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Assessment of thermal comfort with phase change materials in a standard house for different Mexican climates: a simulation study using EnergyPlus

Evaluación del confort térmico con materiales de cambio de fase en una vivienda estándar para diferentes climas en México: un estudio de simulación utilizando EnergyPlus

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Abstract

This study presents a simulation to evaluate the thermal comfort in a standard model of a Mexican home, representative of the type of dwelling where most people in Mexico live, focusing on the effect of phase change materials (PCM) with a fusion temperature of 21°C. Eight representative cities were selected from the different Köppen climatic types in Mexican territory. The study was conducted using EnergyPlus. The simulations predict the time-dependent behavior of indoor temperature and relative humidity for calculating the discomfort index. The results include comparisons of thermal discomfort with and without the use of phase change materials. These indicate that, in most cases, the indoor temperature of the home is attenuated using phase change material, which promotes energy savings by reducing the need to use air conditioning equipment to achieve thermal comfort. This was particularly effective in Monterrey during summer season and Xalapa during winter, reducing 183.91 and 121.71 thermal discomfort hours, respectively (9.22% and 22.63% of hours). Meanwhile, the cities of Tuxtla Gutiérrez during summer and Mérida during winter were affected negatively with the use of phase change material, increasing 246.03 and 50.78 thermal discomfort hours, respectively (27.87% and 5.66% of hours). Overall, the enhancement of thermal comfort using phase change material was more effective during winter than in summer, due to the hot temperatures being constantly higher than the phase change material's melting point.

Keywords: thermal comfort, EnergyPlus, PCM, total discomfort change.

Resumen

Este estudio presenta una simulación para evaluar el confort térmico de un modelo de vivienda estándar en México, que representa el tipo de vivienda en donde gran parte de las personas en México viven, concentrándose en el efecto de los materiales de cambio de fase (PCM) con una temperatura de fusión de 21°C. Se seleccionaron ocho ciudades representativas de distintos tipos climáticos de Köppen. Las simulaciones en EnergyPlus predicen el comportamiento temporal de temperatura interior y humedad relativa para el cálculo del índice de malestar. Los resultados incluyen comparaciones del índice de malestar considerando o no el uso de materiales de cambio de fase. En la mayoría de los casos la temperatura interior es atenuada con el material de cambio de fase, lo que permite reducir el uso de equipos de climatización para lograr el confort térmico. Esto fue especialmente efectivo en Monterrey durante el verano y Xalapa en invierno, reduciendo 183.91 y 121.71 horas de malestar térmico, respectivamente (9.22% y 22.63% de las horas). Mientras que, en Tuxtla Gutiérrez en verano y Mérida en invierno fueron afectadas negativamente con el uso del material de cambio de fase, aumentando 246.03 y 50.78 horas de malestar térmico, respectivamente (27.87% y 5.66% de las horas). En general, se observó que la mejora del confort térmico con el material de cambio de fase fue más efectiva durante invierno que en verano, debido a que las temperaturas en verano eran constantemente más altas que el punto de fusión del material de cambio de fase.

Palabras clave: confort térmico, EnergyPlus, PCM, cambio total de malestar.

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1 Introduction

In Mexico, of the total final energy consumption in 2021, 16.77% comes from residential and commercial consumption. Given the extreme temperatures in different regions of the country, the quality of life of the inhabitants is notably affected, often resulting in consequences for energy consumption due to the use of Heating, Ventilation and Air Conditioning (HVAC) systems or other conditioning systems or devices (Rollos, 1993; SENER, 2022).

Thermal energy storage is an efficient method to improve the energy efficiency of buildings by applying it to building envelopes. Phase change materials (PCMs) play a crucial role in this process. PCMs can be classified according to their chemical composition into organic, inorganic, and eutectic categories. Certain organic, inorganic, and eutectic PCMs are suitable for building applications within the temperature range of 18°C to 40°C. PCMs can be incorporated into construction materials and elements through direct incorporation, immersion, encapsulation, shape-stabilization, and form-stable composite PCMs (Memon, 2014). PCMs are also starting to have applications in various engineering areas, such as aeronautics (Jäckel *et al*., 2020) and the design of thermal transportation devices (Ayala *et al*., 2023). The increasing interest in this subject is reflected in numerous studies, such as the following works: Adilkhanova *et al*. (2021a) investigate the potential of PCM and natural ventilation to strengthen the thermal comfort inside the lightweight relocatable building located in Kazakhstan during the summer period. The quantification of the impact of the PCM on thermal comfort was accomplished using the concepts of maximum operative temperature reduction and discomfort index. The work reported by Lee *et al*. (2016) introduces a model for building walls integrated with PCM, applying a conduction finite difference algorithm for *EnergyPlus*. They validated with experimental data of temperatures, wall heat fluxes, and total wall heat transfer and showing results considering or not the use of PCM. Sheriyev *et al*. (2021) explored the thermal performance of PCM and PCM combined with nighttime natural and mechanical ventilation for a residential building from eight cities of tropical rainforest climate zone. The study was numerical, and they showed the selection of the PCM, which consisted in three theoretical PCMs with determined melting points that were close to the common temperatures during summer in their selected cities, and later, the performances of these PCM were compared with commercial PCMs with the same melting points. Zhussupbekov *et al*. (2023) focused on predicting the energy consumption of residential buildings, also using PCM, in the Mediterranean. Simulations were conducted to build a database, and then machine learning was employed for such prediction. Numerically, it is possible to create models for certain parts of a house, as in Tlatelpa-Becerro *et al*. (2022) where they developed a chimney model to calculate its dynamic properties and created a model with artificial neural networks to predict the temperature dependent on environmental properties and materials. There are still works that evaluate the improvement in refrigeration systems to enhance thermal comfort inside buildings, such as Salazar *et al*. (2016) and Lugo (2013). However, the aim of using PCM in buildings is to reduce energy consumption. According to Auliciems Andris & Szokolay Steven (2007), there is a list of factors that affects thermal comfort, including: personal factors (metabolism and clothing), environmental factors (air temperature, humidity, and solar radiation), and contributing factors (a person's body shape), but there are thermal comfort indicators that are only depending on the climatic conditions. Regarding indicators to assess the thermal comfort, in Epstein & Moran, (2006) a comprehensive review is presented with the advice of adopting a *Discomfort Index (DI)* a heat stress index that is a direct index, only dependent of environmental variables. A novel indicator of *Total Discomfort Change (TDC)* was introduced to select the optimum PCM. There are other thermal comfort indices, such as the Indoor Overheating Degree (IOD), which quantifies the indoor overheating risk for a determined number of occupied hours and considers an outdoor air temperature threshold (Rahif *et al*., 2021), and the Standard Effective Temperature (SET), which represents human physiological factors by considering climate variables, clothing, and activity level in a hypothetical environment (Overbey, 2016).

Studies on the simulation of thermal loads to predict energy consumption in PCM-incorporated buildings exist for different world regions, as mentioned in the foregoing, there exist studies for Kazakhstan, Brazil and New Zealand (Adilkhanova *et al*., 2021a; Sheriyev *et al*., 2021) but not for the Mexican climate and typical dwellings. Even though similar works are available for other regions, to the best of the author's knowledge, there are no studies on thermal comfort calculations using thermal simulations for the Mexican climate in PCM-incorporated buildings. Therefore, it is necessary to predict thermal comfort in a Mexican context to review the impact of PCM use in Mexican homes and reduce energy consumption caused by HVAC systems due to extreme temperatures in Mexico.

Considering the above, this study aims to evaluate the impact of a commercial phase change material with a fusion temperature of 21 °C (Rubitherm PCM RT 21 HC) on thermal comfort in various representative climates across Mexico. There are eight representative climate zones in Mexico. Therefore, eight cities, each representing a different climatic condition indicated on the Köppen-Geiger map for Mexico, were selected for this purpose. The goal is to assess how these materials can potentially improve thermal comfort conditions and thereby decrease the reliance on air conditioning equipment in Mexican households.

