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The impact of human occupancy in thermal performance of a historic religious building in sub-humid temperate climate

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ABSTRACT

The level of human occupancy in historic religious buildings influences the internal heat gains and thus the thermal comfort of the users. The temperate climate represents a challenge due to variations in temperature and relative humidity throughout the year, which are by no means extreme. Knowledge regarding human occupancy in historic religious buildings in temperate climates increases the possibilities of controlling and staying within a given comfort range for the users benefit. The objective was to determine the impact of occupancy on the thermal performance of a historic religious building located in sub-humid temperate climate, to increase the knowledge and to generate opportunities to decrease the excessive use of active systems prevalent today.

The objective was approached with a numerical method that included monitoring periods and dynamic simulation to determine a novel passive cooling system that would maintain a determined comfort temperature for the longest time in summer. By implementing a novel passive cooling system, the results showed an impact on the operative temperature according to occupancy level, which reduced the cooling degree-hour by 80% and 66% at the upper occupancy with 80% and 90% satisfaction levels, respectively.

1. Introduction and background

Religious practice in Mexico is one of the most important social activities with predominantly Catholic groups. In this sense, 29.5% of the total population practices a religion based on Christianity [1]. In Mexico, this percentage corresponds to 84.4% of the population [2]. There are non-Catholic religious buildings built with traditional construction methods. Since 2000, non-Catholic practice has been spreading in the country, reaching 13% of the Mexican population by 2020 [2]. The user's permanence in the spaces destined for this activity depends on each religion, which allows them to experience different levels of comfort related to the occupancy, seasons and construction systems like the envelope thermal design, parameters directly related to energy consumption.

Historic buildings provide resources to learn about the customs developed in different periods, as key manifestations of lifestyles in the past, and are considered an important tangible cultural heritage [3]; created by people with some knowledge about building techniques who use local methods and materials with references to tradition [4]. Historic buildings were commonly built with local materials, as was the case in central Mexico during the 20th century, where walls of fired red brick, adobe and reinforced concrete slabs predominated.

The energy consumption of historic religious building depends on aspects such as the use of active systems, occupancy or existing damages in the envelope, which could also change indoor microclimate conditions [5]. Azmi et al. [6] reviewed different studies to find factors with the greatest influence on the energy efficiency of mosque buildings. They concluded that the thermal design of the envelope and climatic factors are the most significant aspects of the mosque energy use. The thermal design purpose of the envelope is to identify the climatic conditions where the building is located to know the cooling and heating needs throughout the year or during a certain season. Then, by using materials and construction systems and the building typology, propose a system in the area of greatest influence of the envelope that thermally contributes or discriminates solar gains to ensure a greater number of comfort hours for users and a more efficient use of energy.

There are some limitations when performing simulations on historic buildings, such as the thermal properties of some regional materials. If we also consider religious activity, where activities such as prayer or meditation take place, occupancy and climatic

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conditions are key variables in achieving or maintaining acceptable comfort levels; with passive, active, or mixed ventilation systems.

This research analysed the occupancy impact on the thermal performance of a historic religious building in sub-humid temperate climate. The impact of this study would directly benefit the population of 13.5 million km^2 of temperate climates in Mexico [7]. Indirectly, the methodology used would increase the impact on the population attending religious centres in other climates and countries.

The literature review related to historic and religious buildings was divided into three groups: energy saving projections, thermal behaviour and simulation studies. As well as the interaction between the mentioned groups in relation to human occupation. Bienvenido-Huertas et al. [5] assessed the impact of climate change on the conservation of historic buildings with warm climates in Spain. They found that the areas most influenced by climate change were those with high temperatures and relative humidity and therefore considered that conditioning measures based on cooling and dehumidification strategies were necessary. Alternatively, Muñoz González et al. [8] found that as relative humidity increased, there was an increase in energy consumption of 10–15%.

Earlier papers analysed religious buildings in extreme climatic conditions, such as the conducted by Díaz-Salazar et al. [9], who analysed the thermal behaviour of a religious building in a humid warm climate, showing the cooling, heating and comfort tasks with an adaptive model using dynamic simulation and monitoring periods. Azmi et al. [10] conducted a literature review to identify the variables that influence the thermal performance of mosques around the world. They analysed building systems, occupancy level, climatic context and other elements. They found that the occupancy influences of 7% of the thermal load in mosques.

More than 50% of the previous studies consulted related to religious buildings focused on thermal comfort, while 15% examined energy use. Indoor Air Quality (IAQ) deteriorates rapidly with a higher occupancy, and natural ventilation is not sufficient to ventilate churches at peak occupancy times [11]. Atmaca et al. [12] found that acceptable thermal comfort conditions specified by the standards are not always valid for every type of building in humid temperate climate.

The quest for energy efficiency in historic buildings has increased because at least a quarter of the world's buildings is considered historic [8] and there is a lack of information about input parameters [13]. Building occupants were the predominant influence on final energy consumption of offices in different climates, there was one scenario that showed an increase with 2.5 more final energy consumption [14].

In their study, Srithongchai et al. [15] investigated in the field the adaptability of users in three meditation rooms in Thailand focussing on thermal comfort. They found that users' behaviour was the appropriate adaptive solution for the thermal comfort of naturally ventilated meditation buildings. Osman et al. [16] compared design strategies obtained from projections, and showed the need to maximise passive cooling design strategies and filtration control.

Against this background, the objective was to determine the occupancy impact on the thermal performance of a historic religious building to establish a novel passive cooling system for energy savings in sub-humid temperate climate.

The objective was focused on maintaining or achieve the thermal comfort of the occupants during their stay. Although more than 80% of the population in Mexico practices a Christian religion, historical religious buildings have been less explored than the residential sector in relation to thermal behaviour and cooling systems, especially in temperate climates [9,17–20]. Therefore, the main novelty and scientific significance of this study is to analyse numerically and thermally a historic building with religious practices in a sub-humid temperate climate in Mexico with the independent variable occupancy level.

2. Materials and methods

To achieve the stated objectives, a theoretical experimental method combined with monitoring periods and an active system (fan) according to the user's thermal sensation corresponding to an empirically controlled concurrent mixed mode ventilation system was used.

The method consisted of specifying the case study and the occupancy periods. Prior to the monitoring period, the data loggers' accuracy was analysed. The thermal comfort model was determined and finally simulation rounds with energy saving strategies were carried out to determine the passive cooling system with the best opportunity of remaining within the determined thermal comfort. With the observed and projected data, validation was carried out and finally the results were analysed.

2.1. Case study

The case study corresponds to a religious building constructed in the central region of Mexico (coordinates 21°07′13.6″N 101°41′14.2″W) during the 50 s; built with fired brick walls of 0.07X0.14X0.28 m, slabs and columns of reinforced concrete 0.10 m. Due to construction period, this building was not catalogued by the National Institute of Anthropology and History (INAH by its Spanish acronym). Fig. 1(a and b) indicates the geometrical dimensions and the two building floors. Numbers 1 and 2 correspond to the data logger's location on the first floor. Fig. 1 (c) shows the current condition of the ground floor.

The central region where the case study is located corresponds to a sub-humid temperate climate. The climate classification corresponds to climatic characterisation developed by Gómez-Azpeitia [21], supported by climate measurements made by the National Meteorological System for 30 years [22].

Table 1 presents the climatic characteristics for summer (April to September) in the case study.

