaro the percentage of comfort time is higher than 50%, to increase this percentage a heating equipment is needed, i.e., under these climatic conditions the implementation of EGR is sufficient to meet the cooling needs. Therefore, Guanajuato and Querétaro are not considered for the calculation of energy consumption for cooling.

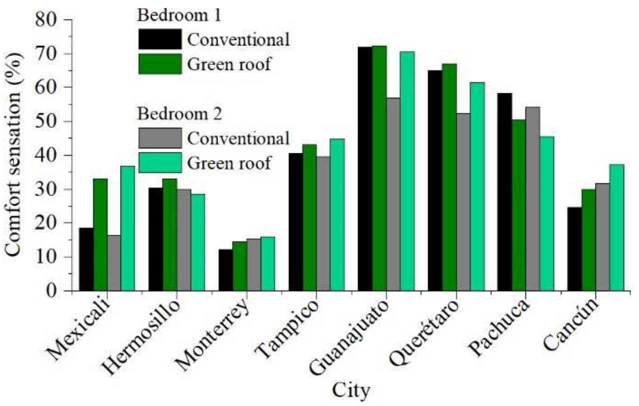

Figure-5. Percentage of annual time with comfortable sensation inside the rooms.

Figure-6 shows the energy consumption of the air conditioning (cooling) system. In all cases there is a decrease in energy consumption because of the EGR; however, this decrease is more noticeable for bedroom 2. The reduction in energy consumption has economic and environmental benefits, one of the latter being the reduction in CO_2 emissions into the atmosphere. Figure-7 shows the kg of CO_2 equivalents avoided each year due to the implementation of the EGR.

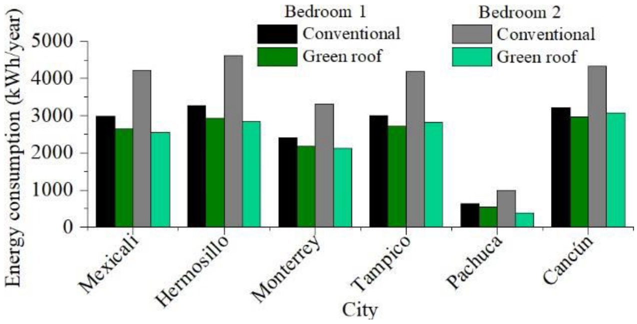

Figure-6. Annual energy consumption for air conditioning (cooling) for the climatic conditions of different cities.

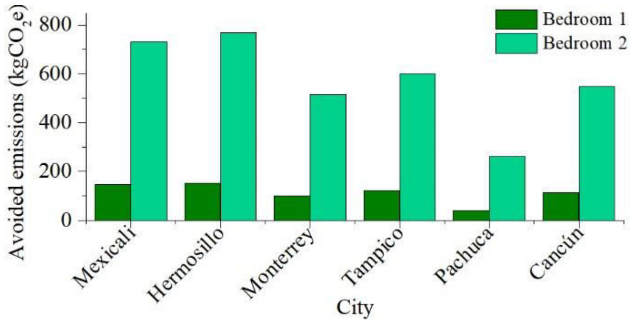

Figure-7. Avoided annual CO_2 emissions due to the implementation of the extensive green roof.

4.2 DISCUSSIONS

In the literature, there is a wide variety of results regarding energy savings from the cooling effect of EGR. Therefore, it is necessary to perform studies for different climatic conditions, considering factors such as building envelope construction materials and EGR composition. In fact, the results of the present study show a remarkable variation in energy savings for different climatic conditions and room location in the house (Figure-6). For the room on the upper floor (bedroom 2) the energy savings are higher compared to the room located on the first floor (bedroom 1) of the house. In bedroom 1 the energy savings range from 8%, for Cancún, to 14%, for Pachuca. While in bedroom 2 the energy savings range from 29%, for Cancún, to 60%, for Pachuca. In fact, the implementation of an EGR under the climatic conditions of Guanajuato and Querétaro is sufficient to achieve thermal comfort conditions inside the house.

These results are consistent with those reported in other studies. Chagolla-Aranda *et al*. (2017) found that the EGR reduces energy consumption by 10.3% with respect to a conventional roof; the study was conducted for a semi-warm climate of Mexico. Avila-Hernandez *et al*. (2020) by simulation demonstrated that in temperate climate locations, EGR reduce the cooling energy demand by up to 99%; while, in hot climate locations EGR reduce the interior temperature of the house by up to 4.7°C. Mungur *et al*. (2020) conclude that EGR reduces interior temperature fluctuations and daily peak indoor temperature, which are significantly attenuated compared to a conventional roof.

Regarding to interior temperature, the results of the present work show a more significant decrease in the maximum temperature, T_{max}, in bedroom 2 with a decrease of almost 11°C in Tampico. The maximum increase in the minimum temperature, T_{min}, is 4°C in bedroom 2 with the climatic conditions of Mexicali. For all case studies the average temperature, $T_{average}$, in bedroom 2 decreases by about 2°C; except for Tampico, where it decreases over 12°C. The results show that the cooling effect provided by EGR is greater on the top floor of the house. In fact, this cooling effect can decrease the comfort time as in Pachuca, where the EGR increases the cold sensation.

All these results were considered satisfactory and motivating for the implementation of EGR in poorly thermally insulated buildings.

Lack of government promotion and incentives, as well as increased maintenance, design, and construction costs, are identified as the main barriers to the implementation of green roofs (Chen *et al*., 2019). However, EGR modeling can be useful for residents, builders, architects, engineers, and policy makers to better understand the potential of this technology to decrease energy consumption. Thus, simulation can be useful in proposing standards or policies to encourage the adoption of this technology.

5. CONCLUSIONS

In this work, the thermal effect of extensive green roofs was analyzed. A complete house (first floor and top floor) was simulated two rooms: temperature, comfort sensation and air conditioning energy consumption were analyzed. The rooms have the same dimensions, one of them is located on the first floor (bedroom 1) and the other one on the second floor (bedroom 2). The house was simulated with the climatic conditions of a year in different cities of Mexico: Mexicali, Hermosillo, Monterrey, Tampico, Guanajuato, Querétaro, Pachuca and Cancún.

The results show that the extensive green roof helps to decrease the maximum interior temperature the bedrooms (T_{max}), especially in bedroom 2 to just over 10°C (see Figure-3 and Figure-4). However, the minimum temperature (T_{min}) can increase significantly in bedroom 2, up to just over 4 °C. While the average temperature ($T_{average}$) does not show such noticeable changes; except for the climatic conditions of Tampico, decreasing to just over 12°C.

In all the cases studied, extensive green roofs contribute to achieve thermal comfort conditions in the bedrooms. In fact, the implementation of an extensive green roof in Guanajuato and Querétaro avoids the use of air conditioning (see Figure-5).

Extensive green roofs contribute to decrease energy consumption for air conditioning in both rooms, but more significantly in bedroom 2 (see Figure-6), with a maximum savings of almost 1,800 kWh/year with the climatic conditions of Hermosillo.

The thermal effect of the extensive green roofs is greater in bedroom 2; i.e., the extensive green roofs have a greater cooling effect on the top floors and this effect decreases on the bottom floors.

The energy savings represent a small decrease in greenhouse gas emissions (see Figure-7); however, the massive implementation of extensive green roofs in the cities studied could represent a significant decrease in greenhouse gas emissions in the Mexican residential sector.

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