2 Methodology

2.1 Problem statement

In this work, the use of phase change materials to enhance thermal comfort inside a house in Mexico is evaluated. To achieve this, a model of a standard Mexican home was created to perform a numerical simulation using the EnergyPlus software package, utilizing environmental data from eight Mexican cities that represent the Köppen climate types in Mexico.

The simulations were implemented with two model types: one without PCM and one with a PCM (Rubitherm PCM RT 21 HC, see Ref. Rubitherm, 2024) included in the walls and roof, to compare thermal comfort in both cases and evaluate the performance of PCM in enhancing thermal comfort in each Mexican city. A direct index with a developed discomfort categorization was employed to measure the thermal discomfort level inside the house model.

2.1.1 Housing model construction

The geometry construction was based on the blueprints provided by INFONAVIT (Instituto del Fondo Nacional de la Vivienda para los Trabajadores (or National Workers' Housing Fund Institute, in English) to make the housing model representative of a typical Mexican home, as presented in Figs. 1a and 1b. To support Mexican workers with lower economic resources to build their homes, INFONAVIT offers documents containing plans and technical specifications for different types of housing, including expansion and construction of spaces for their own businesses. The blueprints for constructing the geometry of an exemplary Mexican home are obtained from a technical manual of INFONAVIT (INFONAVIT, 2024), which consists of a rectangular building of 48 m^2, where the dimensions of the house are 4.80 m vs 10 m vs 2.5 m^2 in height; the housing model contains 4 rooms. The front of the house is included on the west wall, containing a door of 2 m vs 1 m and a window of dimensions 1 m vs 1.2 m (Fig. 1a); likewise, a door and window of the same dimensions were included on the north wall, while on the east and south walls a window of the same dimensions was included, adding a window of

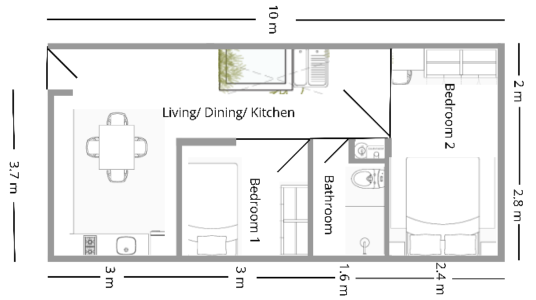

Fig. 1a. Blueprint of the INFONAVIT sample house plan.

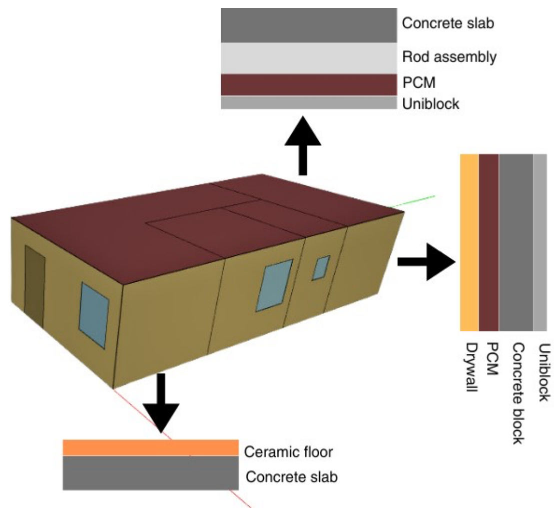

Fig. 1b. Example of a typical Mexican home and materials used for the housing model.

dimensions 0.6 m vs 0.5 m on the south wall (see Fig. 1b). In Mexico, around 42% of the houses have between 30 and 75 m^2; hence, the model constructed is representative of a Mexican standard house (INEGI, 2020).

The materials introduced into the model were selected based on common materials used in housing construction in Mexico (Solano García, 2022). For the windows, glass included in the *EnergyPlus* libraries was used. The materials used and their thermo-physical properties are found in Table 1.

The simulation period used was one winter month, from January 10th to February 10th, and one summer month, from July 15th to August 15th, both from the year 2020. The housing model, being a building with multiple rooms referred to as 'thermal zones' in the EnergyPlus software, includes occupancy schedules, lighting usage, electrical equipment, and gas appliance usage. These factors have been considered for a house inhabited by four people, as shown in Table 2.

Table 1. Materials used and thermo-physical properties.

Component	Material	Thickness (m)	Thermal conductivity (W/m-K)	Density (kg/m^3)	Specific heat (J/kg-K)
Wall	Concrete block	0.12	0.92	2100	880
	Drywall	0.0127	0.1445	615.75	1090
Wall, Ceiling	PCM (Rubitherm RT 21 HC)	0.02	0.2	880	2000
	Uniblock (coating)	0.007	0.2101	1811.27	840
Ceiling	Rod assembly	0.08	44	7800	470
Ceiling, Floor	Concrete slab	0.08	1.5	2400	1050
Floor	Ceramic floor	0.01	1.7	2500	323
Door	Wood	0.05	0.22	400	2300

Table 2. Occupation schedules and parameters considered for housing model.

Thermal zone	Load type	Schedule	Power (W)
1	Activity	06:00 – 08:00; 12:00 – 12:05; 14:00 – 14:05; 16:00 – 16:05; 19:30 – 19:40; 20:40 – 21:00	50/person
	Lighting	06:00 – 08:00; 19:30 – 19:40; 20:40 – 21:00	13.07/m^2
2	Activity	00:00 – 08:00; 21:00 – 24:00	20/person
		06:00 – 08:00 – 14:00 – 18:00	80/person
	Lighting	06:00 – 08:00; 20:50 – 21:00	7.66/m^2
3	Equipment (Computer)	17:00 – 20:00	15.33/m^2
	Activity	00:00 – 08:00; 21:00 – 24:00	20/person
		06:00 – 08:00 – 14:00 – 18:00	80/person
4	Lighting	06:00 – 08:00; 20:50 – 21:00	4.81 /m^2
	Activity	07:00 – 08:00; 14:00 – 21:00	120/person
		12:00 – 14:00	60 person
	Lighting	07:00 – 08:00; 19:00 – 21:00	6.21/m^2
		07:00 – 08:00; 19:00 – 21:00	4.46 m^2
	Equipment (Refrigerator)	All day	20.83/m^2
	Equipment (Television)	07:00 – 08:00; 13:00 – 21:00	9.5 /m^2
	Equipment (Stove)	07:00 – 08:00; 13:00 – 14:30; 19:00 – 20:00	66.6/m^2

Table 3. Selected cities for the study.

Climatic group	Climatic region	City
Tropical	Af	Tuxtla Gutiérrez, Chiapas
	Am	Villahermosa, Tabasco
	Aw	Mérida, Yucatán
Dry	BS	Monterrey, Nuevo León
	BW	Hermosillo, Sonora
Temperate	Cf	Xalapa, Veracruz
	Cw	Guadalajara, Jalisco
	Cs	Toluca, Estado de México
Polar	EB	Omitted

2.1.2 Climatic conditions

For this work, the generalized categorization of different climate types and climatic zones on the Köppen-Geiger map was considered. There are nine climatic regions in Mexico, which are tropical with year-round rainfall (Af), tropical with monsoon rains (Am), tropical with summer rains (Aw), dry steppe (BS), desert dry (BW), temperate with year-round rainfall (Cf), temperate with summer rains (Cw), temperate with winter rains (Cs), and high mountain polar (EB).

For the development of simulations, cities representing the diversity of climates in Mexico were selected. The number of inhabitants was considered in the selection process. The polar climate was omitted because it is not representative of any Mexican city, being only found in the high parts of some mountains in the country. Table 3 shows the selected cities.

Fig. 2. The selected cities in Mexico for conducting the simulations based on the Köppen climate zones.

