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Master of Architecture – Sustainable Design

The Impact of Using Phase Change Material as a Seasonal Energy Storage for Enhancing Thermal Performance of Residential Building's Envelope

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Thesis submitted in partial fulfillment of requirements of the degree

Master of Architecture – Sustainable Design

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The Impact of Using Phase Change Material as a Seasonal Energy Storage with Thermal Insulation for Enhancing Thermal Performance of Residential Building's Envelope in Hebron-Palestine

Bayan Mohammad Iwidat

ABSTRACT

Energy consumption in buildings has increased as a result of the heat gain and loss of the building's envelope. Its materials and layers play an important role in its efficiency. This study aims to provide an environmental solution that contributes to store the heat energy in long-term (seasonally), reducing heat loss and gain, and thus reducing energy consumption, by Using a Sodium Acetate Trihydrate (SAT) phase change material (PCM) and its melting point is (58C) integrated with expanded polystyrene (EPS) thermal insulation material (TIM) on the southern façade of a residential building located in Hebron-Palestine by suggesting different scenarios of the PCM-TIM integration's layers arrangements and design to select the best scenario in seasonal thermal energy storage (TES) by studying the wall layers before and after adding PCM-TIM integration, analyzing, thermal calculations and simulating its thermal performance in summer and winter seasons using Design Builder Software (DB) and Energy Plus engine and simulate the heat flow for the best scenario using ANSYS Fluent software. The results indicated that the use of PCM-TIM integration improved the thermal comfort conditions inside the space, as it was found that the proposed design for M3-A was the best model among all the proposed scenarios in TES and indoor thermal comfort in both summer and winter seasons. This design proved its economic efficiency when it provided annual heating and cooling loads reductions of approximately 72% compared to the CM wall. In terms of cost, this model has proven its economic feasibility with a payback period not exceeding 3 years.

Key words: PCM, thermal insulation, energy consumption, thermal performance, energy storage, long-term, solar energy.

تأثير استخدام مواد تغيير الطور كمخزن للطاقة الحرارية الموسمية متكاملاً مع مادة العزل الحراري لتحسين أداء الطاقة الحرارية لاغلفة المباني السكنية في الخليل- فلسطين

بيان محمد عويضات

المستخلص

لقد زاد استهلاك الطاقة في المباني نتيجة اكتساب الحرارة وفقدانها لغلاف المبنى، وتلعب مواده وطبقاته دورًا مهمًا في كفاءته. تهدف هذه الدراسة إلى تقديم حل بيئي يساهم في تخزين الطاقة الحرارية على المدى الطويل (موسميًا)، وتقليل فقدان الحرارة واكتسابها، وبالتالي تقليل استهلاك الطاقة، وذلك باستخدام مادة تغيير الطور ثلاثي هيدرات أسيتات الصوديوم ونقطة انصهارها (58 درجة مئوية)، مدمجة مع مادة العزل الحراري البوليسترين الموسع على الواجهة الجنوبية لمبنى سكني يقع في الخليل - فلسطين من خلال اقتراح وتصميم نماذج مختلفة لترتيبات طبقات تكامل العزل مع مادة تغير الطور لاختيار افضل نموذج في تخزين الحرارة الموسمية من خلال تحليل وحسابات الطاقة ومحاكاة ودراسة الاداء الحراري لكل نموذج ، في فصلي الصيف والشتاء باستخدام برنامج Design Builder ومحرك Energy Plus ومحاكاة تدفق الحرارة لأفضل نموذج باستخدام برنامج ANSYS Fluent.

أشارت النتائج إلى أن استخدام هذا التكامل أدى إلى تحسين ظروف الراحة الحرارية في الفراغ الداخلي، كما اثبتت النتائج أن التصميم المقترح M3-A كان هوالنموذج الأفضل بين جميع السيناريوهات المقترحة في تخزين الحرارة وفي تحسين ظروف الارتياح الحراري الداخلي في فصلي الصيف والشتاء. ومن حيث التكلفة، أثبت هذا النموذج جدواه الاقتصادية مع فترة استرداد لا تتجاوز الثلاثة أعوام.

DECLARATION

I declare that the Master Thesis entitled “The Impact of Using Phase Change Materials as a Seasonal Thermal Energy Storage Integrated with Thermal Insulation Material for Enhancing Thermal Energy Performance of Residential Building’s Envelop. A Case of Building in Hebron-Palestine” is my own original work, and herby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name: Bayan Mohammad Iwidat

Signature:____________________ Date:________________

DEDICATION

I dedicated this thesis to my family, whose unwavering support, encouragement, and love have been my guiding light throughout this journey. To my parents, for their endless sacrifices and belief in my dreams. To my friends, for their understanding and patience during the long nights and challenging moments. Finally, to my mentors and professors, whose wisdom and guidance have inspired me to reach new heights. This work is a reflection of your influence and belief in me. Thank you.

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This thesis represents not only my hard work but also the support and collaboration of many individuals and institutions that have played a pivotal role throughout my academic journey.

First and foremost, I am profoundly grateful to my supervisor, Dr. Khaled Tamizi, for his exceptional guidance and constant encouragement throughout the course of this research.

I am equally indebted to the members of my thesis committee, Dr. Bader Alatawneh and Dr. Sameh Mona, whose insightful comments, critical analysis, and academic expertise have greatly enhanced the quality of this work.

Special thanks go to the Professors and lecturers in the Master of Sustainable Design program at Palestine Polytechnic University.

List of Abbreviations

PCM: Phase Change Material

TES: Thermal Energy Storage

SAT: Sodium Acetate Trihydrate

TIM: Thermal insulation Material

LHS: Latent Heat Storage

SHS: Sensible Heat Storage

SHGC: Solar Heat Gain Coefficient

EPS: Expanded Polystyrene

q.: Heat flow

ASHRAE: The American Society of Heating, Refrigerating and Air-Conditioning Engineers

HVAC: Heating, ventilating, and air conditioning

LowE: Low-Emissivity

k: Thermal conductivity (W/(m K))

R: thermal resistance (m2 K/W)

T: temperature (°C)

U: thermal transmittance (U-value) (W/(m2 K))

ρ: density (kg/m3)

C: Celsius

DB: Design Builder Software

PPD: Predicted Percentage of Dissatisfied

ASHRAE: The American Society of Heating, Refrigerating and Air-Conditioning Engineers

DB: Design Builder Software

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Chapter 1 Summary

1.1 Preface

Nowadays, the energy shortage and environmental challenges are two pressing significant concerns which require attention. The main reasons for the demand for a more usage of energy sources are the ongoing expansion in its demand, increase in fuel costs, and carbon emissions. When relative to consumption rates in 2017, the global primary energy demand has increased up 1.5% in 2018. (Mofijur et al., 2019) Solar radiation is regarded as the most promising renewable resources in several countries around the world. Since there are no CO2 emissions, it is a clean renewable energy source. Researchers are looking for innovative, alternative energy sources all across the world. Energy storage technology development is one of the choices, which is just as crucial as creating new energy sources. A current problem for scientists is the storing of energy in appropriate forms that can be traditionally transformed into the needed form. (Sharma et al., 2009) (Journal, no date)

1.2 Problem Statement

1.2.1 Introduction

These days, the problem of dependence on non-renewable energy is one of the most prominent environmental and economical challenges in the world, as a result of the increase in population and climatic changes, which led to an imbalance between production and consumption energy (consumption is greater than production). Buildings are the most energy consumers, mainly, the building's envelope, which is the main source of energy loss in the building. On the other hand, worldwide is looking for low-carbon energy sources more quickly since the rising amount of CO2 in the atmosphere is posing increasingly serious difficulties to the planet's changing climate. One source of little to no carbon heat is the sun. For centuries, humans have used the sun as a heat source for space heating and household hot water. The fact that solar energy is an erratic heat source and that it cannot supply all winter energy needs in temperate climates is one of its primary disadvantages.

In Palestine, residential buildings are the most consuming buildings because of using the active energy solutions for heating and cooling to achieve indoor thermal comfort. On the other hand, solar radiation is dependent on the environment as well as the time of day, month, and year, making it one of the most potential renewable energy sources. However, a sensible heat storage system must have to be very big to deal with the unavoidable thermal losses when it requires storing heat during the summer, when the sun's energy supply exceeds the need, to the winter, when the sun's heat supply is limited. One of the best methods for resolving the imbalance between the production of renewable energy and the demand for heat is thermal energy storage.

As a summary of the previous issues, the research problem is concluded to discus and analyzes the use of TIM and TES materials in a southern façade of a residential building in Hebron-Palestine; to maximize the use of solar radiation source that makes the environmental and economical solutions achieve, thus saves energy and guarantees thermal comfort in the long-term (seasonal).

1.3 Research Question(s) and Hypothesis

- How effective is the PCM-TIM integration in improving the environmental performance of residential buildings in Palestine?
  1. How does the arrangement of the wall layers affect the thermal performance of the building envelope?
  2. What are the opportunities and costs of improving building insulation to save energy?

It hypothesized that PCM-TIM in one of the proposed models will have an important role in improving the thermal performance of the building envelope and a significant reduction in energy consumption.

1.4 Research Objectives

The research aims to find environmental solutions to store seasonal thermal energy for residential buildings in Palestine. The main objectives can be summarized as follows:

- ✓ Enhancing the efficiency of the building envelope and improving its thermal behavior in order to reduce heat gain and loss.
- ✓ Saving non-renewable energy consumption in residential buildings in Palestine.
- ✓ Examining the efficiency of using PCM-TIM integration in the building envelope.
- ✓ Finding passive and environmental and economical solutions by using insulation and seasonal thermal energy storage.

1.5 Research Significance and Relevance

Since the use of thermal insulation in building envelopes reduces the transfer of thermal energy to the interior in summer and to the exterior in winter, it still has a thermal storage deficiency, whether daily or seasonally. This deficiency leads to the flow and transfer of heat from the higher temperature area to the lower temperature area until thermal equilibrium is reached. The airflow significantly impacts the internal thermal comfort levels, necessitating the use of heating, ventilation, and air conditioning (HVAC) systems to restore indoor thermal comfort.

The importance of this research lies in studying a set of environmental elements and materials in the outer envelope of a residential building in Hebron in order to provide an environmental solution for storing renewable energy in the long term (seasonally) and reusing it at any time required in an attempt to reduce dependence on non-renewable energy sources and reduce its consumption and in return maximize the benefit from renewable thermal energy to reduce carbon dioxide emissions while studying the extent to which internal thermal comfort conditions and the level of satisfaction for users within the space are achieved.

On the other hand, the integration of PCM-TIM contributes to controlling the heat flow in the building envelope from the outside to the inside in summer (heat gain) and from the inside to the outside in winter (heat loss) to reduce energy consumption and increase the thermal efficiency of the building envelope, as this research studies the heat transfer curve across the outer wall of the building envelope and the methods of absorbing and transferring this heat.

1.6 Research Organization

The overall structure of the study takes the form of five chapters including this chapter which focuses on the research process.

Chapter 2 includes the theoretical aspect and literature review for previous studies, it also defineds the thermal energy storage (TES) and its efficiency when it integrated with buildings' envelops, and this chapter also defines the sensible and latent heat storage. By this chapter, the types of thermal insulation materials (TIMs) were studied. Besides, the phase change material (PCM) definition and types were studied as short and long terms thermal energy storages, as the impact of using these integration materials in the building on the energy consumption. While the construction systems in Palestine were context.

Chapter 3 describes the materials and methods. Is contains the long-term (TES) PCM type selection and thickness, it also describe the PCM charging in discharging operations. In this chapter, the TIM type and thickness were studied and calculated. The model formulation and new walls' designs for the suggested scenarios for new buildings and existing buildings were studied. The final section deals with the software simulation data for each scenario. Also it deals with the mathematical equations to calculate the amount of energy falling from the sun and stored in the PCM and the equations for storage and heat transfer through the layers of the wall.

Chapter 4 shows the simulation results for each design scenario in terms of thermal energy storage, indoor air temperature, indoor thermal comfort and heating and cooling loads. In this section, the best proposed design is decided upon, thus decide its cost efficiency and the system payback period was calculated.

Chapter 5 concludes and summarized the impact of PCM-TIM integration in terms of indoor air temperature and buildings' energy consumption as for seasonal and annual heating and cooling loads.

Chapter 2 State of The Art

2.1 Preface

For the most particular, people's per capita energy consumption has grown significantly, particularly in emerging nations. Recent significant advancements in a number of sectors, including commercial, industrial, and residential, have led to an increase in energy consumption in emerging nations. The most significant sources, which are limited sources produced by geological processes as an outcome of solar energy accumulating in the earth over thousands of decades, are natural gas, heavy oil, as well as other traditional resources. It is crucial to take into account innovative energy-saving strategies in both developed and emerging nations due to the volatility of reserves and prices as well as the rising expenses of power plants.(Ibrik and Mahmoud, 2005)

2.2 Literature Review

Over the past years, there has been an increase in the amount of papers discussing the installation of PCMs in buildings to increase their energy efficiency. There were just 2 papers on this topic published until 2003. More in-depth and focused studies of PCM latent heat systems and their applications have already been made over the recent years, and up to 2013, more than 20 comprehensive study articles about the possibility of applying PCMs in buildings have been reviewed, this mean, that interest in this topic is growing. Yet, during the past few years, the level of interest in PCM has evolved to be concerned with the concept of merging the material with the building for the purposes of indoor thermal comfort and energy saving. (Soares et al., 2013)

(Dannemand et al., 2015) have authored many papers on the application of solar-thermal energy storage (SAT) for seasonal purposes.

(Ma, Bao and Roskilly, 2017) simulated a storage system using TRNSYS and concluded that seasonal solar thermal energy storage with seven PCM modules of 150L each could cover 80% of the annual heating and hot water needs of a residential building in the Danish climate.

2.2.1 PCM-TIM integration

(Yang et al., 2015) research in the efficiency of integrate PCM and TIM while using polyurethane (PU) foam as an insulator to enhance energy efficiency in buildings. It has been demonstrated that PU-PCM foam's ability to store thermal energy is greatly improved; however its mechanical strength is lowered when compared to pure PU foam. They suggest the integration PCM-PU in a capsule, and testing capsule's thermal conductivity, the results shown that these capsules having almost a stable thermal conductivity when increasing the amount of PCM. Their recommendation was to make more studies of PCM-PU integration to evolve it, in order to enhance the thermal energy efficiency and indoor thermal comfort.

(Jia et al., 2021) study the enhancement of the thermal characteristics of hollow extruded blocks that have expanded polystyrene EPS as a (TIM) and (PCM) integration. They studied 7 samples of PCM-TIM in hollow blocks through numerical simulation and experimental results. The results showed that PCM had a great importance in improving the thermal inertia, and filling the bricks with TIM mainly led to increase in the thermal resistance. While filling all gaps with TIM decrease the heat transfer by 29.7%, adding PCM might lower the reduction factor from 12.3%-17.0% to 1.7%-2.2%, increase the delay time from 1.50-2.00 h to 6.17-6.50 h, decrease the peak heat transfer from 38.7 w/ m2 to 19.2 w/ m2 to 26.1 w/ m2, and raise the average heat transfer by 6.1%.

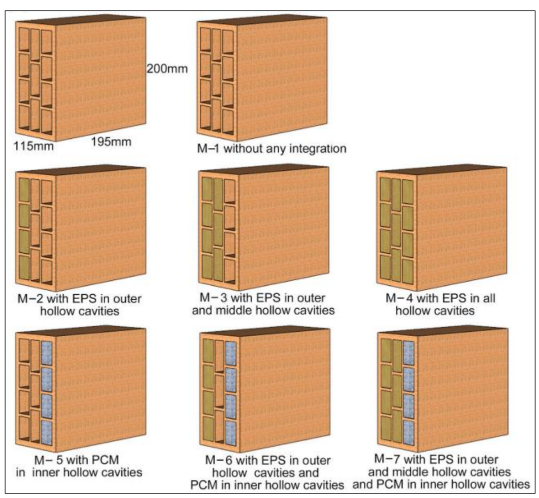


Figure 2-1: The hollow bricks filled with TIM or PCM (Jia et al., 2021)

(Ahmad *et al.*, 2006) conducted a research that compared two models. PCMs and insulation panels were utilized in the test model to increase wallboard efficiency. It became clear by comparing the data of the reference model with the test model that, during the warmest part of the day, the test model's temperature only reached around 40°C, while the reference model's temperature reached well over 60°C. Furthermore, during the winter, while the outdoor temperature was -9°C, the reference model's internal temperature decreased to -6°C, whereas the test model's indoor temperature plummeted to 0°C.

(Kośny et al., 2008) research on cellulose insulation reinforced with PCM. The first phase involved employing acrylic polymer shells with diameters ranging from 2 to 20 micrometres to microencapsulate a paraffin PCM.

.The freshly formed spheres were then placed on top of the insulation. In a lab environment, the mixture's performance was evaluated in a dynamic hot-box. When evaluating the cellulose material improved by PCM to a sample wall that has the same kind and amount of insulation, the walls' overall heat flux was decreased by nearly 40% during the first five hours of the ramp phase.

Using macro-encapsulation techniques, field testing of PCM-enhanced wall insulation systems were carried out with paraffin - PCM (Zhang, Medina et al., 2005) and hydrated salt - PCM (Lee and Medina, 2016). Two identically constructed side-by-side homes were used to evaluate the efficiency of these systems in all-weather circumstances. The highest heat transfer rates across the walls were found to be decreased by 21.0% and 27.3%, respectively, when paraffin-based and hydrated salt-based PCM were utilized.

(Medina, King et al., 2008) investigated the efficiency of structurally insulated panels (SIP) equipped with macro-encapsulated PCM in two adjacent test homes subjected to extreme weather conditions as well as in a lab dynamic wall simulator. These investigations showed that the addition of PCMs might improve the SIPs' capacity for thermal storage.

August 16-17, 2016 (Hasan, Basher et al., 2018) utilized two comparable rooms arranged in accordance with their direction (North wall, South wall, East wall, West wall and ceiling) to study PCM for residential building insulation, and PCM thickness. It was said that installing 1 centimeter PCM in each wall decreased the cooling demand by 20.9%.

(Souayfane et al., 2019) studied the ability of applied PCM-TIM composition to store a latent heat in an office wall and test it in different climates (Mediterranean, Oceanic, Humid, Continental, Continental subarctic and Polar climates) among a year through numerical simulation and experimental results. The results showed that the best orientation of the PCM-TIM integration wall was in the south, and the usage of this integration is better than implement the double glazed windows in all studied climates.

(Lee *et al.*, 2018) The thermal efficiency of PCM-enhanced walls under full weather conditions was evaluated using two tested residences with conventional residential structure wall construction. The latent heat of fusion of the PCM in the combination would not be negatively impacted by the cellulose, according to measurements. According to the experimental findings, there was an average 1.5-hour time delay between the peak heat fluxes. Each of the four walls had a distinct peak heat flux decrease. These were, for the north, west, east and south walls, 26.0%, 20.8%, 38.5% and 16.1% in that order. For each of the individual walls, the daily average peak heat flow decrease was 25.4%.

(Torres-Rodríguez et al., 2020) propose and evaluate two passive wall systems: Results indicated that the structure may be allowed generate heat in an amount of 118 W, 126 W, 134 W, and 157 W in December, January, February, and March, accordingly, as a passive heating strategy. One was for passive heating and consisted of an organic PCM and transparent thermal insulation (TTI) composed of CO_2, and the other was for passive cooling and consisted of a Tromble Wall with nano-film and a CO_2-filled TTI on the south façade of a building placed in Mexico. Moreover, the interior layer surface in the heating scenario achieves a temperature of 9.2°C when external and indoor values are estimated to be 0°C and 21°C, accordingly, based on thermal effectiveness and air flow simulations; in the cooling scenario, when both interior and exterior temperatures. Additionally, when outdoors and interior temperatures are considered to be 0°C and

21°C, accordingly, the inner surface in the heating scenario gets to a temperature of 9.2°C, based on the thermal effectiveness and air flow simulations; in the cooling case, when outdoors and indoor temperatures are considered to be 25°C and 21°C, accordingly, it reaches 22.5°C and has a maximum inside air flow of 0.5 m/s.

2.3 Energy Consumption in Residential Buildings

Residential and commercial buildings accounted for 40% of all energy usage in the United States in 2015, according to annual statistics published by the U.S. Energy Information Administration (EIA). Similarly, 40% of the energy consumed in the EU is attributed to buildings, reported to the European Commission. In 2010, the building sector was responsible for around 32% of the world's energy use. (Robinson *et al.*, 2017)

By 2019, the United States' residential sector accounted for 16% of end-use energy, while the commercial sector accounted for 12%. This suggests that building energy efficiency has had, and continues to have, a significant influence on overall energy conservation efforts.(Fu, Baltazar and Claridge, 2021)

When compared with the industrial and commercial sectors, Palestine's residential sector uses the most electrical energy. 50% of energy is used for residential use, 15% for industrial use, 10% for commercial and governmental use, and 15% for pumping stations across all sectors.(Ibrik and Mahmoud, 2005)

At the present time, buildings are among the most energy consumers, and the walls, roof, and openings that make up the building envelope are an important cause of thermal energy transfer. The wall is a significant component of the building envelope that may prevent up to 25–30% of thermal energy loss(Huang et al., 2020); so the issue of energy efficiency in buildings has become an important goal for energy management in countries. (Soares et al., 2013) Buildings are becoming more and more reliant on active technologies to maintain indoor thermal comfort in non-sustainable ways. (Soares et al., 2013) Large glazing areas in a building have a more significant impact on energy use. For instance, heat loss via windows accounts for around 30% of a building's energy use, and excessive gain is a significant issue that contributes to the high energy use of cooling-dominated spaces in hot climates.(Carlos and Corvacho, 2015)

Both energy usage and related carbon dioxide emissions grow as a result of this, although, building operating stage costs have increased as a result. In order for the buildings to be more energy efficient, there must be decrease in energy usage and an increase in energy saving. (Soares et al., 2013) Reducing energy use and carbon dioxide emissions is required to create a sustainable future. (Tsukada et al., 2021)

According to recent forecasts, the main demand for energy will increase by about 48% in 2040. On the other hand, there is an urgent need to transit from the use of non-renewable energy sources to the use of renewable energy sources. (Sarbu and Sebarchievici, 2018)

Nevertheless, much renewable energy sources, such as solar and wind, have the disadvantage of its limited time span, hourly due to weather, daily due to day and night and seasonally due to the seasons. That’s because, renewable energy depends on climate natural factors like rainfall, winds, and solar energy, which is challenging to manage its availability. If renewable energy could be stored, it can be utilized more effectively since it eliminates the need for fossil fuels, finally minimizes energy losses. It is vital to save additional energy for the short- and long-term in order to keep energy production and consumption. The only way to address this imbalance between both the supply of energy sources and the consumption of resources is to store solar energy. (Mofijur *et al.*, 2019) (Journal, no date)

2.4 Thermal Energy Storage

It is commonly recognized that there is significant potential for energy conservation when suitable thermal energy storage (TES) systems are used in the construction and industrial sectors. Maximum demand moving, reasonable thermal energy consumption and the use of waste heat are all made possible by the use of TES in both active and passive systems. Using TES in an energy system has several benefits, including increased overall efficiency and dependability as well as improved economics due to lower investment and operating costs, less environmental pollutants, and decreased CO2 emissions.(De Gracia and Cabeza, 2015)

Enhancing the thermal efficiency of envelops systems can be achieved by increasing their capacity for thermal energy storage.. This approach offers better control over heat transfer, which lowers energy consumption, improves user thermal comfort, and increases the life of the equipment.(Chow, Li and Lin, 2011)(Gil-Lopez and Gimenez-Molina, 2013)

Using TES might be a useful tactic to encourage a decrease in energy demand. That is, by absorbing, storing, and releasing usable energy, TES materials can shorten the time lag between energy supply and consumption. The most appealing features of TES systems are their high energy storage density and effective charging and discharging of heat. (Solgi *et al.*, 2019)

2.4.1 Integration of the TES in the Building Envelope

Building elements like ceilings or envelopes are utilized as TES systems by storage systems that are incorporated into the building's core. They are often powered by the low nighttime temperatures (a free source of cooling) and made to passively release the building structure's cooling reserve. These systems are suitable for controlling internal heat gains because of their huge area, which permits a high heat transfer rate and even a small temperature differential between the space and the structure, Figure 2-2 show the PCM as a TES in the building envelop in heating and cooling respectively .(Boemi, Irulegi and Santamouris, 2015)

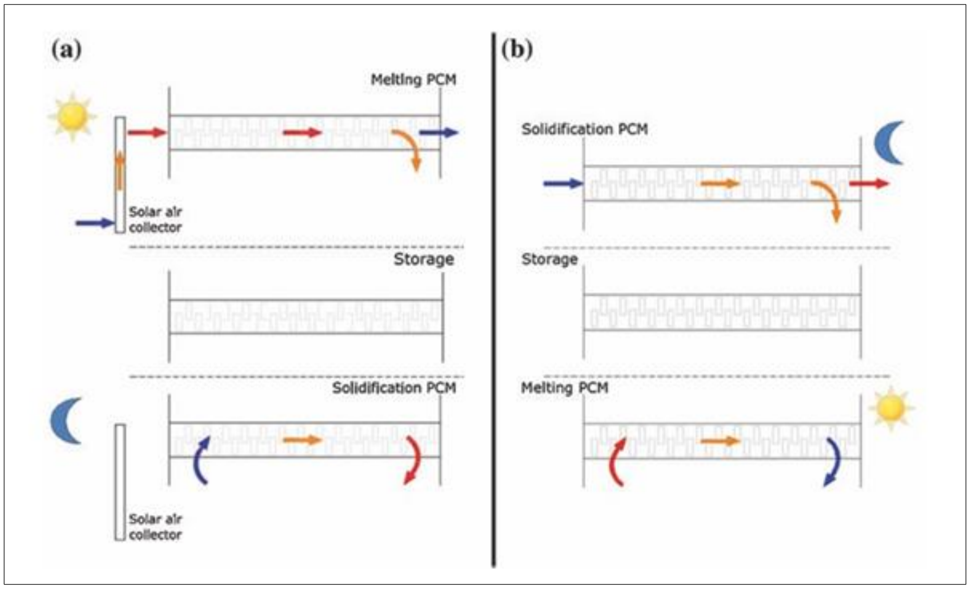


Figure 2-2 Operating principle of the envelope with PCM: a heating, b cooling, (Boemi, Irulegi and Santamouris, 2015)

(Boemi, Irulegi and Santamouris, 2015) suggested that adding storage to outside façades, such double-skin façades, will lower the chance of overheating and enhance system effectiveness in both the summer and winter. Additionally, testing was done on a façade that had TES PCM installed. The façade functions as a solar col lector in the sun absorption phase of the heating season (Figure 2-3). The heat discharge stage starts when the PCM melts and solar energy is required for heating. Until the system is able to supply no more thermal energy, this discharge phase is carried out. Because of the installation of this solar façade, the authors observed a 20% reduction in the electrical power usage of the HVAC systems. Additionally, the system was evaluated for cooling purposes, charging the PCM as well as providing free cooling at low temperatures during the night. The scientists created a numerical model and assessed the system's functionality in various weather scenarios. Based to the Köppen Geiger climate categorization, it was demonstrated that this latent heat system is best suited for usage in temperate regions. However, the system's ability to be beneficial in tropical and desert climates is quite restricted.

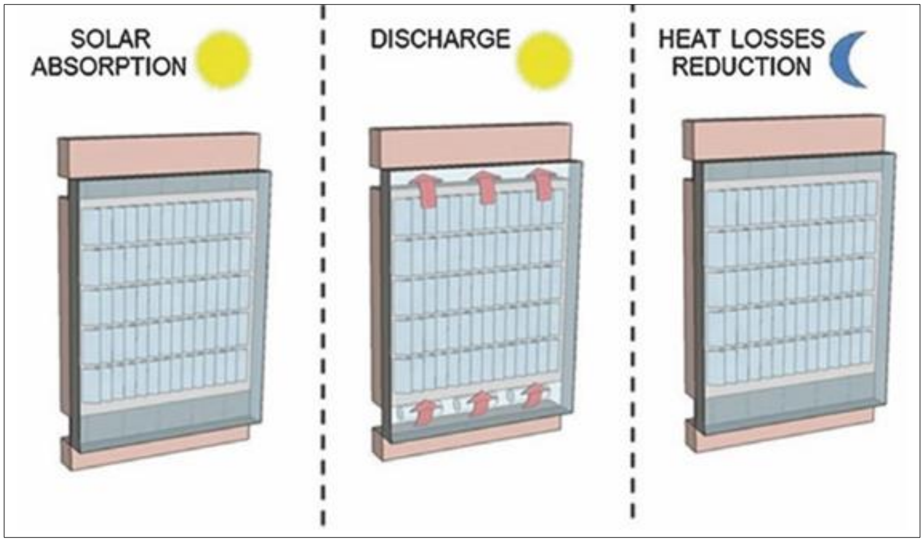


Figure 2-3: Operational mode of the system in a solar-ventilated façade during winter, (Boemi, Irulegi and Santamouris, 2015)

2.5 PCM in the building envelope

In recent researches, building envelopes with PCM were integrated to study impact principles. (**Error! Reference source not found.**) showed how this improved building envelope thermal behavior by using PCM. (Jia et al., 2021)

Table 2-1: Review on the thermal behavior improvement of building envelopes due to PCM. (Jia et al., 2021)

PCM Application	Method	Location	Results on temperature, heat flow and energy consumption
Built as a wall layer	Sim.	Diyarbakır, Konya, and Erzurum in Turkey	Increasing time lag by 13.3 h and saving the energy consumption of 18%;
Built as a wall layer	Exp.	Montreal, Canada	Reducing the heating and cooling loads by 17% and 20%, respectively;
Built as a wall layer	Exp.	Lawrence, USA	Reducing the maximum heat flow by29.7% and 51.3% for west and south walls, respectively;
Built as a wall layer	Sim.	Béchar, Algeria	Reducing the maximum cooling and heating loads by 24.3% and 35.4%, respectively;
Combined with the floor mortar	Exp.	Korean	Reducing the cooling energy consumption by 13.0%–13.6%;
Built as a wall layer	Exp.	Puigverd de Lleida, Spanish	Reducing the 15% cooling electricity, compared to the room without PCM;
Built as a wall layer	Exp. & Sim.	Chengdu, China	Reducing the heat loss by 36.6%–37.6%;
Inserted into the hollow bricks	Exp.	Portugal	Reducing the thermal amplitude by 5°C–10 °C and increasing the time delay by about 3 h;
The SSPCMs-mortar bricks	Exp.	Shanghai, China	Reducing the cooling and heating loads by 24.32% and 10%–30%.
Inserted into the hollow bricks	Sim.	Ancona, Italy	Increasing the delay time by about 6 h and the peak heat flow by 25%;
Inserted into the hollow bricks	Sim.	Chengdu, China	Reducing the attenuation rate from 13.07% to 0.92%–1.93%, and increasing the delay time from 3.83 h to 8.83–9.83 h;
Inserted into the hollow bricks	Sim.	Raebareli and Bhopal, India	Reducing the peak heat flux by 8.31%;
Inserted into the hollow bricks	Exp.	Delhi, India	Reducing inner surface temperature by 4°C–9.5 °C and the heat transfer by 40%–60%;
Inserted into the hollow bricks	Exp.	Delhi, India	Reducing the surface temperature by 5°C–6°C and the heat flow by 8%–12%, compared to conventional bricks.

According to (Jia et al., 2021), installing PCM in the building envelope primarily increased delay period and absorption speed, decreased temperature differences, decreased maximum heat flow, and reduced energy consumption. Additionally, PCM has demonstrated that it was incapable of improving the building envelope's thermal resistance. So, the combination of PCM and TIMs was proposed. While PCM could regulate temperature variation and lower the maximum heat flow, TIM would effectively limit heat transfer by improving thermal resistance. Based on this, combining the TIM and PCM concurrently might be taken into consideration to satisfy the thermal resistance need and decrease the energy consumption in the building life cycle. (Jia et al., 2021)

Currently the world is trending to use solar energy for a variety of purposes. Storage devices that make it possible to save extra energy and then release it whenever it is required considered necessary methods for the efficient usage of solar energy. Utilization of PCMs is a practical way of TES which can be used in different buildings for heating, cooling and domestic hot water.(Mofijur et al., 2019) (Sarbu and Sebarchievici, 2018) (TES) systems may now be utilized to deliver heat consistently, to help make energy consumption more ecologically friendly, and to lessen the reliance of buildings on non - renewable sources. (Soares et al., 2013) Operating temperature and storage density considered as certain crucial factors which must to take into account while using TES systems in buildings. (Goeke and Henne, 2015)

Therefore, insulation materials should be utilized to lower this energy consumption, and from a life-cycle aspect, using insulation materials eventually lessens the effect on the building's structure. Thus, in order to ensure the inhabitants' indoor thermal comfort throughout the year, a sustainable approach to the building's design must take into account the envelope's storage and insulation capacity.(Huang et al., 2020)

Thermal energy can be stored by different ways. (Sharma et al., 2009):

- Mechanical energy storage: include gravitational energy storage or pumped hydropower storage (PHPS) and compressed air energy storage (CAES).
- Electrical storage: Energy storage through batteries.
- Thermal energy storage: by altering a material's stored energy as sensible heat, latent heat, or both.

- Thermochemical energy storage: Its operation depends on the energy received and released during the chemical process of breaks and reforms molecular bonds. (Sharma et al., 2009)

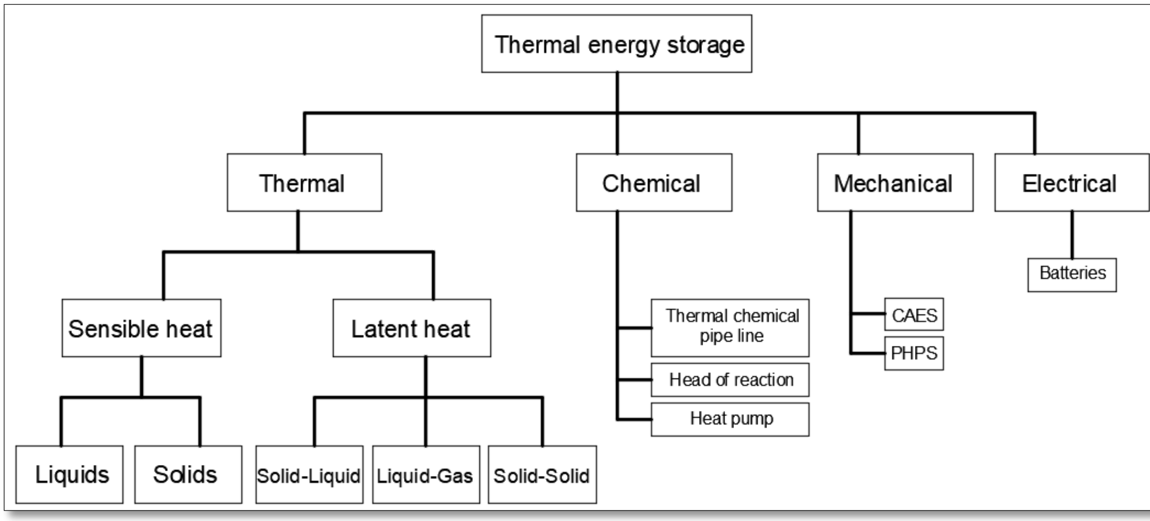


Figure 2-4: the different types TES for solar energy (Sarbu and Sebarchievici, 2018)

The following characteristics can be used to define an energy storage system:

- Capacity: describes the amount of energy stored in the system depending on the method of storage, the transporter medium, and the system's size.
- Power: determines how quickly the system's energies may be stored and released.
- Efficiency: is the proportion of energy supplied to users to energy required to recharge storage systems. It takes into consideration the energy lost throughout the charging and discharging processes.
- Storage period: determines the duration of the energy storage which ranges from hours to months.
- Charge and discharge time: indicates the time required to charge and discharges the system.
- Cost: concern to the capital and operating costs for the storage process as well as its lifespan and can relate to either the storage system's power or capacity. (Sarbu and Sebarchievici, 2018)

2.6 Sensible heat and Latent Heat of materials

Energy storage now plays a vital role in renewable energy systems. TES is a method of storing thermal energy through the heating or cooling of a storage medium. This stored energy can then be utilized at a future time for various applications such as heating, cooling, or electricity production. TES systems are commonly employed in both building and industrial settings. An increasingly crucial component of renewable energy systems is energy storage. Through providing heating or cooling to the storage container, TES stores thermal energy that may be utilized later on for electricity production or other uses like as heating and cooling. TES systems are mostly utilized in manufacturing processes and structures. The benefits of using TES in power systems include improved overall efficiency and increased reliability. Furthermore, this can lead to increased economic efficiency, reduced investment and operating costs, and reduced environmental pollution, leading to reduced carbon dioxide (CO_2) emissions. (Sarbu and Sebarchievici, 2018)

Sensible heat and latent heat are two different types of thermal energy that may be stored. Increasing the temperature from either solid or liquid materials helps to store thermal energy in sensible heat storage.(Mofijur *et al.*, 2019) (Journal, no date)

2.6.1 Sensible heat storage (SHS)

It is the simplest method of storing thermal energy and consists of applying a temperature gradient to a medium (solid or liquid). The heat stored in this medium is the sensible heat stored. Figure 2-5 shows the thermal profile of a substance or material when a temperature gradient is applied to it. The area under the curve is the total amount of heat stored. The most commonly used storage medium for storing energy as sensible heat is water.(Boemi, Irulegi and Santamouris, 2015)

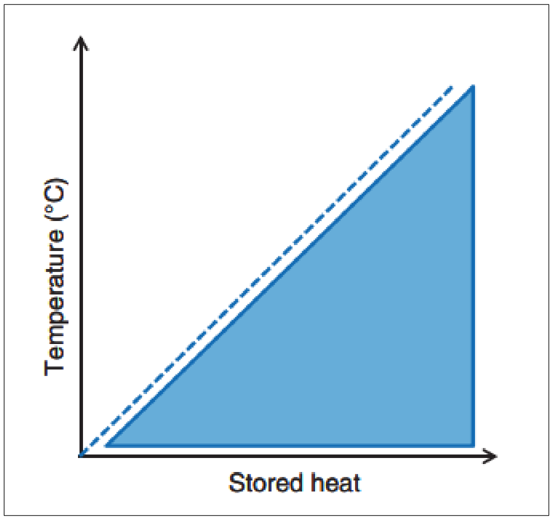


Figure 2-5: Thermal energy storage profile versus temperature when heat is stored as sensible heat,(Boemi, Irulegi and Santamouris, 2015)

Two major benefits of sensible heat storage are its low cost and the absence of hazards related to the usage of hazardous materials. Additionally, the materials used for energy storage are contained in bulk in a container, which makes the system easier to design. The heat capacity is determined by either the content, volume or mass of the material used. Sensible heat is often used in solids such as stone or brick, or liquids such as water (which have a high specific heat). The main materials used to store sensible heat are based on common ceramics (cement, concrete, etc.) or natural stones such as marble, granite, clay, sandstone, or polymers (PUR, PS, PVC). All of these are cheap materials, and the sensible heat depends on the mass and volume used. (Boemi, Irulegi and Santamouris, 2015)

2.6.2 Latent Heat Storage (LHS)

Buildings can use the latent heat of PCMs through two different conceptual systems: passive latent heat energy storage systems (LHES) or active LHES systems. PCM is suggested by TES as a material with a large latent heat storage capacity. Building systems and building envelopes have more thermal mass thanks to PCMs. Numerous academics have already conducted in-depth studies on these materials. Among all materials, paraffin, fatty acids, salt hydrates, and other materials with high storage densities for narrow temperature ranges are categorized as PCM and belong to distinct classes.(Yang *et al.*, 2019)

Nonetheless, a variety of techniques are used to bring PCMs into building systems. Direct incorporation of PCM into walls and ceilings is known as PCM encapsulation in constructions. Large regions for passive heat transmission are provided by these architectural elements in each building zone. One common technique for introducing PCM into porous materials like gypsum, plaster, wood, etc. is impregnation. Several necessary qualities must be met by material selections to be employed as latent heat thermoelectric sensors. The qualities that PCM requires for building applications are listed in (Table 2-2). Segregation—which is the PCM's phase separation when it contains many components—and subcooling—which happens when a PCM begins to solidify at a temperature lower than its congealing temperature—were the first limitations on the storage process. Throughout the material selection process, these two processes need to be examined and either minimized or avoided Figure 2-6). (Yang *et al.*, 2019)

Table 2-2: Requirement for materials to be used as TES media, (Yang et al., 2019)

	Sensible heat thermal energy storage	Latent heat thermal energy storage	Thermochemical storage
Physical and technical requirements	High density (ρ) temperature range fitted to the application High cyclic stability Large-scale production methods Non-corrosive low system complexity Low vapor pressure in the temperature range	Low density variation and small volume change High energy density Small or no subcooling No phase segregation Low vapor temperature Chemical and physical stability Compatible with other materials	Low density and small volume change High energy density No phase segregation Chemical and physical stability Compatible with other materials—non-corrosive
Thermal requirements	High energy density High thermal conductivity (κ) Low thermal diffusivity Good specific heat capacity (Cp) Thermal expansion coefficient (α)	Suitable phase change temperature fitted to application Large phase change enthalpy (ΔH) and specific heat (Cp) High thermal conductivity (except for passive cooling) Reproducible phase change Thermal stability Cycling stability	Reversible reaction Control of the kinetic model Control of the crystallographic structure changes Water stability within crystal structure Proper particle size Control of the impurities Solubility of the TCM in the working conditions (P, T) Suitable working temperature range Large energy involved in the reaction High thermal conductivity Thermal stability Cycling stability
Economical requirements	Low price Non-toxic	Low price Non-toxic	Low price Non-toxic
Recyclability	Recyclable or reusable Low CO_2 foot print Low embodied energy	Recyclable or reusable Low CO_2 footprint Low embodied energy	Recyclable or reusable Low CO_2 footprint Low embodied energy