This building uses a mixed-mode ventilation system during the occupancy hours known as concurrent [23]. The concurrent mixed mode ventilation system is defined as the use of passive systems (natural ventilation) and active systems (mechanical ventilation, in this case 43 W power fan) in the same space at the same time. The ventilation system used empirically does not provide the required thermal comfort at the occupation period, so the analysis focused on the summer. Considering that summer is the season when there is a higher level of discomfort during the occupancy.

More than 50% of the building' users are adults of both genders, with varying age and weight ranges, and average heights of 1.7 m for men and 1.57 m for women. With the occupancy timetable specified in the following section. The central area where this building is located has no immediate vegetation and numerous vehicles. In its beginnings, it was a central neighbourhood destined for housing, so the neighbouring buildings correspond to residential and commercial use due to the central location. The construction period of most of these dwellings is the 1950 s with materials similar to the case study. The height on the ground floor is 3.2 m, while on the first floor it is 2.5 m. The heights, occupancy level, physical properties of the materials and the solar gains generate heat accumulation on the first floor. An important fact for solar gains corresponds to the height of the adjoining buildings; on the east side, there are buildings higher than the case study, generating

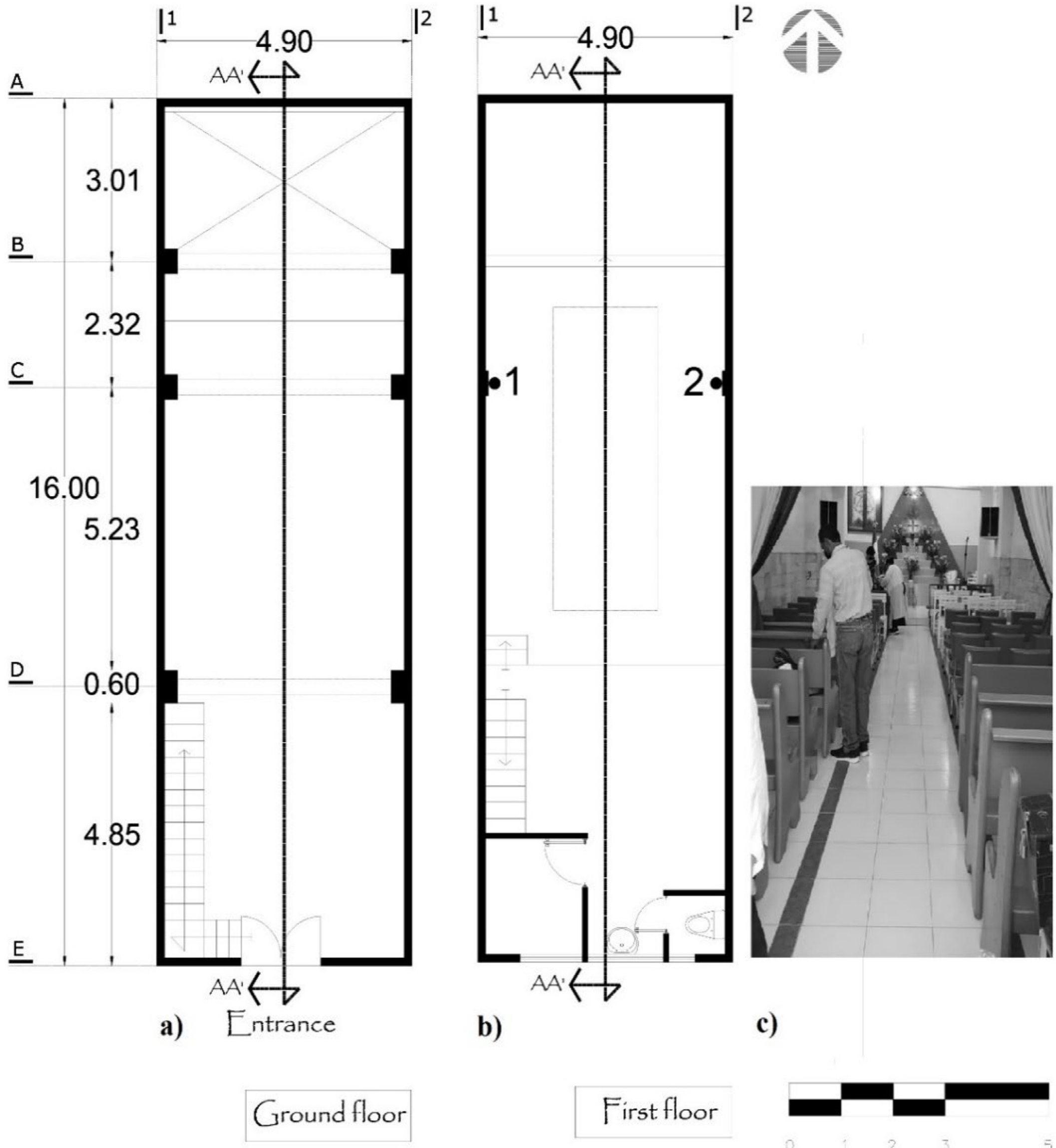

Fig. 1. Geometrical characteristics of the case study.

Table 1
Climatic indicators in summer for the Sub-Humid temperate climate.

Indicator	Data
Average Dry-bulb temperature	21 °C
Average monthly rainfall	88.6 mm
Average relative humidity	63 %
Average absolute humidity	11 g/kg

shadows and a lower solar exposure, while on the west side, the height does not exceed the case study, resulting in a higher exposure to solar gains. Fig. 2 shows the height ratio between the case study and neighbouring buildings.

Due to the historic building characteristics, heat inputs and outputs are performed as shown schematically in Fig. 3. Solar radiation was considered the main heat gain source, and due to the occupancy characteristics, heat generation by human metabolism was added. Air stratification increases heat gains on the first floor, generating greater temperatures during the summer, so the measuring devices were located on the first floor, at 1.7 m height as recommended by ASHRAE Standard 55–2020 [24].

The activities in this religious building are from individual and group prayer to meditation

practices. The access door remains open, which allows air renewal during occupancy periods. In Table 2 the thermophysical properties of the building materials used are shown.

2.2. Occupancy periods

In Table 3, the number of people who attended this religious site and their occupancy hours were quantified for one month during the summer. This quantification does not vary by more than 5% throughout the year, so it was considered as a constant to analyse the results. The highest occupancy was on Sundays, followed by Tuesdays, even so, the whole month was analysed according to the activities, as well as the climatic characteristics and typology of the building in relation to its occupancy.

Fig. 2. Buildings' height adjacent to the case study.

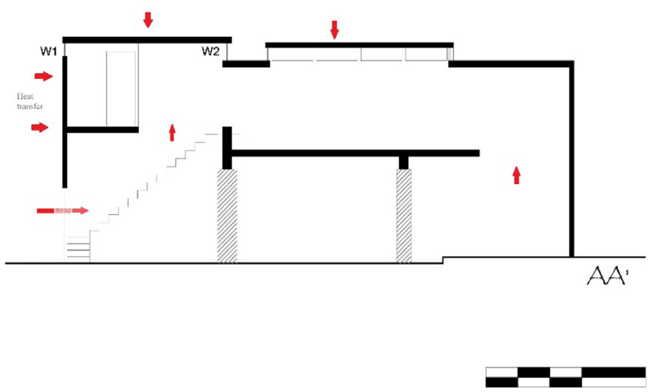

Fig. 3. Heat gains in the building in longitudinal section AA'.