In Fig. 2, a map of Mexico is shown where the selected cities for the simulations are highlighted. The climate data files were obtained from the *Climate One Building* database, retrieved from the reference (Lawrie & Drury B, 2022). In this database, the weather data is derived from a number of public climate sources, primarily the Integrated Surface Database (ISD) (National Centers for Environmental Information, 2024).

2.1.3 Simulation environment and numerical model

The simulations were carried out by combining the use of *OpenStudio*, one of the graphical interfaces of *EnergyPlus*, and the *EnergyPlus* editor.

To simulate phase change materials in *EnergyPlus*, it is necessary to select the *Conduction Finite Differences (CondFD)* algorithm, which involves discretizing the layers of the model's walls, ceilings, and floors into nodes and using an implicit difference scheme. With this algorithm, the thermal contribution of a PCM can be incorporated. To do this, it is necessary to introduce a temperature-dependent enthalpy function, h=h(T), so that the algorithm calculates an equivalent specific heat for each iteration.

For a construction with homogeneous material and uniform nodal space, Eq. (1) is used:

$$c_p \rho \Delta x \frac{T_i^{j+1} - T_i^j}{\Delta t} = k_W \frac{T_{i+1}^{j+1} - T_i^{j+1}}{\Delta x} + k_E \frac{T_{i-1}^{j+1} - T_i^{j+1}}{\Delta x} \tag{1}$$

Where k_W, k_E are the thermal conductivity inside and outside the construction, respectively; c_p is the specific heat of the material, ρ the density of the material, Δx, and Δt are the thickness of the material layer and the time step, *i* is the node being modeled, *j* is the previous time step.

The enthalpy function, which depends on temperature, allows the algorithm to calculate an equivalent specific heat for each time step and is

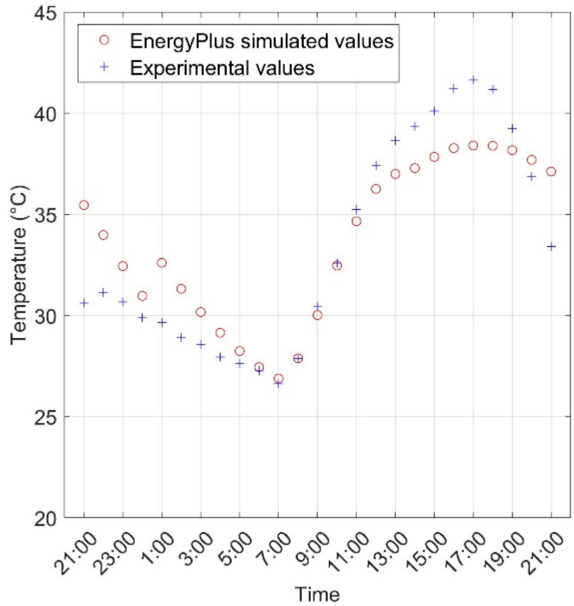

Fig. 3a. Interior temperatures for configuration A.

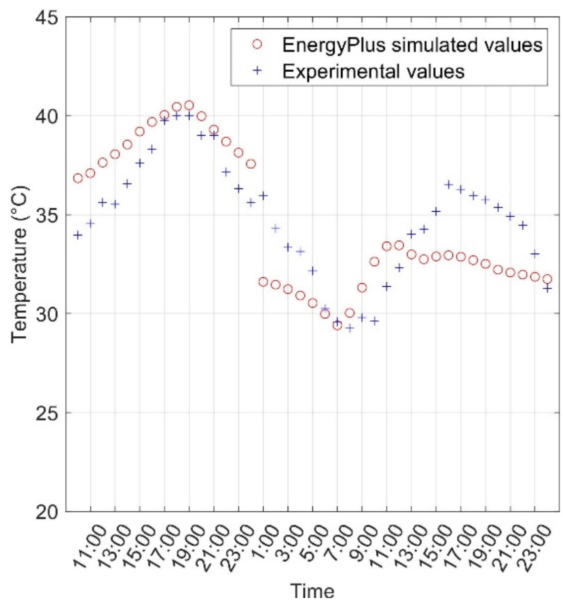

Fig. 3b. Interior temperatures for configuration B.

calculated using Eq. (2):

$$c_p^* = \frac{h_i^j - h_i^{j-1}}{T_i^j - T_i^{j-1}} \tag{2}$$

2.2 *Validation of numerical simulation*

To verify the reliability and correct use of *EnergyPlus* in combination with its OpenStudio graphical interface, a validation was carried out by adapting the experimental conditions from data reported in Li *et al.* (2009) & Zhuang *et al.* (2010) to an EnergyPlus model. Temperature measurements were conducted in a simple structure built with expanded polystyrene, varnished wood, and two PCMs.

Table 4. Materials used and thermo-physical properties for the validation simulations.

Material	Thickness (m)	Thermal conductivity (W/m-K)	Density (kg/m^3)	Specific heat (J/kg-K)
Wood veneer	0.005	0.17	796	1731
EPS Polystyrene	0.05	0.042	56	1189
PCM 33	0.01	0.3	860	1970
PCM 40	0.01	0.3	860	1970

Experiments were carried out with two different configurations of walls, ceiling, and floor. The first configuration, labeled as A, had a PCM with a melting point of 40 °C, while the second one, labeled as B, had two PCMs with melting points of 40 °C and 33 °C respectively. The experiment was replicated in an *EnergyPlus* model using the specifications of the problem. The experiments took place in the city of Chongqing, China, in 2007, hence a climatic file corresponding to that city and year was used. In Figures 3a and 3b, a comparison can be observed between the interior temperatures obtained experimentally by Zhuang *et al*. (2010) and those obtained in simulation using *EnergyPlus* for the days on which the experiments were conducted, which were August 14th and 15th, 2007 for A, and August 23rd and 24th, 2007 for B. The materials that were introduced solely for the validation model and their thermo-physical properties are listed in Table 4. The PCMs used for the validation model were introduced using generic enthalpy-temperature curves for their melting temperatures.

It can be observed in the graphs that there are discrepancies between the experimental and simulated temperatures, primarily due to the lack of data in Li *et al*. (2009) & Zhuang *et al*. (2010) to replicate the simulation. These data include the enthalpy-temperature curves of the PCMs and the complete thermophysical data of the materials. Additionally, errors arise due to discrepancies between the climatic data and possible errors in the experimental measurement. Despite this, the deviations between the experimental and simulated values, calculated by the relative error and considering the experimental values as the real values, are 5.04% for A and 5.41% for B. These deviations are considered acceptable for the analysis carried out in this study.

There are methods to calibrate the numerical simulation according to ASHRAE Guideline 14 (2002) that are beyond the scope of this work due to the lack of physical data collection and experimentation. However, the validation of the EnergyPlus simulation adds reliability to the study.

2.3 PCM selection

The main criterion for PCM selection is the melting point of the material. Because PCMs store and release energy during the phase change process, which occurs when the material is exposed to a temperature close to its melting point, this temperature should be one that commonly occurs in the environment. Therefore, a PCM with a melting temperature of 21°C was selected.

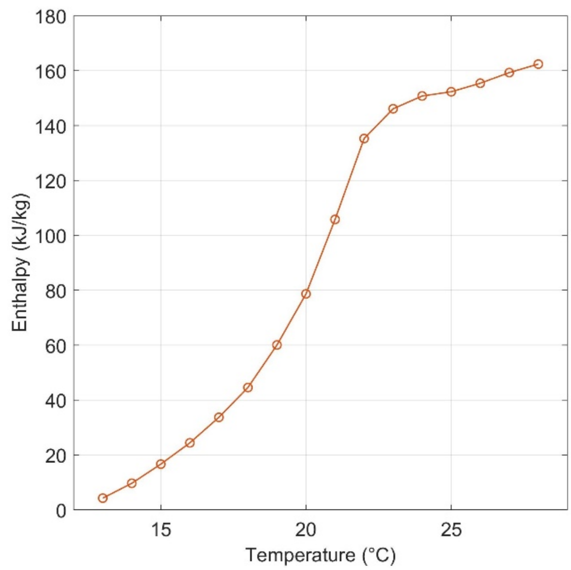

Fig. 4. The enthalpy-temperature curve of PCM RT 21 HC adapted from Adilkhanova *et al*. (2021b).