However, no matter what the system, the PCM needs to be encapsulated or stabilized for engineering applications, and it is introduced into the building system using different methods. PCM encapsulation in structures is inserted directly into walls and ceilings. These architectural components provide a large area for passive heat transfer to all zones of the building. Impregnation is a widely used method to introduce PCMs into porous materials such as plaster, mortar, and wood. This technique has been widely studied recently.(Raul *et al.*, 2018)

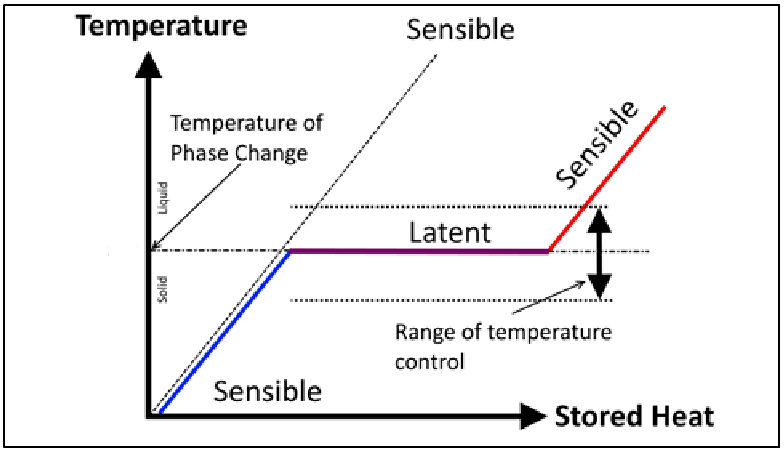


Figure 2-6: Sensible heat vs. latent heat and temperature control during the phase change, (Skovajsa, Koláček and Zálešák, 2017)

2.7 Indoor Thermal comfort

Nowadays, at least 90% of people's lives are spent indoors going about their daily business. Therefore, for them to get the most out of their hobbies, they must feel comfortable. Examining the thermal comfort of an interior space directly depends on measuring physical factors including temperature, humidity, air flow, and radiation. Energy usage will significantly increase when heating, ventilation, and air conditioning systems (HVAC) are used. Since it is well known that energy costs have grown globally, it would be financially advantageous if we could lower the amount of air conditioning that we use. Therefore, we must research ways to lower energy usage while raising thermal comfort.(Morsy *et al.*, 2018)

2.7.1 Thermal Comfort Definition

It is challenging to please everyone in a room due to the significant physiological and psychological differences between individuals. Not every person requires the same set of surroundings to be comfortable. Nonetheless, a large body of field and laboratory data has been gathered, which offers the statistical information required to identify the parameters in which a given proportion of occupants would feel thermal comfort. It is possible to track and preserve thermal comfort using both measurable and non-measurable factors. There are three primary categories into which the quantitative characteristics of thermal comfort may be divided: air, surface, and human-related elements.(Morsy *et al.*, 2018)

(Yao, Li and Liu, 2009) define thermal comfort as "the state of mind, which expresses satisfaction with the thermal environment". On the other way, ASHRAE Standard 55 -2010 defines thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment"

Researchers' investigations aim to solve the estimated interior thermal comfort by prediction models. A steady-state model of the physiological interactions between the human body and its surroundings served as the physiological foundation for the development of several empirical comfort index-based models, including Standard Effective Temperature (SET), Predicted Mean Vote (PMV), and others. The indices that were previously mentioned are utilized to determine a building's requirements for thermal comfort. The commissioning and operating phase of HVAC systems is the other application. Nonetheless, the relationship between people's comfort and the thermal environment has given rise to two distinct concepts: a) the heat balancing method and b) the way of adaptation. (Morsy *et al.*, 2018)

2.8 Thermal Insulation Materials

Approximately one-third of all final energy consumption and one-third of global greenhouse gas emissions connected to energy usage are attributable to the construction industry. Due to population growth, changes in lifestyle brought about by technological advancements and urbanization, consumption is predicted to reach 53% in the coming ten years. This could result in negative effects on the environment, society, and economy in addition to increasing greenhouse gas emissions from this sector. (Ascione *et al.*, 2019)

For sustainability, it is therefore important to reduce building energy usage and CO2 emissions. Because it makes up between 50 and 60 percent of all heat transmission in a building, the envelope is thought to be a crucial component in improving thermal performance. Buildings use insulation to reduce heat transmission, reduce the need for heating and cooling, and enhance the thermal comfort of the occupants. If chosen properly, insulation materials can help reduce fire dangers and attenuate unwanted noise. (Kumar *et al.*, 2020)

Furthermore, an important consideration is the embodied energy of the insulating materials. When the energy required to produce the insulating materials is less than the energy consumed to operate the structure, there is a positive net energy balance and a reduction in greenhouse gas emissions in insulated buildings. Thermal conductivity, thermal energy storage, acoustics, thermal mass, hygroscopicity, fire response, and environmental factors were all examined in a number of review studies. Several studies assessed the performance taking into account operating CO2 emissions, lifespan costs, and dynamic behavior. (Verbeke and Audenaert, 2018) (Kumar *et al.*, 2020)

2.8.1 Types of insulation materials

According to their source, composition, and accessibility, building insulation materials may be categorized into three categories, as illustrated in (Figure 2-7): conventional, state-of-the-art, and sustainable. (Kumar *et al.*, 2020)

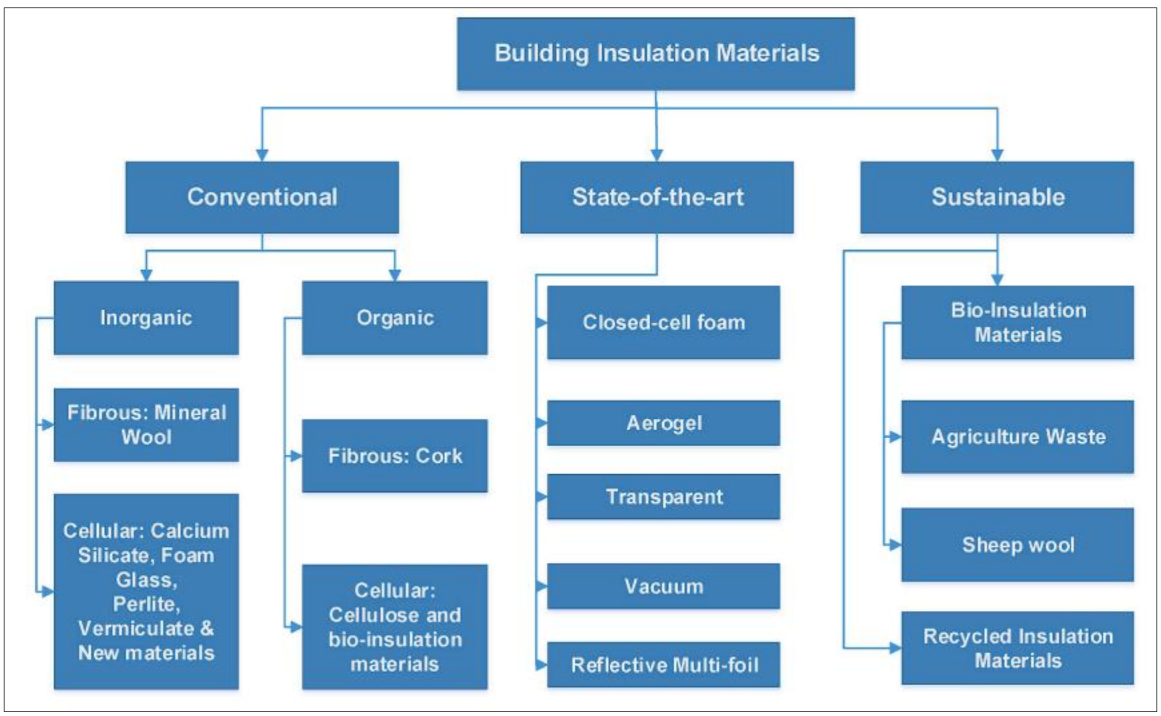


Figure 2-7: Classification of building insulation materials, (Kumar et al., 2020)

The majority of earlier research just used lifetime cost analysis (LCC) to determine the best building insulation materials. Throughout the anticipated lifetime of buildings, LCC takes into account the time value of money related to the initial material cost and ongoing energy-saving costs. And little thought was given to the carbon and embodied energy of insulating materials.

This section analyses the thermal, environmental, economical, hygroscopic, acoustical, and fire-retardant qualities and performances of various insulating materials. While environmental qualities are critical for reducing CO2 emissions in the built environment, thermal characteristics are required for cost savings and operational energy reductions. In a humid environment, the hygroscopic feature is crucial for regulating the relative humidity indoors. Lastly, in the case of a fire, the fire retardant quality is essential to guaranteeing the protection of building inhabitants.(Kumar et al., 2020)

(Table 2-3 24Table 2-4 and Table 2-5) below compare the thermal, physical and economic properties of different types of insulating materials.

Table 2-3: Properties of building insulation materials (conventional and state-of-the-art), (Kumar et al., 2020)

Insulation type	Density	Thermal Conductivity	Specific heat capacity	Vapor diffusion resistance factor	Sound absorption coefficient	Reaction to Fire	Cost	Embodied Energy	Embodied Carbon
Notion (unit)	ρ (kg/m^3)	k ($mW/m\,K$)	c_p (J/g^oC)	μ (–)	α (–)	Φ (–)	C_i (US $\$/m^3$)	EE (MJ/kg)	EC ($kg\ CO_{2\text{-}eq}/kg$)
Conventional building insulation materials									
Glass wool	10–100	30–50	0.8–1	1–1.3	0.45–0.8	A1	9.3–14.7	14–30.8	1.24
Rock wool	40–200	33–40	0.8–1.0	1.0–1.3	0.29–0.9	A1-A2	12–20	16.8	1.05
Slag wool	50	40	0.7	0.5	0.5	–	–	–	
Expanded Polystyrene	18–50	29–41	1.25	20–100	0.22–03.65	E	8.6–17	80.8–127	6.3–7.3
Extruded Polystyrene	32–40	32–37	1.45–1.7	80–170	0.2–0.65	E	18–23	72.8–105	7.55
Polyurethane	30–160	22–35	1.3–1.45	50–100	0.67 or 0.8	D-F	24.91	74–140.4	5.9
Polyisocyanurate	30–45	18–28	1.4–1.5	55–150	–	B	20–24	69.8	5.5
Foamed Glass	100–200	38–55	0.21	∞	–	A1	46–62	20.6–27	–
Perlite	32–176	40–60	0.2	3.5	0.2–0.75	A1	38–42		
Calcium Silicate	200–240	59–65	1.3	6–20	0.71	A1		10	
Vermiculite	64–130	40–64	0.84–1.08	3–5	0.8	A1		7.2	
Phenolic foam	40–160	18–24	1.3–1.4	35	0.3–0.5	B–C	23	13–159	4.15–7.21
Cork	100–120	37–43	1.5–1.7	5–30	0.39–0.85	E	25.6–44.7	26	0.82
Cellulose	30–80	37–42	1.3–1.6	1.7–3.0	0.53–0.9	B–C–E	24.6	3.3–10.5	0.31–1.83
State-of-the-art building insulation materials									
Closed-cell foam	16–55	25–48	–	–	–	–	–		
Aerogel	70–150	13–21	1.0	2.0–5.5	0.54–0.78	A1/C	61–214	53.9	4.3
vacuum insulation panel	160–230	3.5–8	0.8	340,000	0.1–0.3	A1c	90–172	149–226	6.2–11.1
Transparent (aerogel)	–	0.22–1.3*	–	–	–	–	–	–	–
Transparent (no aerogel)	–	0.42–1.8*	–	–	–	–	100-400*	–	–
Nano insulation materials	230	4–15	1.0	5	0.2–0.8	C	3000*	1.4–2.685	
Gas filled panels	–	11–20	–	–	–	–	214	–	–
Reflective multi-foiled	–	160-180*	–	–	–	–	–	–	–

Table 2-4: Properties of building insulation materials (natural), (Kumar et al., 2020)

Insulation type	Density	Thermal Conductivity	Specific heat capacity	Vapor diffusion resistance factor	Sound absorption coefficient	Reaction to Fire	Cost (P/m2)	Embodied Energy	Embodied Carbon
Notion (unit)	ρ (kg/m^3)	k ($mW/m\,K$)	c_p (J/g^oC)	μ (–)	α (–)	Φ (–)	C (US $\$/m^3$)	EE (MJ/kg)	EC ($kg\ CO_{2\text{-}eq}/kg$)
Bamboo fibres	431–538	77–88	1.79–1.96	8.7–15.4	0.2–0.56		–	–	–
Corn	148–257	101–139	1.48–1.72	5.2	0.2–0.8		–	–	–
Durian	357–1456	35–185	0.77	19	0.15–0.95	–	–	–	–
Coconut pith	174–664	42–86	2.6	1–10	0.28–0.74	E	84.35	–	–
Fique	421–128	28–80	–	–	0.2–0.7	–	–	–	–
Flax	20–100	33–90	1.6	1–5.28	0.54–0.84	C	15.18	39.5	20*
Hemp	25–100	39–123	1.7–1.8	1–10	0.52–0.6	E	15–19.4	18.71	0.14
Kenaf	30–180	26–44	0.21–1.7	1.2–2.3	0.3–0.95	E	–	22.7–39.06	0.59–2.09
Reeds	130–190	45–56	1.2	1–2	0.08–0.54	E	–	37	
Sunflower	36–152	38–50	–	–	0.7	–	–	21.11	0.56
Rice husk	130–170	48–80	1.2–2.7	2	0.15–0.66	A	5	1.36	0.6
Coir Fibres	75–125	0.040–0.045	1.3–1.6	5.0–30	0.2–0.75	D-E	–	0.55	
Wheat husk	480	0.1	0.718	2–12	0.29–0.78		–	–	–
Straw bale	80	0.052	0.6	–					
Bagasse	250–350	49–55	1.3–1.5	–	0.46–0.71	–	–	2.96	
Date Palm	187–389	72–85	1.19–1.79	–	0.59–0.83	–	–	–	–
Coffee Chaff	350	76	–	–	0.1–0.9	–	–	0.23	0.05
Jute fibre	–	50	–	–	0.2–0.56	–	–	21.11	0.56
Cotton stalks fibres	150–450	58–82	0.13	–	0.5–74	E	–	44–48	2.4–2.7
Pineapple	178–232	35–57	–	–	0.9	–	–		
Wood fibre	50–270	38–50	1.9–2.1	1–5	0.1–0.32	E	26.6–37.8	20.3	0.124
wood (pine)	450–630	151	1.38	5	0.75–0.95	E	–	–	–
Bio-insulation: Sheep wool	10–20	38–54	1.3–1.7	4–5	0.056–1.12	E	24	5.4	0.12

Table 2-5: Properties of building insulation materials (recycle), (Kumar et al., 2020)

Insulation type	Density	Thermal Conductivity	Specific heat capacity	Vapor diffusion resistance factor	Sound absorption coefficient	Reaction to Fire	Cost (P/m2)	Embodied Energy	Embodied Carbon
Notion (unit)	ρ (kg/m^3)	k (mW/m^2 K)	c_p (J/g^{0}C)	μ (–)	α (–)	Φ (–)	C (US \$/m^3)	EE (MJ/kg)	EC (kg $CO_{2\text{-}eq}$/kg)
Cellulose	85	40–50	1.8	1	–	–	–	–	–
Rubber	500–930	100–140		14	0.2–0.8	D-E	–	67.9–140	3.76
Cotton waste	18–45	38–44	1.6	1–2	0.66–0.95	E	19.32	27.1	1.28
Textile waste	30–80	36–42	1.2–1.6	2.2	–	E-F	–	9.82	0.87
Polystyrene fibres	15–60	34–39	1.2	3.1	0.61–0.75	B	–	14.2–78.24	1.66–2.11
Glass fibres	100–450	31–50	0.83–1.0	–	0.35	–	–	167.71	9.63
Typha Australis-clay	1974–2124	65–112	0.16–0.25	1.29–7.06	–	–	–	–	–
Polystyrene-scrap tyre	146–495	60–100	–	–	–	–	–	–	–
Basalt fibre	165–187	31–32	–	2	0.9	A1	27–30	–	–
Waste paper	170–646	36–61	–	–	0.72	–	–	1.63	0.08
Cork Scrap	195	55	–	–	0.99	–	–	2.33	0.73
Granulated Rubber	550	135	–	–	00.96	–	–	0.34	0.105
Tyre Shred Residues	313	166.3	–	–	0.3–0.5	–	–	–	–
Chrome shaving	150–200	34–42	–	–	–	–	–	–	–
Coal fly ash-scrap tire	290–315	40	0.04–0.56	–	–	–	–	–	–
Linter & Tablecloth textile waste	25–45	33–45	0.17–0.2	–	–	–	–	–	–
Buffing dust	–	24–26	–	–	–	–	–	–	–
Hemp shive composite	210–410	59–73	–	0.90–2.63	0.5	–	–	–	–
coring wool & doper wool	66–58	32	–	–	0.18–0.58	A2	–	–	–

2.8.2 Impact of Using TIMs on Buildings' Energy Consumption

In order to reduce the amount of energy required throughout the building's usage phase and maintain the optimal temperature conditions while providing indoor thermal comfort for its residents, designers are encouraged by the energy efficiency of buildings instructions to integrate insulation materials into the building's envelope. This is in line with the recently introduced nearly zero-energy building (NZEB) concept.(Development, no date) In this context, TIMs have an important role to improve thermal comfort and reduce energy consumption in the buildings. Insulation materials are an important part of a structure and are essential to achieving this goal. Even if the building's energy consumption throughout its usage stage is expected to decrease as insulation thickness increases in its envelope, the environmental effect and cost associated with producing insulation materials are expected to grow significantly due to the increased amount of material required. (Development, no date)

According to (Wilhelm et al.'s, 2012) realization, in Dubai, well-insulated exterior walls can result in a 30% reduction in energy costs for residential buildings. Additionally, (Masoso and Grobler, 2008) discovered that the yearly cooling load drops as interior temperature rises and turns negative when interior set point temperature rises above a predetermined threshold (25.72◦C).Based on empirical and computational research into the relative energy and financial efficacy of air-conditioned enclosure walls, (Surapog et al., 2012) concluded that insulation may typically assist enhance the thermal performance of walls.

The impact of the insulation of the building envelope was examined in the study by (Cabeza et al., 2010), which measured significant energy savings. In insulated buildings with summer and winter Mediterranean climates, the authors experimentally recorded energy reductions of 64% and 37%, respectively.

Therefore, exterior thermally insulated walls can lower the energy usage of HVAC system in addition to improving interior thermal comfort.

However, the problem of thermal inertia of insulated walls remains a real problem and needs to be studied to find solutions for thermal and dynamic transmittance and thermal energy storage.

2.8.2.1 Impact of Using TIMs on Buildings' Energy Consumption in Palestine

It is possible to efficiently cut energy consumption for heating and air conditioning by 27.23% by implementing insulating materials. Given the West Bank's high energy usage and ongoing concern about emissions, this reduction is especially noteworthy. (Falk, 2022)

As for (Haj Hussein et al., 2021) research, the exterior wall with the highest level of thermal insulation, or outside thermal insulation, had the greatest impact on the building's thermal performance both in the summer and the winter. The worst impacts on the building's winter thermal efficiency were seen in the un-insulated walls. Lower levels of thermal mass inside the space (i.e., the outside of thermal insulation) seem to generally have a negative impact on thermal performance and potential energy consumption for the various temperature zones in Palestine. It is anticipated that, in comparison to buildings with outer thermal insulation, structures without thermal insulation and those with internal insulation would use more energy for heating and cooling.

2.9 Phase Change Material (PCM)

In order to use energy as efficiently as possible, PCM usage has lately attracted more attention from researchers. The literature has extensively examined PCM design, analysis, and theory for storing latent heat. (Aditya *et al.*, 2017) Using PCM in the façade system is an efficient way to improve the thermal storage capacity since it allows some solar energy to be absorbed while allowing visible radiation pass into the interior space for natural light. In this sense, studies on the use of PCM in the façade systems to increase energy efficiency have significantly increased in the last several years. Additionally, a great deal of experimental and computational work has gone into integrating PCM into façade systems to reduce building energy usage.(Koláček, Charvátová and Sehnálek, 2017)(Khudhair and Farid, 2004)(Wang and Zhao, 2015)(Li, Darkwa and Su, 2019)

Depending on how they complete a phase shift, PCMs can be classified as solid-solid, solid-liquid, solid-gas, or liquid-gas. Figure 2 illustrates that of these four categories, solid-liquid PCMs are the best at storing thermal energy. They come in the forms of eutectics, inorganic PCMs, and organic PCMs.

2.9.1 Types of Phase Change Materials (PCMs)

The usage of PCMs in construction can serve two purposes: to benefit from solar energy for heating and cooling purposes and utilizing artificial cold and heat sources. (Sharma et al., 2009)Anyway, heating and cooling storages are required to balance both supply and demand in terms of time as well as in power terms. There are essentially three methods for using PCMs for heating and cooling in buildings: Using PCM in buildings' walls, using in other building components (roofs, floors, etc.) and using as thermal storages (heating and cooling).(Sharma et al., 2009) The PCMs can be classified into three categories (Figure 2-8); large numbers of these PCMs are available in different temperature ranges. (Sharma et al., 2009)

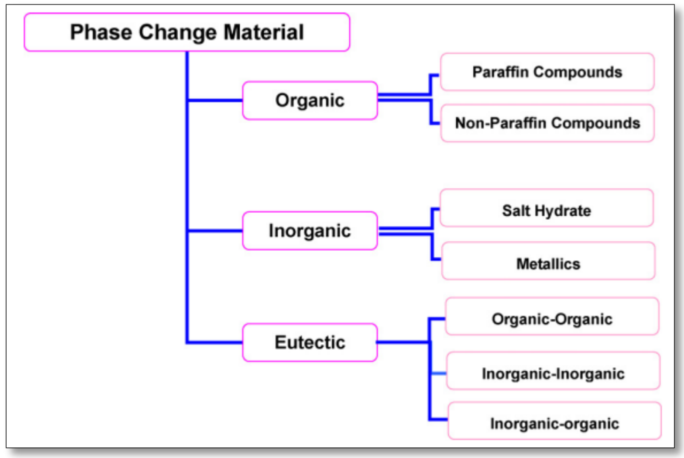


Figure 2-8: Classification of PCMs according to material composition, (Sharma et al., 2009)

Because paraffin wax has a very high heat of melting and can be employed at a wide variety of temperatures, it is considered a PCM. Paraffin wax may freeze without going through a really cold process. Technical grade paraffin wax is therefore the most practical, affordable, and extensively utilized PCM. The writers have done a number of investigations on this subject. In comparison to paraffin wax, fatty acids have a greater heat of fusion value and are organic substances defined by CH3(CH2)2nCOOH. It is possible for fatty acids to repeatedly melt and freeze with little to no supercooling. Fatty acid application is hindered, among other things, by their expense, which can be 2.0–2.5 times more expensive than paraffin wax. (Silakhori et al., 2014)

The chemical formula of salt hydrates is usually MnH2O, where M is an inorganic molecule that is of high density so it is responsible for storing latent heat.

Because of their weight, metals were not considered a viable option for PCM. But when volume is factored in, metals are probably strong candidates due to their high latent heat of fusion per unit volume and high thermal conductivities. (Xie et al., 2017)

PCMs are one novel approach to improve the thermal resistance of façade systems and reduce building energy consumption. In an effort to enhance PCMs, several researchers have attempted adding different compounds in order to improve its performance and effectiveness.(Bland *et al.*, 2017)(Oró *et al.*, 2012)

The thermo physical characteristics of PCM, such as melting temperature and melting enthalpy, provide the selection criteria that are used to solve engineering challenges. (Baetens, Jelle and Gustavsen, 2010) The connection between PCM melting enthalpy and temperature for several PCM material groups is shown in (Figure 2-9).

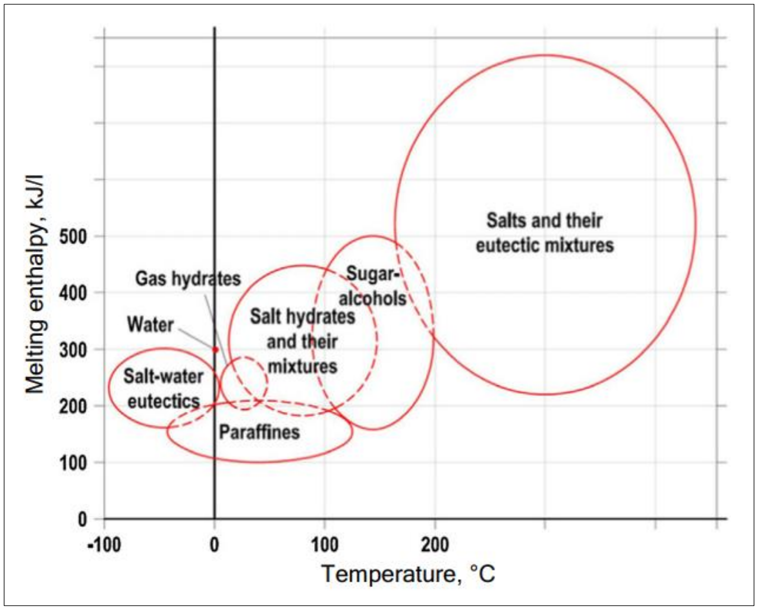


Figure 2-9: Melting enthalpy vs. temperature for different categories of PCMs, (Baetens, Jelle and Gustavsen, 2010)

When the PCM transforms from one physical state to another, this is termed as a phase change. These solid-liquid PCMs function initially like traditional storage materials; but, as they absorb heat, their temperature increases. PCM absorbs and releases heat at a practically constant temperature, in contrast to conventional (sensible) storage materials. So (PCMs) are ‘‘Latent’’ heat storage materials. Furthermore, these materials must possess specific acceptable thermal, kinetic, and chemical characteristics in order to be used as latent heat storage materials. Additionally, it is important to keep in mind the affordability and simple accessibility of these materials.(Sharma et al., 2009) Thus, materials that store latent heat are divided into three categories: solid-liquid, solid-gas, or liquid-gas. Phase transformations include solid-liquid, solid-gas, and liquid-gas transitions. The benefits of solid-solid PCMs include reduced restrictive constraints and more design flexibility. The use of solid-liquid transitions in TES devices has proven to be economically advantageous.(Journal, no date) (Soares et al., 2013) (Sharma et al., 2009)

2.9.2 PCM as a thermal energy storage

The usage of PCM for TES started in 1940s. (Goeke and Henne, 2015)The basic concept of using a PCM for TES in solar heating applications, it is that when the material is exposed to heat, it stores heat and its physical state transforms from the solid state to the liquid state with a constant temperature, and the opposite happens when the temperature of the material is higher than the temperature of the surroundings, it releases the heat stored in it and transforms again from the liquid state to the solid state with a constant temperature. (Journal, no date)(Muthukumar and Niyas, 2020)

TES proposes PCMs as materials capable of storing large amounts of energy as latent heat. PCMs increase the thermal mass of building envelopes and building systems. Such materials have been extensively studied by several researchers in the past. Among all materials, those with high storage density in a narrow temperature range are considered as PCMs and are classified into different groups depending on the nature of the material (paraffins, fatty acids, salt hydrates, etc.). (Boemi, Irulegi and Santamouris, 2015)

An innovative approach to boosting the thermal inertia of façade systems and cutting down on building energy consumption involves incorporating phase change materials. However, before choose and start the design stage; it's important to study a brief overview on the thermo physical and optical characteristics of phase change materials since these factors are essential to maximizing the thermal and optical performance of glazing units. Before, to delving into the characteristics of PCM, it is important to identify the common PCMs types that are often utilized.(Baetens, Jelle and Gustavsen, 2010)(Li et al., 2020)

The energy storage capacity, determined by the solar radiation coefficient, equipment efficiency, and energy consumption for heating/cooling, dictates the density of energy per unit volume or mass. It is therefore worth investigating the possibility of using PCMs in solar applications.(Sarbu and Sebarchievici, 2018)

Storage periods range from short-term daily storage to long-term storage, usually between seasons (called seasonal storage). The use of storage within buildings can pursue different objectives. One is to reduce the energy requirements of a building by reusing high internal benefits or storing external heat or cold for use within the building. A second goal is "peak capping" (also known as "peak shifting"). With this strategy, no energy is saved, but an economic benefit is achieved. TES can also improve HVAC systems by increasing efficiency or reducing emissions. (Boemi, Irulegi and Santamouris, 2015)

2.9.2.1 PCM as a Short-Term Thermal Storage

Various PCMs such as fatty acids, paraffins, coconut oil, calcium chloride hexahydrate, and others have been employed for temporary heat storage in order to enhance the capability of residential thermal heat storage. Many materials with high thermal conductivities, including metals, carbons and aerogels, have been added to PCM in order to boost its poor thermal conductivity.(Wang, Dannemand, *et al.*, 2021)

It has been demonstrated that using PCMs can enhance solar heating systems. In a building in Greece, (Plytaria *et al.*, 2019) introduced PCM to the floor layers. Following the addition of PCM, the underfloor heating system's variable cost was lowered by 20% and the heat load was decreased by 40%. In order to raise the heat content of a water heat storage, (Naghavi *et al.*, 2020) added PCM. In any Malaysian weather, houses may receive the desired hot water (112–170 L) from the PCM-water thermal battery. Buildings that are lightweight and energy-efficient also use PCM heat storage. A solar air heating system including an air vacuum tube solar collector and latent heat sink was able to attain a 63% solar heating fraction with the addition of PCM. (Wang, Dannemand, *et al.*, 2021)

2.9.2.2 PCM as a Long-Term Thermal Storage (Seasonal Storage)

Using PCMs work on a simple concept, the substance absorbs the heat when the ambient temperature rises, changing from a solid to a liquid state. The heat energy that is absorbed by PCM will be as sensible heat and latent heat of fusion. In a similar manner, PCM releases absorbed energy as a material's temperature drops and its phase transitions from liquid to solid (solidification). (Purohit and Sistla, 2021)

Because of having latent heat of fusion, which may maximize storage density when compared to sensible heat storages, PCMs are regarded as potential heat storage materials. Through the use of the supercooling method, the latent heat of fusion in some PCMs may be maintained for an extended time period without losing heat. (Kong et al., 2016) Supercooling is the phenomena when fluid PCM continues to flow even when its temperature falls below the melting point without beginning to solidify. For several PCMs, supercooling is commonplace and is what causes fluid salt hydrates to crystallize. The supercooling degree (ΔT_{sc}) is the difference in temperature between the melting point and the actual temperature of solidification. (Wang, Xu, *et al.*, 2021a) Inorganic (PCMs) as salt hydrates are not formed as expected, When the temperature drops lower than the melting point, the supercooling impact of these PCMs is typically viewed as a negative issue. However, this capability might prove to be useful for the seasonal storage of solar thermal energy, allowing for the collection of solar heat in the summer or early fall and its subsequent storage in supercooled liquid during the transitional months. (Zhou and Han, 2021)The supercooled PCMs might then be turned on to solidify and transfer the latent heat to a liquid for space heating in the winter. While the environment and the supercooled salt hydrate solution are in thermal equilibrium,, less energy is lost for supercooled storage even without insulation. Salt hydrates that have been supercooled may be made to solidify by mechanical, ultrasonic, or percussive stimulation. (Zhou and Han, 2021) also, the latent heat may be maintained at room temperature for a considerable amount of time by using steady super cooling. The variability in ambient temperature has no effect on the supercooling that was accomplished.(Wang, Xu, *et al.*, 2021a) In order to use reliable supercooling for long-term heat storage, the supercooling must be sufficiently stable and unaffected by heating-cooling cycles. Heat loss over the long-term is rather little. Initially, the sensible heat stored can be utilized, and then the latent heat can be preserved at indoor temperature. There is practically no further sensible heat loss in this situation until latent heat is released. (Wang, Xu, *et al.*, 2021a)

2.9.3 PCM thickness

TES systems have shown great promise in the construction industry in recent years, offering significant possibilities for energy reduction. The selection of a TES system is essentially determined by the length of time that must be stored, the operational environment, and the system's economic viability.

Using TES might be a useful tactic to encourage a decrease in energy demand. That is, by absorbing, storing, and releasing usable energy, TES materials can decrease the gap between energy supply and use. The most appealing features of thermoelectric storage (TES) systems are their high energy storage density and effective charging and discharging of heat. In addition to preserving interior comfort levels, passive TES systems can reduce HVAC system loads by using natural sources.

2.9.4 Impact of Using PCMs on Buildings' Energy Consumption

The primary objective of implementing PCM in building envelopes is to minimize heating and cooling demands, consequently managing and decreasing overall energy usage in the building. This results in enhanced energy efficiency and improved indoor thermal comfort. It is important to consider that energy consumption in residential buildings fluctuates throughout the day due to varying daily activities, as well as between seasons such as summer and winter due to temperature differences.

In hot climates, it can be said that regardless of the amount of insulation, a building with high thermal heat capacity walls can perform noticeably better than one with low thermal heat capacity walls. The quantity of energy needed for cooling will change or be less depending on the amount of thermal energy stored in the wall.(Profile, 2023)

In building applications, PCMs have a major impact on heating and cooling. In order to store enormous amounts of thermal energy, the PCM undergoes a phase transition from solid to liquid during the daytime due to high ambient temperature and solar radiation. Heat gain into the building is decreased and HVAC systems use less energy for space cooling during this phase transition process. Low ambient temperatures at night cause the PCM to transition from a liquid to a solid state, which releases heat into the building and into the surrounding air. (Profile, 2023) (Gilbert, Robert B., 2010)

Incorporated PCMs into the walls of the building, the construction will be able to store a significant quantity of thermal energy while keeping the interior temperature fluctuation to a minimum. (Profile, 2023)

2.10 Phase Chang Material (PCM) and Thermal Insulation Material (TIM) integration

Buildings' thermal performance has been enhanced by the use of Phase-Change Material (PCM) or Thermal Insulation Material (TIM).

The TIM's role in reducing average heat transfer was certainly quite effective, but its influence on thermal inertia was negligible. Because PCM has a large thermal storage capacity at constant temperature, it was a logical choice to increase the thermal inertia of envelopes. For instance, PCM has a 5–10 times greater heat storage capacity than concrete at the same thickness. In several investigations, the influence rules were examined through the incorporation of PCM into building envelopes. (Kant, Shukla and Sharma, 2017)(Gao *et al.*, 2020)

(Table 2-6) presents an overview of the enhancement in thermal behavior of building envelopes resulting from using PCM. This table demonstrates the significant impact of incorporating PCM into the building envelope, which resulted in decreased temperature fluctuations, lower peak heat flow, longer delay times, reduced debility rates, and lower energy consumption.(Jia *et al.*, 2021)

Table 2-6: Review on the thermal behavior improvement of building envelopes due to PCM. (Jia *et al.*, 2021)

PCM Application	Method	Location	Results on temperature, heat flow and energy consumption
Built as a wall layer	Sim.	Diyarbakır, Konya, and Erzurum in Turkey	Increasing time lag by 13.3 h and saving the energy consumption of 18%;
Built as a wall layer	Exp.	Montreal, Canada	Reducing the heating and cooling loads by 17% and 20%, respectively;
Built as a wall layer	Exp.	Lawrence, USA	Reducing the maximum heat flow by29.7% and 51.3% for west and south walls, respectively;
Built as a wall layer	Sim.	Béchar, Algeria	Reducing the maximum cooling and heating loads by 24.3% and 35.4%, respectively;
Combined with the floor mortar	Exp.	Korean	Reducing the cooling energy consumption by 13.0%–13.6%;
Built as a wall layer	Exp.	Puigverd de Lleida, Spanish	Reducing the 15% cooling electricity, compared to the room without PCM;
Built as a wall layer	Exp. & Sim.	Chengdu, China	Reducing the heat loss by 36.6%–37.6%;
Inserted into the hollow bricks	Exp.	Portugal	Reducing the thermal amplitude by 5°C–10 °C and increasing the time delay by about 3 h;
The SSPCMs-mortar bricks	Exp.	Shanghai, China	Reducing the cooling and heating loads by 24.32% and 10%–30%.
Inserted into the hollow bricks	Sim.	Ancona, Italy	Increasing the delay time by about 6 h and the peak heat flow by 25%;
Inserted into the hollow bricks	Sim.	Chengdu, China	Reducing the attenuation rate from 13.07% to 0.92%–1.93%, and increasing the delay time from 3.83 h to 8.83–9.83 h;
Inserted into the hollow bricks	Sim.	Raebareli and Bhopal, India	Reducing the peak heat flux by 8.31%;
Inserted into the hollow bricks	Exp.	Delhi, India	Reducing inner surface temperature by 4°C–9.5 °C and the heat transfer by 40%–60%;
Inserted into the hollow bricks	Exp.	Delhi, India	Reducing the surface temperature by 5°C–6°C and the heat flow by 8%–12%, compared to conventional bricks.

Thus, whereas PCM might regulate temperature fluctuations and lower peak heat flow, TIM could decrease heat flow by effectively improving thermal resistance. Based on this, combining the TIM and PCM concurrently might be taken into consideration in order to fulfill the thermal inertia requirement in buildings structures and lower the energy consumption in the building operation by heat storage and insulation. (Jia *et al.*, 2021)

2.10.1 Impact of Using PCM-TIM Integration on Buildings' Energy Consumption

The impact is amplified when PCM is added to an insulated constructive system since PCM retains the heat generated by the internal loads and external circumstances, limiting the amount of heat dissipated into the surrounding environment.(Navarro *et al.*, 2015)

Recently, several thermal inertia-related parameters—such as thermal mass and specific heat capacity—have been considered when characterizing the materials employed in the building envelope. Recent published research demonstrating the qualities of materials' thermal inertia and constructive systems' properties have made these developments practical. It is necessary to include thermal inertia in addition to thermal resistance when imposing design constraints.

According to (Al-Sanea et al., 2012) building walls should have a minimum quantity of thermal mass, to offer the possibility of energy savings in buildings with constantly running air conditioning. PCMs have been extensively researched to increase building envelope thermal energy storage capacity (Cabeza et al., 2011). This could present an intriguing way to lower HVAC system energy demand. (Navarro *et al.*, 2015)

Furthermore, a summertime energy consumption decrease of 15% was seen in an experimental investigation conducted by (Castell et al., 2010) on the use of PCM in the isolated building envelope.

2.11 Construction Systems in Palestine

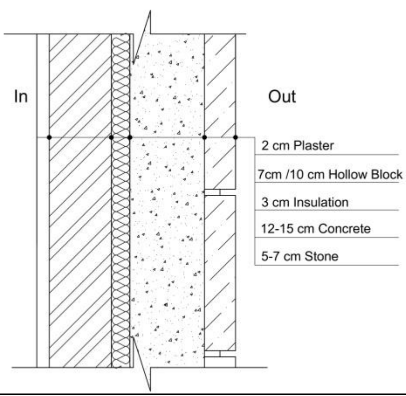
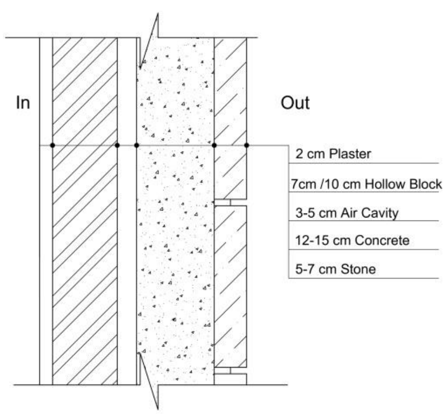
(Salameh, 2012) Concluded that the Palestinian building system does not consider the idea of sustainability, and as a result, the building processes in Palestine make the environment more complex and increase the building's operating and maintenance costs.

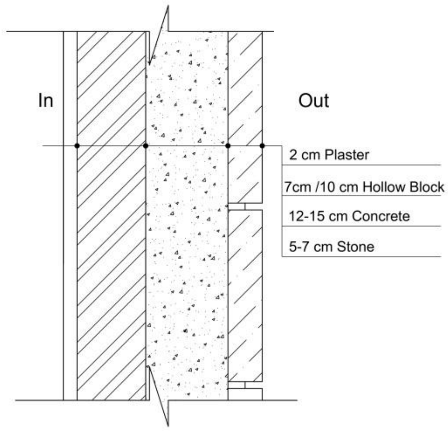
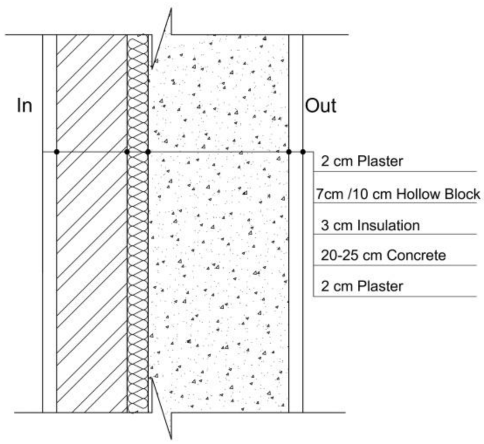
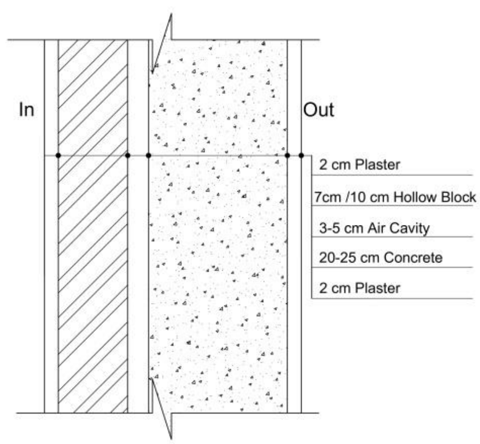
The writer asserted that even with fundamental issues such as excessive heat absorption or dissipation, leading to higher building and operational demands requiring continuous upkeep, individuals were gravitating towards contemporary construction materials because of their affordability, visual appeal, and simplicity of use. Additionally, the construction sector's inclination to utilize innovative materials for building facades, like glass and metal, has compromised the sustainability of construction and diminished focus on aesthetics, irrespective of the effectiveness of the materials.