2.3. Monitoring period

Due to the user's thermal discomfort during the occupancy period, monitoring was carried out for one month during the summer (see Table 3). Data loggers were used with the technical specification detailed in Table 4. Prior to the monitoring month, the data loggers' accuracy was checked for one week to ensure their proper function. There was a difference of less than 0.1% between each device, so the data obtained for temperature and relative humidity technically corresponds to the actual space measured during the monitoring period.

The data logger's location followed the ASHRAE Standard 55–2020 recommendations [24]; due to the significance level for the building occupants. The data loggers were located on the first floor, at 1.7 m height (see Fig. 4). Strategic location where the most extreme values of the thermal parameters were estimated to be found, due to the basic heat transfer principles described in section 2.1 and the occupancy level during the monitoring month. Measurements were taken at hourly intervals.

The monitoring results are shown in Fig. 5. Data logger 1 corresponds to the west wall and data logger 2 to the east wall. A larger oscillation was observed in the temperature variation of the west wall; an expected result due to the thermal inertia of the fired red brick in the walls, as well as the roof slab concrete.

The west wall showed a temperature difference up to 4 °C compared to the east wall. The difference in temperature and oscillation also corresponds to the neighbouring buildings height. On the east, there is a building height are 2 m higher, which generates shadows that decrease the solar exposure time, while on the west side, no building is higher than the case study, which increases the exposure hours and therefore the solar gains.

However, relative humidity did not show significant variations in frequency or oscillation during the monitoring month for both

Table 2
Thermophysical properties of materials [25,26].

Element	ρ Kg/m^3	C_eJ/KgK	λ W/mK	U W/m^{2}K
Red fired brick	1920	840	0.72	0.360
Concrete, reinforced	2400	900	2.15	0.556
Glazing 3 mm	2200	750	0.93	1.800
Mortar (cement:sand 1:3)	2800	896	0.88	–

Table 3
Occupancy observed May 2021.

Month	day	Occupancy	Occupancy timetable
May	2	0	0
	3	31	16:30 to 18:30
	4	74	16 to 19
	5	79	17 to 19:30
	6	45	17 to 19:30
	7	29	17 to 19:30
	8	0	0
	9	77	9 to 12
	10	40	17 to 19:30
	11	75	16 to 19
	12	14	16:30 to 18:30
	13	53	17 to 19:30
	14	0	0
	15	0	0
	16	79	9 to 12
	17	38	16:30 to 18:30
	18	85	16 to 19
	19	19	16:30 to 18:30
	20	53	17 to 19:30
	21	61	17 to 19:30
	22	0	0
	23	93	9 to 12
	24	33	16:30 to 18:30
	25	58	16 to 19
	26	29	16:30 to 18:30
	27	52	17 to 19:30
	28	0	0
	29	0	0
	30	103	9 to 12
	31	24	16:30 to 18:30
Jun	1	93	16 to 19
	2	25	16:30 to 18:30

Table 4
Technical parameters of measuring devices.

Devices	Variable	Measuring range	Accuracy range	ASHRAE Standard 55
1, 2	Temperature	−30 °C ~ +70 °C	±0.5 °C (-20 ~ +40 °C) ±1 °C (others)	outdoor-indoor temperature and humidity differences were not less than 50% of the representative sky conditions
	Relative humidity	0% ~ 100% RH	±3%RH (20% ~ 80% RH) ±5% RH (others)	

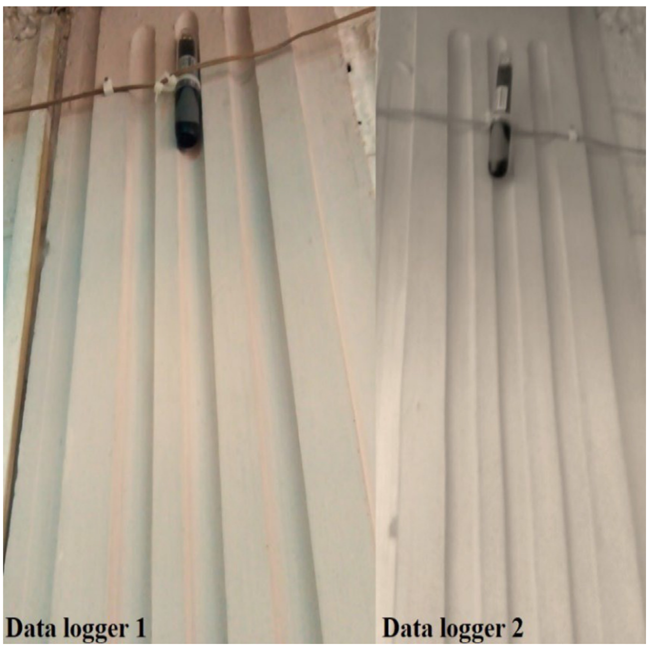

Fig. 4. Data logger's location in the first level.

devices. However, during the second half of the month, relative humidity discomfort reached 20%. It was important to know the temperature performance and relative humidity prior to the simulation process to compare the results and determine their feasibility.

2.4. Thermal comfort model

As a reference of the discomfort expressed through interviews with users generated by indoor heat gains during occupancy period, three of the main comfort models developed were analysed. The International Standard ISO 7730, the European Standard EN 16798–1 and ASHRAE Standard 55. It was determined to use the comfort model based on ASHRAE Standard 55, for buildings without installed HVAC systems. The Standard specifies that an average outdoor temperature between 10 °C and 33.5 °C should prevail and that occupants' activities should be sedentary (met between 1.0 and 1.3) [27].

The comfort temperature was quantified with Eq. (1) [28]. This comfort model considers naturally ventilated buildings operated empirically by the users. In addition, it can be used in spaces where mechanical cooling systems (fan) are used as long as they are not air-conditioned. It is therefore relevant for buildings with concurrent mixed mode ventilation systems such as this study.