The PCM selected for incorporation into the simulations is a commercial one, chosen from the versatile organic paraffin-based PCMs section of Rubitherm (Rubitherm, 2024) with a thickness of 2 cm. The PCM, named RT 21 HC, has a melting point of 21°C, and the thermophysical data for it are: heat capacity of 190 kJ/kg, ρ=800 kg/m^3, and Cp=2 kJ/kg-K.

Since *EnergyPlus* requires the enthalpy of the PCM, as a temperature-dependent function for the housing model for simulations, the enthalpy-temperature curve of PCM RT 21 HC was adapted from Adilkhanova *et al*. (2021b), as shown in Fig. 4. To better study the PCM's ability to affect thermal conditions inside the housing model, no HVAC system or ventilation is being used in the simulations.

2.4 Thermal comfort indicators

The objective of conducting thermal simulations is to predict thermal comfort within the housing model. Therefore, a mathematical indicator is required to measure such comfort.

Table 5. Comfort criterion according to discomfort index.

Range of DI	Label	Discomfort conditions	Weighing
DI < 7	A	Severe cold discomfort with possible health risk	1
7 < DI < 8.5	B	Great discomfort from cold	8/9
8.5 < DI < 9.5	C	Everyone feels discomfort from cold	7/9
9.5 < DI < 11	D	Most people experience cold discomfort	2/3
11 < DI < 12.5	E	More than 80% of people feel discomfort due to cold	5/9
12.5 < DI < 14	F	Between 60% to 80% of people feel cold discomfort	4/9
14 < DI < 15.5	G	Between 40% to 60% of people feel cold discomfort	1/3
15.5 < DI < 17	H	Between 20% to 40% of people feel cold discomfort	2/9
17 < DI < 18.5	I	Less than 20% of people feel discomfort from cold	1/9
18.5 < DI < 20.5	J	There is no discomfort	0
20.5 < DI < 22	K	Less than 20% of people feel discomfort from heat	1/9
22 < DI < 23.5	L	Between 20% to 40% of people feel heat discomfort	2/9
23.5 < DI < 25	M	Between 40% to 60% of people feel heat discomfort	1/3
25 < DI < 26.5	N	Between 60% to 80% of people feel heat discomfort	4/9
26.5 < DI < 28	O	More than 80% of people feel heat discomfort	5/9
28 < DI < 29.5	P	Most people experience heat discomfort	2/3
29.5 < DI < 30.5	Q	Everyone feels discomfort from heat	7/9
30.5 < DI < 32	R	Great discomfort from heat	8/9
DI > 32	S	Severe heat discomfort with possible health risk	1

The variables obtained by the *EnergyPlus* simulations are the dry bulb indoor temperature and the indoor relative humidity. Thus, a direct index can be utilized for this task.

The *Discomfort Index (DI)* (Epstein & Moran, 2006) is a way to measure thermal comfort, through Eq. (3) (Siami & Ramadhani, 2019):

$$DI = T_{db} - 0.055(1 - 0.01RH)(T_{db} - 14.5) \qquad (3)$$

where T_{db} is the dry bulb temperature and RH is the relative humidity in percentage, both measured inside the building, and determined through simulations in *EnergyPlus*.

The Discomfort Index was selected instead of other indices such as IOE or SET, mentioned in the Introduction, due to its simplicity and its utility with the variables measured in EnergyPlus, making it easier to compare the performance of PCM in reducing thermal discomfort.

For both summer and winter days, there is a comfort criteria, assuming normal clothing, depending on the value of the DI, determined through the classification presented in Table 4.

The conditions of thermal discomfort due to cold were determined based on the existing classification for high temperatures. The classification shown in Table 4 is a proposed range of Discomfort Index based on the one used in the literature (Siami & Ramadhani, 2019), but the resolution of the ranges was increased to enhance classification changes using PCM.

Total Discomfort Change (TDC) is a concept used to measure the thermal impact of PCM in housing. This is measured by determining the hours during the simulation period in which a specific range of Discomfort Index is maintained (Adilkhanova *et al.*, 2021b).

The TDC is measured with Eq. (4):

$$TDC = \sum_{1}^{k} n\ (Discomfort\ Reduction) - \sum_{1}^{k} n\ (Discomfort\ Increase) \qquad (4)$$

Where k represents the total number of hours in the simulation period and n is a natural integer number.

Discomfort reduction represents the sum of hours in which discomfort decreases from a higher level to a lower level, according to the ranges shown in Table 4, while discomfort increase represents the sum of hours in which discomfort increases from a lower level to a higher level. TDC values are obtained by comparing the discomfort categories for each hour of the simulation period using PCM and comparing them with the hours in which PCM is not used. To calculate the total hours of discomfort in the simulation period, a weight was assigned to each discomfort category. For both winter and summer, a weight of 1/9 was assigned, adding 1/9 more for each category as it moves away from the thermal comfort range.

Figure 5 shows a flowchart for calculating the TDC for each simulation hour using the results of indoor temperature and relative humidity in *EnergyPlus*. Figure 6 illustrates graphically how the TDC is obtained for a single category. In the case without PCM, the obtained DI value for a given hour is in a specific thermal discomfort range. For the same hour, in the case with PCM, if the DI value transitions to a lower discomfort range, the TDC adds a positive

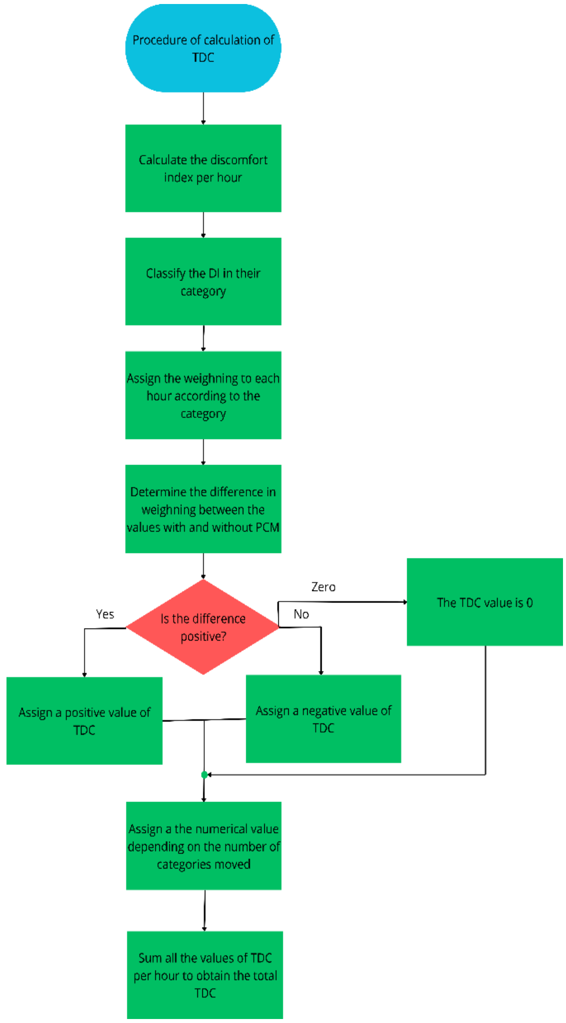

Fig. 5. Flowchart for calculating the TDC for each hour of the thermal simulation.

value. Contrariwise, if using PCM causes a transition to a higher discomfort range, the TDC adds a negative value. The numerical value of the TDC for a specific hour represents the number of ranges it jumps.