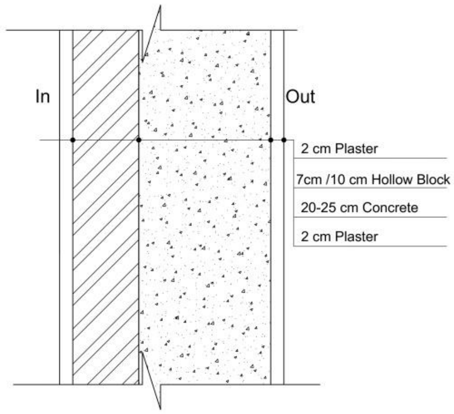
However, in recent years, the Palestinian inclination has changed to depend more on renewable energy sources, which is in line with the growing worldwide trends in the use of alternative energy sources. In Palestine, solar, biomass, wind, and geothermal energy are the main trends. (Abdallah *et al.*, 2020)

The common construction system in Palestine is based on concrete structure. The cladding of the external wall varies from one building to another and from one city to another according to the geographical nature, temperature and rainfall conditions, and local building materials. In general, the external wall is usually made of concrete structure with or without stone cladding. In some buildings, some facades may have stone cladding and the other facades (in the same building) without stone cladding, and only covering the outer surface with plaster layer. As for thermal insulation, some buildings may be thermally insulated with a layer of mineral wool insulation, and some buildings may be thermally insulated with air cavity, and others may not be thermally insulated, as shown in (Table 2-7) below.

Table 2-7: The common external walls constructions systems in Palestine, researcher.

Walls' Cross Sectional	**Walls' Description**
	In this case, a stone layer for cladding, and use a thermal insulation layer between the concrete and the concrete hollow block layer.
	In this case, a stone layer for cladding, and use an air cavity layer between the concrete and the concrete hollow block layer.

	In this case, a stone layer for cladding, and there's no any layer between the concrete and the concrete hollow block layer.
	In this case, there's no cladding layer, and use a thermal insulation layer between the concrete and the concrete hollow block layer, the outer surface covered by a plaster layer
	In this case, there's no cladding layer, and use an air cavity layer between the concrete and the concrete hollow block layer, the outer surface covered by a plaster layer

	In this case, there's no cladding layer, there's no any layer between the concrete and the concrete hollow block layer and the outer surface covered by a plaster layer

2.12 Physical Characteristics of Palestine

- Climate: Palestine has a Mediterranean climate, characterized by a hot, dry, long summer and a cold, wet, short winter.
- Temperature: Palestine has a rather high temperature. The warmest places are Jericho and the Jordan Valley. The temperatures are inversely correlated with height and fall from south to north, reaching their maximum in the southern region around the Dead Sea. The West Bank has monthly average temperatures ranging from 20.8 ◦C to 30 ◦C throughout the summer months of June, July, and August. The West Bank experiences monthly average temperatures in the range from 8.7 ◦C to 14.7 ◦C throughout the winter months of December, January, and February. In the Gaza Strip, the average monthly temperature varies from 13°C in the winter to 25°C in the summer.(Abdallah *et al.*, 2020)
- Sunshine Duration: The amount of sun radiation in Palestine varies per city. The longest day in the sun is June, while the shortest day in the sun is December. Summertime sunshine intensifies solar radiation, whereas wintertime cloud cover decreases solar radiation. (Abdallah *et al.*, 2020)

In general, the daily average global horizontal irradiance (GHI) in Palestine is 5.4 KWh/m2. With over 3000 hours of sunlight annually, it varies from area to region and throughout the year with average brightness around 8 hours/day. (Figure 2-10) display the annual sum of irradiance and GHI averages for some Palestinian cities. (Ajlouni and Alsamamra, 2019)

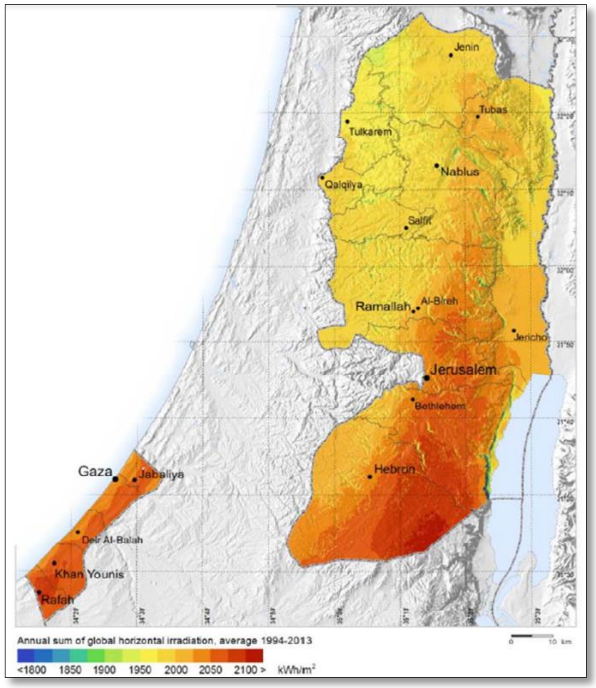


Figure 2-10: Annual sum of irradiance for surface inclined to the south with 270 degree, period 1994-2013, (Ajlouni and Alsamamra, 2019)

Figure 2-11 illustrates the monthly solar radiation levels in 2010 for four different cities in the West Bank: Hebron, Ramallah, Tubas, and Salfeet, representing the north, center, and south regions respectively. In December, the solar radiation on the horizontal surface is 2.63 kW h/m2 /day, while in June, it is 8.4 kW h/m2 /day. (Said, 2019)

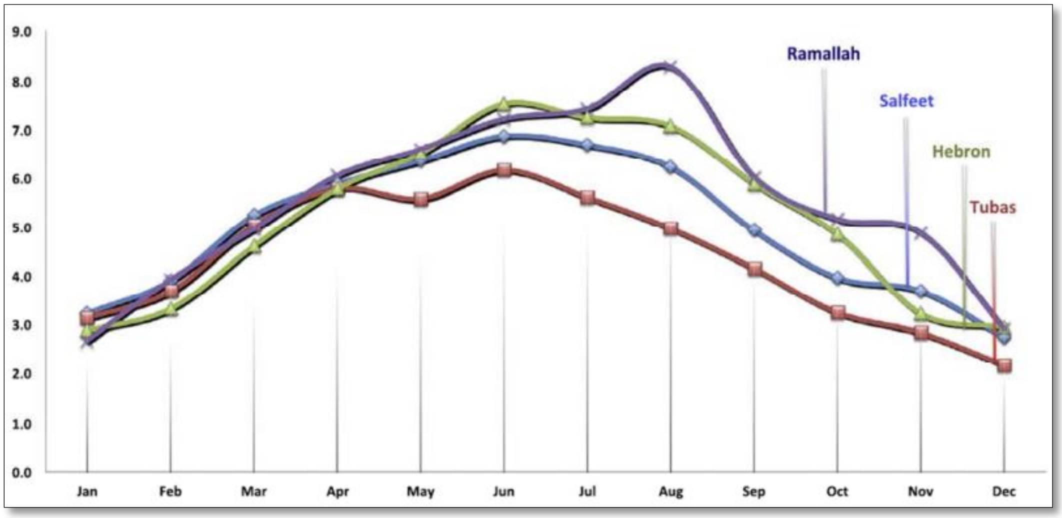


Figure 2-11: Monthly average of solar radiation in different cities in West Bank 2010, (Ajlouni and Alsamamra, 2019)

The previous results appear to support the utilization of solar energy in daily and seasonal thermal storages.

Chapter 3 Methodology

3.1 Introduction

This study aims to investigate the quantitative performance of PCM-TIM integration in the southern facade of a residential building located in Hebron- Palestine.

Specifically, the methodology will measure energy efficiency, thermal comfort, and reduction in heating/cooling loads by using PCM in different building facade configurations in term of material and layers arrangement. The research will use numerical simulations to obtain and analyze data.

3.2 Study Area

3.2.1 Climatic Data

While the southern façade is the most exposed elevation to the sun radiation in the winter season (critical days for sun radiation). Although the sun's rays on the eastern and western facades in the summer are greater than on the southern facade, a significant amount of radiation falls on it in the summer.

According to the statistical results, it is possible to forecast the sun irradiation on a horizontally oriented surface with accuracy (31° 57' N latitude angle of Hebron).

Palestine's home consumption of solar energy over time has the ability to provide domestic hot water for example over of 330 sunny days/year using solar panels, due to the country's high and consistent solar irradiation. (Ajlouni and Alsamamra, 2019) Because of the sun's varied locations and the unpredictable weather, solar irradiance fluctuates with the season and time of day. (Alsamamra, 2013)

The average solar energy value in Hebron City was found to be 5324 kWh/m2 day. Hebron gets maximum solar energy in June (mean value = 7995 kWh/m2 day) and July (mean value = 7875 kWh/m2 day) and minimum solar energy in December (mean value = 2676 kWh/m2 day), as expected (figure17). And for the sunshine duration, the largest value in Hebron is recorded in June and July (mean values of 11.86 h and 12.05 h, respectively), while the lowest SH length is recorded in December (mean value of 5.14 h), as shown in (Figure 3-1, Figure 3-2 and Figure 3-3). (Alsamamra, 2013)

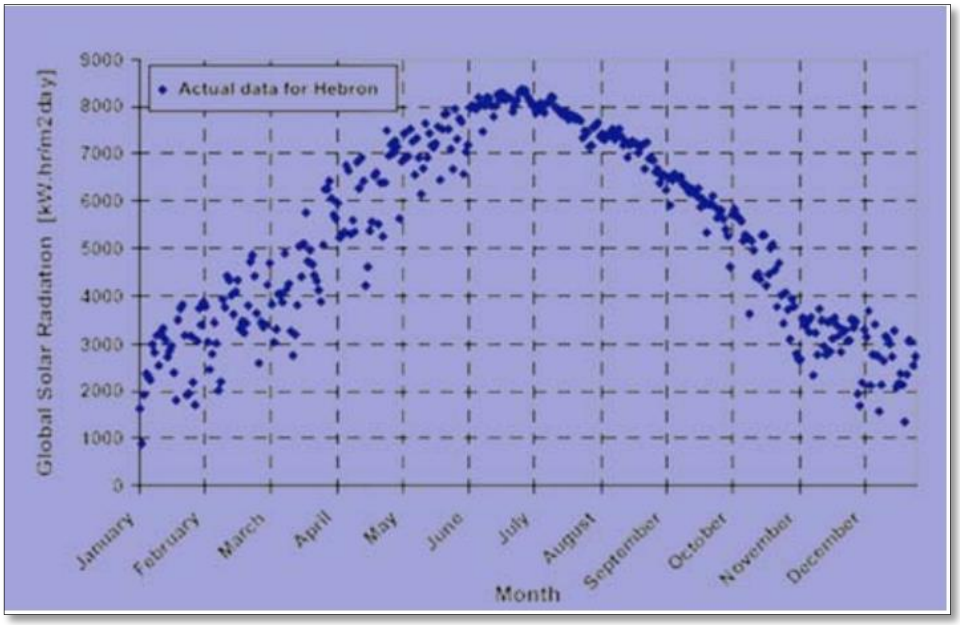


Figure 3-1: Global daily solar radiation data for Hebron, Palestine, (Alsamamra, 2013)

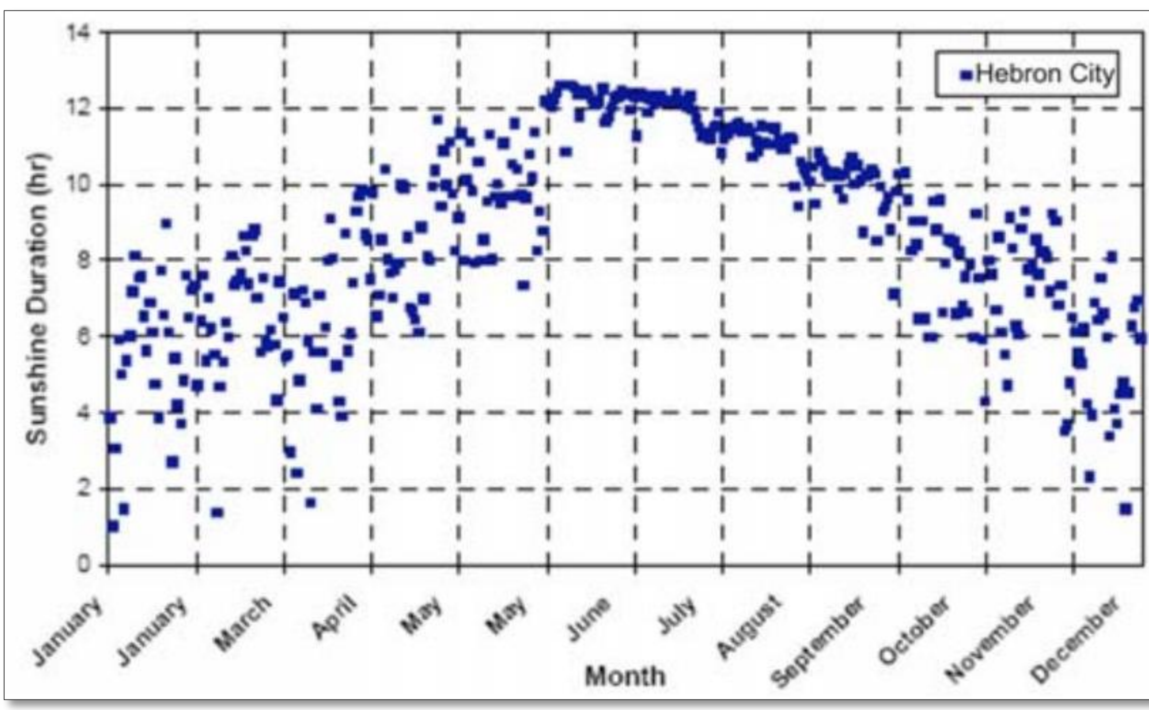


Figure 3-2: Measured average sunshine duration (SH) data in Hebron, Palestine by days, (Alsamamra, 2013)

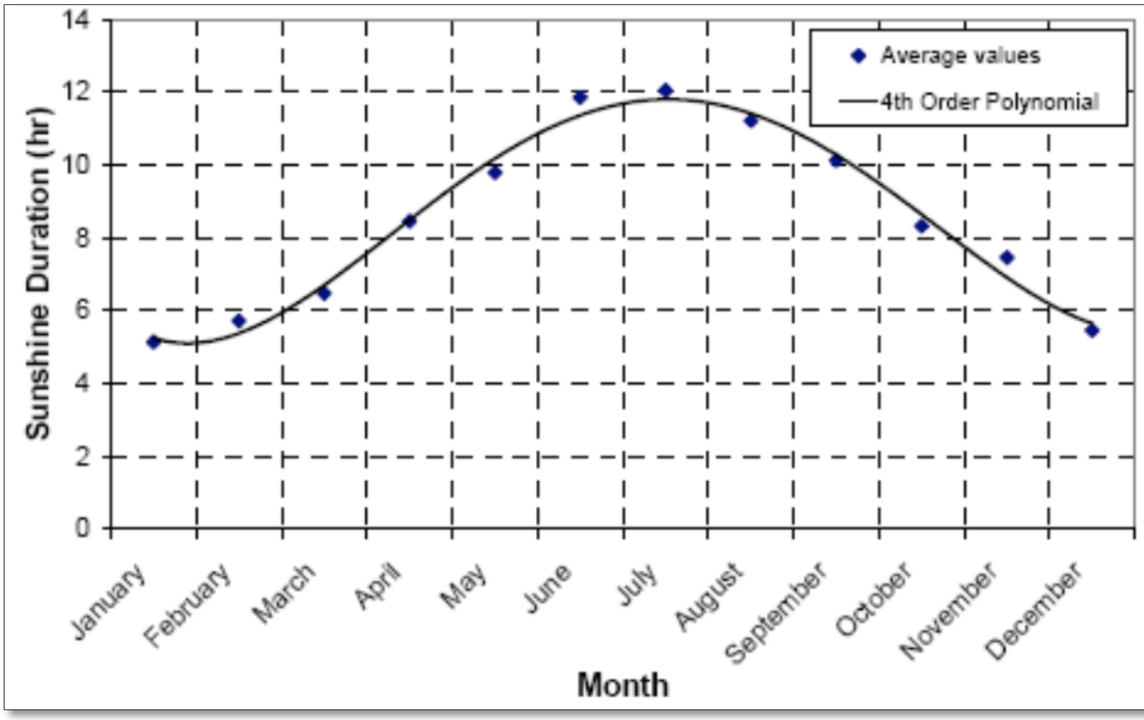


Figure 3-3: The mean value of the monthly sunshine duration in Hebron, Palestine, (Alsamamra, 2013)

According to latitude, slope, aspect, topographic shadowing, and time of year, the potential solar radiation is calculated. Monthly sunlight hours and cloudiness variables are factored in. Measurements of solar radiation yield highly spatially dispersed data. Numerous advanced models have been created to calculate solar radiation, taking into account a greater number of astronomical, meteorological, and surface factors. Palestine has a great potential for solar energy in general. The average daily solar radiation intensity on a horizontal surface is 5.4 kWh/m2 day, and the average solar energy ranges from 2.63 kWh/m2 day in December to 8.4 kWh/m2 day in June.(Alsamamra, 2013)

In addition, our modern way of living has led to the development of numerous new uses for thermal energy, thereby contributing to the growing demand for it. Presently, the three main energy sources we use are heat, electricity, and mechanical work. During the energy crisis of the 1970s, the world woke up to the importance of renewable energy sources. The reserves of fossil fuels are finite and non-renewable, hence, energy conservation and the transition to clean, renewable energy resources are urgently needed. All of the main thermal energy sources may save energy thanks in large part to thermal energy storage.

The main thermal energy generators may save energy thanks in large part to thermal energy storage. The potential of solar energy is clearly not fully exploited, with the right solar thermal supplies; solar radiation may be utilized for absorption cooling, hot water heating, and room heating. Electricity is also generated from solar radiation using photovoltaic cells (PVs) or concentrated solar power plants (CSP). As solar radiation is only available intermittently and not during peak consumption periods, energy storage systems such as TES systems or battery-based energy storage systems are needed.(Alva, Lin and Fang, 2018)

3.2.2 Sample Selection Criteria

In this part, the building sample was chosen to apply the PCM-TIM integration. The selected sample was a type of common residential building design located in Hebron-Palestine.

Building description: a living room (18 m^2 area) in the first floor of (3 floors) building, the rooms' façade dimentions are 3.6m width and 3.12m high while the windows' dimentions are 1.8m width and 1.25m high as shown in (Figure 3-4).The southern façade is the most exposed to solar radiation, and therefore it has the most influence on the façades in terms of heat gain and loss, so it was the targeted façade in this study.

Because the southern facade is most exposed to sunlight in winter in Palestine, and considering that winter is the worst case for heat storage, the southern facade was studied in this research.

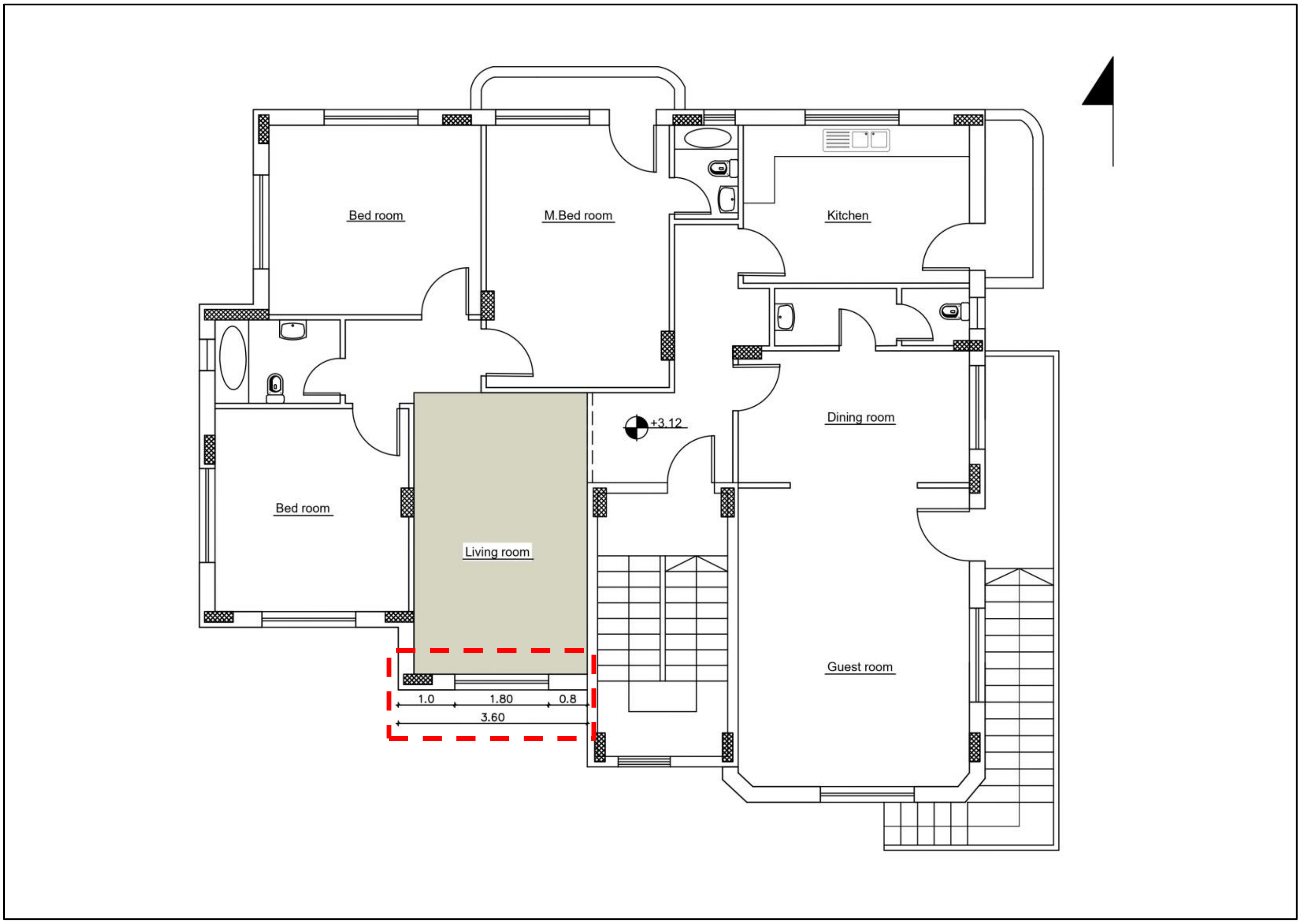


Figure 3-4: the selected building plan, the south façade bordered by red line and the targeted room is highlighted, Researcher

3.3 Model formulation

❖ **Assumptions:**

- Steady state system
- The indoor temperature in the calculations was taken as constant (using HVAC) at 22°C.
- PCM temperature 58 °C
- Outdoor temperature varies every day based on weather data

- The studied phases in the PCM are the sensible heat in the solid phase and the latent heat phase, as shown in (**Error! Reference source not found.**)

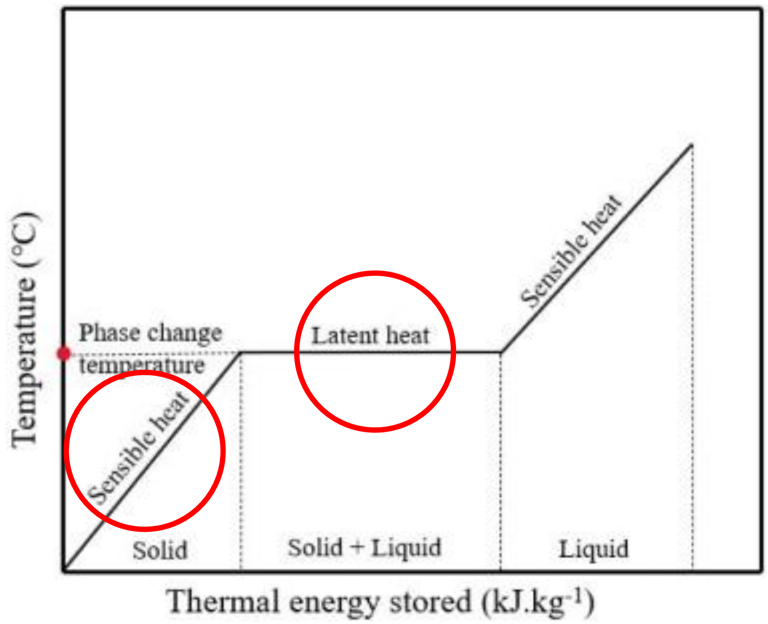


Figure 3-5: The studied phases in the PCM

This study data collection depends on the analysis simulation software tools by using design builder software with the energy plus engines to simulate the indoor temperature and thermal comfort, also, the ANSYS software used for simulate the heat flow rate between inside and outside.

3.4 Material

Power, capacity, and discharge time all rely one on another. Charge and discharge time, capacity, and power are all dependent on each other Power and capacity may be interdependent in several storage systems. (Table 3-1) displays typical TES system metrics such as capacity, power, efficiency, storage time, and cost. (Sarbu and Sebarchievici, 2018)

Table 3-1: Typical parameters of TES systems, (Sarbu and Sebarchievici, 2018)

TES System	Capacity (kWh/t)	Power (MW)	Efficiency (%)	Storage Period	Cost (€/kWh)
Sensible (hot water)	10–50	0.001–10.0	50–90	days/months	0.1–10
Phase-change material (PCM)	50–150	0.001–1.0	75–90	hours/months	10–50
Chemical reactions	120–250	0.01–1.0	75–100	hours/days	8–100

A storage system needs to include both a high energy storage density and a high power capacity for both charging and discharging. As mentioned before, there are three methods for TES; Thermochemical heat storage related with chemical processes, sensible and latent heat related with PCM (Figure 3-6). (Sarbu and Sebarchievici, 2018)

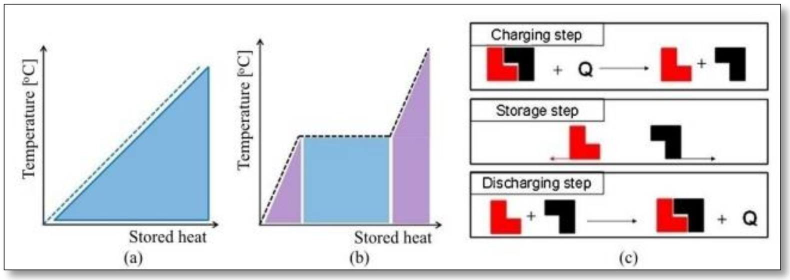


Figure 3-6: Methods of thermal energy storage: (a) sensible heat; (b) latent heat; (c) thermo-chemical reactions (Sarbu and Sebarchievici, 2018)

Actually: The framework of the research is divided into main parts

3.4.1 Long-Term (seasonal TES) PCM

In this part it's important to search for the PCM's characteristics which have high thermal energy storage.

Paraffins and salt hydrates are two intriguing alternatives for building applications, even though PCMs have been the subject of extensive research for many years. Both of these materials have high melting energetics, typically between 100 and 200 kJ/kg, and melting temperatures between 0 and 100 °C, making them suitable for a variety of uses in buildings(Hirschey et al., 2018). Because of that, the scope of PCM selection at this stage was confined to these two types.

Under the same temperature range, the characteristics of paraffins and salt hydrates were studied (Table 3-2 and Table 3-3). The findings demonstrated that salt hydrates have opportunities over paraffins in PCMs with melting temperatures above 20 °C, which include higher thermal energy density (45–120 kWh/m3 for salt hydrates vs. 45–60 kWh/m3 for paraffins) and lower material energy costs (1–20 $/kWh for comparable salt hydrates vs. 20–30 $/kWh for paraffins) as shown in table 3 and table 4. (Hirschey et al., 2018) Because of its larger mass density, salt hydrates often have a larger TES density than paraffins. Its range from 40-125 kWh/m3 for salt hydrates, but that of paraffins is relatively limited at 40 - 60 kWh/m3. Salt hydrates can be a better solution than paraffins in systems where volumetric limitations are relevant since paraffins usually have a lower energy storage density than salt hydrates. (Hirschey et al., 2018)

Table 3-2: Salt Hydrate Thermophysical Properties, (Hirschey et al., 2018).

Name	Chemical Formula	T_m (°C)	ΔH (kJ/kg)
Lithium Chlorate Trihydrate	$LiClO_3 \cdot 3H_2O$	8.1	253.0
		8.0	253
Dipotassium Hydrogen Phosphate Hexahydrate	$K_2HPO_4 \cdot 6H_2O$	14	108
		13.3	109.3
Potassium Fluoride Tetrahydrate	$KF \cdot 4H_2O$	18.7 ± 0.1	231.4 ± 19.3
		18.7 ± 0.1	200.5 ± 26.9
		18.5 ± 0.2	246 ± 2
Manganese Nitrate Hexahydrate	$Mn(NO_3)_2 \cdot 6H_2O$	25.0	128.5
Calcium Chloride Hexahydrate	$CaCl_2 \cdot 6H_2O$	29.7	171
		24	140
		29	170
		29.2	172.5
		30.0	170
Sodium Sulfate Decahydrate	$Na_2SO_4 \cdot 10H_2O$	32.4	251.2
		32.4	254
		32.4	239
Sodium Hydrogen Phosphate Dodecahydrate	$Na_2HPO_4 \cdot 12H_2O$	36	280
		36.5	279
		35.0	281
Zinc Nitrate Hexahydrate	$Zn(NO_3)_2 \cdot 6H_2O$	36	134
		36.4	147
Iron (III) Chloride Hexahydrate	$FeCl_3 \cdot 6H_2O$	36.1	226
		37.0	186.2
Calcium Chloride Tetrahydrate	$CaCl_2 \cdot 4H_2O$	44.2	99.6
Calcium Nitrate Tetrahydrate	$Ca(NO_3)_2 \cdot 4H_2O$	43	138
		47	142
Sodium Thiosulfate Pentahydrate	$Na_2S_2O_3 \cdot 5H_2O$	48	209
		48.0	200
		48.0	206
		48	201
		48	201
		48.0	201
Sodium Acetate Trihydrate	$C_2H_3NaO_2 \cdot 3H_2O$	58	289
		58	272
		58.0	248
		58	226
		58	252
		58	226

Table 3-3: Paraffin Thermophysical Properties, (Hirschey et al., 2018).

Name	Carbon Distribution	T_m (°C)	ΔH (kJ/kg)
n-Tetradecane	C14	5.5	215
n-Hexadecane	C16	17.75 ± 0.006	235.13 ± 0.13
n-Octadecane	C18	28	244
		27.5	243.5
		27.07 ± 0.095	243.68 ± 0.096
n-Eicosane	C20	35.69 ± 0.15	247.05 ± 0.14
6106	C16-C28	42	189
P116		45	210
5838	C20-C33	48	189
6035	C22-C45	58	189
6403	C23-C45	62	189
6499	C21-C50	66	189
Paraffin Wax (1)		53	184.48
Paraffin Wax (2)		41.92	207.22

In terms of cost, (Table 3-4) shows the cost comparison for both types, and it shows that salt hydrates are the more cost effective option than paraffins. (Hirschey et al., 2018)

Table 3-4: Phase change materials costs, (Hirschey et al., 2018).

Name	Material Cost ($/kg)	Vendor	Material Energy Cost ($/kWh)
Salt Hydrates			
Lithium Chlorate Trihydrate	5.21 [A,B]	Famouschem Technology (Shanghai) Co., Ltd.	74.10
Dipotassium Hydrogen Phosphate Hexahydrate	1.45 [B]	Sinoright International Trade Co., Ltd.	47.76 – 48.33
Potassium Fluoride Tetrahydrate	4.85 [B]	Shanghai Richem International Co., Ltd.	70.98 – 87.07
Manganese Nitrate Hexahydrate	0.29 [B]	Zibo Jiashitai Chemical Technology Co., Limited	8.15
Calcium Chloride Hexahydrate	0.39 [B]	Tianjin TYWH Import & Export Co., Ltd.	2.30 – 2.83
Sodium Sulfate Decahydrate	0.11 [B]	Lianyungang Huaihua International Trade Co., Ltd.	1.53 – 1.63
Disodium Phosphate Dodecahydrate	1.38	Langfang Huinuo Fine Chemical Co., Ltd.	17.66 – 17.78
Zinc Nitrate Hexahydrate	0.60 [B]	Zouping Changshan Town Zefeng Fertilizer Factory	14.69 – 16.12
Iron (III) Chloride Hexahydrate	2.64	Taian Health Chemical Co., Ltd.	41.99 – 50.95
Calcium Chloride Tetrahydrate	0.39 [B]	Tianjin TYWH Import & Export Co., Ltd.	3.98
Calcium Nitrate Tetrahydrate	0.32	Zhenjiang Ginte Materials Company Limited	8.11 – 8.35
Sodium Thiosulfate Pentahydrate	0.19	Lianyungang Huaihua International Trade Co., Ltd.	3.24 – 3.38
Sodium Acetate Trihydrate	0.85	Lianyungang Crown Sue Industrial Co., Ltd.	10.55 – 13.49
Paraffins			
n-Tetradecane	2.48	Shaanxi Dideu Medichem Co., Ltd.	41.48
n-Hexadecane	4.00	Beyond Industries Ltd.	61.24
n-Octadecane	8.17	Shaanxi Dideu Medichem Co., Ltd.	120.47 – 120.71
n-Eicosane	2.05	Hangzhou Fanda Chemical Co., Ltd	29.87
6106	1.31 [C]	–	24.89
P116	1.31 [C]	–	22.40
5838	1.31 [C]	–	24.89
6035	1.31 [C]	Beijing Dongke United Technologies Co., Ltd.	24.89
6403	1.31 [C]	–	24.89
6499	1.31 [C]	–	24.89
Paraffin Wax (1)	1.31 [C]	–	25.50
Paraffin Wax (2)	1.31 [C]	–	22.70

Based on the above-mentioned, the choice fell on the salt hydrate PCM as a seasonal TES. It can be said that salt hydrates are preferred over paraffins in several points such as: (1) high latent heat of fusion per unit volume at its melting point, (2) higher thermal conductivity (as much as two times compared to paraffin), (3) small volume change during phase change process, (4) slightly toxic,(5) no or limited risk to fire and (6) inexpensive, a wide range of material available in the market. (Purohit and Sistla, 2021)

- The next step was to search for a suitable type of PCM salt hydrate that could be used in the long term, has a high melting point and has the ability to supercooling.

  The PCM sodium acetate trihydrate (SAT), with the chemical formula NaCH3COO 3H2O, has a melting temperature of 58 C and a reasonably high heat of fusion (264 kJ/kg). These properties make it a potential long-term heat storage option for solar heating systems and may supercool stable to ambient temperatures and it composites from 60.3% (wt. %) sodium acetate and 39.7% (wt. %) water. (Kong et al., 2016) Since they can store heat nearly without losing it over time, heat storages that employ steady supercooling of SAT may be very advantageous to the energy system. The considerable supercooling level of SAT can be used as a benefit for seasonal heat storage, though, if the heat storage is carefully designed and crystallization is controlled. Latent heat of SAT may be long-term stored in liquid SAT by stable supercooling of SAT. (Wang, Xu, *et al.*, 2021a)

The potential of SAT-based PCM storage to supercool is one of its fundamental ideas. This allowed the device to maintain the heat of fusion by charging the modules during periods of high heat and let them to cool to room temperature without the SAT hardening.

So the choice fell on (SAT) because of its suitable properties in terms of melting point, specific heat and density as shown in (Table 3-5):

Table 3-5: Typical values of SAT properties, (Wang, Xu, et al., 2021a).

Property	Value	Unit
Melting Temperature	58	℃
Heat of Fusion	264	kJ/kg
Specific Heat	2.9/3.1	kJ/(kg·K)
Thermal conductivity	0.6/0.385	W/(m·K)
Density	1450/1280	kg/m^3
Kinematic viscosity	5.81	mm^2/s (20 ℃)
Dynamic viscosity	7.49	m·Pas (20 ℃)
Molecular Mass	136.08	g/mol
Solubility	762	g/L (20 ℃)
Water Percentage	39.7	wt.%
Sodium Acetate Percentage	60.3	wt.%
Congruent melting	No	
Hydrogen Bond Donor Count	3	
Hydrogen Bond Acceptor Count	5	
Topological Polar Surface Area	43.1	Å^2

Long-term heat storage is combined with short-term heat storage in a heat storage system that uses steady super cooling of SAT. From the perspective of the energy system, it is advantageous since it provides excellent flexibility. Instead of focusing on the requirements of the heat storage itself, it is possible to manage how much energy is charged and discharged from the store.

The store may serve as short-term heat storage by using the sensible heat, meeting the daily and weekly needs of the energy system, and it can serve as long-term heat storage by using the supercooled material's latent heat, meeting the monthly and seasonal needs of the energy system, (Figure 3-7). (Wang, Xu, *et al.*, 2021a)

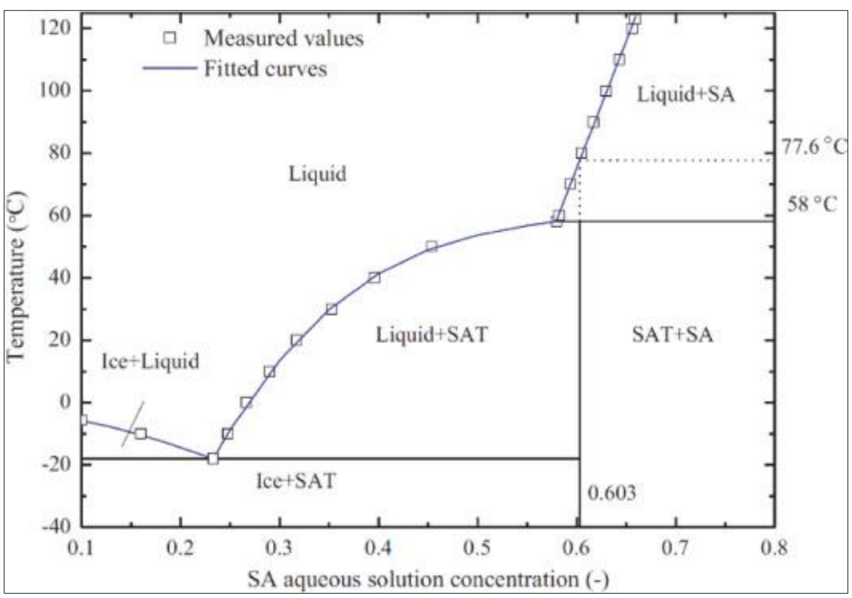


Figure 3-7: Phase diagram of sodium acetate solution, (Wang, Xu, *et al.*, 2021b)

3.4.2 (SAT-PCM) Thickness

The optimum thickness of (SAT) PCM for seasonal TES depends on several factors such as the specific climate conditions (temperature range, solar radiation), insulation efficiency of the storage system, and the duration of thermal storage required. Typically, for seasonal thermal storage applications, thicker PCM layers are preferred to store more thermal energy.

However, specific thickness recommendations can vary based on the design criteria and objectives of the thermal storage system. In general, thicker PCM layers allow for more energy storage capacity but may require longer times for charging (storing energy) and discharging (releasing energy).

For SAT, which has a melting point of around 58°C, common thicknesses for thermal storage applications can range from several centimeters to tens of centimeters. Detailed engineering calculations or simulations are often necessary to determine the exact optimum thickness based on factors like:

1. Heat transfer rates: Thicker layers may require longer times to charge and discharge due to slower heat transfer rates through the material.

2. Energy storage requirements: The amount of energy that needs to be stored over a seasonal period influences the thickness needed.

3. Temperature stability: Ensuring that the PCM can store and release energy effectively within the desired temperature range without significant thermal losses.

4. Cost considerations: Thicker PCM layers can increase material costs and may require additional structural support.

However, in practical applications, it's important to conduct thermal modeling and simulations to optimize PCM thickness alongside other system parameters to achieve the best balance between energy storage capacity, efficiency, and cost-effectiveness for seasonal thermal storage solutions.

In this research, different thicknesses of SAT-PCM will be tested to achieve the highest energy efficiency and thermal comfort for users.

3.5 Charging and discharging for SAT PCM

Heat is transmitted to and stored in the PCM during charging. In a similar vein, the heat that the PCM has accumulated is released into the environment when discharging. Initially, heat is only stored or released as sensible heat while the PCM is in the solid or liquid state during charging or discharging. Latent heat is the result of heat being stored or released by the PCM when it approaches the phase transition temperature. Similar to this, heat is released or retained as sensible heat following the melting or solidification of the PCM.(Muthukumar and Niyas, 2020)

(Johansen *et al.*, 2016) made an experimental research to study the SAT PCM charging and discharging, They concluded that a SAT PCM module was heated using solar radiation, passively cooled to room temperature, and then kept in a supercooled condition for almost a month. Following the introduction of a seed crystal to the SAT in the module, the temperature inside the material rose from 17.1 °C to 58.5 °C as it crystallised. After then, the fusion heat was released into the buffer tank.

After 39 days of supercooling, a solidification event occurred and 11 kWh of heat were released into the buffer tank. The energy storage capacity of supercooling SAT has been shown in earlier lab experiments with the identical modules to be much longer. As a component of the solar combination system test government, the SAT units had been warmed by solar heat 53 times over the course of the six-month evaluation duration to a temperature over 80°C. The testing validated the idea of using a PCM's stable supercooling for small, long-term heat storage with SAT.

Temperatures sufficiently high to enable steady supercooling may be reached by heating the modules, which store approximately 200 kg of SAT plus additives. With 135 kWh of heat, the PCM heat storage did make a contribution. A module's SAT was deliberately solidified after spending 39 days in a supercooled condition and releasing 11 kWh of heat.