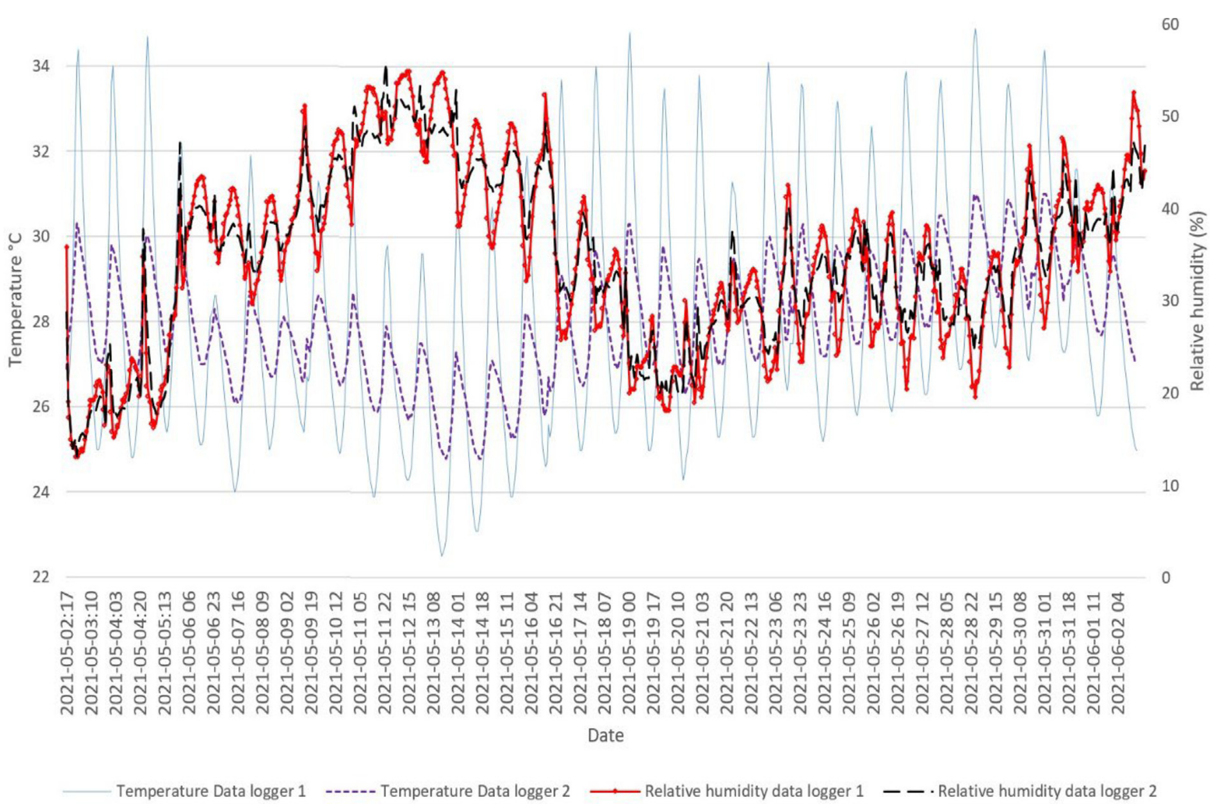

Fig. 5. Monitoring period results for dry bulb temperature and relative humidity.

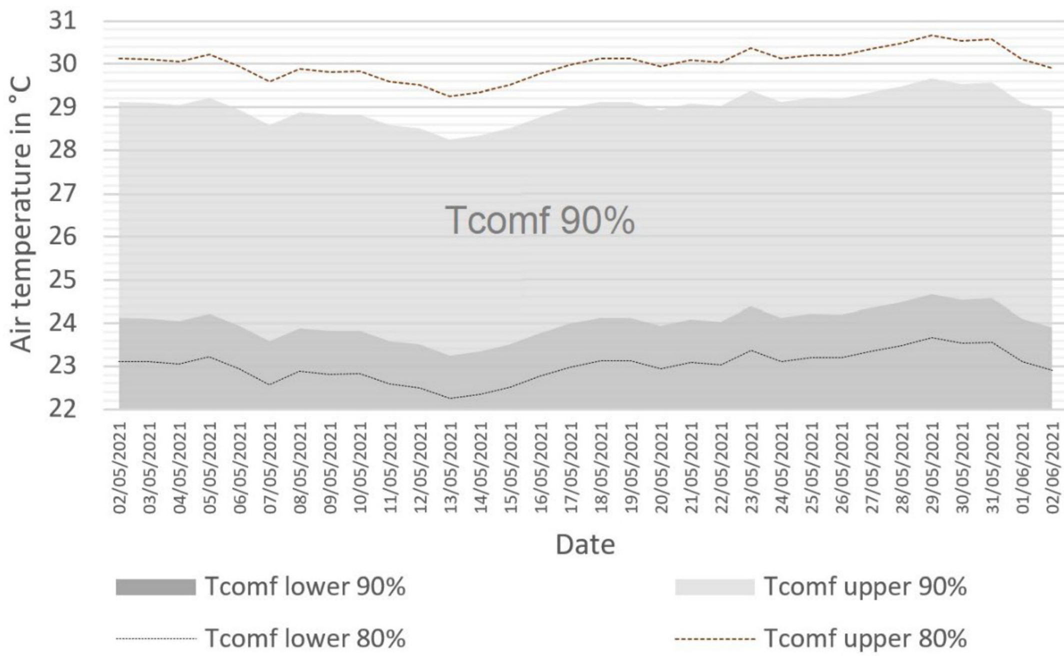

Fig. 6. Analysis of the comfort range according to the satisfaction level.

Table 5
Occupancy profiles used in simulation process.

Occupancy level	Average occupancy	Density Persons/m^2	Metabolic rate W/persons
Zero (Saturday)	0	0	0
Medium (Monday)	33	0.4	29
Highest (Sunday)	88	1.1	79

$$\text{Tcomf} = 0.31\text{Tout} + 17.8 \quad (1)$$

The comfort temperature (Tcomf) was determined from the average daily air temperature (Tout) calculated with data from measurements taken in the selected locality over 30 years [22]. The ASHRAE 55–2020 standard considers two satisfaction percentages, 80% with a 7 °C amplitude range and 90% satisfaction with a 5 °C amplitude range when a higher comfort level is sought. As a result, Fig. 6 shows the comfort thresholds for 80% and 90% satisfaction [24].

2.5. Simulation and validation process

Geometrically, the simulation process was considered with axis dimensions, and the same comfort model mentioned in section 2.4 was used in Design Builder v7. Due to the building characteristics, a poor infiltration was used with an air renewal rate of 0.7 ren/h during the whole week [29]. The roof slab parapet was considered an adiabatic element. The thermal properties of the materials shown in Table 2 were used [30] based on [31].

An occupancy template was used for sedentary activities with many people sitting and it was determined to analyse the lowest, average and highest occupancy days to establish the influence on thermal performance as shown in Table 5. No computers or other office equipment were selected, so the detailed internal gains correspond to the occupancy level.

The people occupancy per area method was used, defined in terms of people per floor area, where the latent gains per occupancy refer to the moisture contributed by people through transpiration and respiration based on the indoor temperature and metabolic rate [32].

The metabolic rate, represented in W/persons, indicates the heat generated by the human body through oxidation. A value of 0.9 W/person was used for mixed groups (men and women). Different simulations were carried out to modify the occupancy level as shown in Table 5. Single glazing of 3 mm was used in the windows.

751 data obtained during the measurement period were analysed against the simulation data resulted for the same period at hourly intervals. For the validation process, the collection of 751 pairs (measured vs. simulated data) was used to compare two indices developed by Willmott (Eq. (2)) [33] and Ali et al. (Eq. (3)) [34].

$$d = 1 - \frac{\sum_{i=1}^{N}(O_i - P_i)^2}{\sum_{i=1}^{N}[O'_i + P'_i]2} \quad (2)$$

Where: $O'_i = |O_i - \overline{P}|$, $P'_i = |P_i - \overline{P}|$, O_i is the observed value and P_i is the simulated value and $\overline{P}$ is the simulated mean.

Ali et al. developed the statistical method of the Percent Mean Absolute Relative Error (PMARE) representing in Eq. (3).

$$\text{PMARE}(\%) = \frac{100}{n}\sum_{i=1}^{n}\frac{Abs(O_i - P_i)}{O_i} \quad (3)$$

Where:

$$\text{O}_\text{i} = \text{Observeddry} - \text{bulbtemperature}$$

$$\text{P}_\text{i} = \text{Simulateddry} - \text{bulbtemperature}$$

Abs = Absolute value

Lower PMARE values indicate less errors and better model simulation. In both indices, the results were rated as well indicating a good model performance ranking (see Table 6).