3 Results and discussion

The simulations in *EnergyPlus* provided the temperature and relative humidity inside the housing model during the simulation period, both without PCM and with PCM.

To evaluate the effect of PCM on the interior temperature, Fig. 7a and 7b present a comparison of interior temperatures with and without PCM, as well as the exterior temperature and relative humidity, which represent the climatic data. This comparison in Fig. 7a, which covers 5 winter days in the city of Monterrey (BS) during winter, shows that during high exterior temperature peaks, which coincide with low relative humidity peaks, the interior temperature with PCM decreases compared to the interior temperature

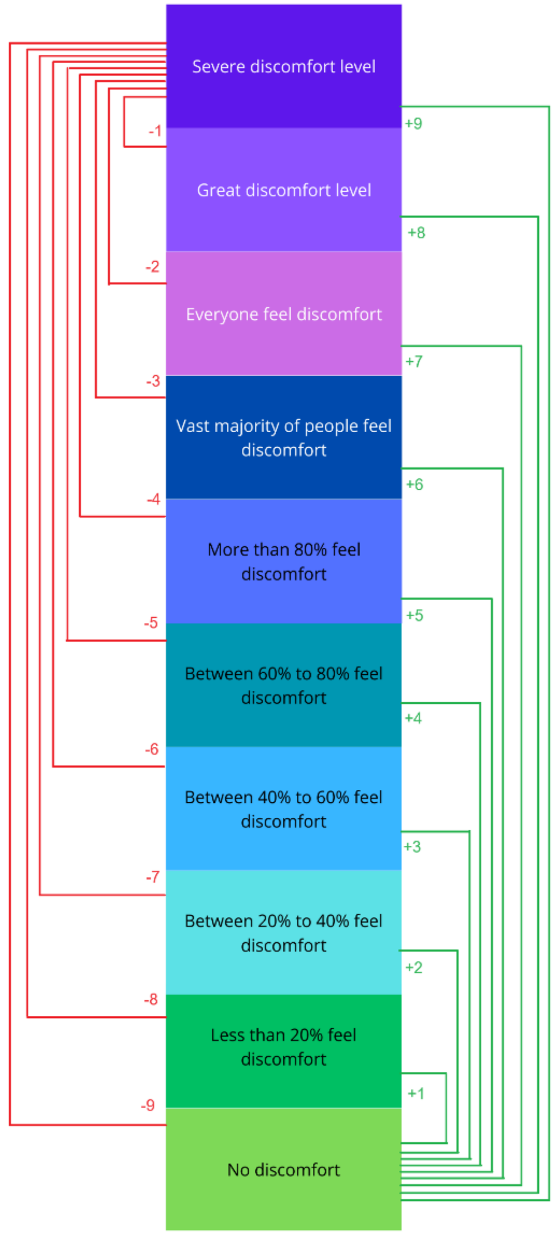

Fig. 6. Schematic representation for the determination of the TDC with respect to the comfort intervals.

without PCM. On the other hand, during low exterior temperature peaks, which coincide with high relative humidity peaks, the interior temperature with PCM increases.

This behavior is the damping effect of the PCM due to the absorption or liberation of latent heat during exterior temperatures close to the PCM's melting temperature, allowing the interior temperature with PCM to remain more constant and closer to a comfort temperature. For the case of summertime in Monterrey (BS), this effect is intensified because the exterior temperature tends to fluctuate along the PCM's melting point, which is 21 °C. However, when the exterior temperature remains consistently above the PCM's melting point, this behavior changes considerably as

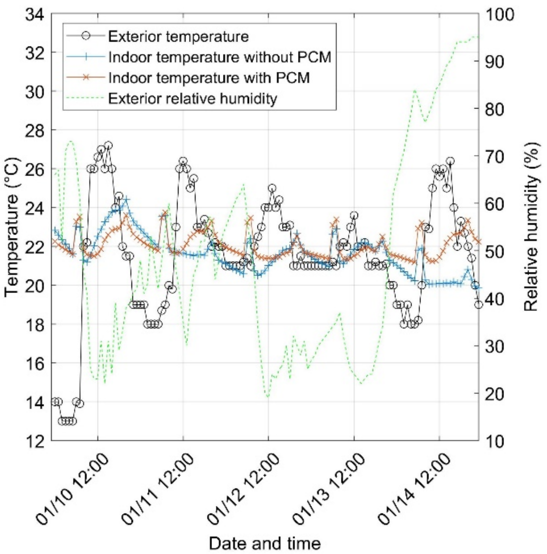

Fig. 7a. Comparison between the interior temperatures in Monterrey (BS) during winter with and without PCM.

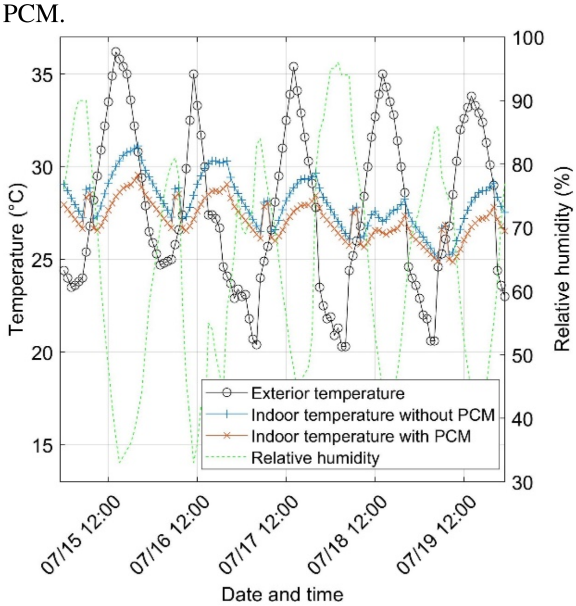

Fig. 7b. Comparison between the interior temperatures in Monterrey (BS) during summer with and without PCM.

observed for the case of wintertime in Monterrey (BS) (compare Fig. 7b). Under conditions of very high exterior temperatures, the interior temperature with PCM decreases compared to the interior temperature without PCM.

In Figure 8, the variation of the internal temperature of the simulated housing model in Monterrey (BS) during the summer is shown hourly over 192 hours (8 days) of simulation. The temperature curves are compared with and without the incorporation of PCM in the walls, focusing on the hours of the first 36 hours. Upon observing the figure and comparing both curves, it is noticeable that the internal temperature with incorporated PCM smoothens temperature fluctuations compared to the

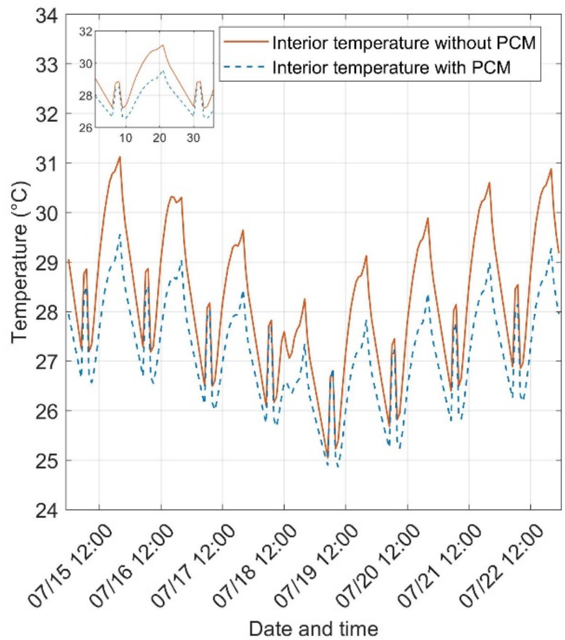

Figure 8. Variation of indoor temperature in Monterrey (BS) during the summer, hourly, with and without PCM, with a zoom on the first 36 hours.