However, heat transmission by conduction is the PCM's domain mode during the early phases of charging; however, as the proportion of liquid PCM rises, natural convection becomes more and more important and because of high-temperature liquid PCM rising owing to forces of buoyancy and natural convection inside the PCM, the PCM at the top of the storage melts more quickly than the PCM at the center and bottom, nevertheless, it was discovered that convection had a little effect on the solidification process. On the other hand, the rising in the heat transfer fluid volume flow rate during charging and discharging reduces the time required for melting and solidification, with melting requiring less time than solidification. (Oriented and Heat, 2020)

3.5.1 Choose the thermal insulation material (TIM).

In this part it was important to search for suitable insolation with low thermal conductivity and thermal stability.

Consideration of density, thermal conductivity, material category, thickness and mechanical characteristics of the insulation performance is crucial for determining design values for thermal conductivity of insulating materials. Expanded polystyrene (EPS), extruded polystyrene (XPS), and foamed polyurethane (PU) all had optimal insulation thicknesses that ranged from 0.053 to 0.236 m and payback times that ranged from 1.9 to 4.7 years during a 20-year lifespan. (Yucel, Basyigit and Ozel, 2003) (Huang et al., 2020)

Table 3-6 shows the main thermal performance parameters of some TIMs types. Due to its positive properties in density, thermal conductivity, lifetime and cost; the expanded polystyrene EPS was chosen.

Table 3-6: Thermal performance parameters of some TIMs types.

Type	Density(Kg/m3)	Thermal conductivity (W/m-K)	Durability	Max. service temp.	Cost (€/m3)	Useful lifetime (years)	Typical applications
Fiberglass (sand & recycled glass)	12-56	0.04–0.033	Compression reduces R-value	4–260			Frame wall or ceiling, partitions, prefabricated houses, irregularly shaped surfaces, ducts, and pipes. Settling is expected
Rockwool (natural rocks)	40–200	0.037	Compression reduces R-value	240–800	102.08-179.5	30-50	
Polyethylene	35–40	0.041	R-value decreases w/time	40–90			Ceilings, hangers, wrapping, carpet underlay, expansion joints.
Expanded Polystyrene EPS	16–35	0.038–0.037	R-value decreases w/time	100	61.42-186.56	50	Walls, roofs, and floors. Must be covered inside for

(closed cell foam)							fire and against outside weather.
Extruded Polystyrene XPS (closed cell foam)	26–45	0.032–0.030	R-value decreases w/time	100	156-180	50	
PUR	35	0.028		60-80			
Cellulose (waste paper	24-36	0.054–0.046	fire retardant chemical may corrode metals	80	175.71		Attics retrofitting, wood frame sidewalls (experienced help needed). Needs time to dry before enclosing to avoid moisture problems.

3.5.1.1 Independent variables

Some variables have been fixed as shown in the Table 3-7 below.

Table 3-7: the constant values in calculations, Researcher

θe	Tpcm	cond. λ	ho	Area	Energy stored	Mass	Latent heat
C	**C**	**W/m2 K**	**W/m2K**	**cm2**	**Wh**	**kg**	**kj/kg**
20	58	0.037	16.67	20	694.5	10	250

3.5.1.2 TIM thickness calculation

To calculate the thickness of the appropriate insulator it's depending on its properties; and by fixing some variables (table 14) in across sectional wall (figure 14), such as the assumption of external temperature (20 C) and sectional area(20 cm^2), through mathematical equations (4-1) and (4-2) the R-value, U-value, q, power losses and discharging time were calculated, as shown in (Table 3-8).

Table 3-8: the calculated values of EPS insolation, Researcher

Thickness	R-value	U-value	q	Power losses	Discharging time
cm	m2K/W	W/m2K	w/m2	W	H
1	0.3303	3.0279	115.06	0.23	3018.0
2	0.6005	1.6652	63.28	0.13	5487.7
3	0.8708	1.1484	43.64	0.09	7957.5
4	1.1411	0.8764	33.30	0.07	10427.3
5	1.4113	0.7085	26.92	0.05	12897.0
6	1.6816	0.5947	22.60	0.05	15366.8
7	1.9519	0.5123	19.47	0.04	17836.6
8	2.2221	0.4500	17.10	0.03	20306.4
9	2.4924	0.4012	15.25	0.03	22776.1
10	2.7627	0.3620	13.75	0.03	25245.9
11	3.0330	0.3297	12.53	0.03	27715.7
12	3.3032	0.3027	11.50	0.02	30185.4
13	3.5735	0.2798	10.63	0.02	32655.2
14	3.8438	0.2602	9.89	0.02	35125.0
15	4.1140	0.2431	9.24	0.02	37594.8
16	4.3843	0.2281	8.67	0.02	40064.5
17	4.6546	0.2148	8.16	0.02	42534.3
18	4.9249	0.2031	7.72	0.02	45004.1
19	5.1951	0.1925	7.31	0.01	47473.9
20	5.4654	0.1830	6.95	0.01	49943.6
21	5.7357	0.1743	6.63	0.01	52413.4
22	6.0059	0.1665	6.33	0.01	54883.2
23	6.2762	0.1593	6.05	0.01	57352.9
24	6.5465	0.1528	5.80	0.01	59822.7
25	6.8167	0.1470	5.57	0.01	62292.5
26	7.0870	0.1411	5.36	0.01	64762.3
27	7.3573	0.1360	5.16	0.01	67232.0
28	7.6276	0.1311	4.98	0.01	69701.8
29	7.8978	0.1266	4.81	0.01	72171.6
30	8.1681	0.1224	4.65	0.01	74641.4

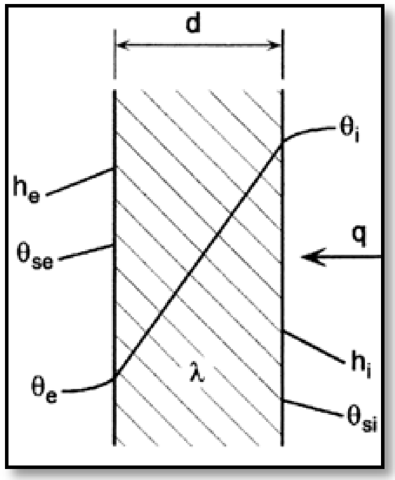


Figure 3-8: cross sectional wall

Were,

θ_i: Temperature inside

θ_e: Temperature outside

T_{pcm}: PCM melting temperature

λ: thermal conductivity

h_e: outside heat transfer coefficient

q: heat flow rate

h_i: inside heat transfer coefficient

U total: U-value

$$U_{total} = \frac{1}{R_{total}} = \frac{1}{R_{si} + \Sigma\left(\frac{d_i}{\lambda_i}\right) + R_{se}} = \frac{1}{\left(\frac{1}{h_i}\right) + \Sigma\left(\frac{d_i}{\lambda_i}\right) + \left(\frac{1}{h_e}\right)} \qquad \text{Eq 3-1}$$

$$q = \theta_i - \frac{\theta_e}{\left(\frac{1}{h_i}\right) + R + \left(\frac{1}{h_e}\right)} \qquad \text{Eq 3-2}$$

The calculation results show that the appropriate thickness of the insolation is ranged between 3-5 cm where heat flow and discharging time are suitable for seasonal (long-term) storage, as shown in Figure 3-9), the selected thickness of TIM in the suggested models is 3 cm.

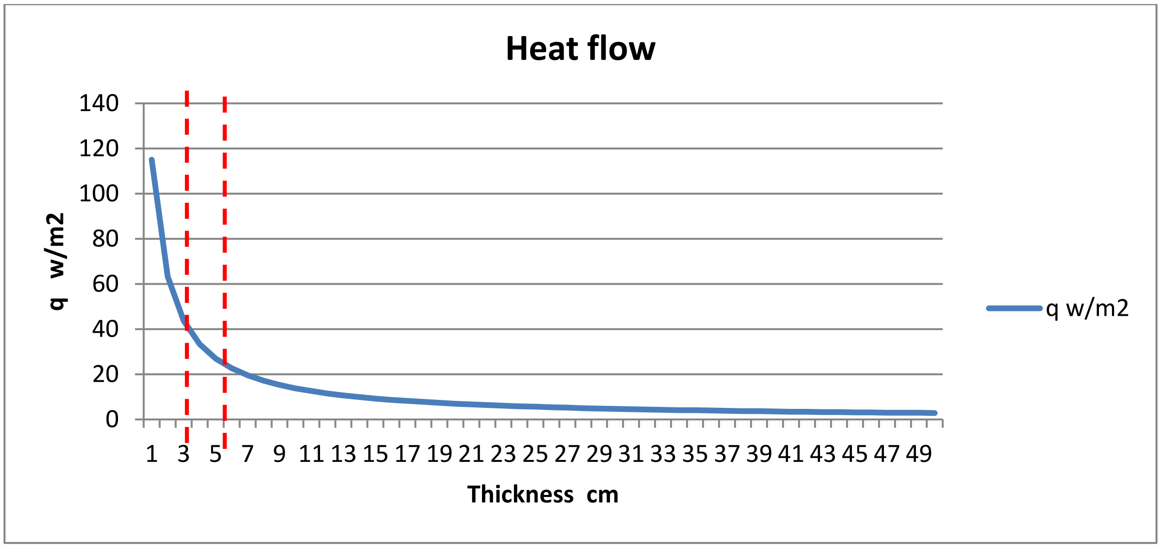


Figure 3-9: the relation between thickness and heat flow, Researcher

However, innovative wall designs and TIMs have the potential to significantly lower the energy consumption and carbon emissions from the construction industry. In this study, a passive wall system composed design by PCM-TIM integration is proposed and evaluated. The objective is to provide an analytical method for calculating the thermal performance of the recommended wall designs. As a case study, a south façade of a residential building located in Hebron-Palestine has been studied.

The use of the PCM-TIM integration in the southern external walls has been studied in two cases:

a) Design and Simulate wall models in the suggested integration cases during construction: according to the wall layers' arrangement and thickness.
The designs were proposed based on the common cases of the construction system in Palestine, with care taken to ensure that the PCM layer is on the outer part of the wall section, while care was taken to ensure that the insulation layer is on the inner part to prevent the heat flow from reaching the indoor space.

The cross sectional wall, heat flow and walls' description each model has been studied, analyzed and simulate the heat loss, heat gain and thermal comfort for each scenario in summer and winter seasons. These scenarios were as shown in tables (Table 3-9 to Table 3-12) below,

Table 3-9: The cross sectional wall, heat flow and description for CM, Researcher.

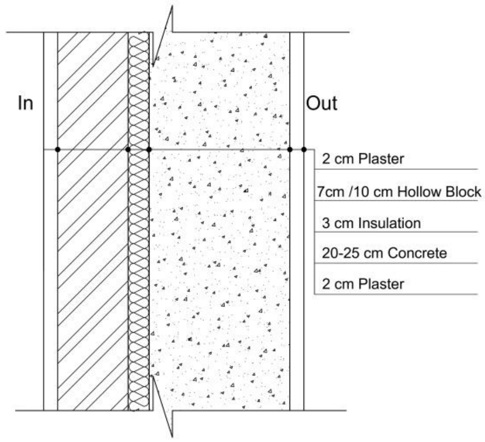
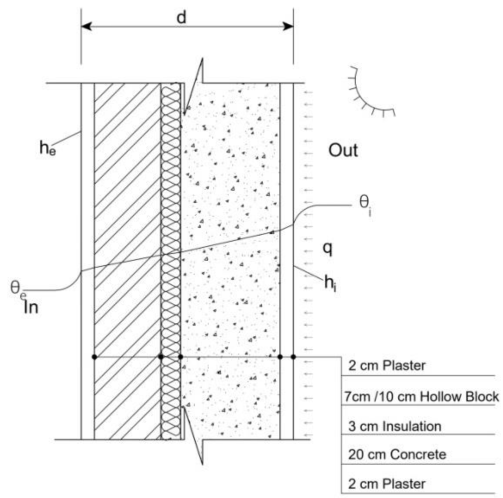
Common Wall Model (CM)	**Description**
	The one of common insulated walls' structures in concrete buildings in Hebron, which contains plaster, concrete block, thermal insulation layer, heavyweight concrete layer and covered by a plaster layer; respectively from inside to outside.
Conceptual Heat Flow Diagram	
	

Table 3-10: The cross sectional wall, heat flow and description for M**1**, Researcher.

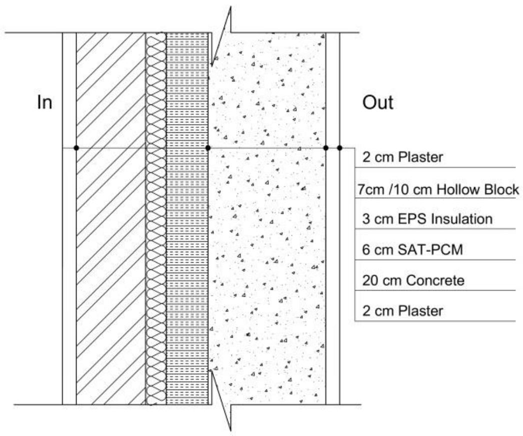
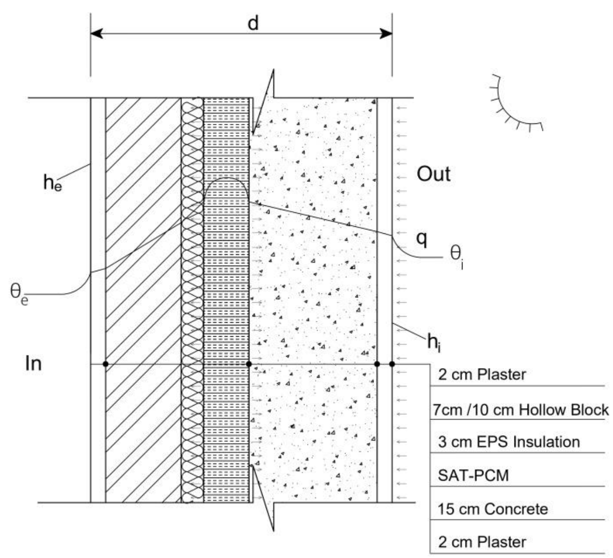
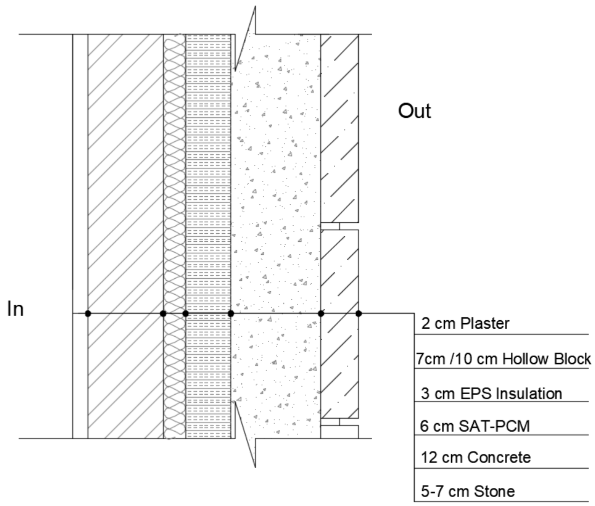
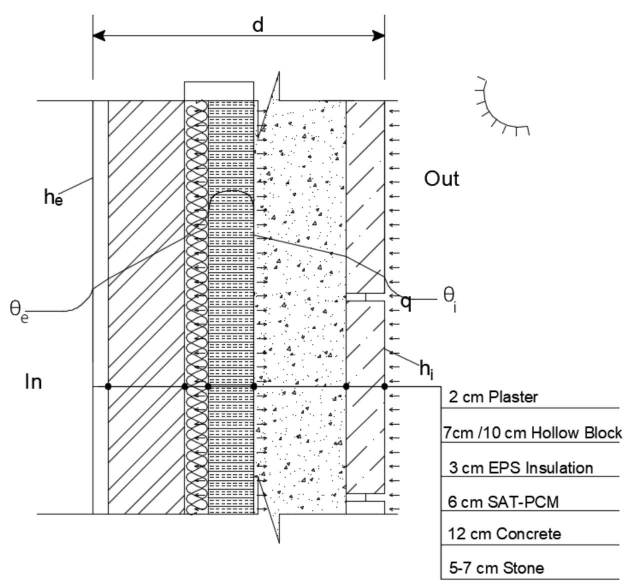
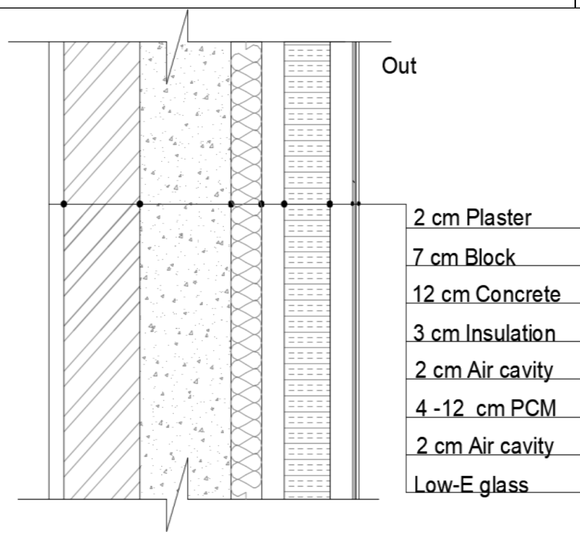
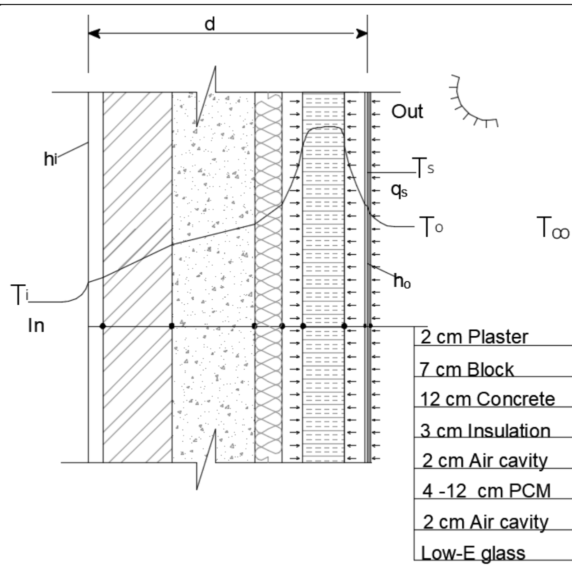
<table>
<tr><th>Model 1 (M1)</th><th>Description</th></tr>
<tr><td>
</td><td>In this case, layers arrangement related to one of the common walls; So, it was proposed to integrate EPS and PCM in a compact manner between the block and concrete layers, while the PCM layer closer to the outer surface and the EPS closer to the inner surface; in order to study the effect of the location of the insulator and PCM in the wall and evaluate its thermal behavior.</td></tr>
<tr><td colspan="2">Conceptual Heat Flow Diagram</td></tr>
<tr><td colspan="2">
</td></tr>
</table>

Table 3-11: The cross sectional wall, heat flow and description for M**2**, Researcher.

<table>
<tr><th>Model 2 (M2)</th><th>Description</th></tr>
<tr><td>
</td><td>In this case, layers arrangement related to other one of common walls; so, it was suggested to integrate the EPS with the PCM in a compact manner in the inner layers of the wall so that the PCM is closer to the outer surface in order to enhance heat absorption and the EPS is closer to the inner surface to enhance insulation and prevent heat flow. While keeping the stone layer on the outer surface of the wall.</td></tr>
<tr><th colspan="2">Conceptual Heat Flow Diagram</th></tr>
<tr><td colspan="2">
</td></tr>
</table>

In the final developed model, a Low Emissivity (LowE) glass layer was added in the external walls' surface, while the PCM layer was added in the middle of two 2 cm air cavity layers which worked as an insulating medium to keep heat inside the PCM and prevent it from being transferred to the outside or inside the room.

Table 3-12: The cross sectional wall, heat flow and description for M**3**, Researcher.

Model 3 (M3)	**Description**
	In this model, the wall layers were arranged in a different way so the external layer was a double (Low E) glass layer, this type of glass allows high wavelength to pass in and prevents short wavelength to pass out, this heat entered in an air cavity (steady flow), this heat will store in the PCM layer, in order to achieve a better seasonal heat storage in the PCM, an air cavity layer was added before the thermal insulation which contact to the concrete layer.
Conceptual Heat Flow Diagram	
	

By this model, a pane of double glass with a Low E coating transfers less heat through it. LowE coatings help lower heating and cooling expenses by reflecting radiant heat (Table 3-13) and allows high wavelength to pass in and prevents short wavelength to pass out.

Table 3-13: different glazing types properties, allweatherwindows website.

	Code	Description	U-Value	R-Value	Solar Heat Gain	Visible Light Transmittance
Clear	Dual	Dual pane, clear glass, no coatings	0.480	2.084	0.760	81%
Clear	Tri	Triple pane, clear glass, no coatings	0.310	3.226	0.685	74%
LOW-E	HS1-C180	Dual pane, one Low-E coating, Argon	0.260	3.846	0.685	79%
LOW-E	HS2-C180	Triple pane, one Low-E coating, Argon	0.184	5.433	0.615	73%
LOW-E	HS3-C180	Triple pane, two Low-E coatings, Argon	0.133	7.521	0.560	70%
SUNSTOP	HS4-C270	Dual pane, one SunStop coating, Argon	0.248	4.033	0.367	70%
SUNSTOP	HS5-C270	Triple pane, one SunStop coating, Argon	0.186	5.377	0.338	63
SUNSTOP	HS6-C270	Triple pane, two SunStop coating, Argon	0.124	8.065	0.310	54
SYSTEM V	HS1V-C180/i89	Dual pane, two Low-E coatings, Argon	0.209	4.783	0.623	77
SYSTEM V	HS4V-C270/i89	Dual pane, one Low-E & one SunStop coating, Argon	0.200	4.998	0.361	69

Visible Light Transmittance: quantifies the amount of visible light that enters the structure through the windows. A value of 1.0 would indicate complete light transmission, whereas a value of 0 would indicate no light transmission at all. Five percent of visible light is naturally filtered off by our atmosphere. About 90% of visible light may pass through uncoated clear glass. (allweatherwindows.com)

3.5.2 Green House effect

The glass's spectral transmissivity curve, which appears as an inverted U in (Figure 3-10). With reference to this figure, we can see that at practical thicknesses, glass transmits more than 90% of visible light and is essentially opaque (nontransparent) to longer-wavelength infrared radiation (about l. 3 mm). Because of this, glass has a clear window that lets in almost 90% of solar light in the wavelength range of 0.3 mm to 3 mm. (Hoffman, no date)

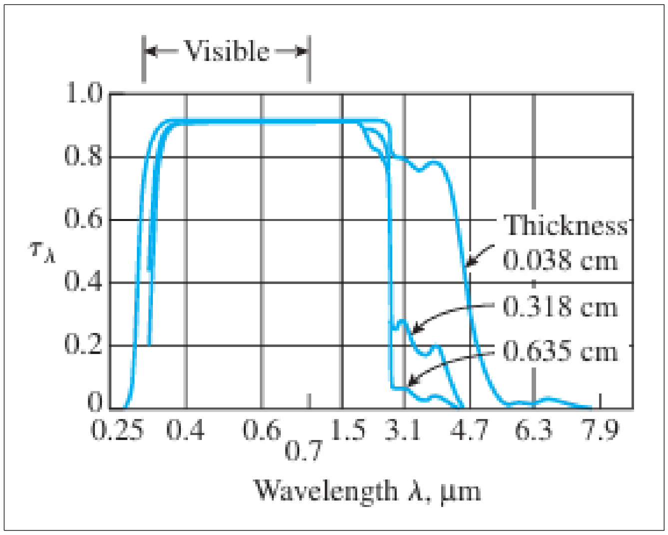


Figure 3-10: The spectral transmissivity of lowE glass at room temperature for different thicknesses,(Hoffman, no date)

However, at ambient temperature, all of the radiation that surfaces emit is in the infrared spectrum. Glass thereby permits solar energy to enter but prevents infrared radiation from interior surfaces from escaping. The energy accumulation in the automobile as a result raises the interior temperature. The term "greenhouse effect" refers to this heating effect which results from the nongray nature of glass or clear polymers, as shown in (Figure 3-11). (Hoffman, no date)

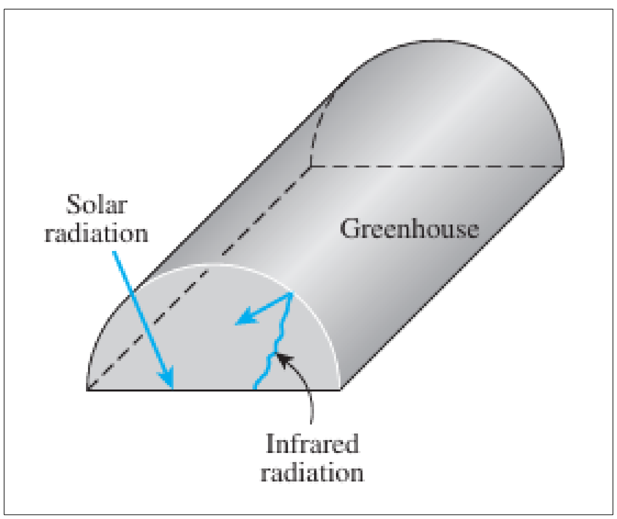


Figure 3-11: A greenhouse traps energy by allowing the solar radiation to come in but not allowing the infrared radiation to go out,(Hoffman, no date)

So, the lowE glass works as the greenhouse effect by allows solar radiation to pass through and prevents the return of infrared rays from escaping outside. (Figure 3-12) showed the lowE glass work concept in winter and summer respectively).

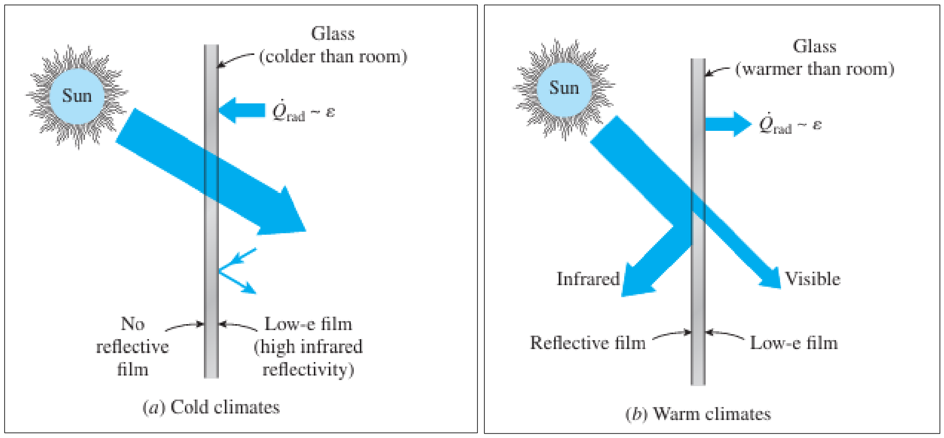


Figure 3-12: lowE glass work concept in a) winter and b) summer,(Hoffman, no date)

The optical characteristic includes the visible range of light that flows through a specific type of glass. For glass, it usually varies from 90% in clear glazing to 10% for highly reflective coated glazing. The kind of glazing, number of panes and the existence of coatings are all affect transparency and thermal transmittance (U-value) for this element as shown in (

Table 3-14 and

Table 3-15). Greater daylight presence in a given room and often lower electric lighting and heating demands are associated with high visual transmittance. Ordinary double-pane windows have a visual transmittance of 78%.(Aguilar-Santana *et al.*, 2019)

With a conventional emissivity grade of 0.33, low-emissivity, or low-E films' glass, reflects 67% of the heat back into the space. For low- E glass as 0.07, which indicates that 93% of heat gets reflected back into the space, newer low-e window films can reduce heat loss significantly.

Table 3-14: Typical U-values on different glazing types, (Aguilar-Santana *et al.*, 2019)

Glass configuration	*U*-value (W/m^2K)
Uncoated single glass 6 mm	5.70
Uncoated double glass 12 mm cavity	2.80
Uncoated double glass 15 mm air cavity	1.40
Uncoated double glass 15 mm argon cavity	1.20
Uncoated triple glass 16 mm with argon	0.79
Uncoated double glass 22 mm monolithic aerogel	0.65
Uncoated double glass 33 mm granular aerogel	0.44

Table 3-15: Comparison of thermal performance of different types of glazing systems, (Ghoshal and Neogi, 2014)

Type of Glazing system	Description	U-Value ($W\,m^{-2}K^{-1}$)
Single Glazing	One glass sheet	5.79-6.3
Double Glazing	Two glass sheets with air filled cavity	2.78-3.24
Double glazing	Two glass sheets with argon filled cavity	2.61-2.95
Double glazing	Two glass sheets with argon filled cavity and having night insulation	1.5-1.99
Double glazing	Two glass sheets with evacuated space in between	0.86
Double glazing	Two glass sheets with monolithic aerogel in between	0.63
Double glazing	Two glass sheets with granular aerogel in between	1.69
Electrochromic evacuated glazing	Two glass pane forming evacuated glazing with a third pane having EC layer	Slightly less than 1
Triple evacuated glazing	Three glass panes with two evacuated space in between	0.26

In order to slow down the absorption process of the PCM to charge seasonally, it has been suggested to coat it by a layer of unoxidized aluminum with a thickness of 1.0µm, which in turn absorbs heat by 20%. (Table 3-16, Table 3-17 and Table 3-18)

Table 3-16: Different materials emissivity values

Material	**Emissivity Values**		
	1.0µm	**1.6µm**	**8-14µm**
Aluminum			
Unoxidized	0.1-0.2	0.02-0.2	n.r.
Oxidized	0.4	0.4	0.2-0.4
Alloy A3003			
Oxidized	n.r.	0.4	0.3
Roughened	0.2-0.8	0.2-0.6	0.1-0.3
Polished	0.1-0.2	0.02-0.1	n.r.
Brass			
Polished	0.8-0.95	0.01-0.05	n.r.

Table 3-17: Different materials emissivity values

Material	Emissivity Values		
Inconel			
Oxidized	0.4-0.9	0.6-0.9	0.7-.95
Sandblasted	0.3-0.4	0.3-0.6	0.3-0.6
Electoropolished	0.2-0.5	0.25	0.15
Iron			
Oxidized	0.4-0.8	0.5-0.9	0.5-0.9
Unoxidized	0.35	0.1-0.3	n.r.
Rusted	n.r.	0.6-0.9	0.5-0.7
Molten	0.35	0.4-0.6	n.r.
Iron, Cast			
Oxidized	0.7-0.9	0.7-0.9	0.6-0.95
Unoxidized	0.35	0.3	0.2
Molten	.035	0.3-0.4	0.2-0.3
Iron, Wrought			
Dull	0.9	0.9	0.9
Lead			
Polished	0.35	0.05-0.2	n.r.
Rough	0.65	0.6	0.4
Oxidized	n.r.	0.3-0.7	0.2-0.6
Magnesium	0.3-0.8	0.05-0.3	n.r.
Mercury	n.r.	0.05-0.15	n.r.
Molybdenum			
Oxidized	0.5-0.9	0.4-0.9	0.2-0.6
Unoxidized	0.25-0.35	0.1-0.35	
Nickel			
Oxidized	0.8-0.9	0.4-0.7	0.2-0.5
Electrolytic	0.2-0.04	0.1-0.3	n.r.
Platinum			

Table 3-18: Different materials emissivity values

Material	Emissivity Values		
Black	n.r.	0.95	0.9
Silver	n.r.	0.02	.n.r
Steel			
Cold-Rolled	0.8-0.9	0.8-0.9	0.7-0.9
Ground Sheet	n.r.	n.r.	0.4-0.6
Polished Sheet	0.35	0.25	0.1
Molten	0.35	0.25-0.4	n.r.
Oxidized	0.8-0.9	0.8-0.9	0.7-0.9
Stainless	0.35	0.2-0.9	0.1-0.8
Tin (Unoxidized)	0.25	0.1-0.3	n.r.
Titanium			
Polished	0.5-0.75	0.3-0.5	n.r.
Oxidized	n.r.	0.6-0.8	0.5-0.6
Tungsten (Wolfram)	n.r.	0.1-0.6	n.r.
Polished	0.35-0.4	0.1-0.3	n.r.
Zinc			
Oxidized	0.6	0.15	0.1
Polished	0.5	0.05	n.r.

n.r.=not recommended

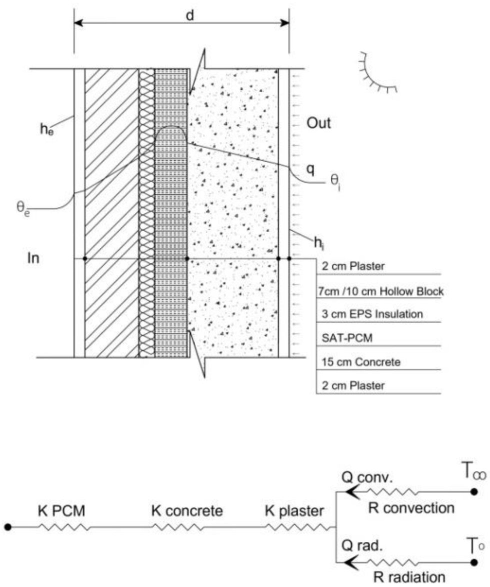
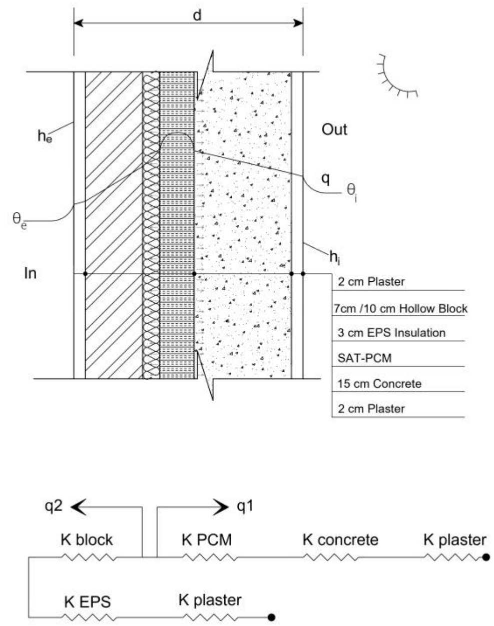
In this research, indoor thermal comfort and energy consumption will be evaluated with each thickness for the SAT-PCM. Then, the best thickness of the PCM will be studied to achieve the best thermal comfort and energy consumption.

3.6 Charging and Discharging Models

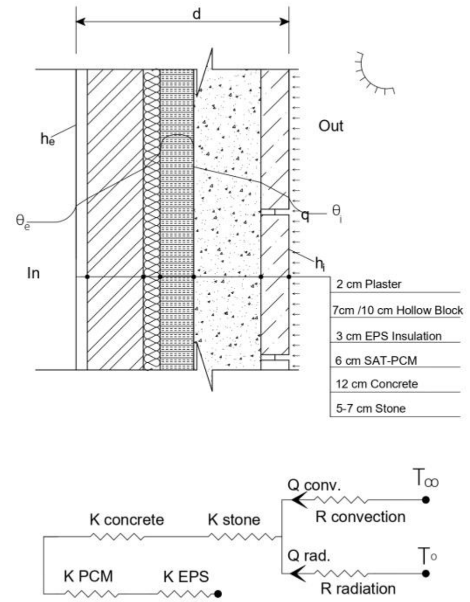
The charging process occurs when the sun's rays fall on the outer wall of the building envelope and these rays are transmitted until they reach the PCM layer, which in turn absorbs and stores it as a latent heat. The discharge process occurs when the medium surrounding the PCM layer cools, then the PCM begins to release the stored latent heat to warm the medium. The discharge process occurs when the medium surrounding the PCM layer cools, then the PCM begins to release the stored latent heat to warm up the medium.

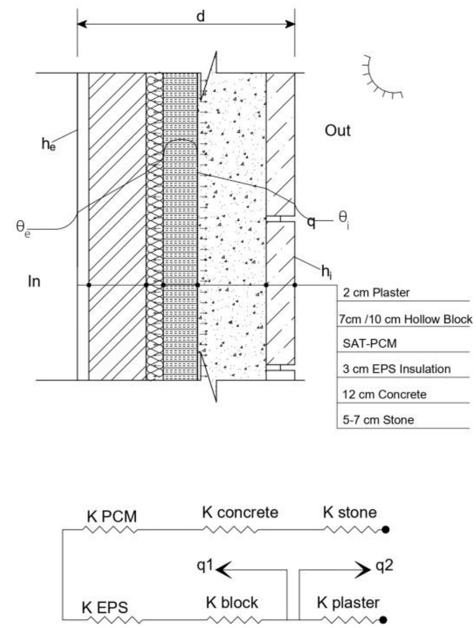
To describe the models' charging and discharging, the heat flow equations (Equ.4.1 - Equ.4.9) have been used according to the materials properties, thickness and according to the heat transfer method (conduction and convection), as shown in (Table 3-19).

Table 3-19: Charging and discharging models for each scenario, Researcher.

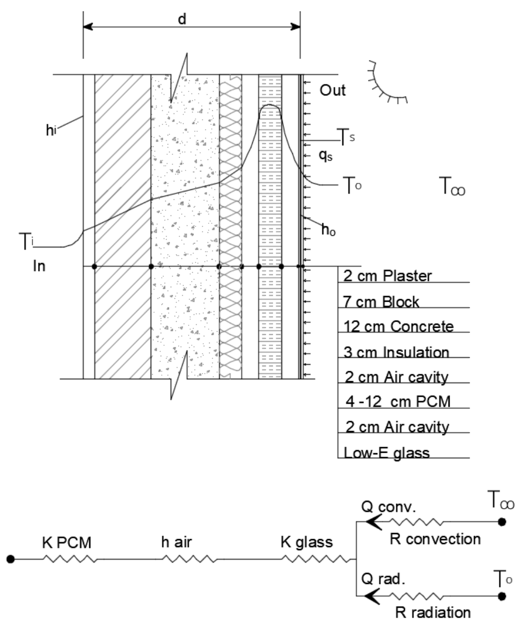
<table>
<tr><th>Model</th><th>Charging</th><th>Discharging</th></tr>
<tr><td>M1</td><td>
</td><td>
</td></tr>
</table>

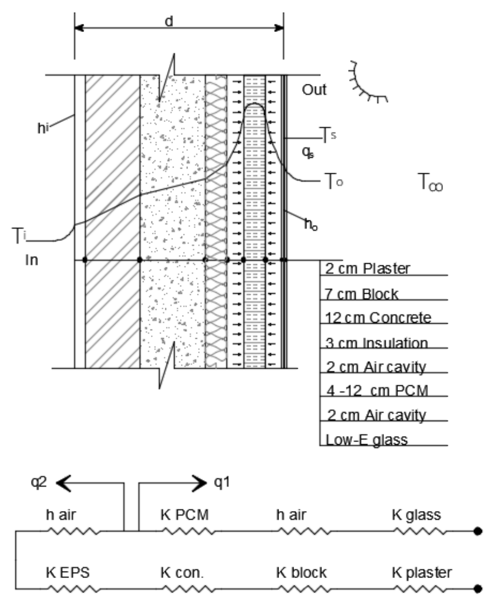
M2





M3





$$q_1 = U_1(T_{PCM} - T_o) \qquad \text{Eq 3-3}$$

$$q_2 = U_2(T_{PCM} - T_i) \qquad \text{Eq 3-4}$$

Were,

q: heat flow

T: temperature

K: thermal conductivity

U: thermal transmittance

$$U = 1/R_t \qquad \text{Equ 3-5}$$

And,

$$R_t = R_{\text{conduction}} + R_{\text{convection}} \qquad \text{Eq 3-6}$$

Were,

T_S is surface absolute temperature in kelvin and T_∞ is the absolute temperature in kelvin far from the surface

$$Q_{conv}. = \Delta T/R_{\text{convection}} \qquad \text{Eq 3-7}$$

And,

$$R_{conv}. = \frac{1}{\text{h} * \text{A}} \text{, in K/W} \qquad \text{Eq 3-8}$$

Were, A is the surface area and h is a convection heat transfer coefficient in w/m^2k.

$$Q_{rad}. = \Delta T/R_{\text{radiation}} \qquad \text{Eq 3-9}$$

And,

$$R_{radiation}. = \frac{1}{\text{h}_{\text{rad}}.* \text{A}} \text{, in K/W} \qquad \text{Eq 3-10}$$

Were,

$$h_{rad}. = \varepsilon\sigma(\text{T}_s^2 + \text{T}_{\text{suur}}^2).(\text{T}_\text{s} + \text{T}_{\text{surr}}) \qquad \text{Eq 3-11}$$

Were,

σ is the Stefan–Boltzmann constant (5.67×10^{-8} $W/m^2 \cdot K^4$) and ε is the surface emissivity.