2.6. Passive cooling system strategy

Based on experimental and simulation studies, such as those developed by [35–39], it was proved that the use of passive cooling

Table 6
Results of validation process.

Date	Oi	Pi	Willmott	PMARE
02/05/21	28.4	32.4	15.3	0.1
03/05/21	28.4	30.1	2.9	0.1
04/05/21	28.3	29.6	1.9	0
05/05/21	28.8	30.3	2.3	0.1
06/05/21	27.9	31.0	10	0.1
07/05/21	26.7	29.7	9	0.1
08/05/21	27.7	28.9	1.4	0
09/05/21	27.5	27.2	0.1	0
10/05/21	27.5	27.1	0.2	0
11/05/21	26.7	27.4	0.4	0
12/05/21	26.5	27.7	1.6	0
13/05/21	25.6	26.6	1.0	0
14/05/21	25.9	26.8	0.8	0
15/05/21	26.5	26.7	0	0
16/05/21	27.3	27.0	0.1	0
17/05/21	28.0	27.2	0.7	0
18/05/21	28.5	27.1	1.8	0
19/05/21	28.5	26.4	4.5	0.1
20/05/21	27.9	29.1	1.4	0
21/05/21	28.3	31.2	8.4	0.1
22/05/21	28.2	30.9	7.3	0.1
23/05/21	29.3	29.5	0	0
24/05/21	28.4	28.4	0	0
25/05/21	28.7	29.4	0.5	0
26/05/21	28.7	29.9	1.3	0
27/05/21	29.2	29.9	0.5	0
28/05/21	29.6	29.9	0.1	0
29/05/21	30.2	29.1	1.4	0
30/05/21	29.8	28.2	2.3	0.1
31/05/21	29.9	27.4	6	0.1
01/06/21	28.4	27.3	1.2	0
02/06/21	27.7	27.3	0.2	0
Index result			**0.6**	**4.6**

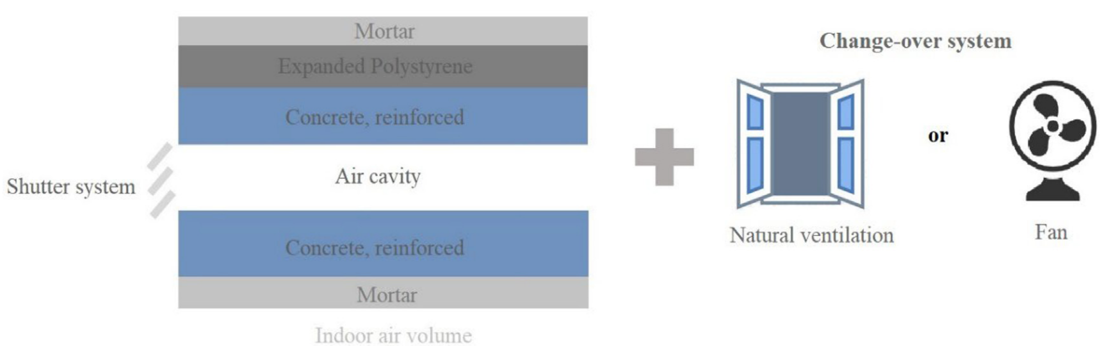

Fig. 7. Characteristics of the proposed PCS.

Table 7
Layers and thermal properties of materials used in the double skin roof system [25,26].

Element	Thickness in m	ρKg/m^3	C_eJ/KgK	λW/mK
Mortar	0.03	2800	896	0.88
Expanded Polystyrene	0.05	15	1400	0.04
Concrete, reinforced	0.1	2400	900	2.15
Air gap	0.1	1000	1000	0.3
Concrete, reinforced	0.1	2400	900	2.15
Mortar	0.03	2800	896	0.88

systems saved energy in extremely warm humid and dry climates. In Mexico, it is common to find studies on passive cooling systems and thermal analysis in extreme or hot climates [17,18,40–42], and generally in the residential sector. The capacity of these systems in sub-humid temperate climates has been less studied and this percentage decreases more in religious historical buildings. To expose the potential of passive systems in sub-humid temperate climate, a passive cooling system (PCS) was incorporated, which would also have lower visual impact due to the historical characteristics of the case study. The proposed PCS consisted of incorporating 3 strategies: a double skin roof with an air cavity, a change in the mixed mode ventilation system and roof insulation, as it is the area of greatest exposure to solar radiation.

Fig. 7 shows the characteristics of the proposed double skin roof to reduce the cooling task on summer. The PCS was reinforced with insulation according to the Mexican standard NMX-C-460-ONNCCE-2009 [41] and an air cavity in a double skin roof. A major impact was considered in the reduction of solar gains on the roof slab due to the exposure area (78.4 m^2).

The cooling capacity of the double skin roof was quantified by dynamic simulation and a simple solution to the ventilation system was also incorporated into modifying two of the first floor windows (see W1 and W2 in Fig. 2) with a shutter system that can be programmed to remain open during the summer and closed in winter.

The modification of the ventilation system involved a mixed change-over system (use of natural ventilation or ventilation with active systems as required) [15,32]. Table 7 shows the layers used in the double skin roof system and their thermal properties.

3. Results

The data shown in Fig. 8 correspond to the first floor where the measuring devices were located, as well as the comfort range established (80% and 90% of satisfaction). The results belong to the three occupancy levels described in the previous section. May corresponds to the summer period, so the results showed cooling needs during the whole month, which decreases in the middle of this period. The cooling needs presented a difference of two degrees between the lowest and highest occupancy. A 90% satisfaction level implies a lower comfort range and an increase in the cooling degree-hour. The 90% satisfaction level had 539 h°C at the upper occupancy without PCS, while the 80% satisfaction level showed 269 h°C.

The heating needs showed a difference less than one degree Celsius between the three occupancy levels. Fig. 9 shows the simulation results for the relative humidity percentage. As expected, the results showed a lower relative humidity when the occupancy was zero. The relative humidity increased by 20% between each occupancy level due to the metabolic rate. At higher occupancy, greater oscillation and therefore greater relative humidity discomfort.

An upper occupancy resulted in a relative humidity above 60% at the beginning and during the last two weeks of May. A medium occupancy represented more desirable relative humidity levels throughout the month. In a sub-humid temperate climate, the occupancy level had a greater impact on the relative humidity.

Fig. 10 indicates the results of the PCS (double skin roof), with preference given to medium and upper occupancy models. Medium and Upper refer to the occupancy level and simulation results without a passive system; PCS refers to the simulation results including the passive cooling system. The temperature reduction reached more than 3 °C, reducing oscillations and cooling requirements. According to the satisfaction level, a reduction in cooling needs of 29% was found between 80% and 90%. In addition to promoting and increasing knowledge about passive systems in sub-humid temperate climate in relation to the occupancy of historic buildings, this solution allows predicting the thermal performance.

Due to the selected climate, heating needs were also observed, which can be controlled with the mixed mode change-over ventilation system, giving priority to the passive system over the active system. It is worth mentioning that the results focused on the operative temperature because the implementation of the PCS did not significantly change the relative humidity presented in Fig. 9.