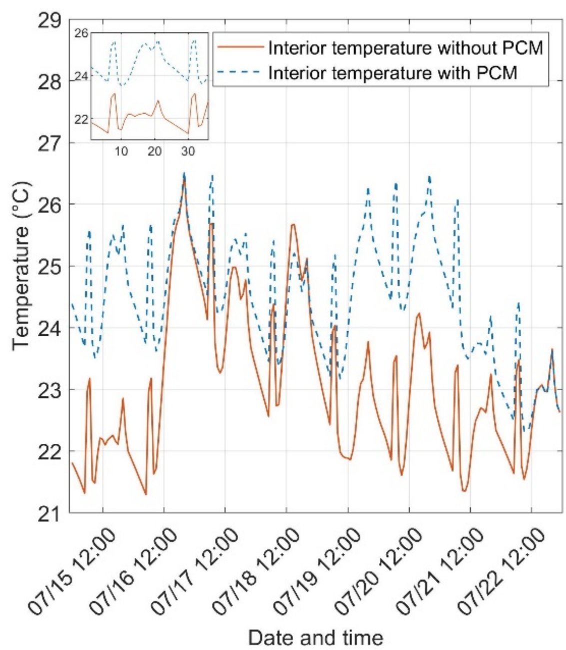

Figure 9. Variation of indoor temperature per hour in Tuxtla Gutiérrez (Af) during the summer, with and without PCM, with a zoom on the first week.

case without incorporated PCM. This is reflected in a reduction of high temperatures within the simulation model. Therefore, it can be stated that PCM provides a damping effect within the housing during high temperature extremes in Monterrey's (BS) summer.

Figure 9 illustrates a scenario where the use of PCM globally results in an increase in indoor temperature, showing a comparison of internal

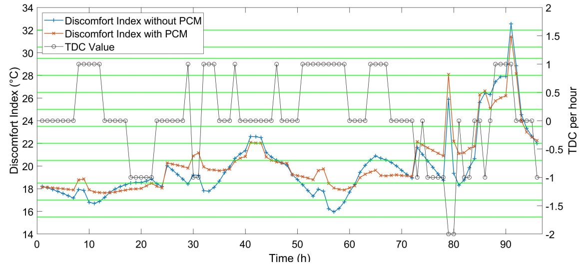

Fig. 10. Variation of the Discomfort Index per hour in Monterrey (BS) during winter with and without PCM compared with TDC values.

temperatures of the housing model in Tuxtla Gutiérrez (Af) during the summer. Here, it is observed that the internal temperature using PCM increases at temperature peaks. Hence, it can be concluded that the use of PCM in Tuxtla Gutiérrez (Af) during the summer leads to higher internal temperatures. This surprising observable will be discussed further.

In Figure 10, the variation of the DI over time is shown during a four-day simulation period in Monterrey (BS) during winter. The resulting curves with and without the use of PCM are compared, along with the TDC values per hour. The TDC value indicates the change of the thermal discomfort range when PCM is used in the housing model. The numerical value of the TDC represents the number of DI range that changes with the use of PCM, while the sign indicates whether the change decreases (positive sign) or increases (negative sign) discomfort. Changes in categories are observed in the DI curves, with horizontal lines representing thermal discomfort categories. For example, at hour 10, the DI without PCM indicates a discomfort category H (20-40% cold discomfort), while with PCM, it changes to I (less than 20% cold discomfort), indicating a decrease in discomfort and thus a TDC value of +1 for that hour. Contrariwise, at hour 80, the DI without PCM indicates the null discomfort category J, while with PCM, it indicates between 22 – 23.5 °C (20-40% heat discomfort), resulting in an increase in discomfort and thus a TDC value of -2 due to a change of two categories.

In hours where DI values remain in the same category, the TDC value is 0, indicating that the range of thermal discomfort remains constant.

To visualize the overall performance of using PCM, Fig. 11a presents a bar graph showing the total weighted discomfort hours in summer. These hours represent the periods when the residents of the dwelling experience some degree of thermal discomfort, calculated by the sum of all the weight assigned to each hour of simulation, according to the corresponding category of thermal discomfort. Figure 11a compares thermal discomfort with and without PCM for each of the cities studied in summer. It is observed that in Villahermosa (Am), Monterrey (BS), and Toluca (Cs), the use of PCM considerably reduces the total hours of thermal discomfort. In Xalapa (Cf) and Guadalajara (Cw), the discomfort hours are similar with and without PCM, while in Tuxtla Gutiérrez (Af) (as shown in Fig. 9), Mérida (Aw), and Hermosillo (BW), the use of PCM increases the hours of thermal discomfort.

Sheriyev *et al*. (2020) mention that similar results are reported both in literature and in their own studies for cities in Kazakhstan during summertime, where the temperatures are also high. In cities with high temperatures in summer, the use of PCM can increase the hours of thermal discomfort, as PCM tends to release heat during the hours of low external temperature, generally at night, which can infiltrate heat into the interior of the dwelling and negatively affect thermal comfort. Nevertheless, in some selected cities during summer, such as Tuxtla Gutiérrez (Af) and Hermosillo (BW), the exterior temperature during the day remains mainly above the PCM melting point of 21 °C, maintaining the PCM in liquid state, and later in the night the exterior temperature is close to the PCM melting point, the material releases the heat causing an increase in the indoor temperature. In Mérida (Aw), the exterior temperatures during summer are mostly higher than the PCM melting point, therefore the PCM may act as another material layer in the dwelling and causes an increase of the indoor temperature. On the other hand, Fig. 11b shows a bar graph with the total weighted discomfort hours in winter. In this case, it is observed that, except in Mérida (Aw), all cities experienced a reduction in discomfort hours when using PCM. This indicates that the use of PCM is more suitable in reducing thermal discomfort in winter than in summer.

Table 6. Percentage reduction or increase of thermal discomfort hours for each city.

City	Season	Reduced or increased thermal discomfort hours	Percentage reduction or increase (%)
Tuxtla Gutiérrez (Af)	Summer	246.03	-27.87
	Winter	52.84	5.35
Villahermosa (Am)	Summer	156.93	7.64
	Winter	91.82	8.06
Mérida (Aw)	Summer	213.44	-13.53

	Winter	50.78	-5.66
Monterrey (BS)	Summer	183.91	9.22
	Winter	117.27	20.71
Hermosillo (BW)	Summer	32.39	-1.42
	Winter	52.65	10.72
Xalapa (Cf)	Summer	4.7	-0.47
	Winter	121.71	22.63
Guadalajara (Cw)	Summer	12.71	1.28
	Winter	26.01	5.46
Toluca (Cs)	Summer	168.65	35.47
	Winter	117.13	19.4

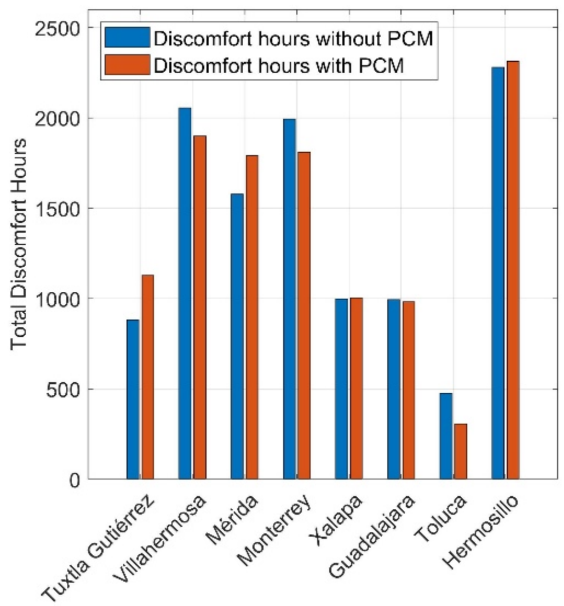

Fig. 11a. Total weighted discomfort hours in summer.