According to the Weather Spark data, the hottest day in summer in Hebron in last 5 years (2020-2024) was Jul. 30. So, this day considered as a worst day, thus, the calculations were made based on its data. (Figure 3-13)

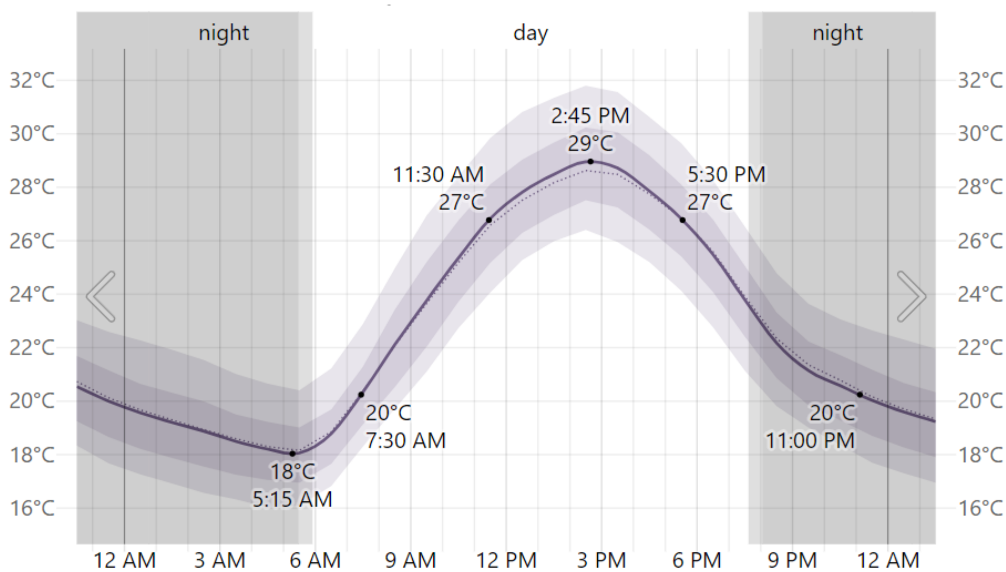
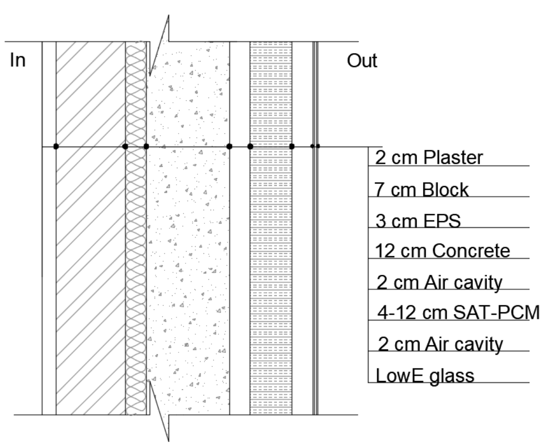
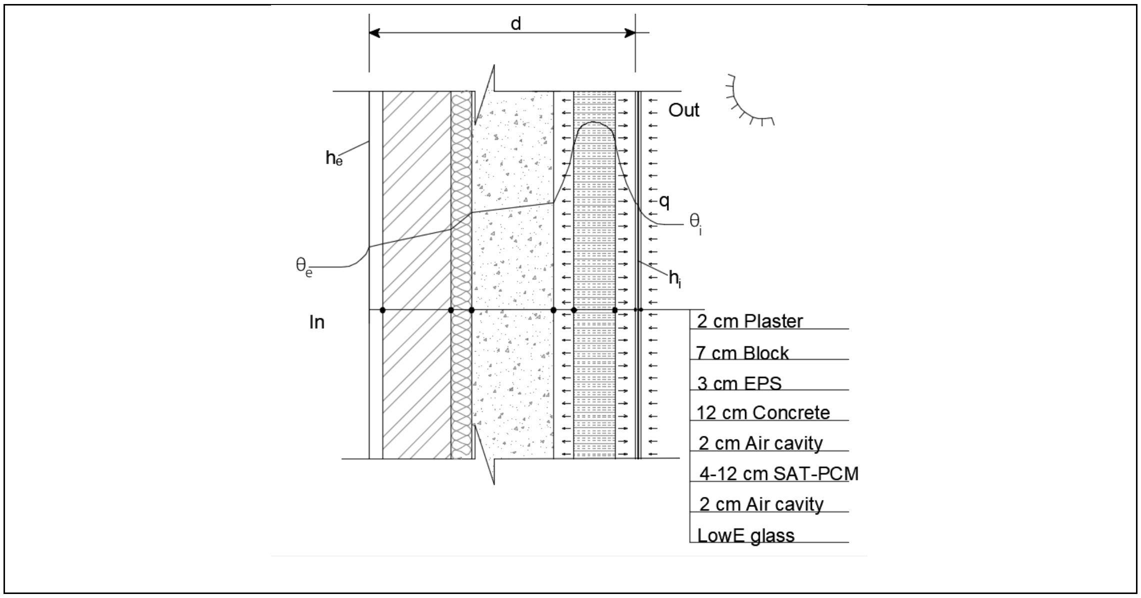


Figure 3-13: Average Temperature on July 30 in Hebron

b) Design and Simulate wall model in case of existing buildings (Table 3-20).

Table 3-20: The cross sectional wall, heat flow and description for M**4**, Researcher.

Model 4 (M4)	**Description**
	In the case of an insulated wall in the existing building; air cavity, PCM and double glass layers were added from the outer layer in the existing external wall.
Conceptual Heat Flow Diagram	



3.7 Software Simulation

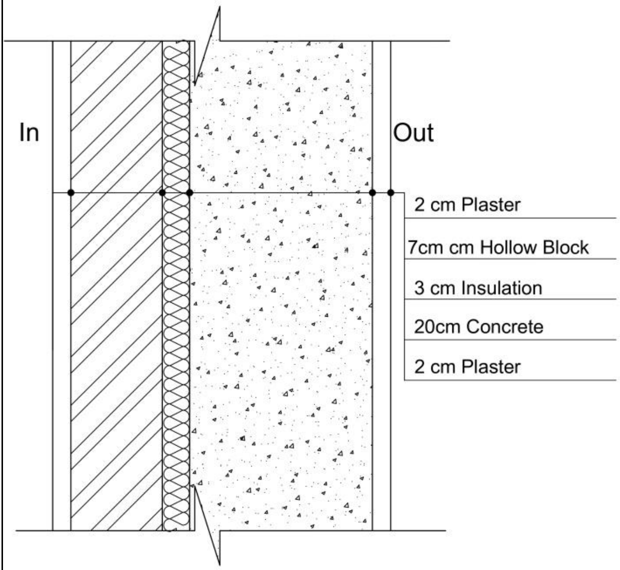
Design Builder (DB) software was used to test the suggested cases of PCM-TIM integration on the southern façade's wall to do simulation using the Energy Plus engine; to determine the best scenario so achieve thermal comfort and energy saved.

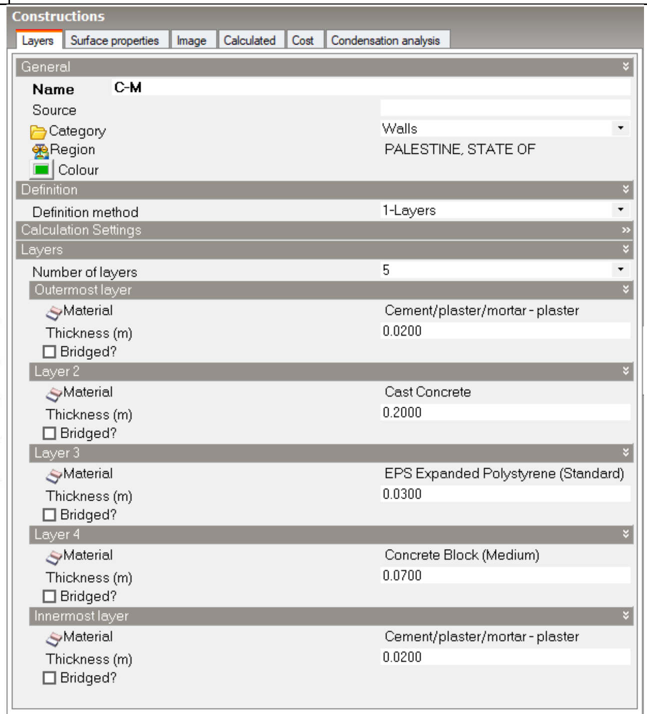
Each scenario has been simulated in summer and winter seasons in terms of thermal comfort, heating and cooling loads in winter and summer seasons thus compare data in each case with the common wall and between suggested cases to each other, in order to make the decision of what is the best scenario that achieve thermal comfort, energy saving and cost effective as a seasonal thermal storage integration wall construction.

The construction data in DB software in each model were as shown in the (Table 3-21 and Table 3-22) below:

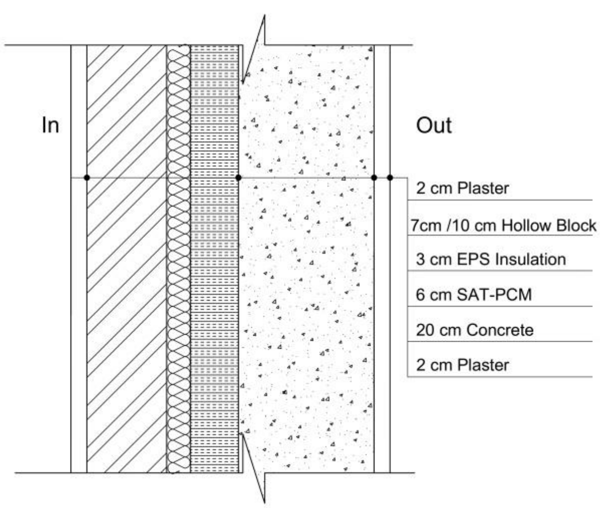
Table 3-21: The construction data in DB software for CM, M1, M2, M3 and M4,Researcher.

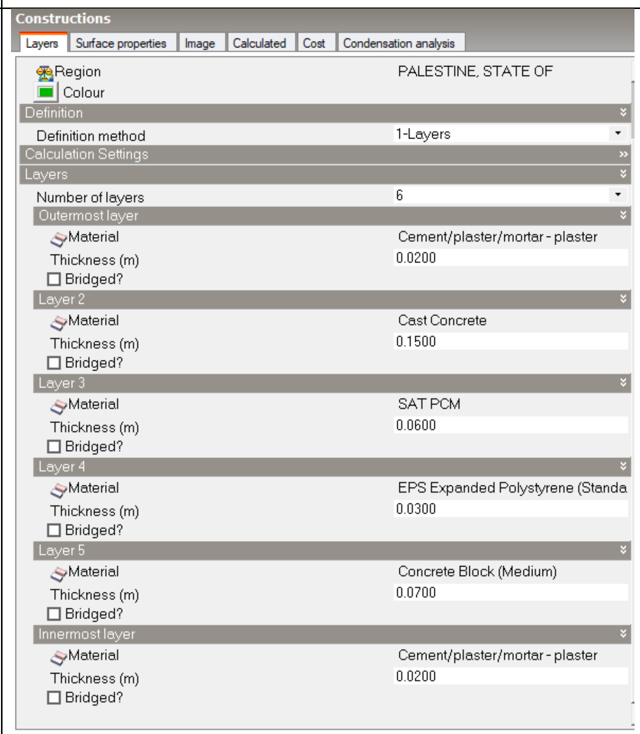
Cross Sectional of Common Wall Model (CM)	DB construction data

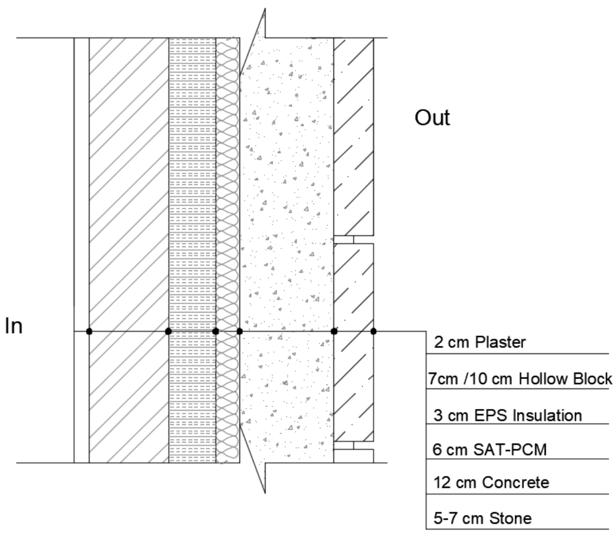
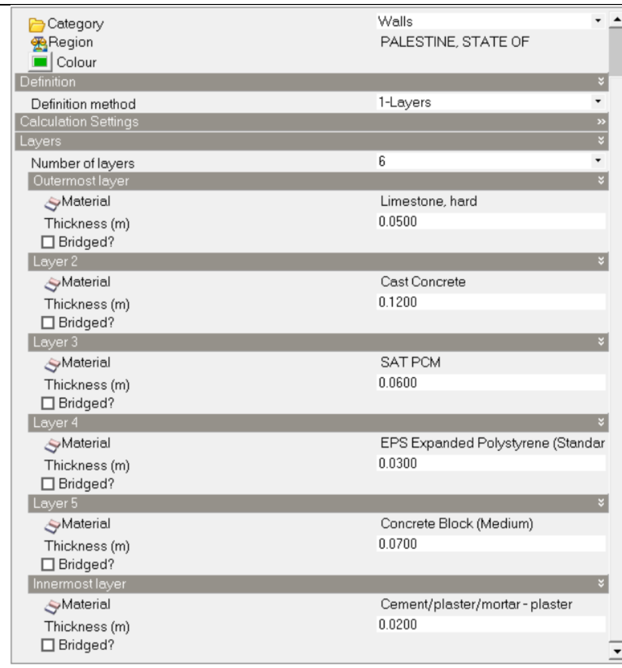


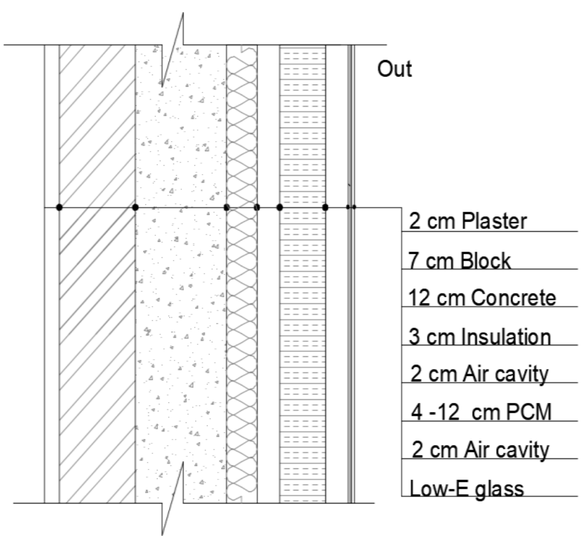
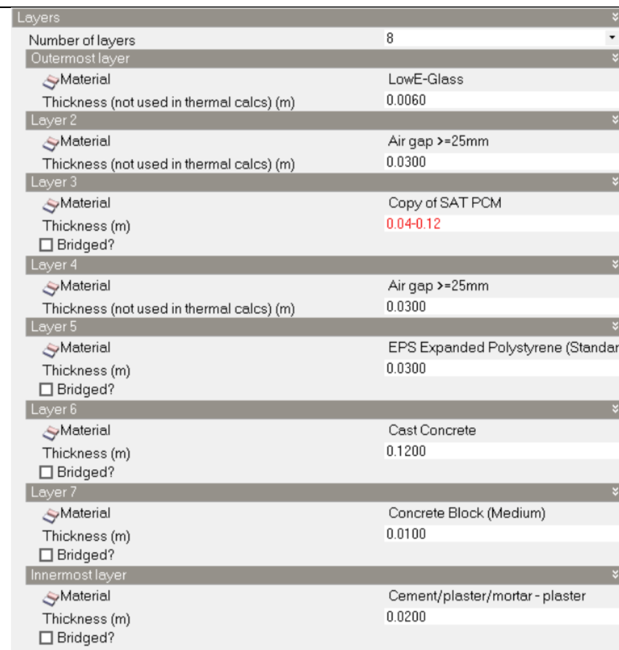


Cross Sectional of Model 1 (M1)	DB construction data



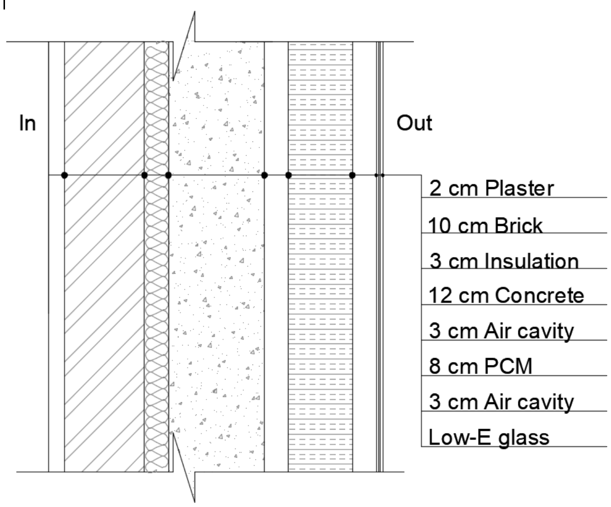
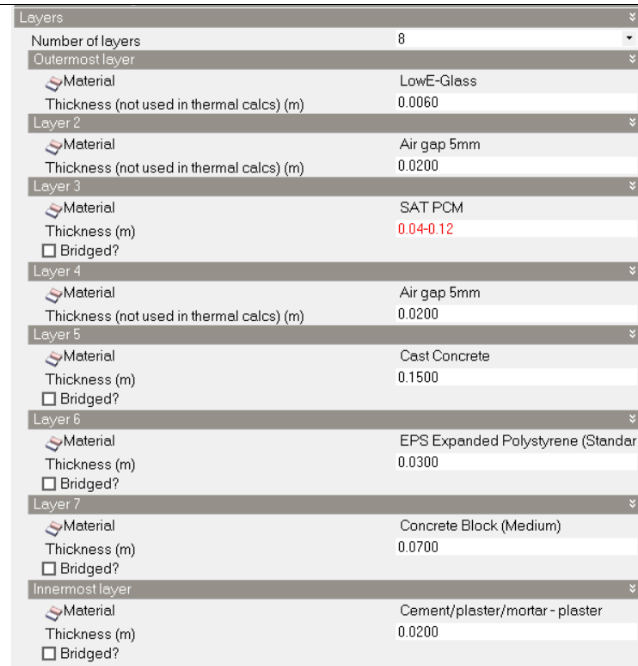


Cross Sectional of Model 2 (M2)	**DB construction data**
	

Cross Sectional of Model 3 (M3)	**DB construction data**
	

In M3 case, PCM thickness was differ from 4, 6,8,10 and 12 cm in M3-a, M3-b, M3-c, M3-d, and M3-e respectively, in order to decide the best possible thickness.

Table 3-22: The construction data in DB software for M**4**, Researcher.

Cross Sectional of Model 4(M4)	**DB construction data**
	

In M4 case, PCM thickness has been chosen according to the M3 thickness decision.

Each model has been simulated in DB software in terms of thermal comfort, summers' heat gains and winters' heat losses.

3.8 Thermal energy

To calculate the stored energy value in the PCM, the following parameters and equations were used,

3.8.1 Sun angles calculation

First, the sun angles, radiation and buildings' orientation were studied and calculated according of these equations:

$$\beta = 90 - L + \delta \qquad \text{Eq 3-12}$$

$$\delta = -23.45 * \cos\left(\frac{360}{365}(n + 10)\right) \quad \text{Eq 3-13}$$

L: Latitude angle

β: Altitude angle

δ: Declination angle

n: The day number

Solar flux striking the wall will be a combination of:

Direct-beam radiation (DBR)

Diffuse radiation (DR)

Reflected radiation (RR)

$$\text{Total radiation} = \text{DCR} + \text{DR} + \text{RR} \quad \text{Eq 3-14}$$

In a clear day radiation, the extraterrestrial solar insolation (I_0) calculated by the following equation:

$$I_o = S_c(1 + 0.034 \cos 360 \frac{n}{365}) \quad \text{Eq 3-15}$$

S_c: is solar constant =1.377kW/$\boldsymbol{m^2}$.

$$BR = A * e^{-km} \quad \text{Eq 3-16}$$

$$A = 1160 + 75 \sin\left(\frac{360}{365}(n - 275)\right) \qquad W/m^2 \quad \text{Eq 3-17}$$

$$k = 0.174 + 0.035 \sin\frac{360}{365}(n - 100) \qquad W/m^2 \quad \text{Eq 3-18}$$

$$m = \frac{1}{\sin(\beta)} \quad \text{Eq 3-19}$$

Were,

BR: is the beam portion of the radiation reaching the earth's surface

A: is an "apparent" extraterrestrial flux

k: is optical depth factor

m: is air mass ratio

$$\mathrm{DBR} = \mathrm{BR}\cos\theta \qquad W/m^2 \qquad \text{Eq 3-20}$$

Were,

θ is an angle between a sun beam and the surface.

$$\cos\theta = \cos\beta\cos(\phi_s - \phi_c)\sin\Sigma + \sin\beta\cos\Sigma \qquad \text{Eq 3-21}$$

ϕ_s: solar azimuth angle ,

ϕ_c: surface azimuth angle,

Σ: tilt angle, (Figure 3-14)

As for the southern façade (vertical surface oriented to the south), the tilt angle will be 90° and surface azimuth angle is 0°

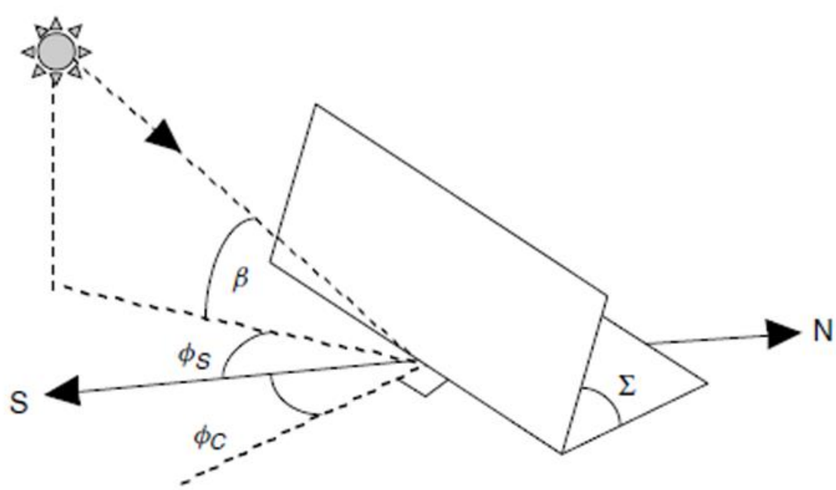


Figure 3-14: solar angels on a surface

$$\mathrm{DR_h} = \mathrm{C} * \mathrm{BR} \qquad \mathrm{W/m^2} \qquad \text{Eq 3-22}$$

$$C = 0.095 + 0.04\sin\frac{360}{365}(n - 100) \qquad \text{Eq 3-23}$$

Were,

C: the sky diffuse factor

$$ID_s = DR_h * \left(\frac{1 + \cos\Sigma}{2}\right) \qquad W/m^2 \qquad \text{Eq 3-24}$$

ID_s: Diffuse insolation in surface

$$RR = \rho * BR(\sin\beta + C)\left(\frac{1 - \cos\Sigma}{2}\right) \qquad W/m^2 \qquad \text{Eq 3-25}$$

RR: is produced due to reflecting by surfaces in front of the surface, ground reflectance (ρ) range from 0.8 for fresh snow to 0.1 for a gravel roof.

$$IT_s = DBR + ID_s + RR \qquad W/m\text{^}2 \qquad \text{Eq 3-26}$$

$$IT_s = Ae^{-km}[(\cos\beta\cos(\phi_s - \phi_c)\sin\Sigma + \sin\beta\cos\Sigma + C\left(\frac{1 + cos\Sigma}{2}\right) + \rho(\sin\beta + C)\left(\frac{1 - cos\Sigma}{2}\right)] \qquad W/m\text{^}2 \qquad \text{Eq 3-27}$$

IT_s: Total insolation on the surface

3.8.2 Thermal energy calculations

To calculate the energy losses (q losses) during the day, the procedure was according to the walls’ materials conductivity (Table 3-23) and the heat flow directions, as shown in (

Table 3-24).

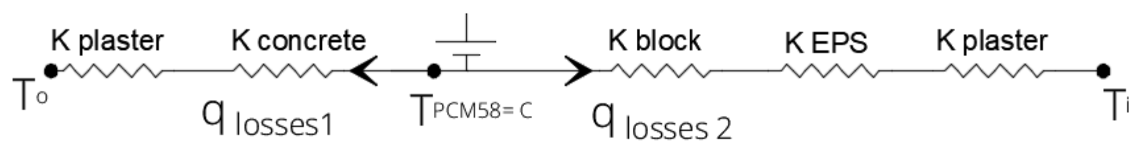
Table 3-23: materials conductivity

Material	**K: Conductivity (W/mK)**
Glass	1.11
Air (conduction)	0.024
Concrete	1.13
Stone	1.7

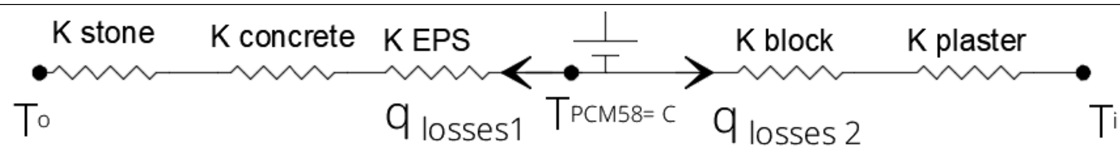
EPS	0.04
Block	0.51
Plaster	0.35

Table 3-24: models' heat flow directions, researcher

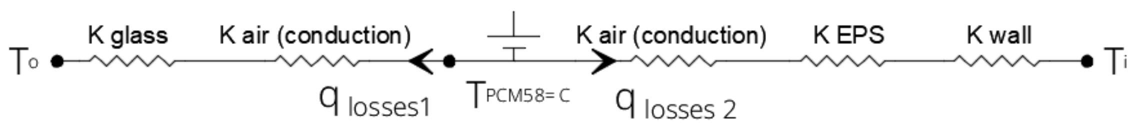
M1



M2



M3



$$q\ losses_1 = \Delta T\, \Sigma K_{out}$$ Eq 3-28

$$\Sigma \mathrm{K_{out}} = \mathrm{K_{glass}} + \mathrm{K_{air(conduction)}}$$ Eq 3-29

(In the last model as an example)

$$\Delta T = T_{PCM} - T_O$$ Eq 3-30

While T_o is differ during the time of the day and T_{PCM} is 58 C.

$$q\ losses_2 = \Delta T\, \Sigma K_{in}$$ Eq 3-31

And,

$$\Delta T = T_{PCM} - T_i$$ Eq 3-32

While T_{pcm} is 58C and assuming that the internal temperature was always 22 C (using HVAC to stabilize the temperature).

$$Total\ losses = q_{losses1} + q_{losses2} \qquad \text{Eq 3-33}$$

In the final developed model, according to the glasses characteristics, the energy pass in is as following:

Energy passes (in W/m^2) = thermal absorbance for the glass * IT_s

While the thermal absorbance for the selected glass is 50%, and as mentioned before, the PCM has been coated by a unoxidized aluminum layer and its thermal absorption to 20%. So,

The stored energy in PCM (in Wh) = unoxidized aluminum thermal absorption * energy passes

While the maximum energy that SAT-PCM can stored is depending on the PCM mass, volume, density and its latent heat as following (equations)

$$Mass(M) = density\ (\rho) * volume\ (V) \quad [\frac{Kg}{m^3} * m^3] \qquad \text{Eq 3-34}$$

$$Latent\ heat\ (LH) = \frac{Q}{M} \qquad [kJ/kg] \qquad \text{Eq 3-35}$$

Q: energy absorbed during phase change (kJ/kg)

For the SAT-PCM layer thickness (4-12cm) latent heat for the PCM storage capacity were calculated in the targeted wall in the south façade,

Area = room facades' area – windows' area = (3.6*3.0)-(1.8*1.25) = 8.55 m^2

While the PCM density is 1280 kg/m^3 and PCM LH is 264kJ/kg, the energy capacity for each thickness was as shown in (Figure 3-15).

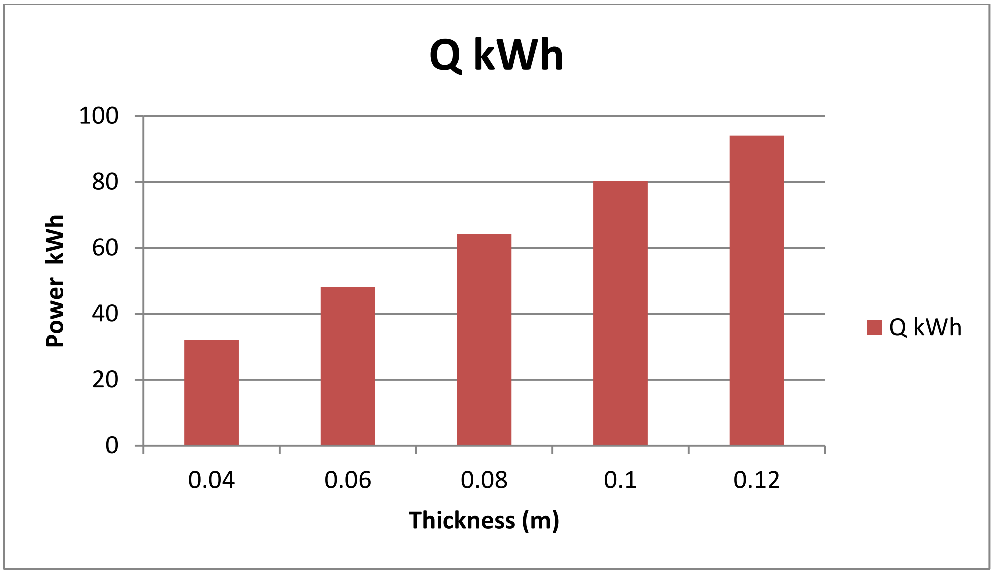


Figure 3-15: Maximum energy capacity in PCM in related to its thickness, researcher

According to the weather data, for the selected zone façade; the SAT-PCM thickness mustn't be less than 6 cm basing on its capacity.

3.8.3 Wavelength data

Based on the black body diagram (Figure 3-16), all energy less than 4.7 will be allowed to pass through the glass (Figure 3-17). Since the PCM temperature is 58 °C = 331.15 K, based on the (Figure 3-18) we found that the wavelength of the heat emitted by the PCM is greater than 10 µm, this wavelength can't be passes through the selected glass while the wavelength that the selected glass allows to pass is 4.7 µm (Figure 3-17). The energy is trapped inside because the base wavelength founded by the (Figure 3-18) Figure 3-18=10µm and this wavelength is more than the allowable wavelength that can be passes through the selected glass.

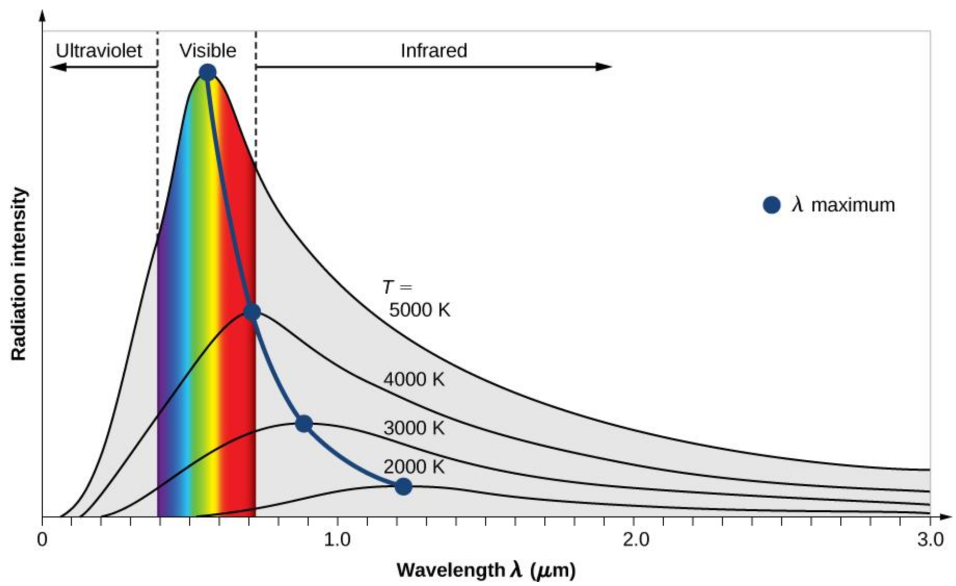


Figure 3-16: the black body diagram

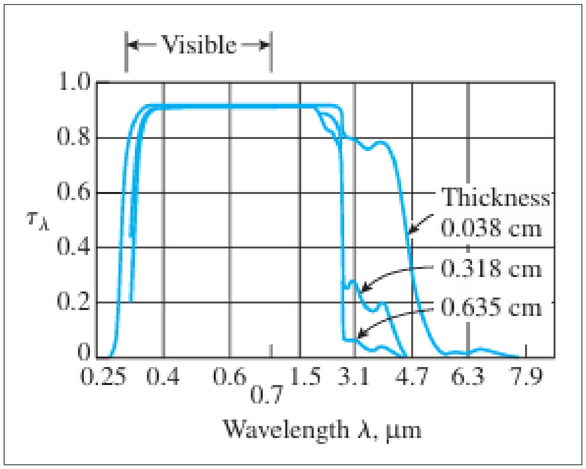


Figure 3-17: The selected lowE glass wavelength diagram for different thicknesses,(Hoffman, no date)

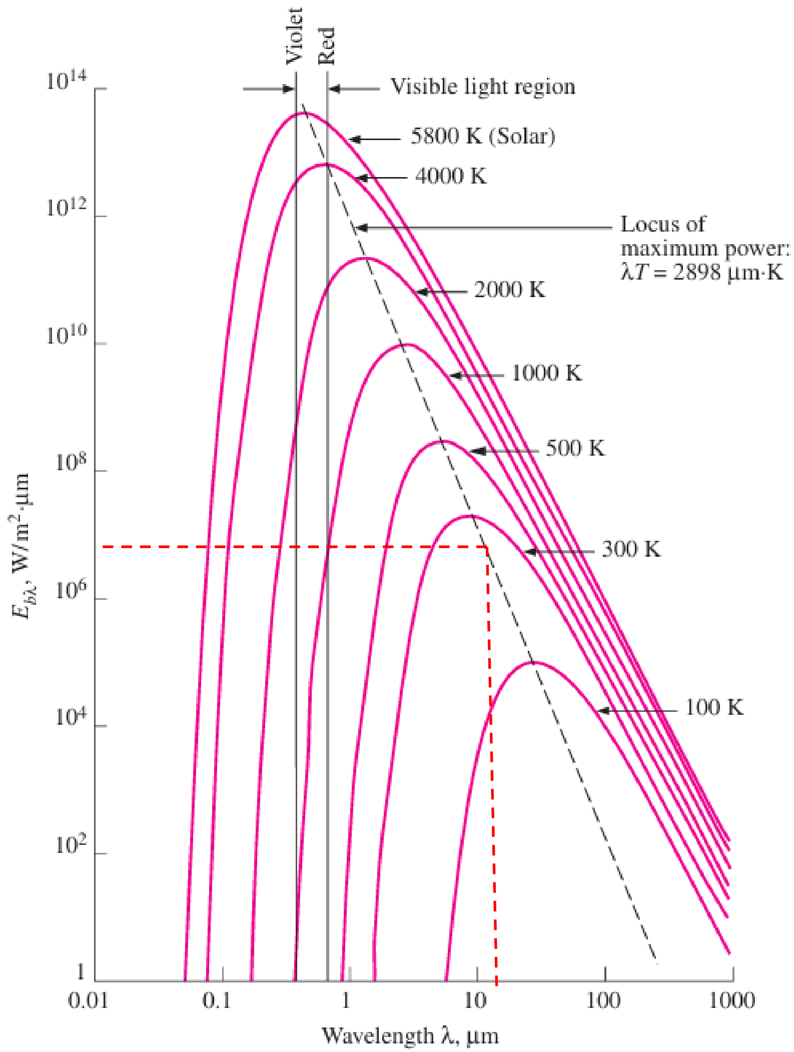


Figure 3-18: The variation of the blackbody emissive power with wavelength for several temperatures.(Wujek and Dagostino, 2010)

Chapter 4 Results

4.1 Introduction

The kind of heating and cooling system in a building affects how much energy it uses. Buildings should be built to sustain an interior temperature in accordance with the Ashrae requirements. In the winter, comfortable room temperatures can range from 20°C (68°F) to 23.3°C (74°F), and in the summer, from 22°C (73°F) to 26°C (79°F). Maintaining indoor human comfort levels requires the use of heating and air conditioning systems. The efficiency of the building envelope and its HVAC systems may be increased to lower the amount of energy used for heating and air conditioning. (Profile, 2023)

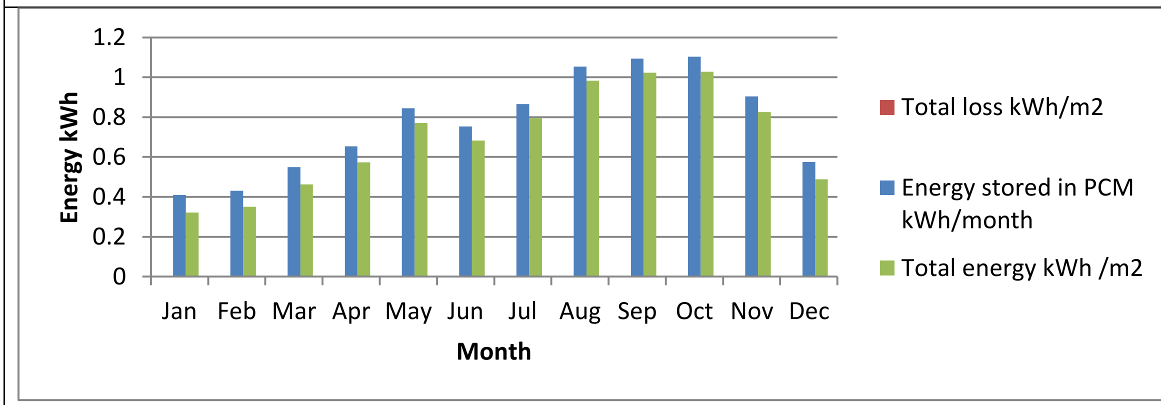
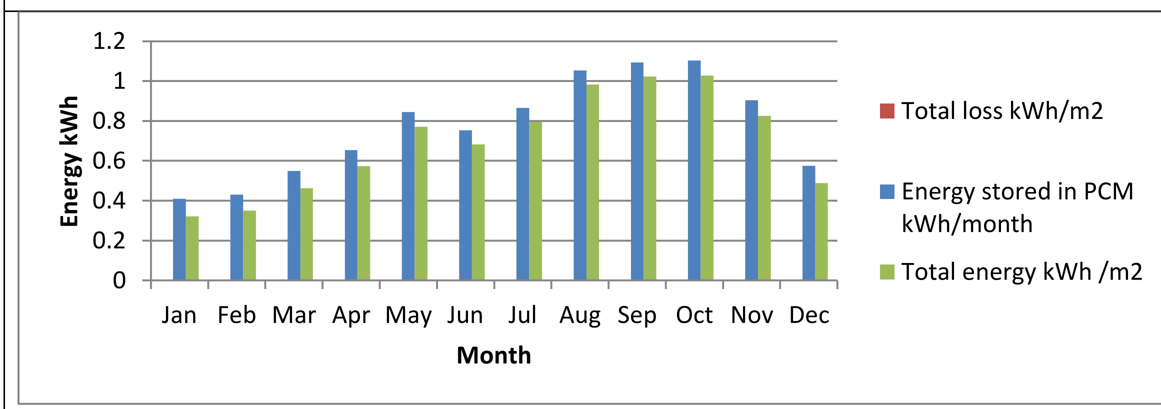
The results showed that the use of PCM-TIM integration in the proposed scenarios, when comparing each scenario to one of the common walls in Hebron, significantly and effectively reduces heat gain in summer and heat loss in winter in varying degrees between these scenarios when the wall layers' arrangement differ or when the thickness of the PCM differs.

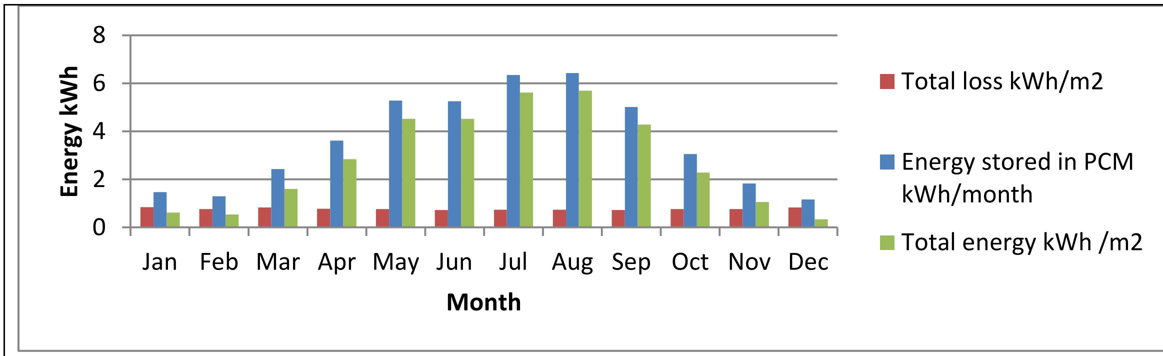
4.2 Thermal energy storage

Significant amounts of energy may be stored and released by PCM-based thermal energy storage. The material's phase change is what allows the system to store and release energy. However, the energy that can be stored in the PCM depends on many conditions such as the temperature, day, sun radiations, latitude, longitude and surfaces' orientation. While the southern façade is the most exposed façade to the solar radiation, it is the most effective façade to store thermal energy from the sun in the PCM during summer to reuse it in the winter. On the other hand, this heat stored in the PCM is subject to losing some of it due to the difference in temperature between the PCM and the inside and the PCM and the outside. The amount of this loss depends on the temperature on each day of the year and depends on the type of material (thermal resistance and thermal conductivity). To calculate the amount of energy stored in the PCM, the position of the sun, the temperature, solar azimuth angle and the amount of solar radiation were studied on each day of the year with an accuracy of half an hour for 365 days using the weather data from The National Renewable Energy Laboratory (NREL) website, by Solar Position Algorithm (SPA) Calculator.

According to the equations mentioned in chapter 5, the amount of energy stored in the PCM, the amount of energy losses and the total energy results in each model were as following in (Table 4-1):

Table 4-1: The thermal energy results for each model, researcher

The thermal energy results M1

The thermal energy results M2

The thermal energy results M3



As showed in the (Table 4-1), the calculation results showed a difference in the amount of thermal energy that can be stored in the PCM in each model depending on the arrangement of the wall layers, the thickness of each layer, and the location of the PCM layer.