Additionally, the cooling degree-hour (CDH) on the days with the upper occupancy obtained from the observed and simulated data were analysed. The CDH was defined as an approximation of the cooling load [43] resulting from the subtraction between the

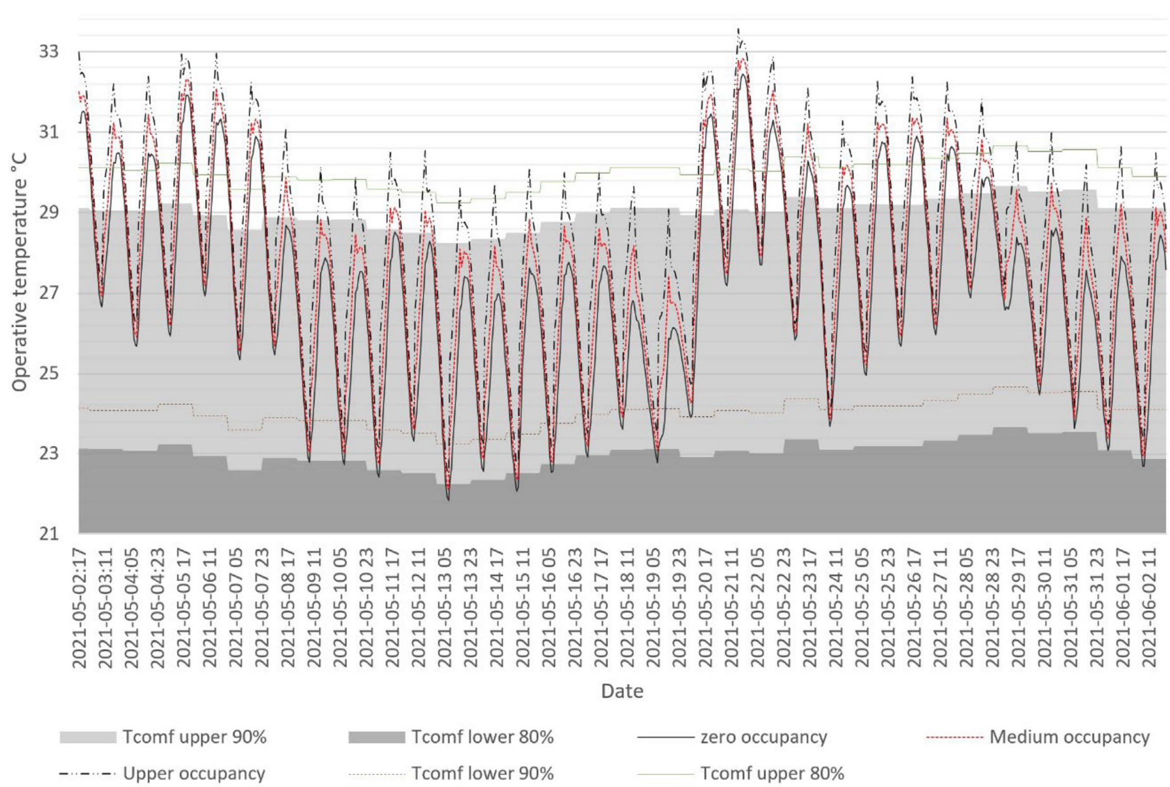

Fig. 8. Operative temperature results according to occupancy levels.

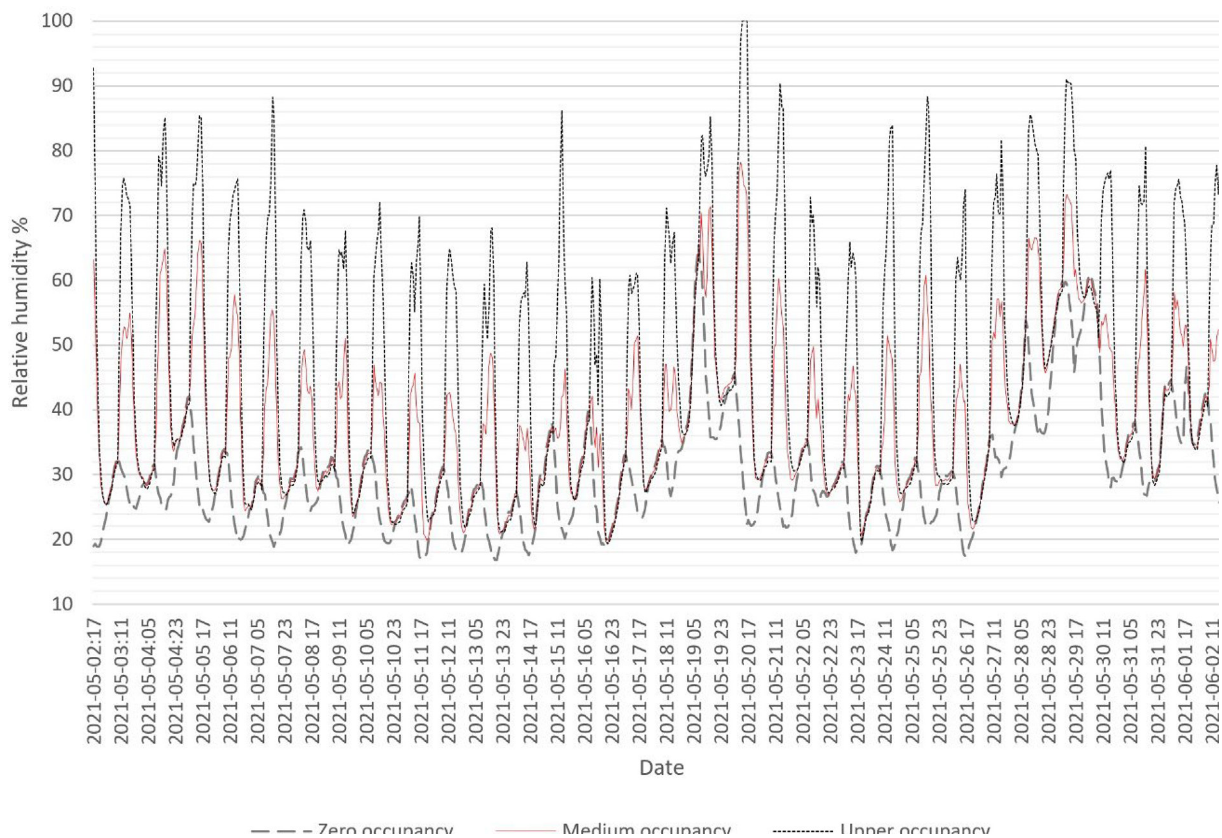

Fig. 9. Relative humidity according to occupancy levels.