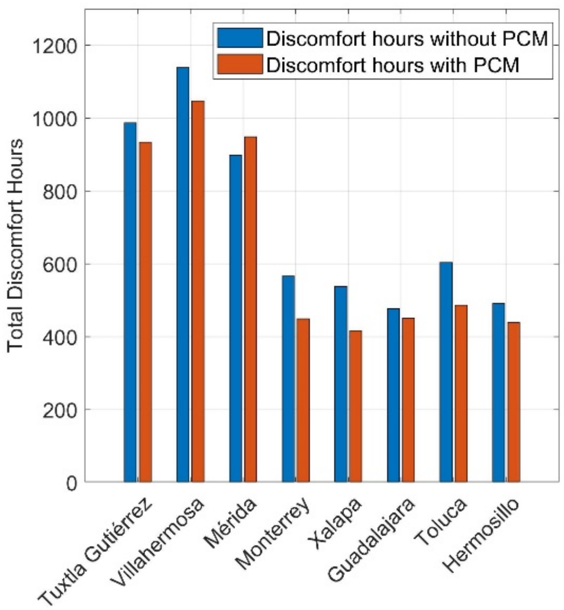

Fig. 11b. Total weighted discomfort hours in winter.

Table 6 presents the reduction or increase in thermal discomfort hours for each city and season, comparing the total hours and percentage of discomfort hours without PCM. The percentage represents the hours of thermal discomfort that are reduced or increased with the use of PCM as a relative error, with the discomfort hours without PCM being the fixed hours. A negative sign represents discomfort increase. In this case, Toluca (Cs) had the highest percentage reduction in summer due to fewer discomfort hours without PCM. For winter, Xalapa (Cf) had the highest percentage reduction.

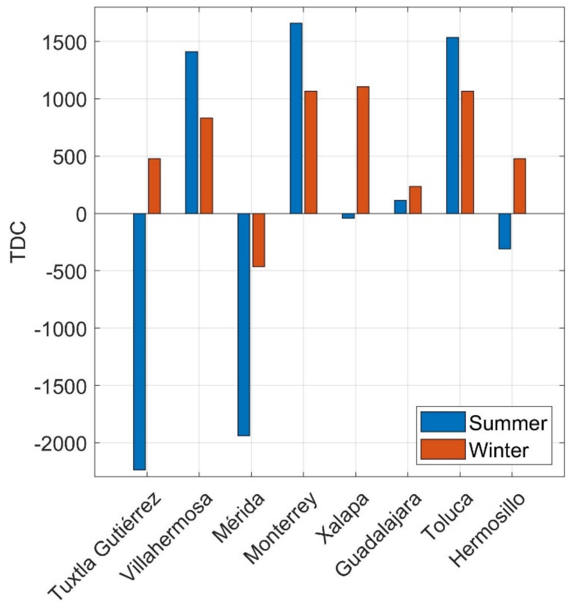

Fig. 12. TDC of the PCM in each city and season of the simulation period.

Figure 12 shows the total TDC of the PCM in each city and each season of the simulation period. It can be observed that the TDC value aligns with the discomfort hours shown in Figs. 11a and 11b, where cities with higher discomfort hours using PCM have a negative TDC. A negative TDC indicates an increase in thermal discomfort with the use of PCM, while a positive TDC indicates the opposite.

In Fig. 12, It is noted that the highest TDC for summer is in the city of Monterrey (BS), that is 1660, while for winter it is in the city of Xalapa (Cf), that is 1106. Conversely, the lowest TDC for summer is in the city of Tuxtla Gutiérrez (Af), that is -2235, while for winter it is in the city of Mérida (Aw), that is -463.

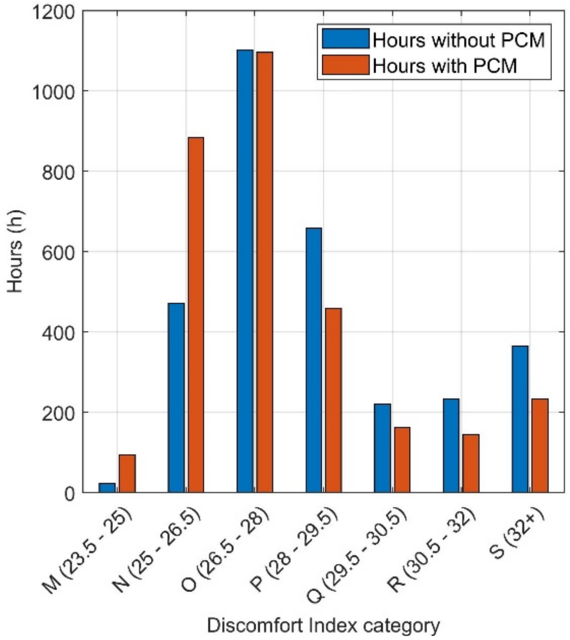

Fig. 13a. Hours in a determined Discomfort Index category with and without PCM for Monterrey (BS) during summer.

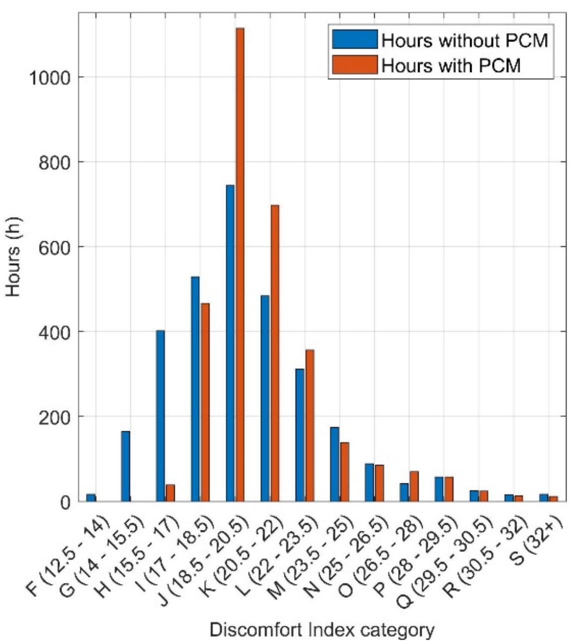

Fig. 13b. Hours in a determined Discomfort Index category with and without PCM for Xalapa (Cf) during winter.

It is also observable that the cities of Villahermosa (Am), Monterrey (BS), Guadalajara (Cw), and Toluca (Cs) had a positive TDC for both seasons of the simulation period, while the city of Mérida (Aw) had a negative TDC in both cases. We can conclude that Monterrey (BS) showed better performance in improving thermal comfort with the use of PCM, as it had the highest TDC value combining both winter and summer values, while Mérida (Aw) exhibited the worst performance, having a negative TDC for both seasons. It is noteworthy that within the same climatic group (compare Table 3), there are differences in the obtained TDC results for each city, indicating that the behavior of PCM cannot be generalized within a same climatic group. Each city within a specific climatic group has a different PCM performance, even though they share certain environmental characteristics. For example, cities with better performance include one with a dry climate (Monterrey, BS), one with a tropical climate (Villahermosa, Am), and two with a temperate climate (Toluca, Cs and Guadalajara, Cw). Despite this, cities with a temperate climate experienced an overall improvement in thermal comfort. Although Xalapa (Cf) had a negative TDC with PCM in summer, this TDC value is very small, and it had the highest TDC value for winter. The better performance in a temperate climate may be due to the fact that the use of PCM reduced thermal discomfort to a greater extent in winter, as observed in Fig. 12 with positive TDC values in winter. This is because of the heat release from PCM, which benefits colder seasons and temperate climates that typically have lower temperatures throughout the year. Sheriyev *et al*. (2020) mention that combining PCM with natural ventilation in homes significantly improves the reduction of thermal discomfort, preventing the heat release from PCM from significantly affecting the thermal comfort of the building.