As expected, the model with the least heat storage was M2, where the presence of the stone layer with the thermal insulation layer before the PCM layer reduced the amount of radiation penetrating the PCM to store it. On the other hand, the model with the most thermal storage was M3, where the selected glass layer enhanced the entry of a large amount of solar radiation and prevented its return to the outside, and the two air layers next to the PCM layer reduced the loss of a large amount of energy, thus storing more energy.

It should be noted that in all models the amount of energy that can be stored in the PCM was less than the maximum amount of energy that the PCM can store as shown in (Table 4-1).

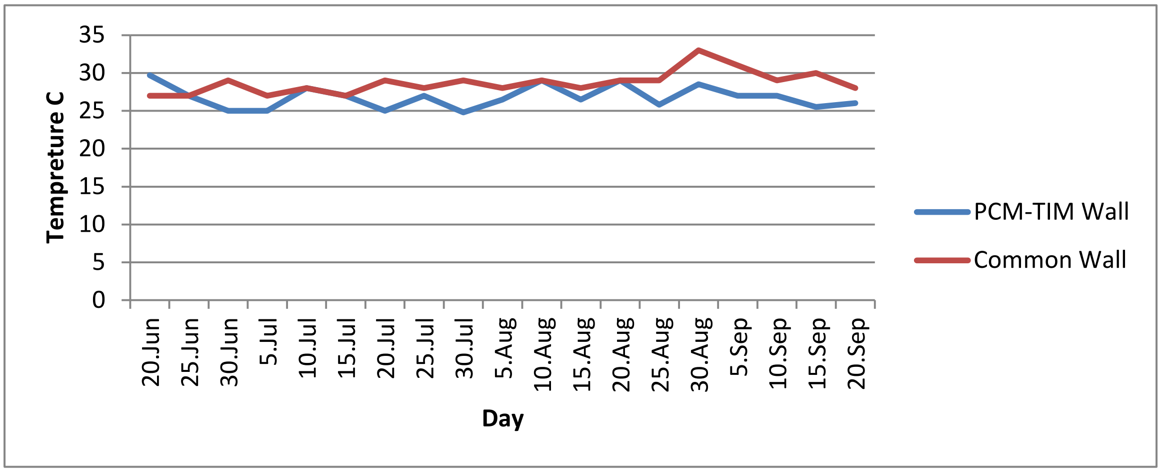
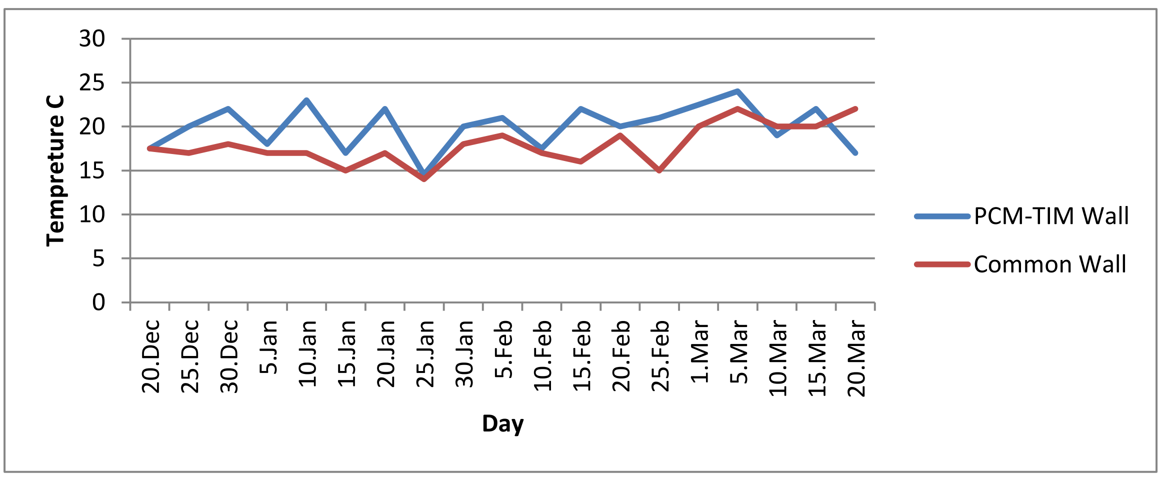
- As for the case of increasing the amount of energy absorbed, I suggest for future studies to connect the system with domestic hot water systems in tanks and suggesting to ventilate the wall by making ventilation holes in to discharge the excess heat.

4.3 Indoor Air Temperature

The simulation result for indoor air temperature in each model has been compared to the CM in summer and winter seasons, and the results were as follows:

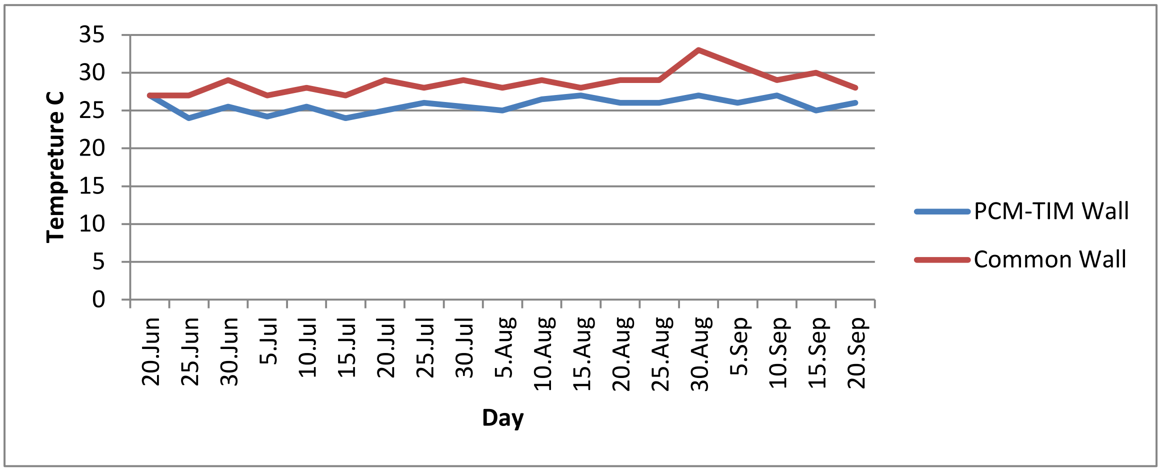
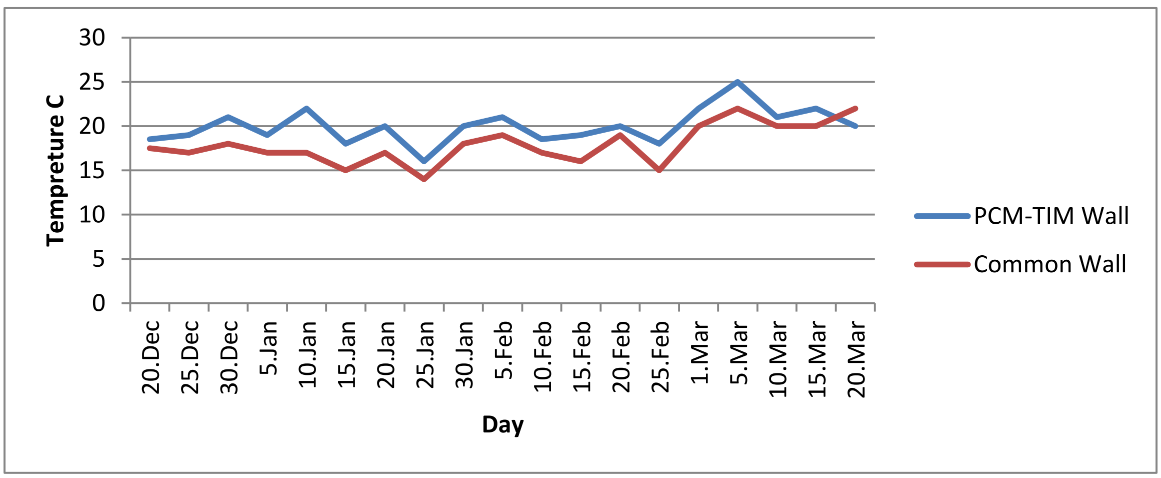
The simulation result showed a positive effect of the M1 in reducing the indoor air temperature on the most days compared to the CM, while in winter, M2 gave a negative effect in heating, as the indoor air temperature was lower compared to the indoor air temperatures in the case of CM, as shown in (Table 4-2).

Table 4-2: Indoor Air Temperature results for M**1** and CM in summer and winter, Researcher

Indoor Air Temperature in M1 and CM	
Summer	
Winter	

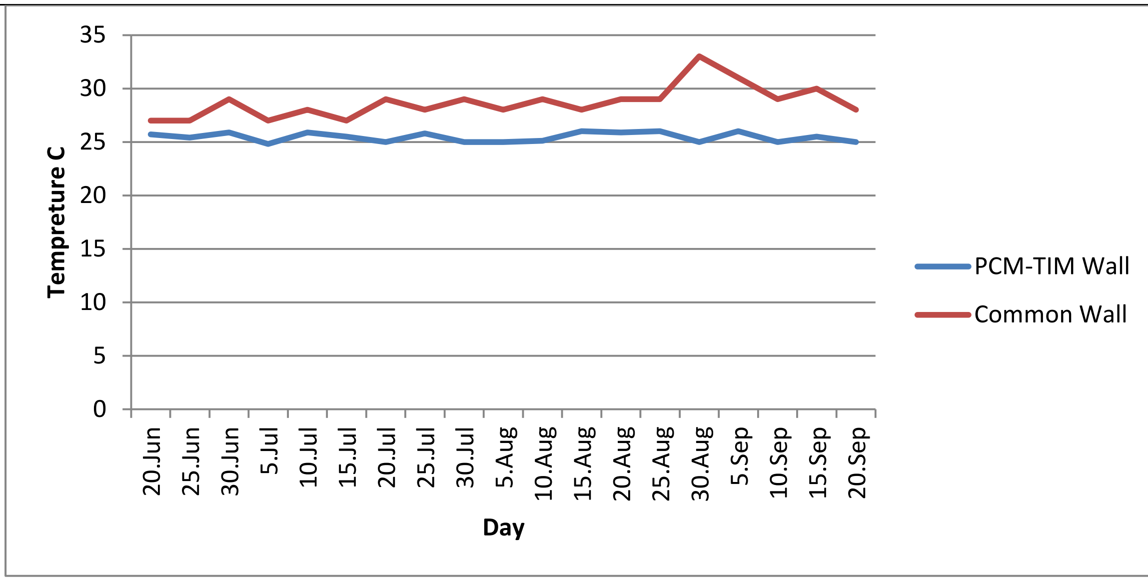
In M2, when using 6 cm PCM in a stone wall face, the results showed a positive effect in reducing indoor air temperature on all summer days and a positive effect in increasing indoor air temperature on most winter days compared to the indoor air temperature in the CM, as shown in (Table 4-3).

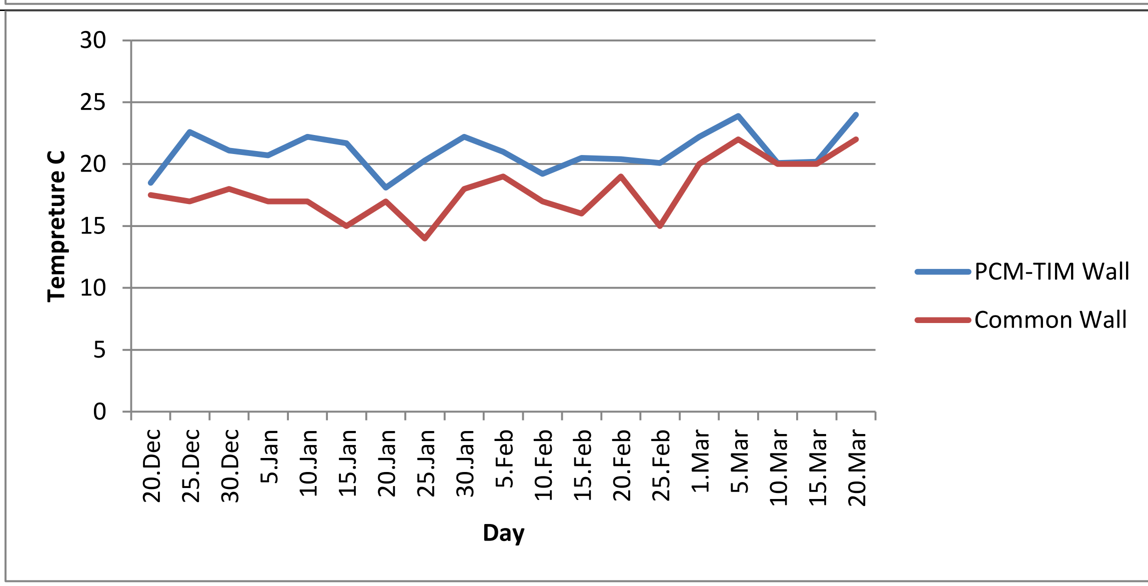
Table 4-3: Indoor Air Temperature results for M**2** and CM in summer and winter, Researcher

<table>
<tr><th colspan="2">Indoor Air Temperature in M2 and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
</td></tr>
</table>

In M3-A, when using 6 cm PCM with two air cavity layers and LowE glass layer, the results showed a positive effect in decreasing indoor air temperature in all summer days and a positive effect in increasing indoor air temperature in all winter days compared to the indoor air temperature in the CM, as shown in (Table 4-4).

Table 4-4: Indoor Air Temperature results for M**3**-A and CM in summer and winter, Researcher.

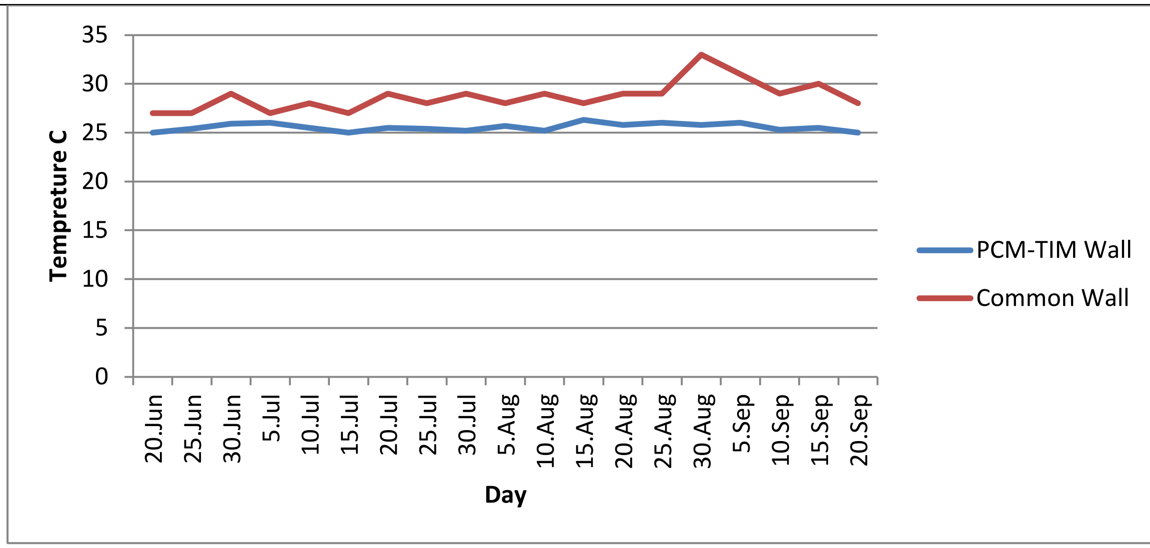
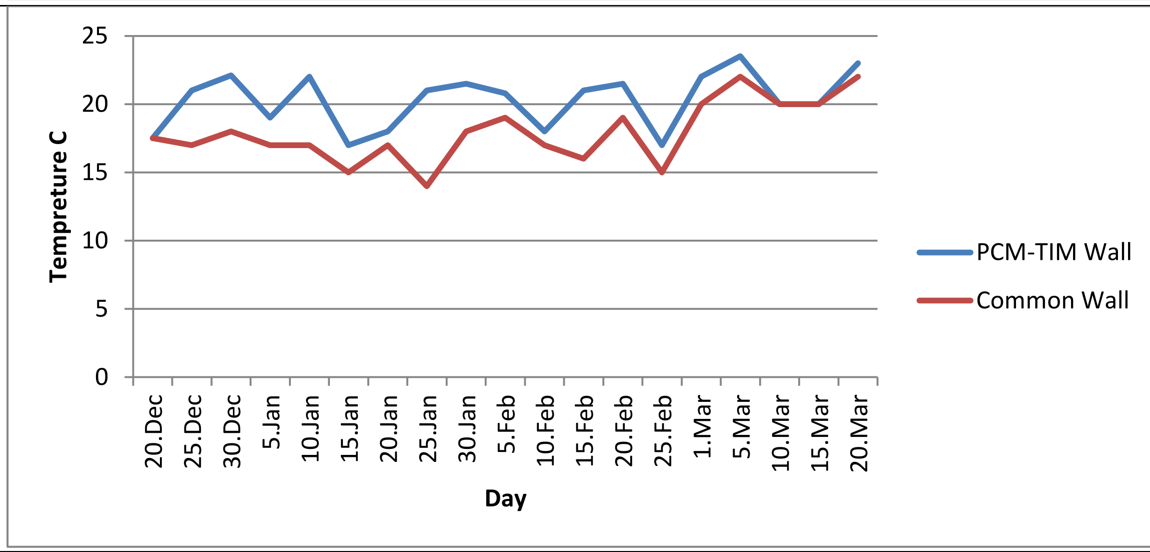
<table>
<tr><th colspan="2">Indoor Air Temperature in M3-A (6 cm PCM) and CM</th></tr>
<tr><td>Summer</td><td>


</td></tr>
<tr><td>Winter</td><td>


</td></tr>
</table>

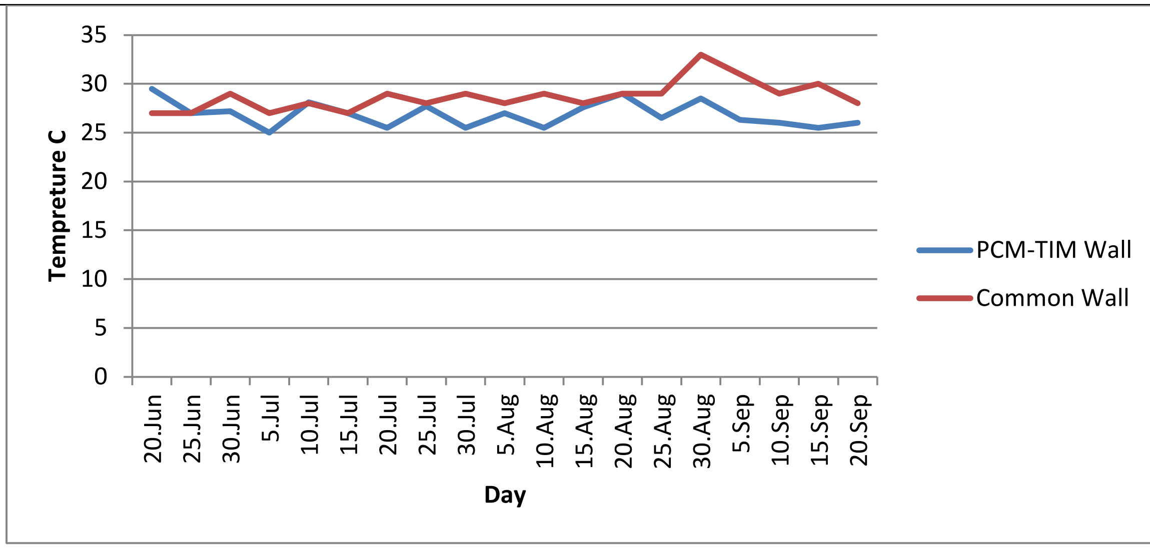
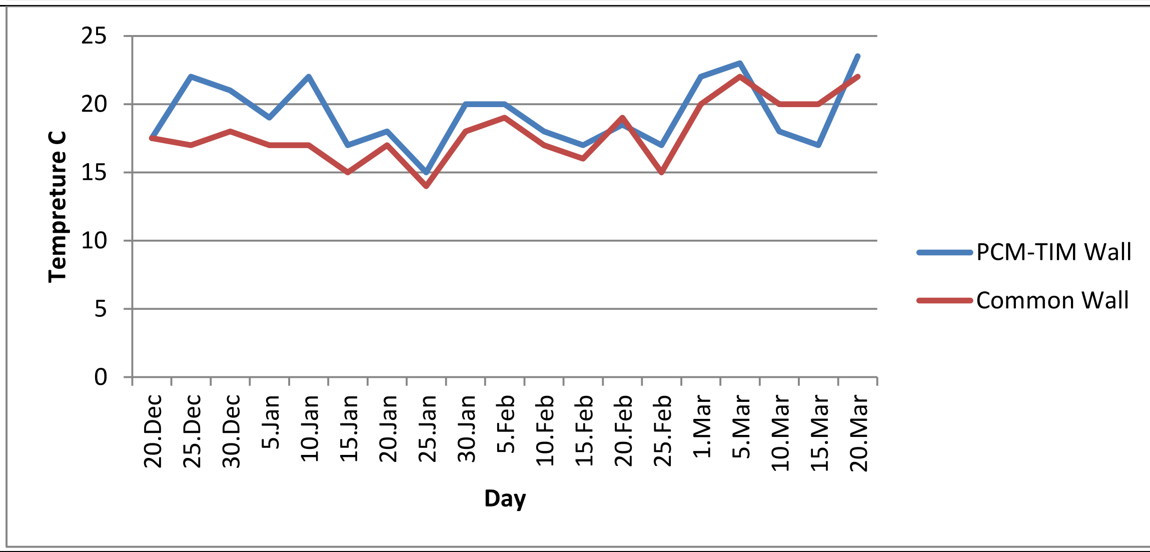
In M3-B, when using 8 cm PCM with two air cavity layers and LowE glass layer, the results showed a positive effect in decreasing indoor air temperature in all summer days compared to the indoor air temperature in the CM and a positive effect in increasing indoor air temperature in most winter days. In some winter days, M3-B gave the same effect as the CM, as shown in (Table 4-5).

Table 4-5: Indoor Air Temperature results for M3-B and CM in summer and winter, Researcher.

<table>
<tr><th colspan="2">Indoor Air Temperature in M3-B (8 cm PCM) and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
</td></tr>
</table>

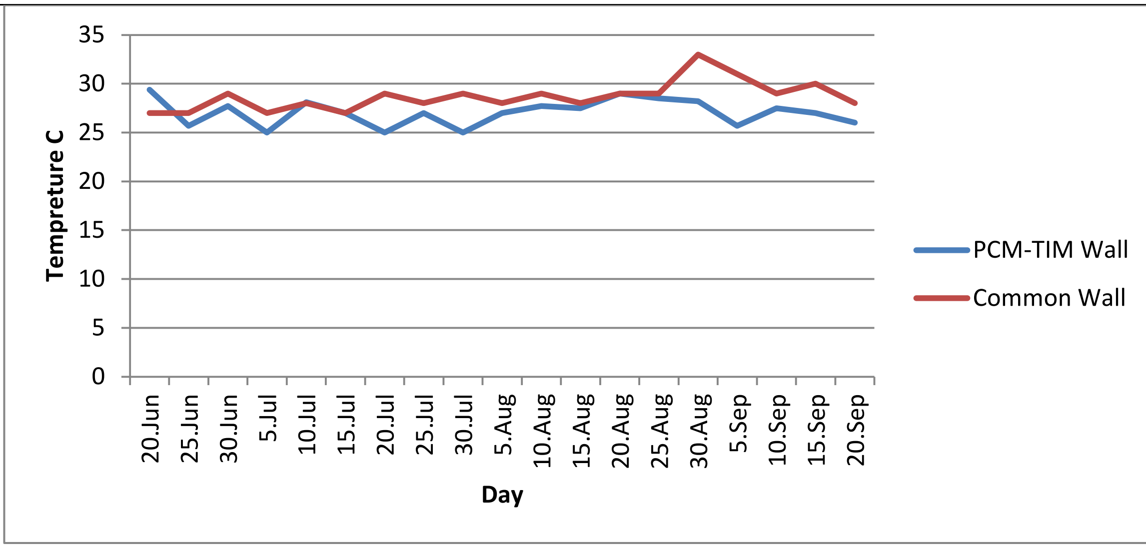
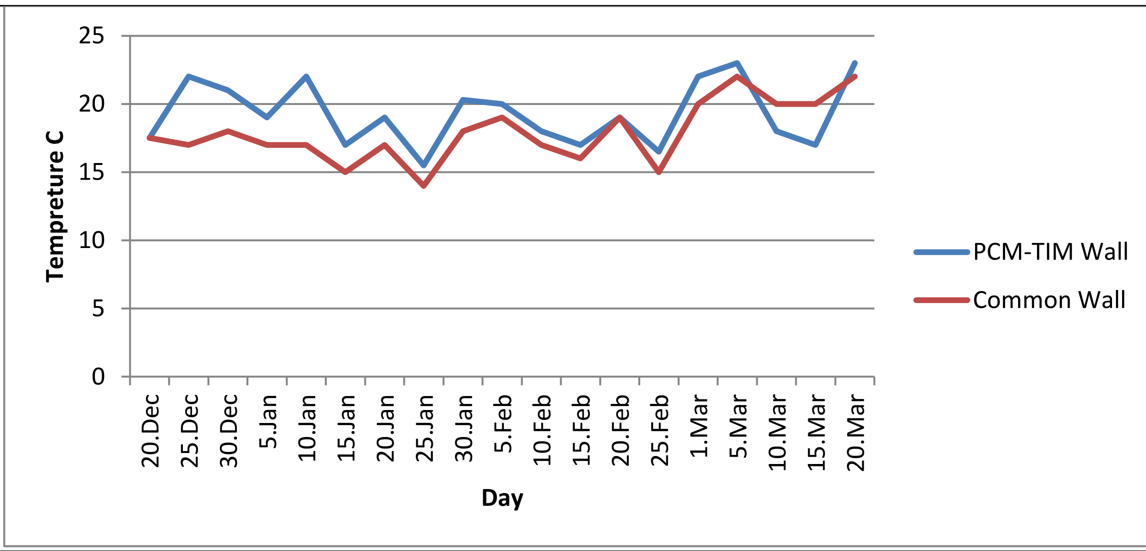
In M3-C, when using 10 cm PCM with two air cavity layers and LowE glass layer, the results showed a positive effect in decreasing indoor air temperature on most summer days compared to the indoor air temperature in the CM and sometimes gave the same effect as using the CM. The same happened in winter, where using M3-C showed a positive effect in increasing indoor air temperature on most winter days and sometimes gave the same effect as the CM, as shown in (Table 4-6).

Table 4-6: Indoor Air Temperature results for M3-C and CM in summer and winter, Researcher.

Indoor Air Temperature in M3-C (10 cm PCM) and CM	
Summer	
Winter	

In M3-D, when using 12 cm PCM with two air cavity layers and LowE glass layer, the results showed a positive effect in decreasing cooling energy on most summer days compared to the indoor air temperature in the CM, and sometimes it gave the same effect as using the CM, and at other times it showed a negative effect in terms of the indoor air temperature. As for the winter, the results showed a positive effect in increasing indoor air temperature on most winter days compared to the indoor air temperature in the CM, and sometimes it gave the same effect as using the CM, as shown in (Table 4-7).

Table 4-7: Indoor Air Temperature results for M3-D and CM in summer and winter, Researcher.

<table>
<tr><th colspan="2">Indoor Air Temperature in M3-D (12 cm PCM) and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
</td></tr>
</table>

4.4 Indoor Thermal comfort

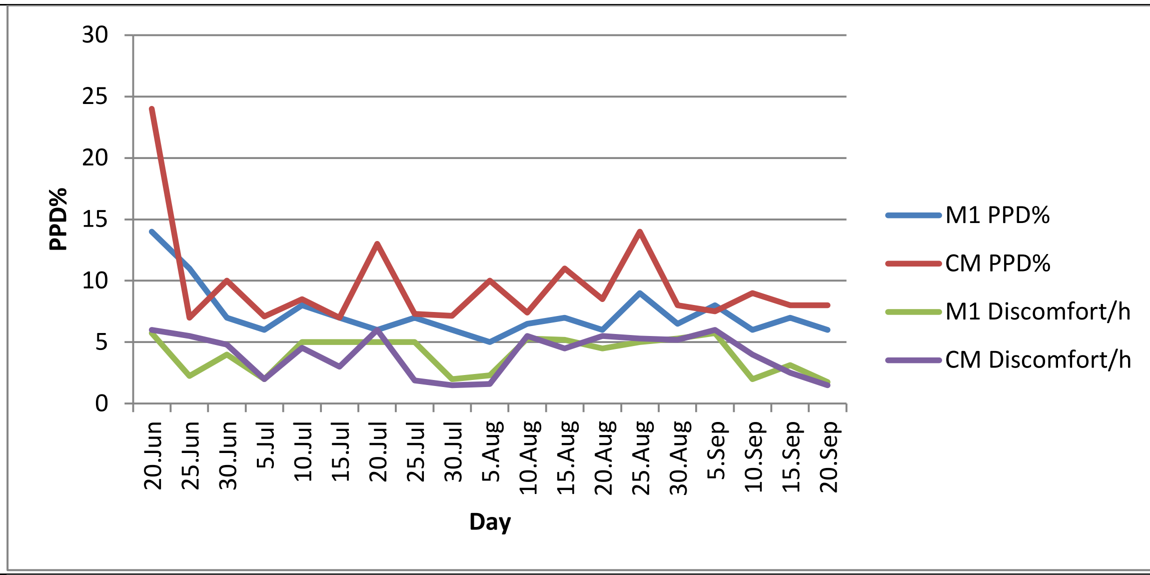
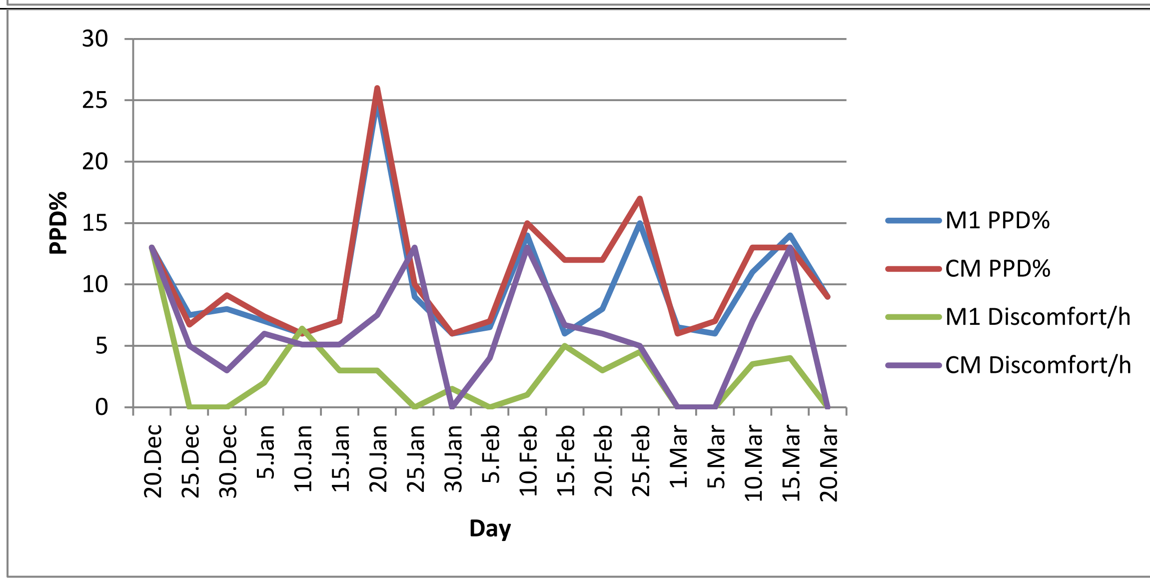
The internationally recognized ASHRAE 55 and ISO 7730 standards for assessing indoor settings define thermal comfort as "that condition of mind that expresses satisfaction with the thermal environment."

According to ASHRAE 55, the predicted percentage of dissatisfied (PPD) index for thermal comfort usually provides the proportion of people who would be dissatisfied with the temperature in the space. According to established guidelines, all inhabited parts of a facility should be reduced fewer than 20% PPD to provide thermal comfort.

In this section, by using DB simulation results; thermal comfort has been studied by analyze PPD and comfort/discomfort hour for each model and compared these values for each suggested scenario whit the CMs' values, and the results were as follows:

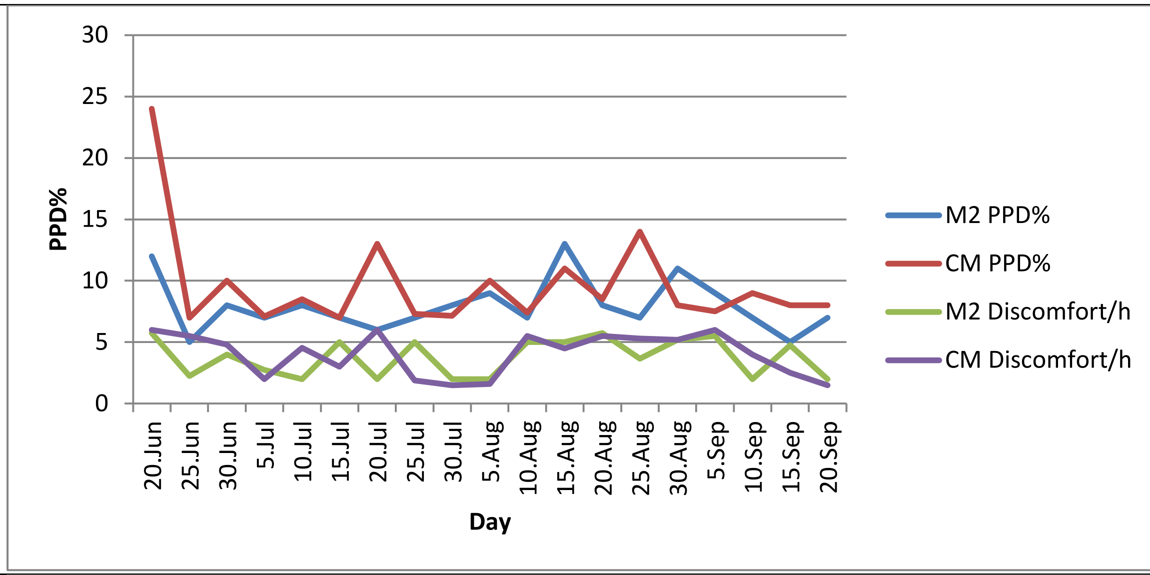
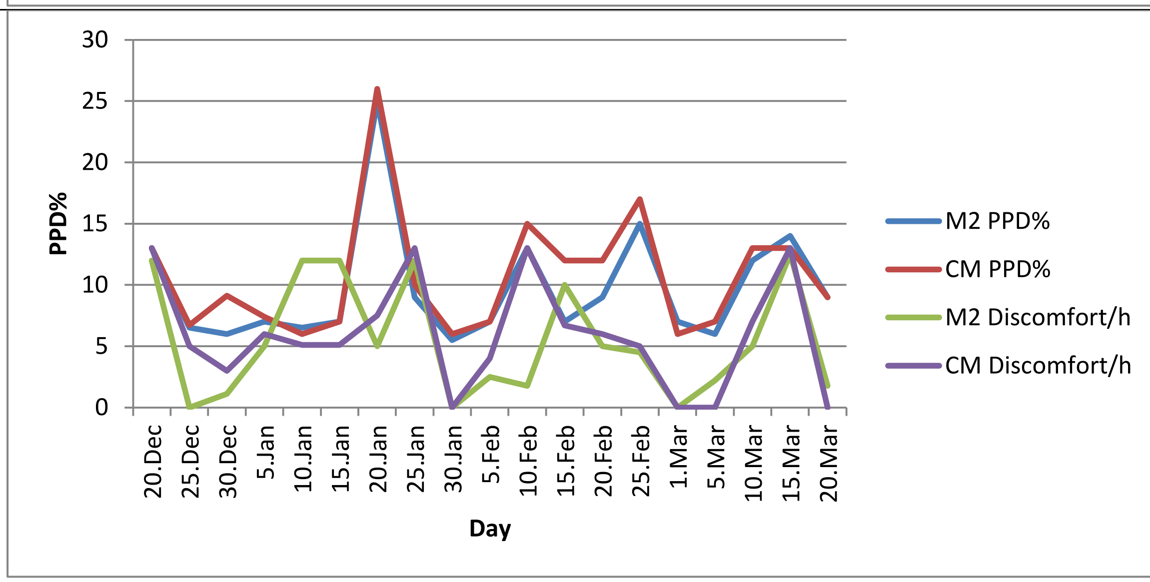
As for the indoor thermal comfort/discomfort hours and PPD based on (ASHRAE 55), the results indicated that the indoor thermal comfort/discomfort hours were close in the case of M1 and CM case in the summer, and sometimes the CM outperformed M1. As for winter, M1 showed a clear superiority over CM, as the efficiency of M1 in winter was higher than in summer compared to CM, as for the PPD%, the M1 showed a clear superiority in the satisfaction rate in the summer, while in winter both models showed a PPD higher than 20% on some days, as shown in (Table 4-8).

Table 4-8: PPD% and Discomfort Hours for M1 and CM in summer and winter, Researcher.

<table>
<tr><th colspan="2">PPD% and Discomfort Hours in M1 and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
</td></tr>
</table>

As for the indoor thermal comfort/discomfort hours and PPD% in M2 compared to CM, the results indicated that the two models were close at times, with M4 outperforming sometimes, and at other times CM outperforming in the summer. In the winter, there was a noticeable difference between the two models on some days, with M2 outperforming sometimes and CM outperforming at other times, as shown in (Table 4-9).

Table 4-9: PPD% and Discomfort Hours for M2 and CM in summer and winter, Researcher.

<table>
<tr><th colspan="2">PPD% and Discomfort Hours in M2 and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
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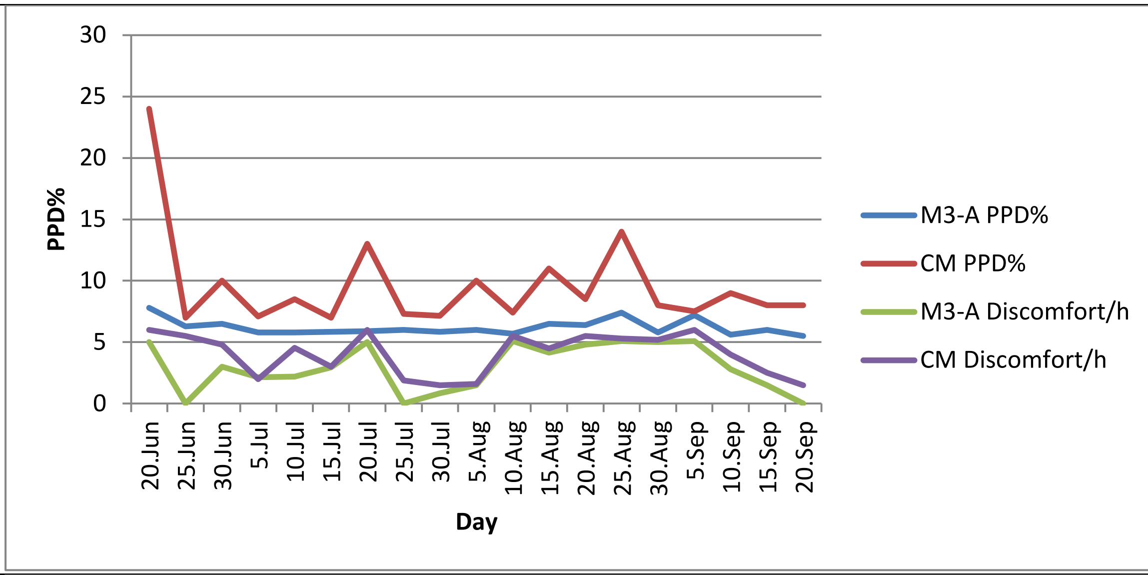
</table>

As for the indoor thermal comfort/discomfort hours, the results indicated that the M3-A outperformed the CM on most summer days and gave the same values on some days. In the winter, the M3-A showed a noticeable superiority over the CM on all uncomfortable days. As for PPD%, M3-A clearly outperformed CM, as it maintained a PPD% is less than 20% throughout the summer and winter seasons, unlike CM, whose PPD% exceeded 20% on some days, as shown in (Table 4-10).

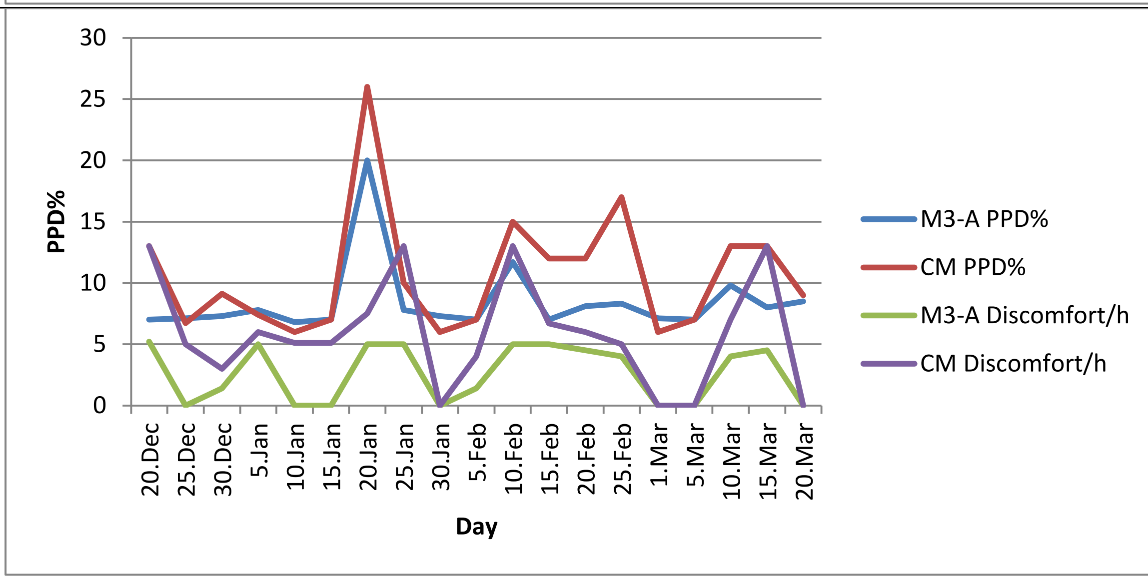
Table 4-10: PPD% and Discomfort Hours for M3-A and CM in summer and winter, Researcher.