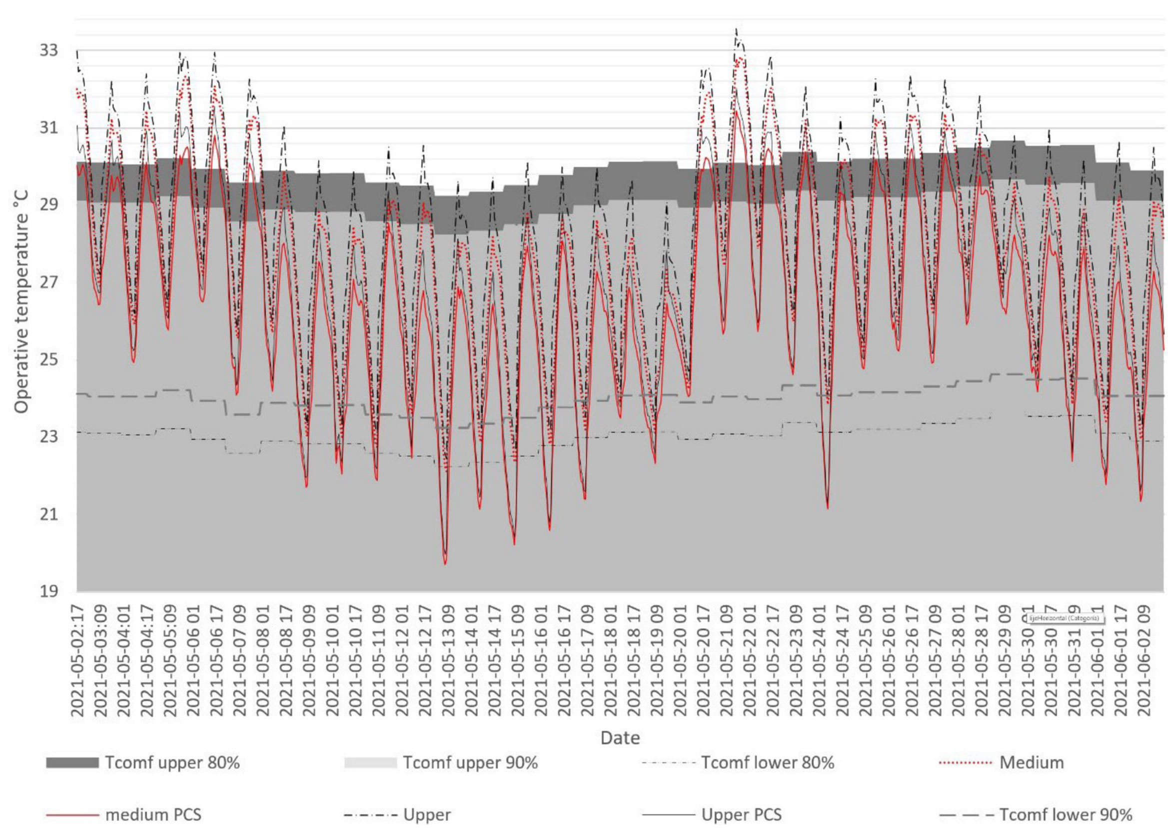

Fig. 10. Operative temperature results with PCS.

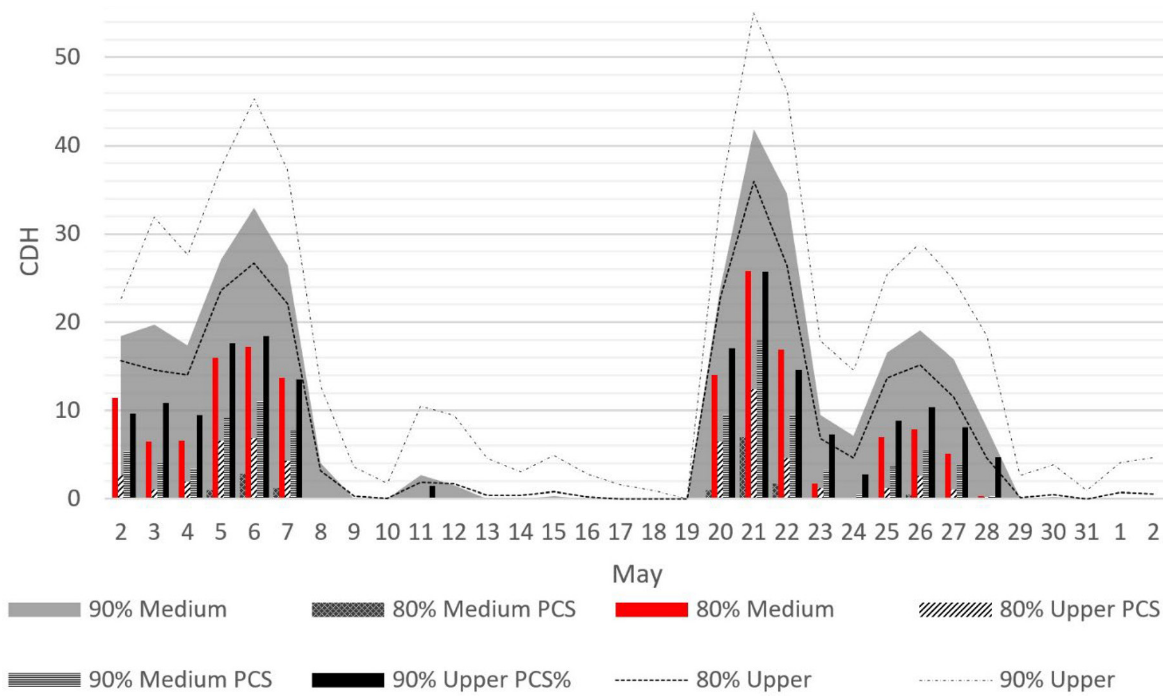

Fig. 11. CDH during the representative month.

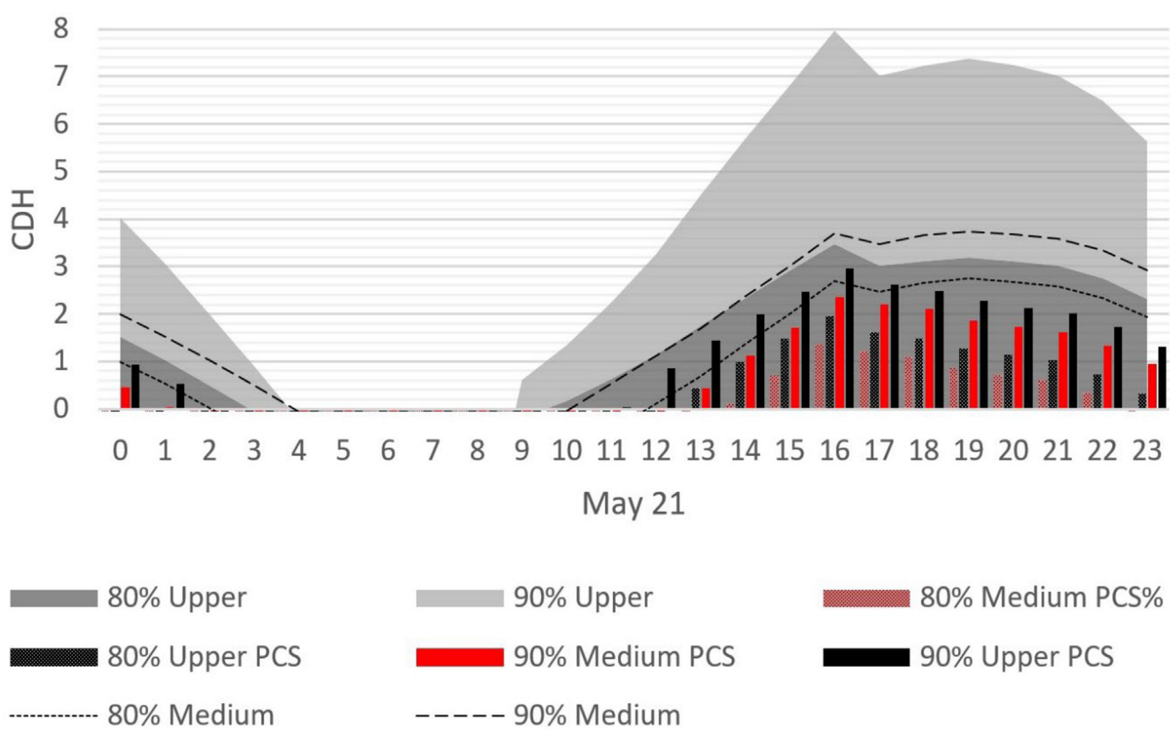

Fig. 12. CDH on May 21.

operative temperature and the upper comfort range, in this case for 80% and 90% satisfaction as determined in Fig. 6. Estimated at each hour during the reference month.