To observe in more detail how PCM changes the range of discomfort during the simulation period, bar graphs show hours within a certain range of thermal discomfort in different cities. Figures 13a and 13b show these bar graphs for Monterrey (BS) in summer and Xalapa (Cf) in winter, respectively, which are the cities with the best PCM performance reducing thermal discomfort. On the other hand, Figs. 14a and 14b present the bar graphs for Tuxtla Gutiérrez (Af) in summer and Mérida (Aw) in winter, respectively, which are the cities with the worst performance.

In Fig. 13a, it can be observed that, despite the absence of hours in the comfort range due to the high temperatures experienced in Monterrey (BS) during the summer, most of the discomfort hours with PCM with high heat discomfort levels decrease significantly. Instead, they are mostly concentrated in category N, where the range where 60% - 80% of the people in the enclosure experience heat discomfort, which represents a significant improvement by reducing severe discomfort caused by high temperatures.

On the other hand, in Fig. 13b, it is observed that when using PCM, the hours in the comfort ranges and those in the category J (where less than 20% of people experience discomfort) increase considerably, although the hours of intense discomfort increase slightly. Additionally, hours of discomfort due to cold are also reduced.

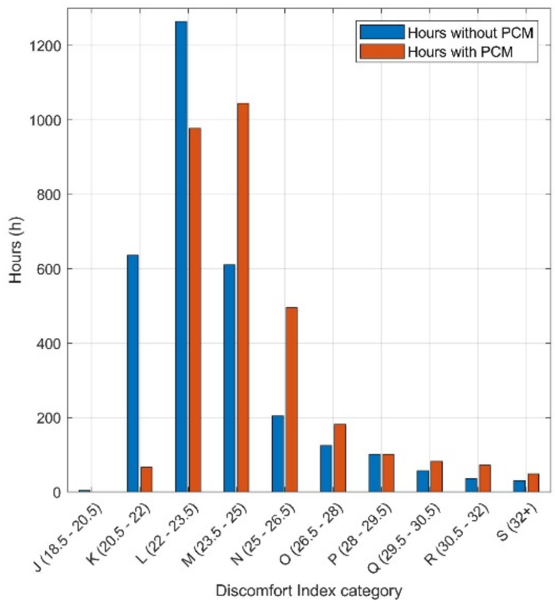

Fig. 14a. Hours in a determined Discomfort Index category with and without PCM for Tuxtla Gutiérrez (Af) during summer.

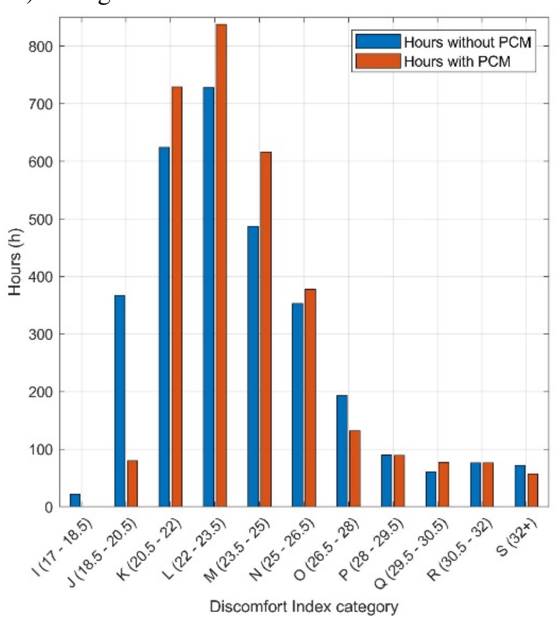

Fig. 14b. Hours in a determined Discomfort Index category with and without PCM for Mérida (Aw) during winter.

In contrast, Fig. 14a shows that hours with PCM decrease in the lower heat discomfort ranges. This is because the damping effect of the PCM causes the hours to tend to concentrate in category N, where 40% - 60% of people experience heat discomfort.

In Figure 14b, it can be observed that, similarly to Fig. 14a, the hours concentrated in the comfort ranges decrease, focusing on the ranges where 20% - 40% and 40% - 60% of people experience heat discomfort. This is because the damping effect causes the hours to centralize in these categories, thereby increasing thermal discomfort: in both cases the hours tend to concentrate in the moderate discomfort categories due to the PCM behavior of absorb and release heat during the daytime.

In this study, the cities and climate types were identified where the PCM RT 21 HC, with a melting temperature of 21°C, works better for summer and winter to enhance thermal comfort. This PCM performs better for this task in winter than in summer. The heat liberation during low exterior temperatures improves thermal comfort. Additionally, climate type and high temperatures were not determining factors for the PCM's performance.

This study presents several key findings and contributions, notably its novelty within the Mexican context by employing the concept of thermal discomfort to evaluate the PCM's effectiveness, specifically quantifying the reduction and increase in thermal discomfort hours facilitated by the PCM. While the analysis focused on a specific type of PCM, future research could explore the comparative performance of PCMs with different melting points. Additionally, further studies could address the variability in climate data and incorporate various thermal comfort indices to provide a more comprehensive evaluation of PCM effectiveness.

Conclusion

A simulation was conducted in this study to demonstrate the influence of using phase change materials with a melting temperature of 21 °C considering the different climates of Mexico. A low-cost standard Mexican model was used, located in a representative city from the different climatic zones of Mexico: Guadalajara (Cw), Toluca (Cs), Xalapa (Cf) (Temperate); Hermosillo (BW), Monterrey (BS) (Dry); Tuxtla Gutiérrez (Af), Villahermosa (Am), Mérida (Aw) (Tropical). The study yields the following conclusions:

- The use of PCM decreased thermal discomfort, except for the cities of Tuxtla Gutiérrez (Af) (summer), Mérida (Aw), and Hermosillo (BW) (summer).
- The use of PCM decreases thermal discomfort to a greater extent in winter than in summer due to the high exterior temperatures during summer that maintain the PCM in liquid state, and when the exterior temperature is at the lowest point of the day, the heat release from PCM during these coldest hours of the day negatively impacts thermal comfort during summer. This is the case for Tuxtla Gutiérrez (Af) and Hermosillo (BW) in summer.
- In cases such as Mérida (Aw) in summer, where the temperature is mostly above the PCM melting point, the PCM may just act as another insulation layer, negatively affecting indoor thermal comfort. It is

recommended to choose a PCM with a melting point that allows activation during daytime.

- Even though the PCM worse performance during summertime compared to wintertime, high temperatures were not a determining factor for worse PCM performance. The cities of Villahermosa (Am) and Monterrey (BS) had good PCM performance despite the elevated temperatures they experience during the summer period. In these cities, the exterior temperatures during the night were mostly close to the PCM melting point, allowing the PCM to release heat.

- Individually, Monterrey (BS) had the best performance in reducing thermal discomfort, and in terms of climate type, cities belonging to the temperate climate had the best performance.

- The proposed refinement of the DI ranges was helpful in making the system more sensitive to capturing changes in thermal discomfort and better visualizing the PCM's performance in changing the thermal comfort inside the house model. The proposed methodology for TDC refinement can be utilized in thermal comfort studies to evaluate the performance of PCM, increasing the sensitivity of thermal comfort predictions.

As future work, different melting points of PCM will be compared and the impact of the climate type and climatic group on PCM performance should be studied. Additionally, the thermal comfort evaluation when the use of PCM is combined with natural ventilation needs to be investigated.

It is recommended to study the combination of natural ventilation and the use of PCM in regions where the use of PCM alone was not favorable for the thermal comfort inside the dwelling under the climatic conditions in Mexico.

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Nomenclature

cp	specific heat of the material
i	node being modeled
j	previous time step
k_W	thermal conductivity inside the construction
k_E	thermal conductivity outside the construction
RH	relative humidity in percentage
T_{db}	dry bulb temperature
ρ	density of the material
Δt	time step
Δ x	thickness of the material layer

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