PPD% and Discomfort Hours in M3-A (6cm PCM) and CM

Summer

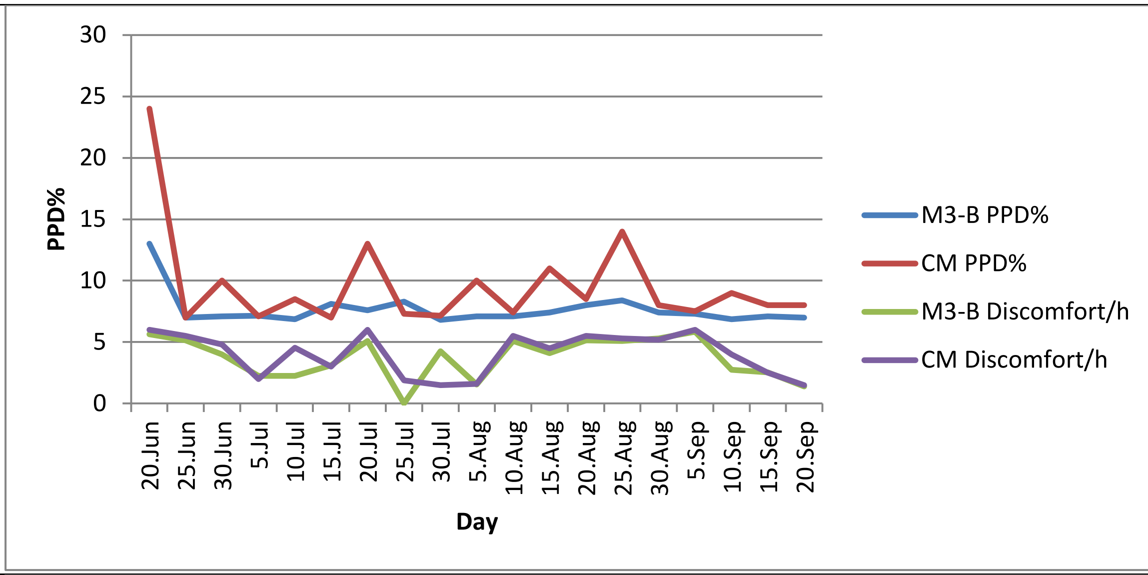
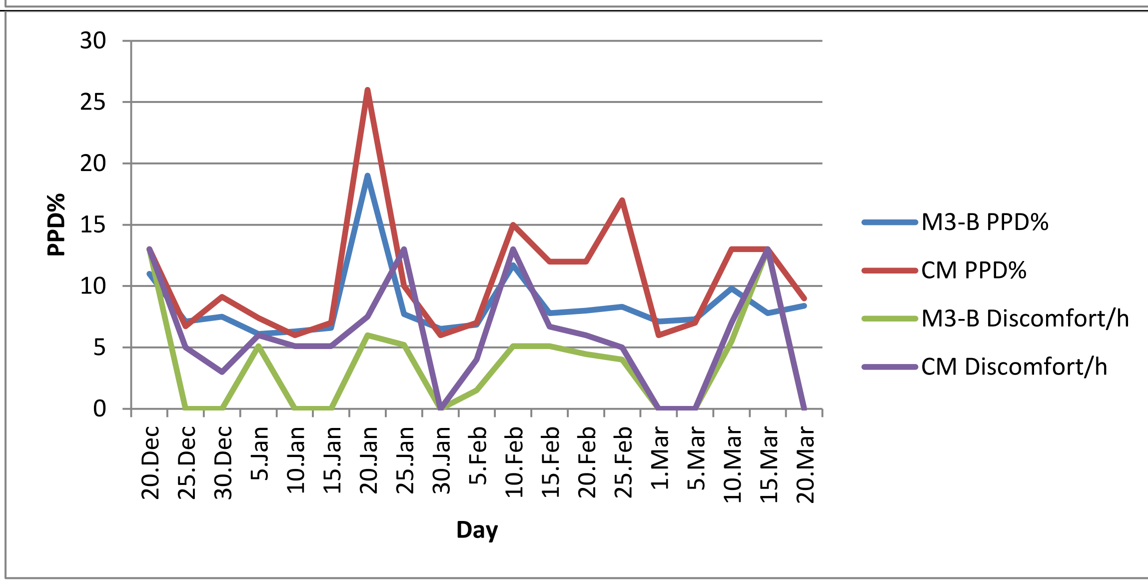


Winter



By coming to the indoor thermal comfort/discomfort hours for M3-B, the results indicated that the values between the two models were close in the summer, although the M3-B was superior at times and the CM at other times. In the winter, the M3-B showed a noticeable superiority on most winter days, while the values were similar on some days. For PPD% The M3-B kept the PPD below than 20% on all summer and winter days, unlike the CM that the PPD% exceeded than 20%, as shown in (Table 4-11).

Table 4-11: PPD% and Discomfort Hours for M3-B and CM in summer and winter, Researcher.

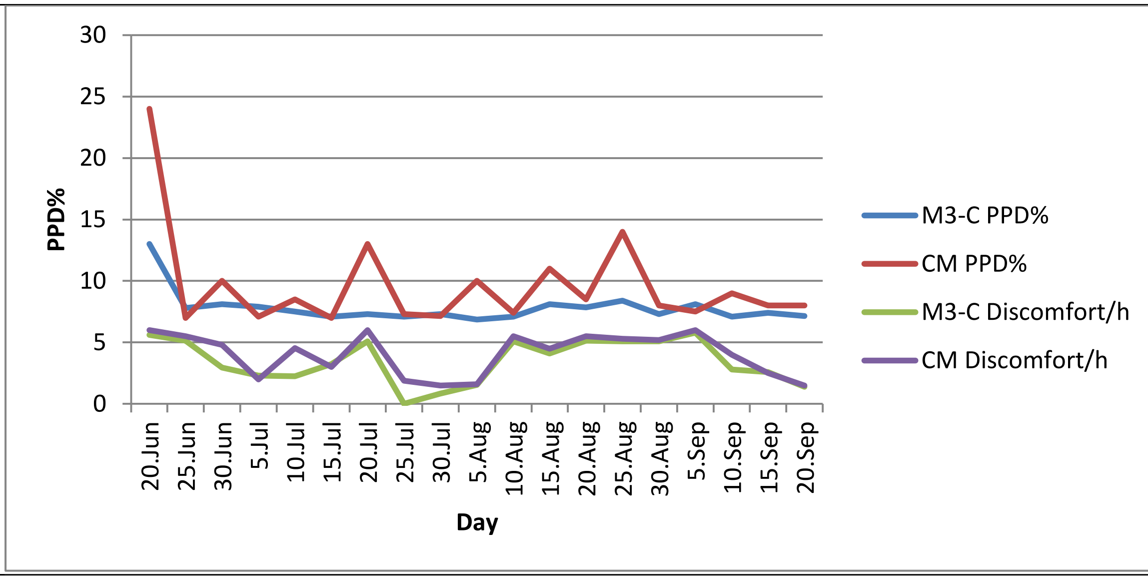
PPD% and Discomfort Hours in M3-B (8 cm PCM) and CM	
Summer	
Winter	

As for the indoor thermal comfort hours in M3-C compared to CM, the results indicated that the values between the two models were close on most summer days, while M3-C was superior on some summer days. In winter, the values varied when compared the two models, however the M3-C was superior on most days, the CM was superior on some days and the values were similar on other days. And for PPD%, M3-C in summer kept the PPD less than 20%, but in the winter some days it exceeded 20% in both models, as shown in (Table 4-12).

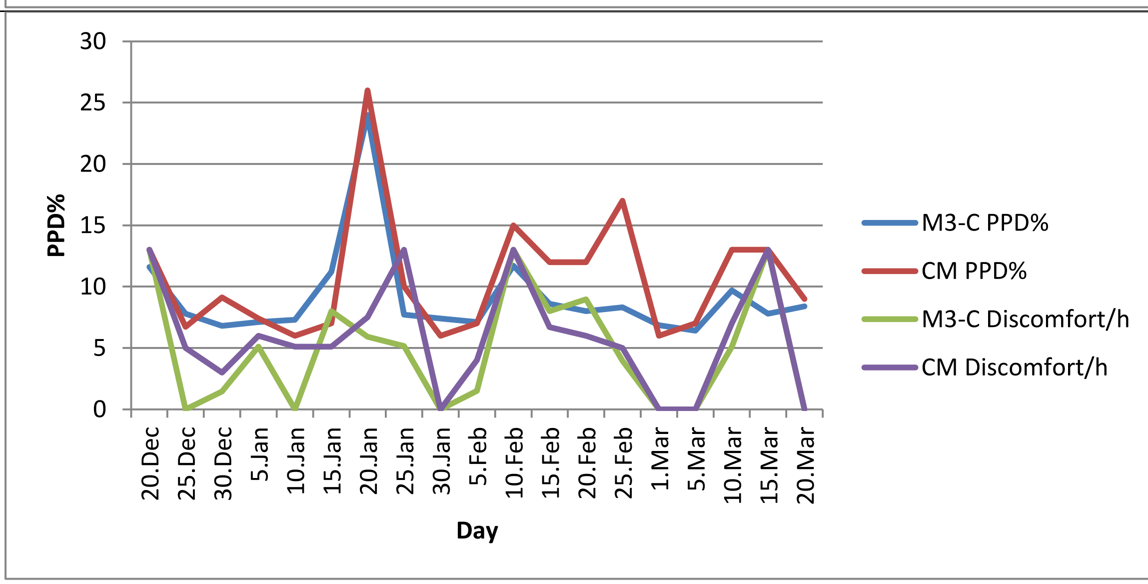
Table 4-12: PPD% and Discomfort Hours for M3-C and CM in summer and winter, Researcher.

PPD% and Discomfort Hours in M3-C (10 cm PCM) and CM

Summer

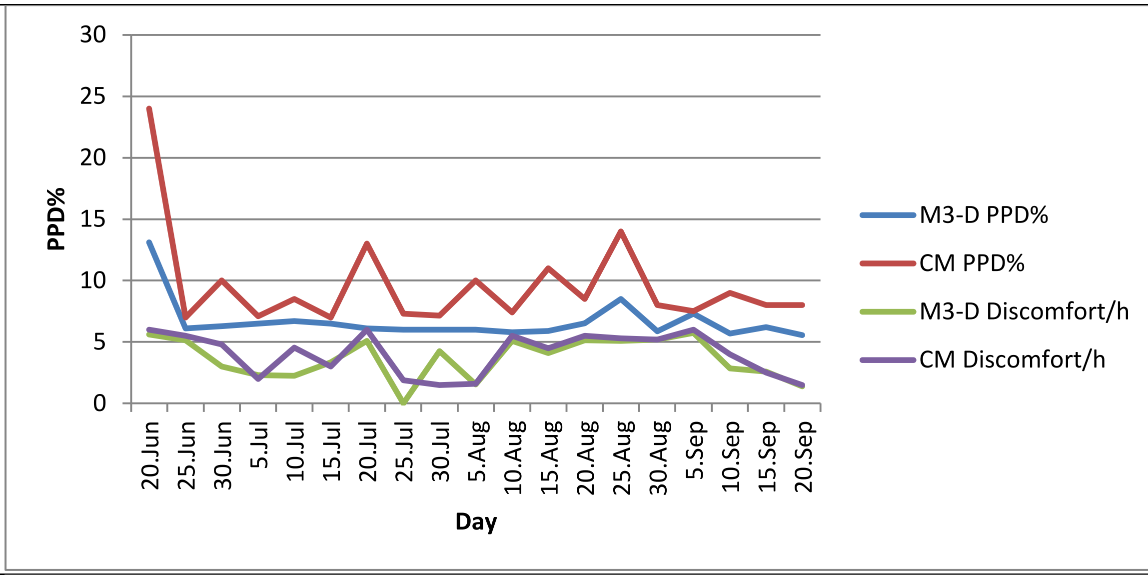
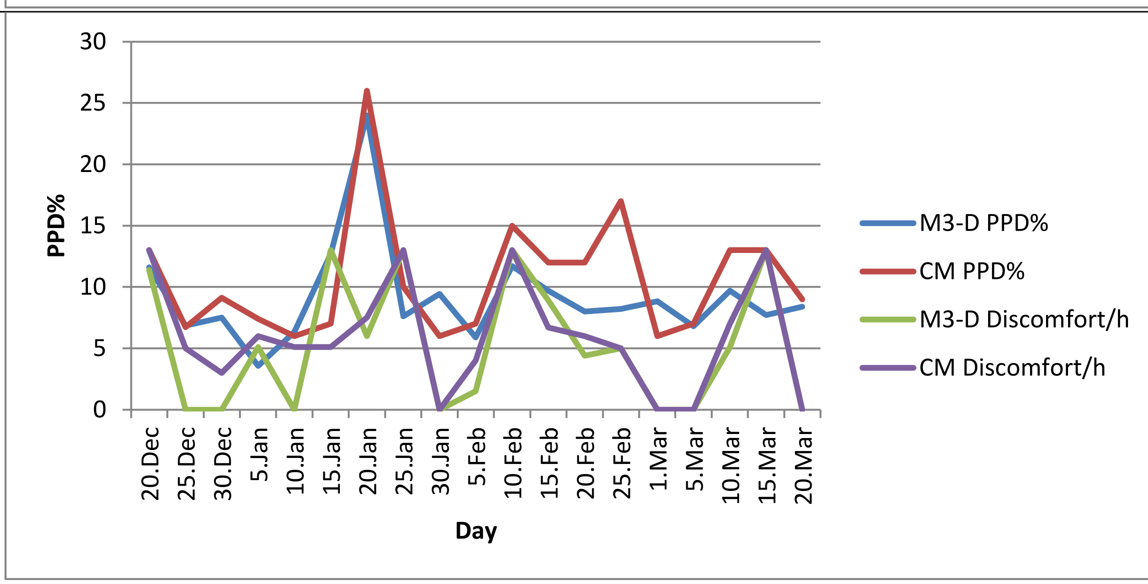


Winter



For the indoor thermal comfort hours for M3-D compared to CM, the values discomfort hours of this model were similar to the CM on some summer days, and on some other days it outperformed the CM. In winter, the values was varied, nevertheless, the M3-D was superior on some winter days, so the CM was superior on some days and the values were similar on other days. As for PPD%, M3-D kept the PPD% less than 20% in summer, while in winter the PPD% of M3-D was generally lower than the CM, but exceeded 20% on some days, as shown in (Table 4-13).

Table 4-13: PPD% and Discomfort Hours for M3-D and CM in summer and winter, Researcher.

<table>
<tr><th colspan="2">PPD% and Discomfort Hours in M3-D (12cm PCM) and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
</td></tr>
</table>

4.5 Heating and Cooling Loads

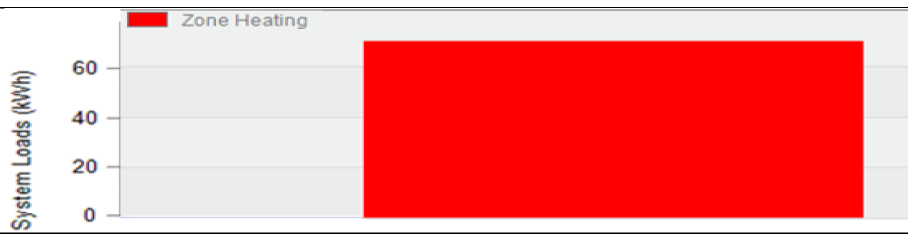
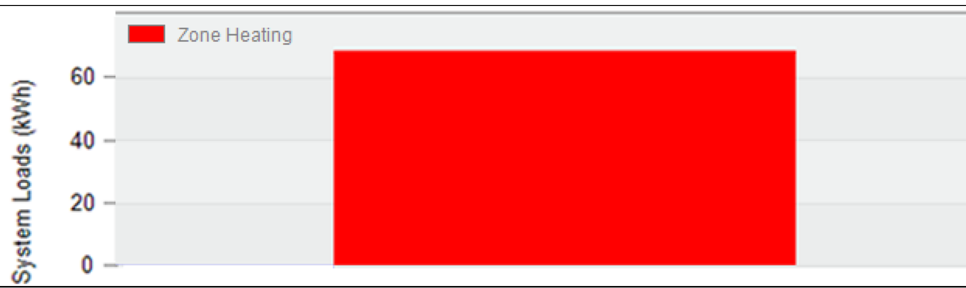
In this section, the DB results of heating and cooling loads in winter and summer respectively for each suggested scenario were studied and analyzed, and comparing it with the heating and cooling loads results for the base model CM.

4.5.1 Heating Loads Results

First, the heating loads results for the all models (including CM) in winter were as shown in (Table 4-14)

Table 4-14: Heating Loads for CM, M1, M2, M3-A, M3-B, M3-C and M3-D, Researcher.

	Heating Loads for CM	**System Loads**
Winter		140kWh
	Heating Loads for M1	**System Loads**
Winter		81.6 kWh
	Heating Loads for M2	**System Loads**
Winter		85.6 kWh
	Heating Loads for M3-A	**System Loads**

Winter		64.5 kWh
Heating Loads for M3-B		**System Loads**
Winter		71.2 kWh
Heating Loads for M3-C		**System Loads**
Winter		70.02 kWh
Heating Loads for M3-D		**System Loads**
Winter		69 kWh

The results of the heating loads in winter indicate that all PCM-TIM integration models were outperformed of CM significantly, and in varying degrees when compared to each other, as the results of M1 was close and outperformed M2, while at the same time M3 outperformed M1 and M2. On the other hand, when comparing the heating results of the M3, we find that M3-A results were the best among all the proposed and studied models, as shown in (Figure 4-1).

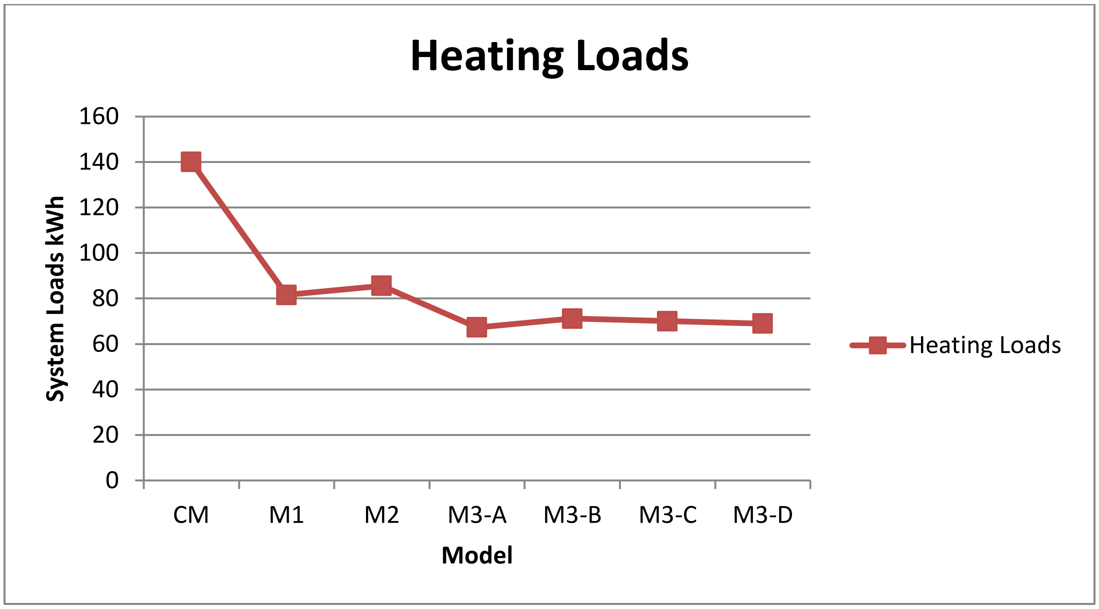
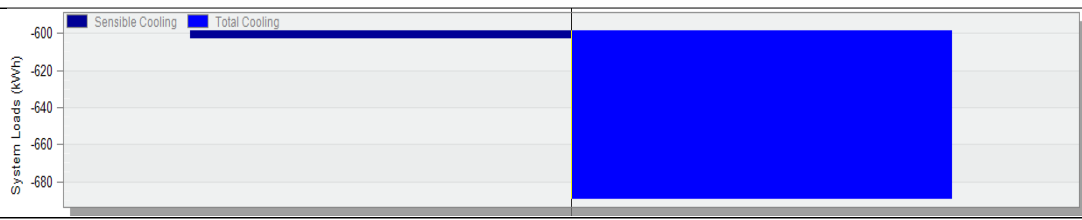
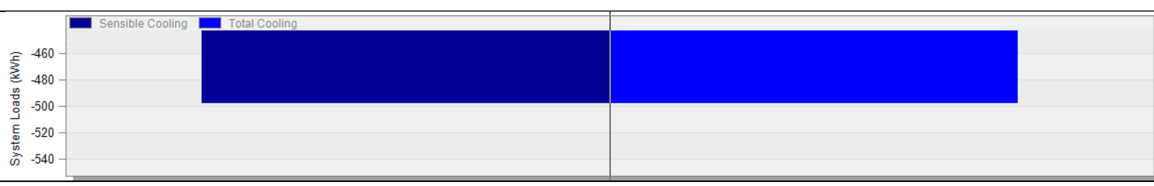


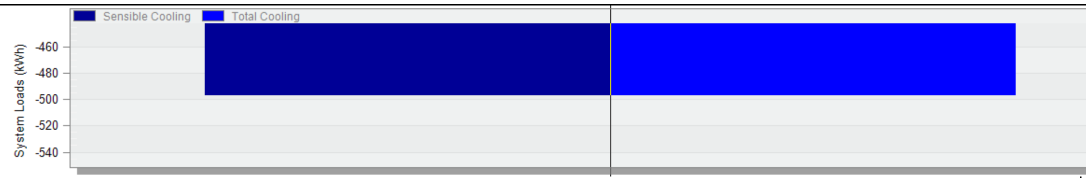
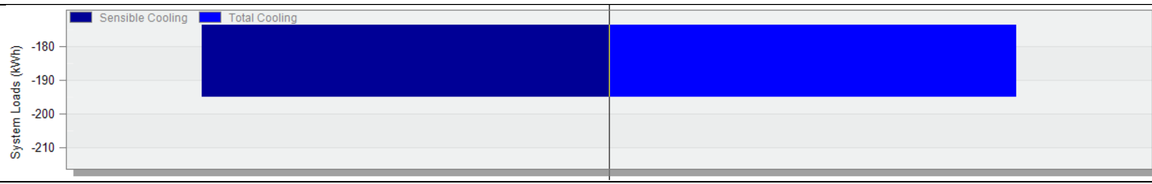
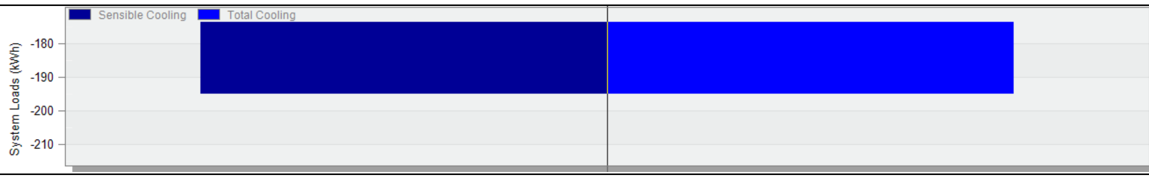
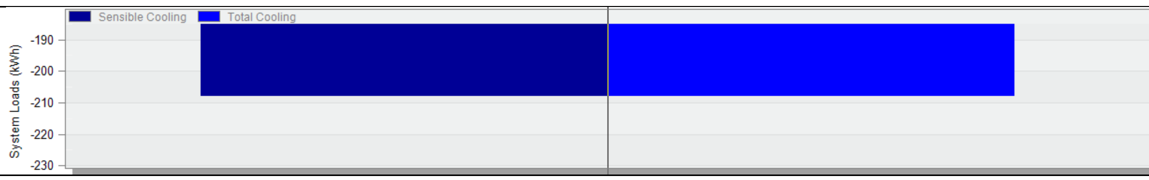
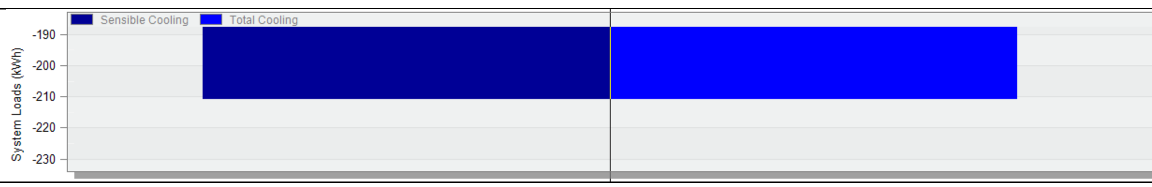
Figure 4-1: Heating loads for CM, M1, M2, M3-A, M3-B, M3-C and M3-D, Researcher.

4.5.2 Cooling Loads Results

The cooling loads results for the all models in summer were as shown in (Table 4-15)

Table 4-15: Cooling Loads for CM, M1, M2, M3-A, M3-B, M3-C and M3-D, Researcher

	Cooling Loads for CM	**System Loads**
Summer		689.3 kWh
	Cooling Loads for M1	**System Loads**
Summer		497.5 kWh
	Cooling Loads for M2	**System Loads**

Summer		496.7 kWh
Cooling Loads for M3-A		**System Loads**
Summer		194.8 kWh
Cooling Loads for M3-B		**System Loads**
Summer		196 kWh
Cooling Loads for M3-C		**System Loads**
Summer		207.8 kWh
Cooling Loads for M3-D		**System Loads**
Summer		210.7 kWh

The results of the summer cooling loads indicate that all PCM-TIM integration models were outperformed of the CM significantly when compared to each other, as the results of M1 was outperformed of M2, at the same time, M3 outperformed of M1 and M2. When comparing the results of the M3 scenarios, we find that they were all close to each other with an advantage for M3-A and M3-B, while the results of M3-A were the best among all the proposed and studied models as shown in (Figure 4-2).

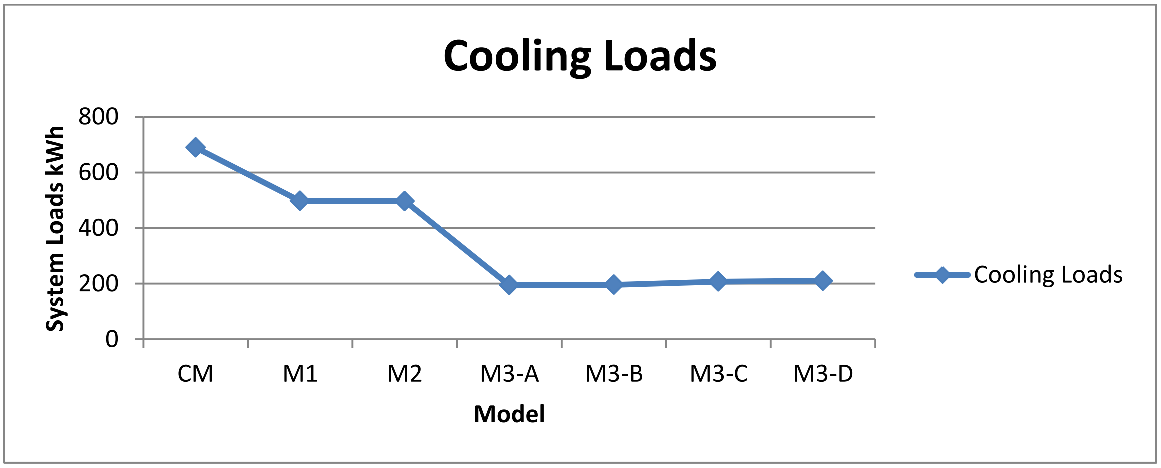


Figure 4-2: Cooling loads for CM, M1, M2, M3-A, M3-B, M3-C and M3-D, Researcher.

After analyzing the indoor air temperature, indoor thermal comfort and heating and cooling loads results by comparing each proposed scenario with the CM in Hebron, the M3 proved its worth in achieving the best thermal comfort level and thus the greatest reduction in the use of HVAC.

Regarding the best PCM thickness, 6 cm was the best choice, while the 8 cm and 10 cm thickness did not give greater tangible effects than the 6 cm in thermal comfort. As for the 10 cm thickness, it showed opposite results in heat gain results on some days, such as a greater increase in the temperature inside the space during the summer and thus the building's need for cooling energy would be higher.

Therefore, after analyzing the results of the indoor air temperature, the M3-A proved its efficiency in reducing the indoor air temperature and thus the cooling energy in summer and raising the indoor air temperature thus reducing the heating energy in winter.

On the other hand, all models outperformed the CM in reducing heating and cooling loads in winter and summer. In general, the results indicated that the M3 gave an advantage in reducing these loads, and in particular the M3-A was the best in reducing loads in both seasons.

Accordingly, M3-A was the best scenario for storing thermal energy in the summer and using it again to heat the building in the winter by absorbing thermal energy and storing it in the PCM and isolating it from the surroundings; for reuse when the temperature of the indoor space becomes less than the comfort level, thus improving the thermal comfort conditions in the indoor space and at the same time reducing the use of non-renewable energy by reducing the heating and cooling loads.

Regarding the heat flow for the selected model (M3-A), the PCM will act as an energy generation and this energy will be transferred from the PCM to the inside and outside, as shown in (Figure 4-3).

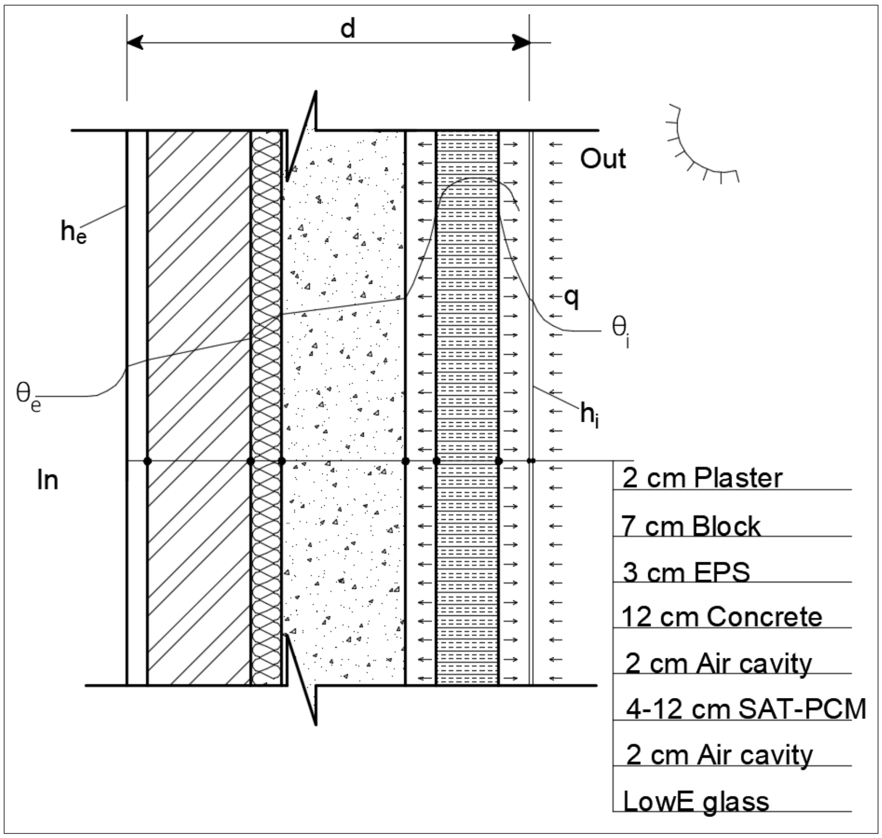


Figure 4-3: heat flow for the M3-A, Researcher.

4.6 Heat Flow Simulation results

For the selected model, a heat flow simulation using Ansys Fluent 2024 R1 Software was performed for this wall in summer (outside temperature 35 C) and winter (outside temperature -2 C), and it were as shown in (Figure 4-4, Figure 4-5, Figure 4-6 and Figure 4-7).

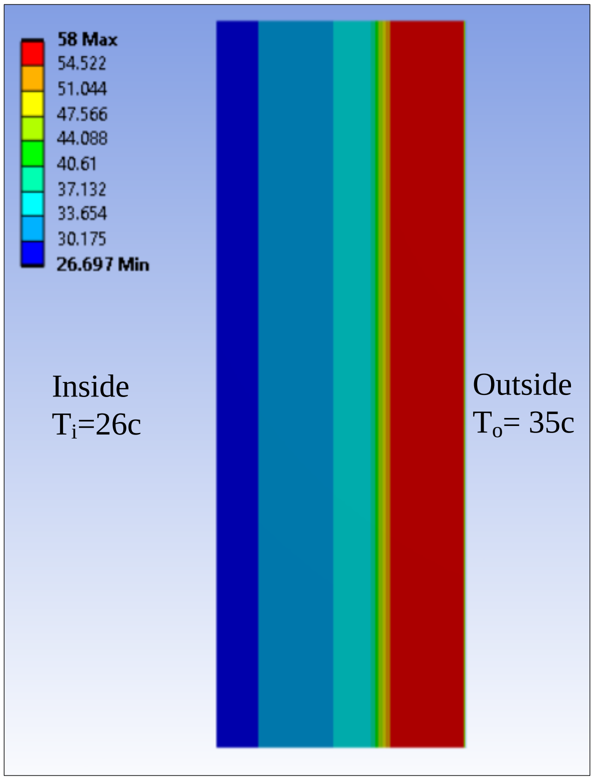


Figure 4-4: Heat flow simulation for M3-A in a summer day, Researcher using ANSYS Fluent Software, researcher

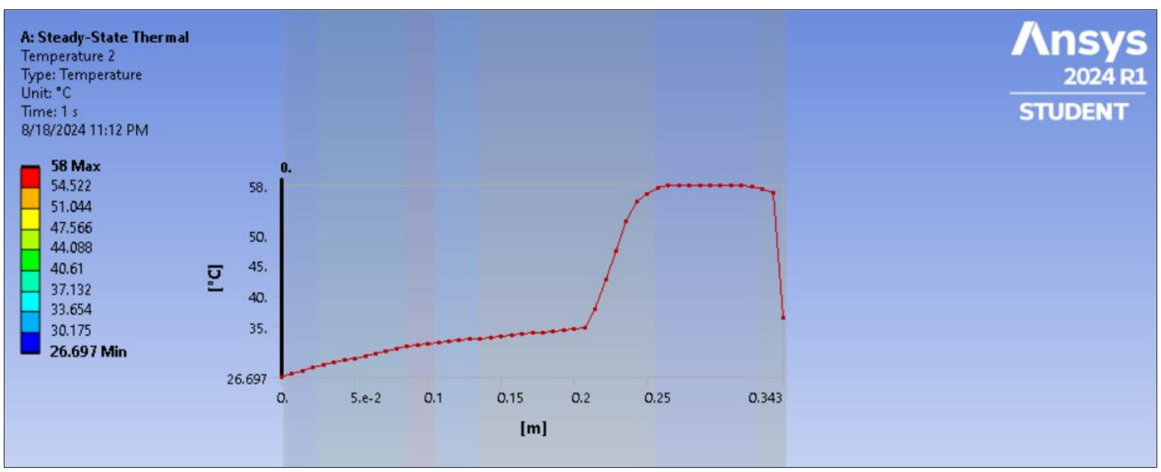


Figure 4-5: Heat flow temperature diagram for M3-A in a summer day, Researcher using ANSYS Fluent Software, researcher

As shown in (Figure 4-4), the outside temperature is 35 C while the SAT-PCM temperature is 58 C; by using the LowE glass layer absorbs infrared rays and prevents them from returning to the outside again, and by using the air cavities before and after the PCM layer which act as insulating mediums to save the energy in the PCM layer as much as possible; also, the insulation layer works an important function to isolate unwanted heat to the interior space; so, by using these layers the indoor temperature has decreased from 35 C to about 26 C.

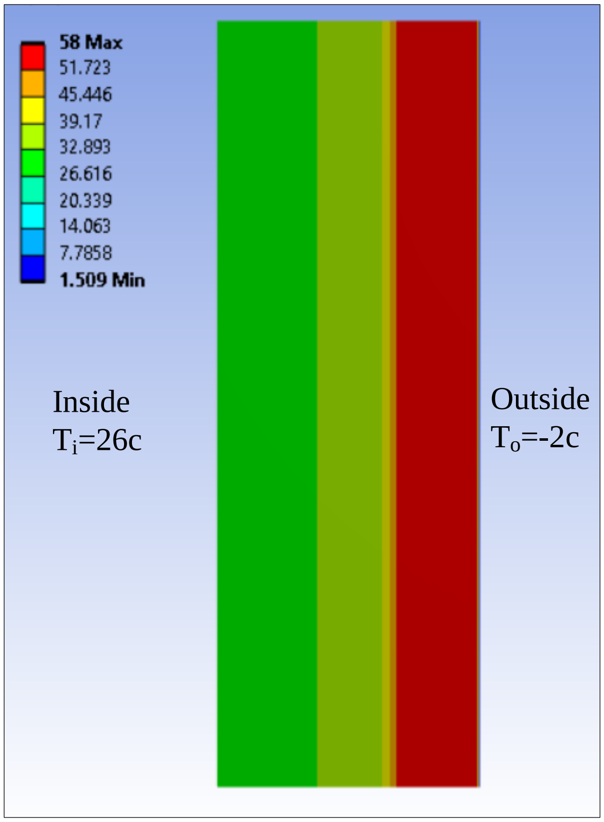


Figure 4-6: Heat flow simulation for M3-A in a winter day, Researcher using ANSYS Fluent Software, researcher

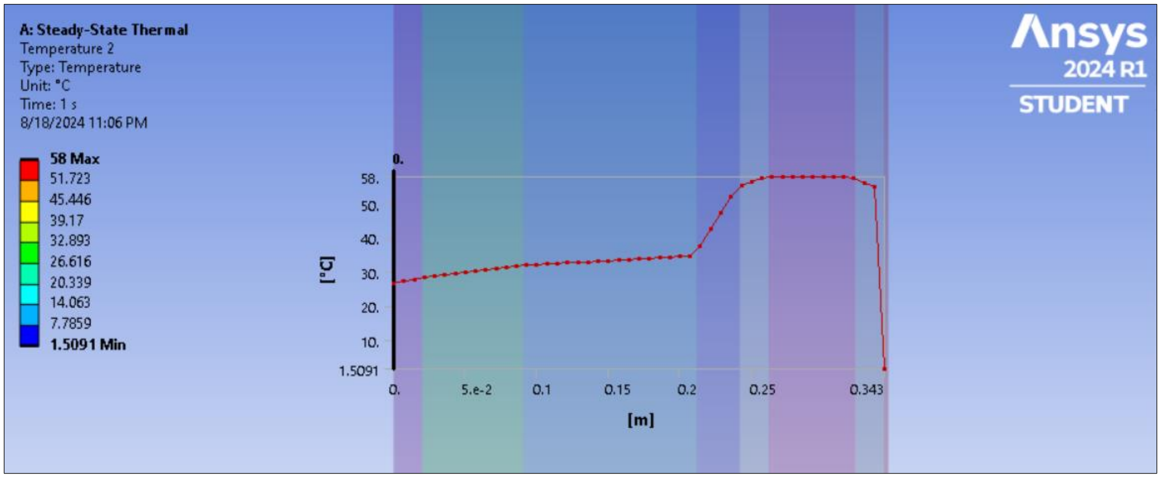


Figure 4-7: Heat flow temperature diagram for M3-A in a winter day, Researcher using ANSYS Fluent Software, researcher

In winter heat flow simulation, as shown in (Figure 4-6), when the outside temperature is -2 C while the SAT-PCM temperature is 58 C; by using the M3-A wall design, the indoor temperature has increased from -2 C to about 26 C. All of these contributions are to control the indoor air temperature so achieve thermal comfort while reducing HVAC consumption.