Fig. 11 shows the CDH in May and the first two days of June. PCS refers to the results according to the occupancy level simulated with the passive cooling system. As the Figure indicates, the results presented that cooling needs decreasing significantly from 13 to 19 May in different proportions according to the satisfaction level. From 13 to 19 May, cooling needs were observed at the medium and upper occupancy levels and at both satisfaction levels (80% and 90%), while with the PCS, at both satisfaction and occupancy levels, no cooling needs were observed. When using the PCS,

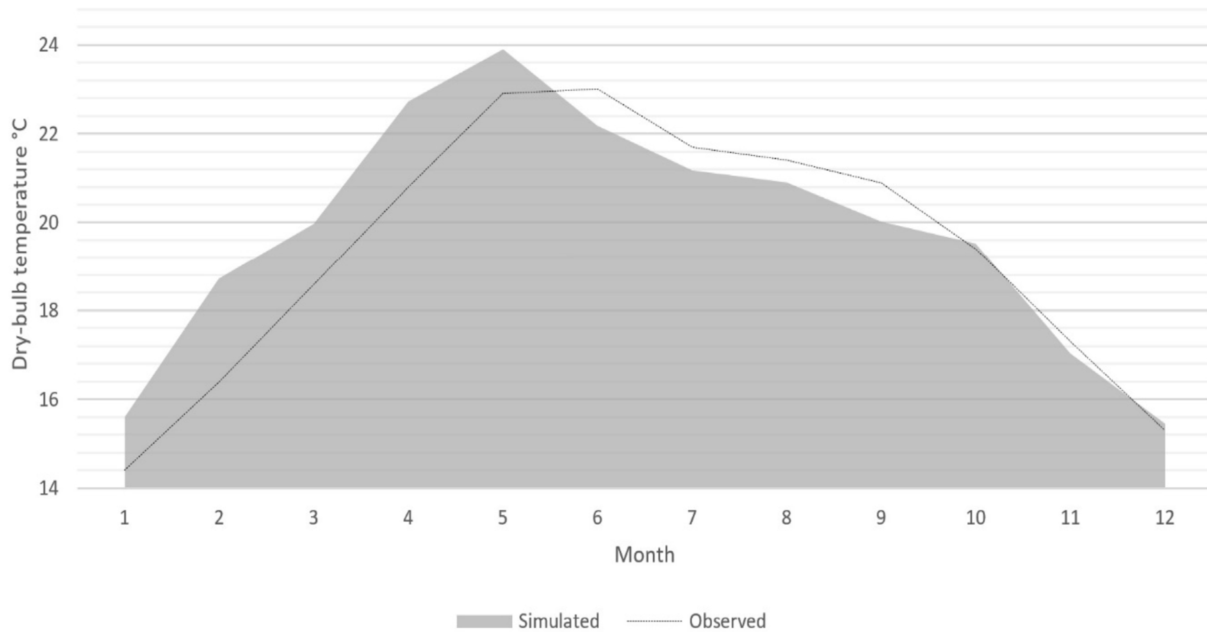

Fig. 13. Simulated & observed average dry-bulb temperature.

CDH decreased at both occupancy and satisfaction levels. At upper occupancy level, an 80% decrease in CDH was observed at a satisfaction level of 80% and a 66% decrease if the satisfaction level is increased to 90%.

In contrast to extreme climates, where cooling or heating tasks are seasonally defined, temperate climates present cooling and heating needs throughout the year to a different extent, depending on the season analysed, making them less predictable and at the same time enriching the thermal energy analysis of their buildings and open spaces.

This phenomenon is observable in May, being a representative month of the summer, there were heating and cooling needs. To demonstrate this phenomenon, it was presented the results of a day with the greatest cooling needs. Fig. 12 shows the results for May 21, where decreased the CDH when using PCS at both satisfaction and occupancy levels. The cooling needs decrease from 4 to 9 h, due to the decrease in temperature during the night and the insulation system used in the PCS.

The results obtained highlight the effectiveness of PCS and thermal insulation as strategies to improve the thermal conditions of historic religious buildings and increase the area of opportunity to use this system in other sectors.

4. Discussion

La Roche defines a PCS as the capable of reducing the average indoor temperature below the average outdoor temperature [44]. Fig. 13 shows the average dry-bulb temperature simulated with the PCS in a sub-humid temperate climate against the average outdoor dry-bulb temperature observed by the National Meteorological System for 30 years [22]. The data presented in Fig. 13 correspond to the twelve months of the year. In this Figure the PCS determined for the months with the highest cooling needs also works to reduce heat losses to the outside during the months with heating needs.

These results correspond to the characteristics of the sub-humid temperate climate for which the system was designed and imply an increase in the opportunities for prioritising the use of passive systems in locations with climatic characteristics that are not considered extreme.

To combine natural ventilation with a PCS such as evaporative cooling has been studied in walls with reductions of up to 9 °C [45]; and on roofs with a reduction of 2.4 °C [46] in warm climates. In their study, Rawat et al. [47] found that the reduction in temperature in different climate zones when using passive cooling in slabs ranged from 1.4 °C to 4.7 °C. In this study, the temperature reduction for the summer was 0.9 °C at upper occupancy levels in a historic religious building, while the temperature increase during the cold season was 1.9 °C. Increasing the stay in a comfort range with sub-humid temperate climate.

5. Conclusions

In this study, a historical religious building in sub-humid temperate climate was analysed from the occupancy level. A simulation process was carried out in Design Builder v7 and measured data for one month in the summer period. The results clearly showed cooling needs.

Due to the historical conditions of the building analysed, as well as the data obtained, a PCS was implemented consisting of a double roof skin with insulation that complies with the requirements of the Mexican standard NMX-C-460-ONNCCE-2009. The proposed double skin roof allowed the PCS to be established over the largest possible area without a visual impact that would compromise the original form of the building.

An impact on the operative temperature was observed according to occupancy level, which reduced the CDH by 80% and 66% at the upper occupancy with 80% and 90% satisfaction level, respectively.

The thermal conditions in sub-humid temperate climate showed cooling and heating needs in the summer, without becoming extreme, as expected. The implemented mixed mode changeover ventilation control system contributed to the reduction of the heating needs that were less than expected.

The thermal insulation incorporated into the PCS, as well as the mixed mode ventilation used in sub-humid temperate climate, reduces the cooling and heating needs and therefore contributes to energy savings in historic buildings.

The results obtained for sub-humid temperate climate imply a contribution for the user's benefit of historic religious buildings that can increase their impact on other sectors with high occupancy levels. The next steps involve a modification of the layer thicknesses in the developed PCS and an expansion to other sectors and climates to increase the social impact, as well as an analysis of the indoor environment related to comfort and conservation for historic buildings.

Among the opportunity areas, it is recommended to implement the novel PCS developed in dwellings with different occupancy levels and with reduced areas, and the implementation of different air cavity dimensions according to climatic conditions is recommended to increase the knowledge and possibilities for energy savings and efficiency.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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