In case of discharge (at night and in winter season), fans suggested to suck warm air from the air cavity into the room mechanically (to warm up the room), as shown in (Figure 4-8)

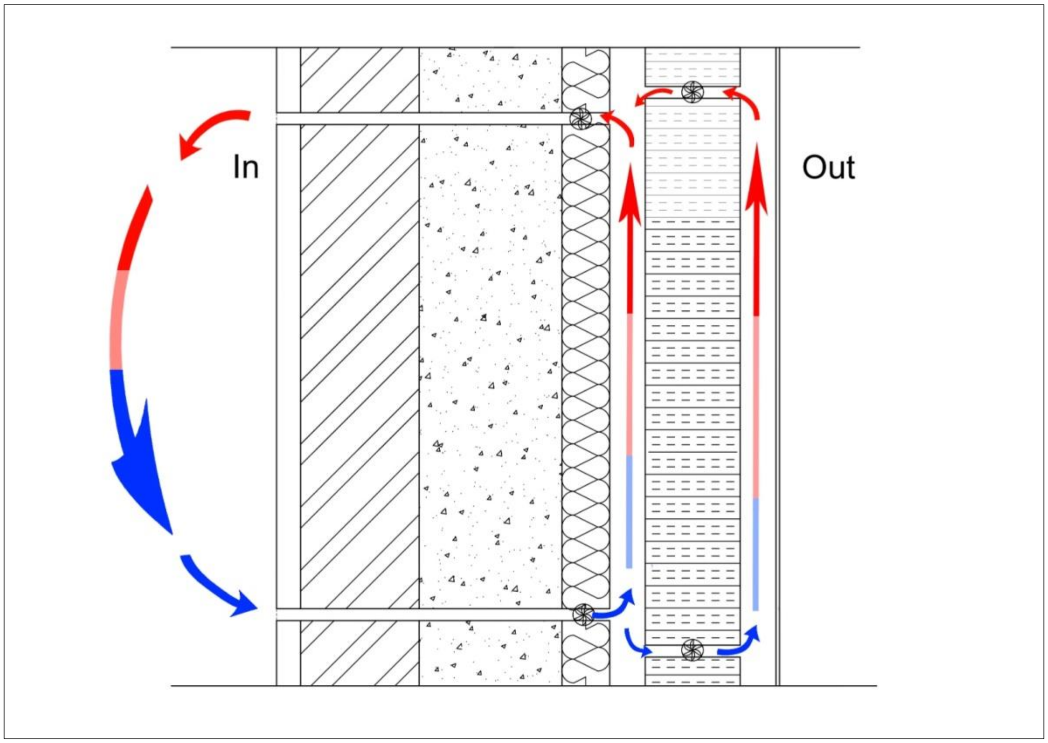


Figure 4-8: air circulation in M-3, Researcher

In order to reduce energy losses for the building environment, it will be far more effective to use air conditions to manage the physical parameters of thermal comfort; using walls with a thermal mass to regulate the energy demands entering or leaving the building. This wall will serve as a modulator of outside ambient temperature and a source of comfort for building occupants, requiring less use of air conditioning equipment.

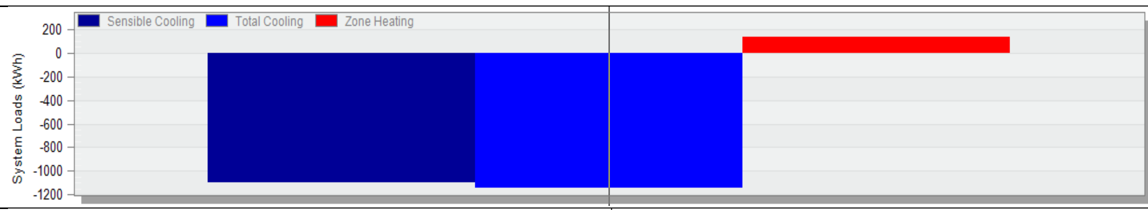
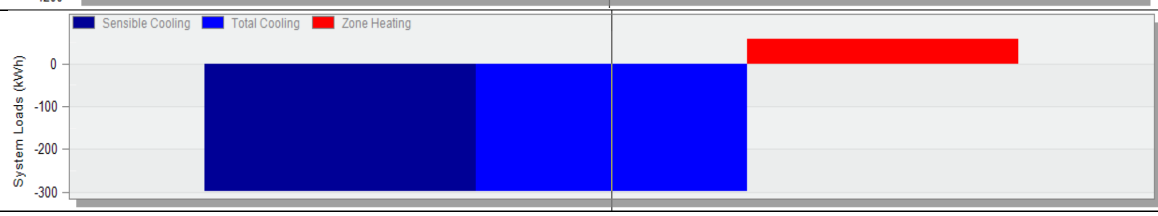
- For the installation concept, it was suggested that the glazing layer will install in a steel structure, with 60*60 panels, so that the panel can be disassembled and maintained or replaced in the event of breakage or damage. While the PCM is in the form of 60*60 molds and mounted on frames, these molds can be installed and disassembled for maintenance or in the event of any defect in the mold, it can be replaced also it can be used for install electrical extensions. And it can be conducted in future studies.

4.7 Cost Calculations

Cost calculations were made to determine whether the PCM-TIM integration system for the selected model (M3-A) was economically viable, the extent of this feasibility and the payback period.

Initially, the annual heating and cooling loads for CM and M3-A were calculated and were as follow (Table 4-16):

Table 4-16: Annual Heating and Cooling Loads for CM and M3-A, Researcher.

Annual Heating and Cooling Loads		Annual Loads
CM		1279.5 kWh
M3-A		357.5 kWh

According to Hebron Electric Power Co.(HEPCo) in 2024, the electricity price per kilowatt hour is 0.5607 Nis which equal 0.21 US$ for the prepaid electric meters.

First, to calculate the initial cost of the PCM, first; the PCM volume in the external southern wall for the studied zone is 0.513 m^3 and the PCM density is 1280 kg/m^3, according that; the total mass material is 656.64 kg, while the price of SAT is 0.85$/kg; the PCM cost equal 558.144$.

So, the price of the annual saving electricity equal 922*0.21=193.62$. While the payback period equation is the Initial Cost / Annual Energy saved= 558.144/193.62= 2.88 years which is almost 3 years.

As shown in (Table 4-17) the saving cooling and heating loads when using M3-A is equal 71.7% and 53.9% respectively while the annual saving loads were 72% when compared to the CM loads results.

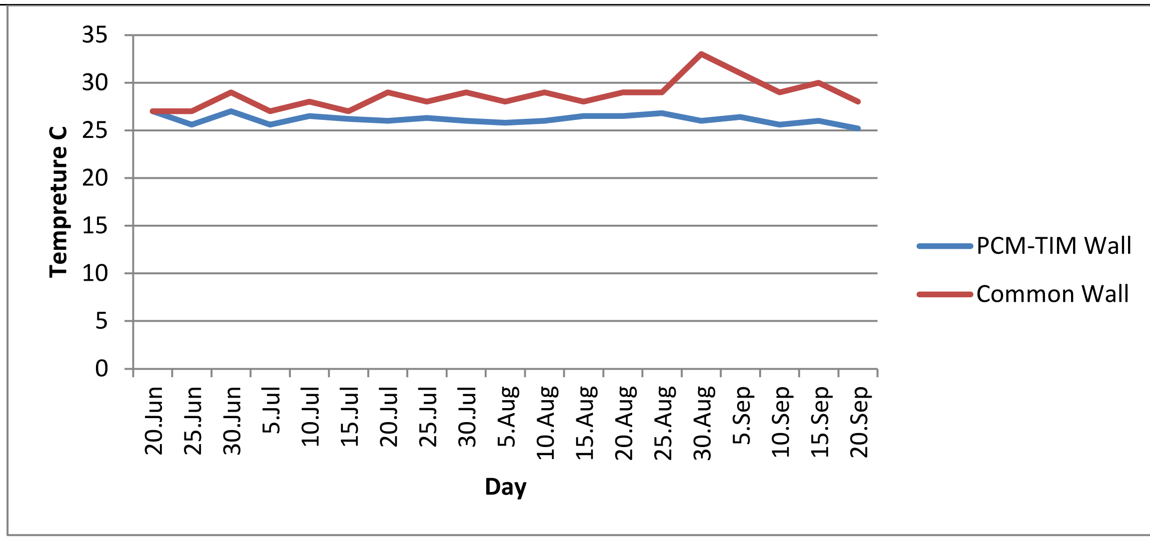
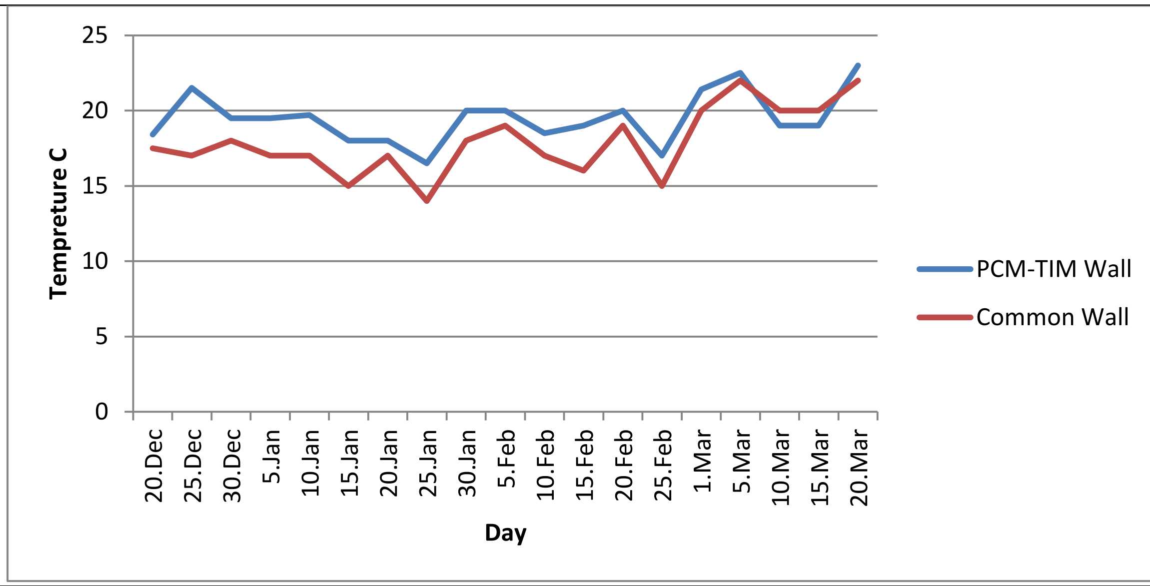
Table 4-17: Heating and cooling loads: results, saving and payback period for M3-A, Researcher.

	Summer cooling loads kWh	**Winter heating loads kWh**	**Annual loads**
CM	689.3	140	1279.5
M3-A	194.8	64.5	357.5
Energy saved	494.5	75.5	922
Saving%	%71.7	53.9 %	72 %
Payback period	3 years		

4.8 PCM-TIM integration in the existing building

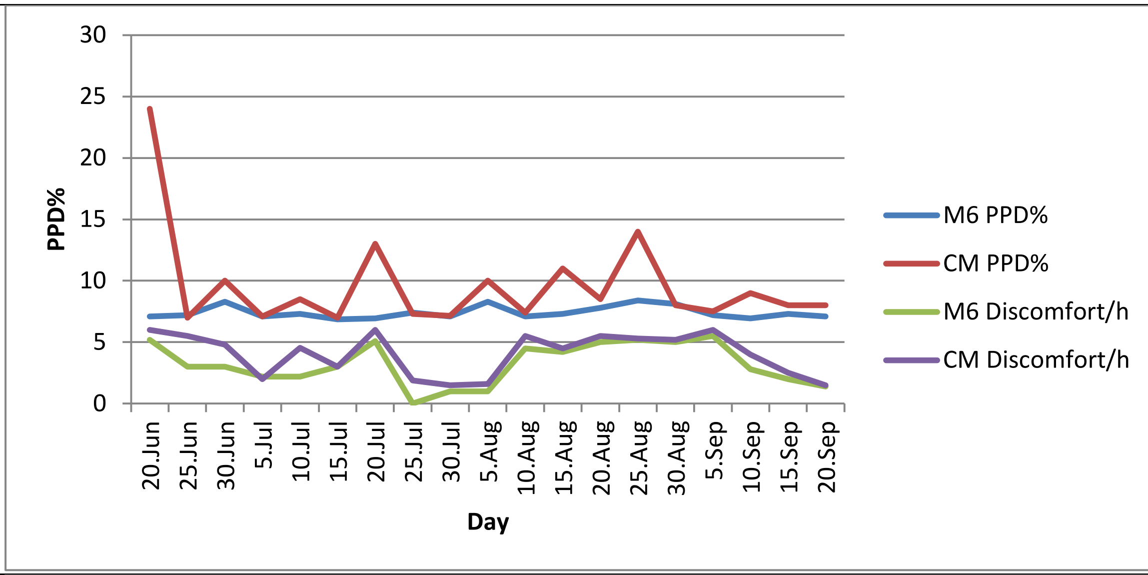
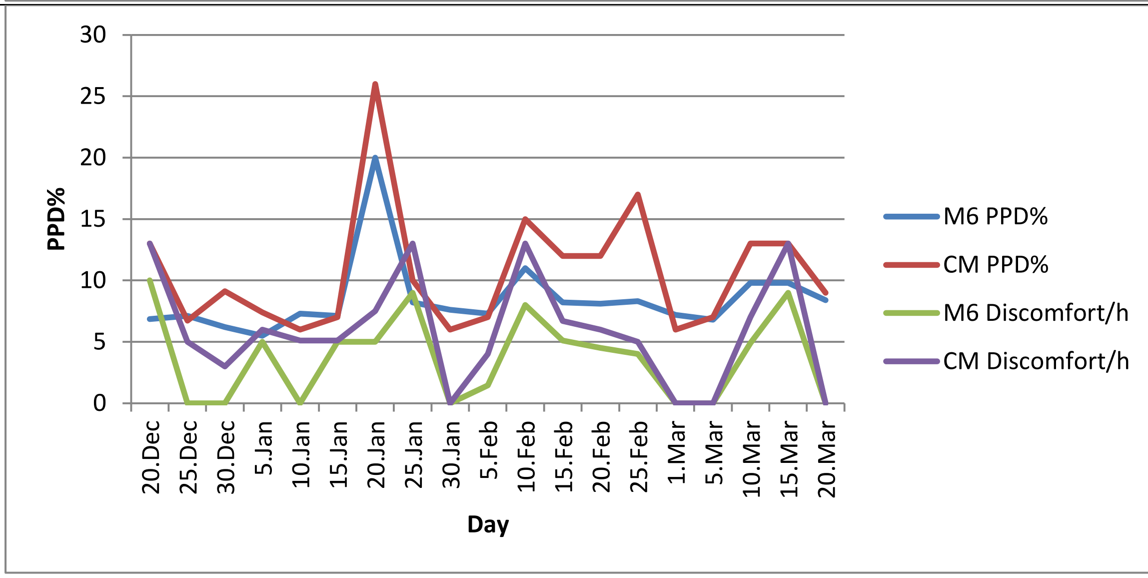
In the case of the existing building, when applying the selected model and PCM thickness in an insulated wall, the results showed a significant and positive enhancement in reducing the indoor air temperature which reducing the cooling energy in the summer when compared to the CM, as well as in the winter, where the use of M4 showed a significant improvement by increasing the indoor air temperature and thus reducing the heating energy in the winter, as shown in (Table 4-18).

Table 4-18: Indoor Air Temperature results for M4 and CM in summer and winter, Researcher.

<table>
<tr><th colspan="2">Indoor Air Temperature in M4 (6 cm PCM) and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
</td></tr>
</table>

By coming to the results of the indoor air temperature, the results indicated that the values between the two models were close on some summer days, while M4 was superior on most of summer days. In winter, the M4 showed a significant advantage in the number of comfort hours over the CM on all discomfortable days. As for PPD%, M4 kept the PPD% less than 20% on all summer and all winter days unlike CM, as shown in (Table 4-19).

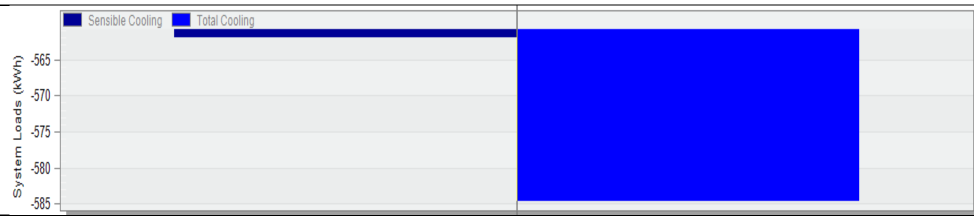
Table 4-19: PPD% and Discomfort Hours for M4 and CM in summer and winter, Researcher.

<table>
<tr><th colspan="2">PPD% and Discomfort Hours in M4 (6 cm PCM) and CM</th></tr>
<tr><td>Summer</td><td>
</td></tr>
<tr><td>Winter</td><td>
</td></tr>
</table>

4.8.1 Heating and Cooling Loads

And when talking about the heating and cooling loads in winter and summer for M4, the results were as shown in Table 4-20)

Table 4-20: Heating and cooling loads for M6, Researcher.

	Heating Loads for M4	System Loads
Winter		72.2 kWh
	Cooling Loads for M4	**System Loads**
Summer		584.6 kWh

When comparing the existing building before adding PCM and applying the proposed wall design on the southern facade to it, the results showed that PCM gave a noticeable positive effect in reducing the heating and cooling loads in the existing insulated buildings compared to the traditional insulated building, as shown in (Figure 4-9)

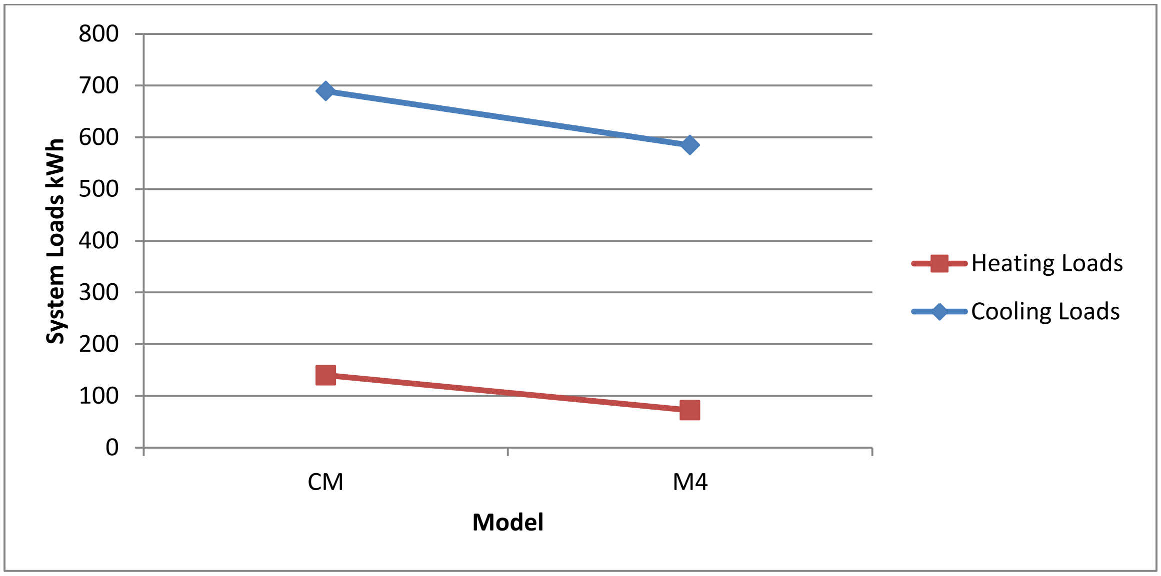
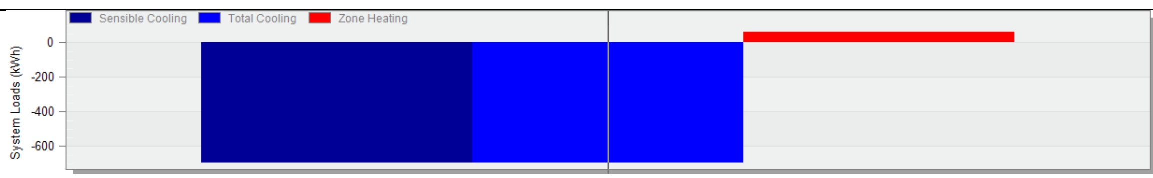


Figure 4-9: Heating and cooling loads for M4 in winter and summer, Researcher.

4.8.2 Cost Calculations

For the cost calculation for the M4, by calculate the annual heating and cooling loads the result was as following (Table 4-21):

Table 4-21: Annual Heating and Cooling Loads for M4, Researcher.

Annual Heating and Cooling Loads for M4	Annual Loads
 	756.6 kWh

As shown in (Table 4-22) the saving cooling and heating loads when using M4 is equal 15.2% and 48.4% respectively while the annual saving loads were 40% when compared to the CM loads results.

By applying the previous cost calculation at the same volume, the payback period was as following;

The electricity price per kilowatt hour is 0.21 US$ for the prepaid electric meters.

For PCM cost calculation for the same volume wall, the total mass material is 656.64 kg, while the price of SAT is 0.85$/kg; the PCM cost equal 558.144 $.

So, the price of the annual saving electricity equal (522.9*0.21=109.81$). While the payback period equation is the Initial Cost / Annual Energy saved= 558.144 /109.81= 5 years.

Table 4-22: Heating and cooling loads: results, saving and payback period for M4

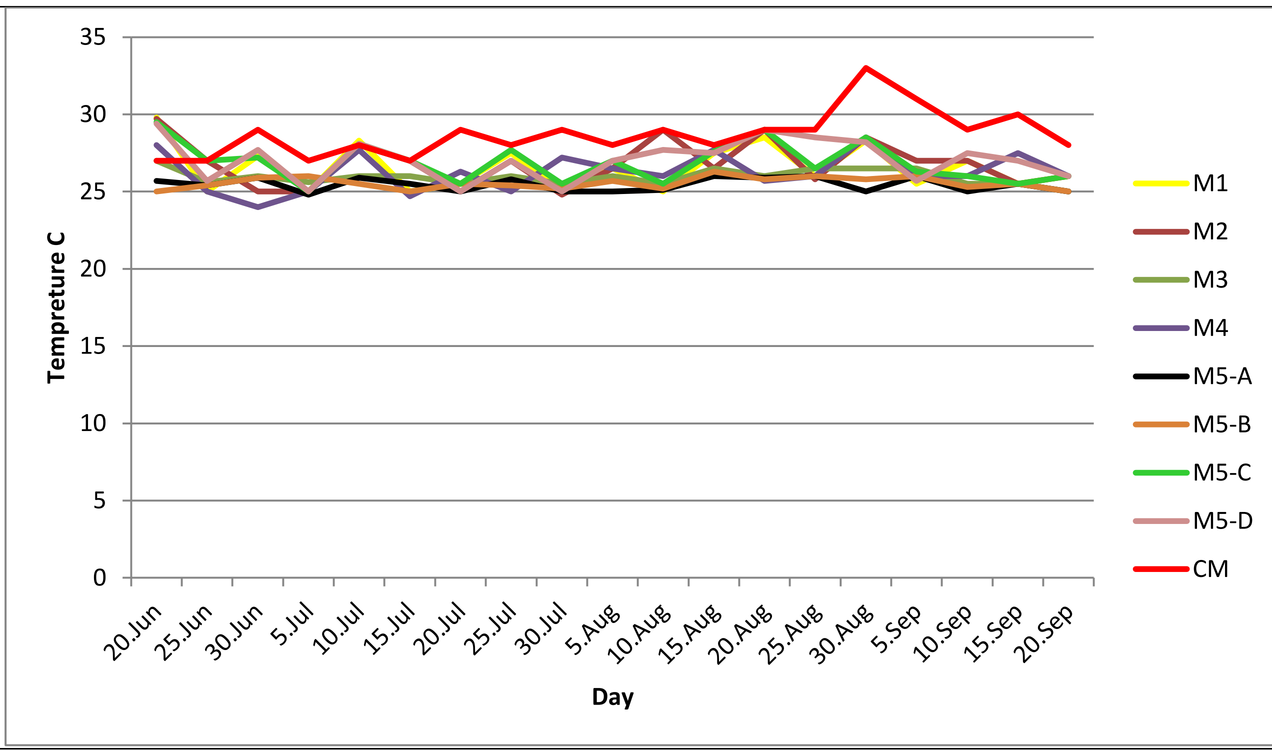
	Summer cooling loads kWh	Winter heating loads kWh	Annual loads kWh
CM	689.3	140	1279.5
M4	584.6	72.2	756.6
Energy saved	104.7	67.8	522.9
Saving%	15.2%	48.4 %	40 %
Payback period	5 years		

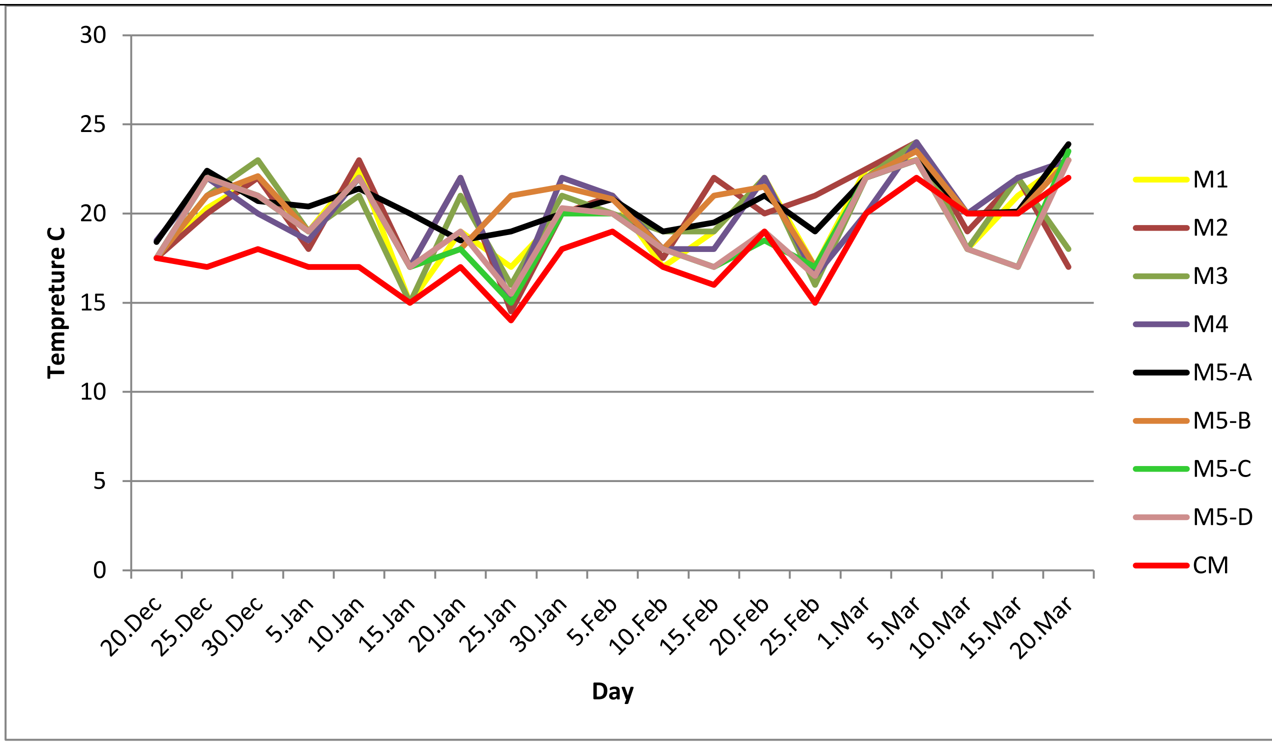
Chapter 5 Conclusion

5.1 Indoor Air Temperature

In conclusion, after comparing all the proposed models with the CM and with each other as shown in (Table 5-1), and after analyzing the results, it was found that M3 outperformed all the proposed models due to enhancing the storage of thermal energy from the sun by using Lowe glass and isolating it from the surroundings by the presence of an air cavity, as well as enhancing the thermal storage and isolating the heat transfer by using the insulator after the internal air cavity. The M3-A model also proved its efficiency in particular in storing seasonal energy in the summer and winter climatic conditions in Hebron city in Palestine.

Table 5-1: Indoor air temperature of all suggested scenarios in summer and winter, Researcher.

Indoor Air Temperature comparison in all suggested scenarios	
Summer	

Winter	

For the indoor thermal comfort, and when comparing all models with the CM, the results showed that the CM is a bad case in achieving thermal comfort for occupancy in summer (Figure 5-1) and winter (Figure 5-2), while M3-A kept the PPD% less than 20%in both winter and summer seasons; which according to ASHRAE 55 standards achieve thermal comfort standards for users, (Figure 5-3 and Figure 5-4).

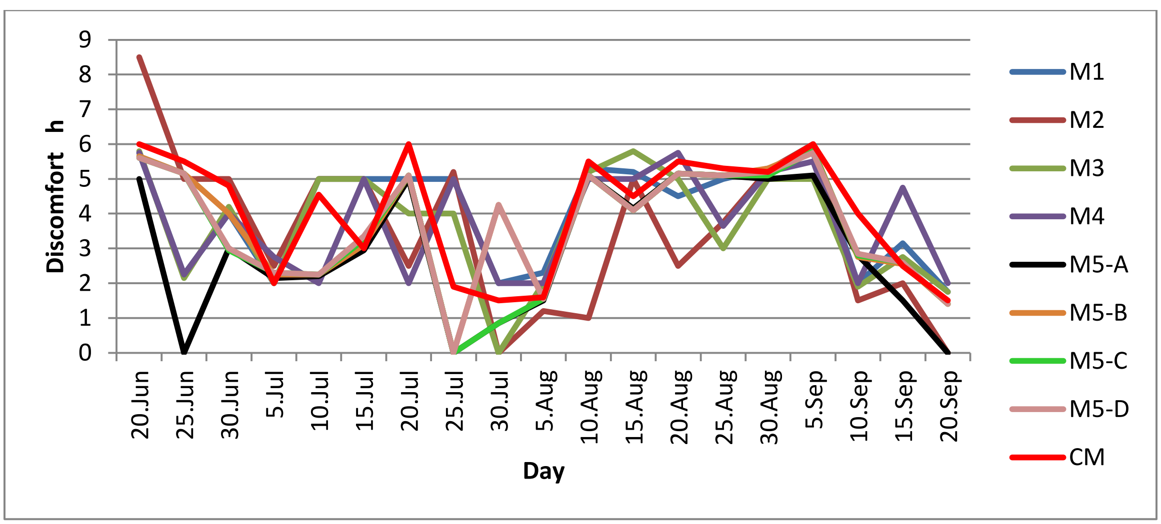


Figure 5-1: Discomfort Hours for all suggested models in summer, Researcher.

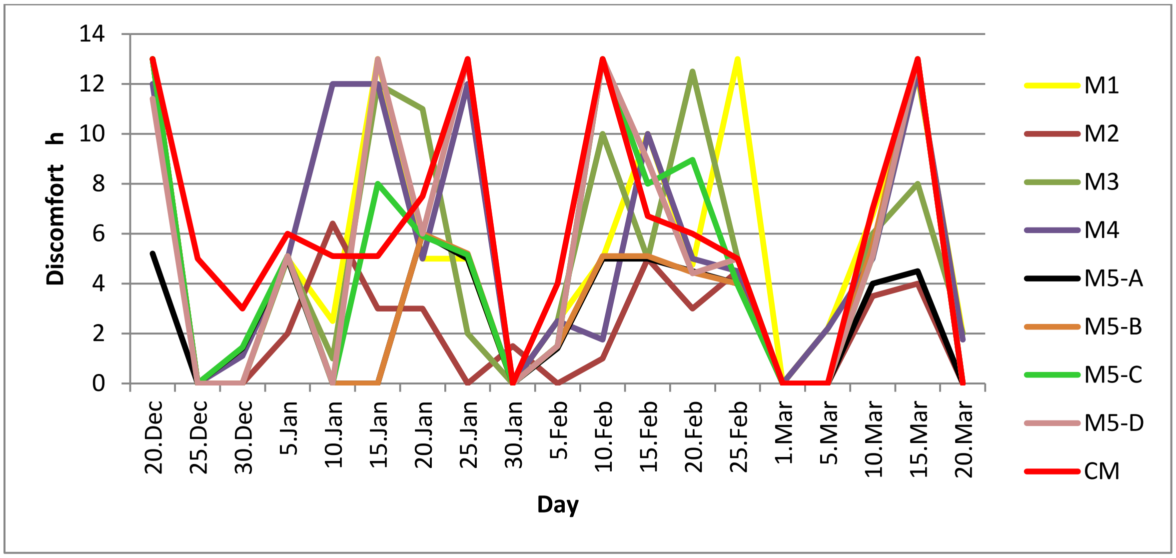


Figure 5-2: Discomfort Hours for all suggested models in winter, Researcher.

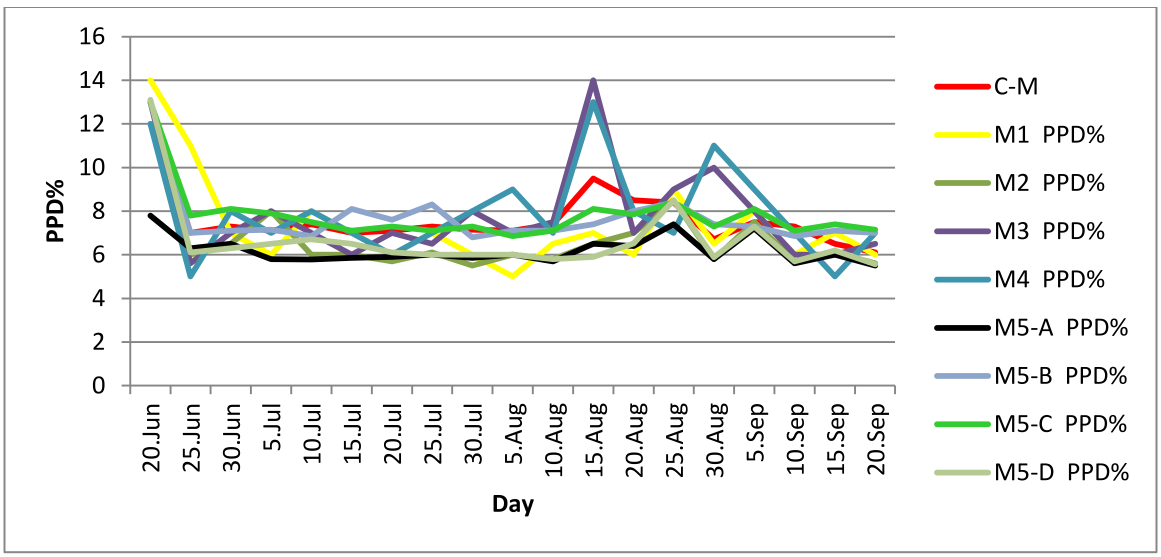


Figure 5-3: PPD% for all suggested models in summer, Researcher.

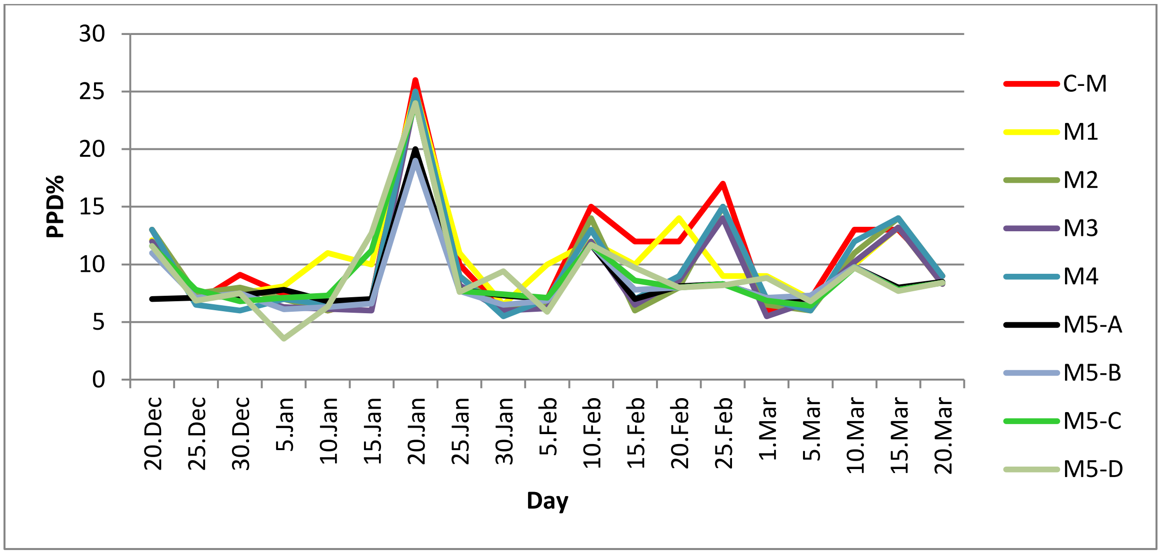


Figure 5-4: PPD% for all suggested models in winter, Researcher.

5.2 Heating and Cooling Loads

In general, as expected, when comparing heating and cooling loads for all the proposed models with the CM and with each other (Figure 5-5 and Figure 5-6), all PCM-TIM integration models outperformed of CM, and in particular the M3 outperformed the rest of the scenarios. The M3-A results were the best in reducing heating loads in winter by more than 50% when compared to CM, and reducing cooling loads in summer by 71.7%. The annual savings rate for heating and cooling loads when using the M3-A was about 72%, and thus the best savings in HVAC costs and in non-renewable energy consumption. For the cost calculation, the payback period was calculated according to the annual energy saved, PCM initial cost, PCM properties and the electricity cost in Palestine; the result of the payback period is equal almost 3 years, which is consider as a cost effective design.

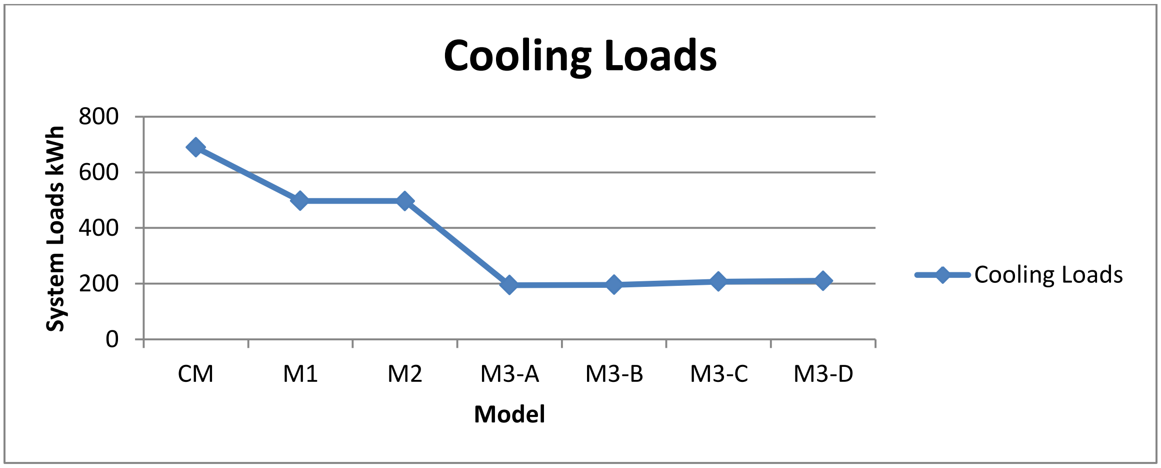


Figure 5-5: Cooling loads for all models in summer, Researcher.

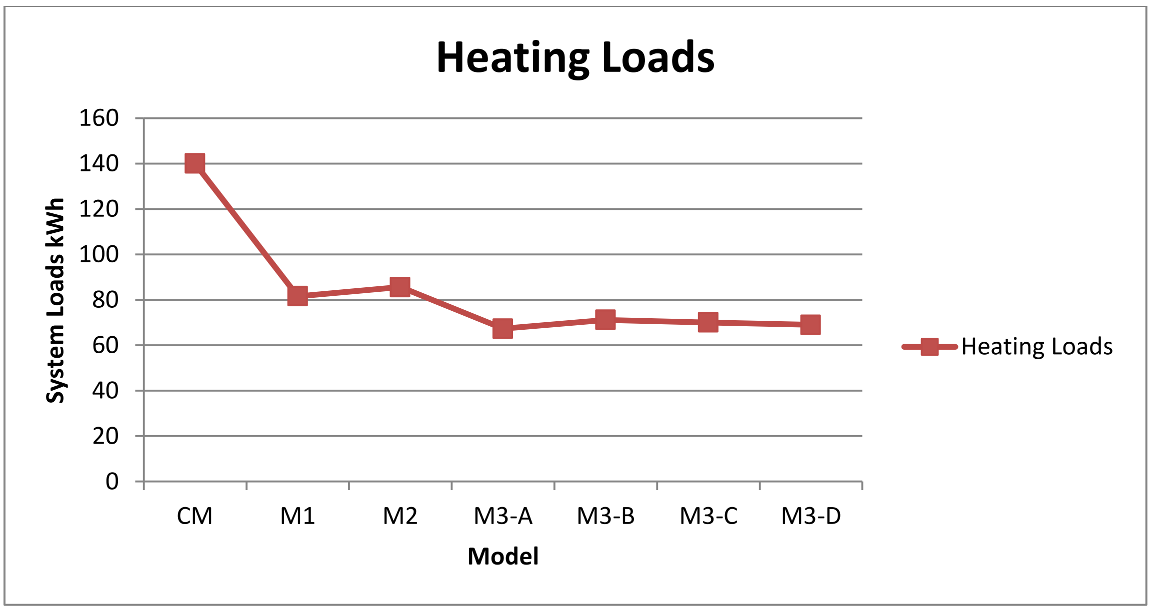


Figure 5-6: Heating loads for all models in winter, Researcher

5.3 Summery

After studying and analyzing the results, the M3-A proposed design proved its efficiency in storing seasonal heat, as the lowE glass layer helps absorb a greater amount of thermal energy and prevents it from returning to the outside. Then this heat is transferred by convection to the SAT-PCM layer, which in turn absorbs and stores this heat in the summer and begins to solidify thanks to its latent heat properties. When the temperature of the PCM reaches 58C, this material begins to melt to release this stored heat; in order to preserve the thermal energy as much as possible and for the longest possible period in this material, it was suggested to place another air cavity after the PCM layer, followed by the insulation layer. In the discharge process, it was suggested to place vents in the wall sections that work mechanically. When the air inside the room cools, these vents draw hot air from the PCM surroundings and then introduce it into the room, while at the same time drawing cold air from the room to the PCM surroundings to reheat it again.

Regarding the thickness of the PCM, after reviewing the literature, they mentioned that its thickness ranges from several centimeters to tens of centimeters. Accordingly, the PCM was studied in several different thicknesses, starting in some models from three centimeters to 12 cm, in the final proposed design the same model was studied each time with changing the thickness of the PCM from 6,8,10 and 12 cm as M3-A, M3-B, M3-C and M3-D respectively, all the proposed cases were better than the CM case as well as better than the other proposed scenarios, and on the other hand, when comparing the results of the internal thermal comfort and the level of satisfaction among the users, it was found that the M3-A with a thickness of PCM 6 cm was sufficient to achieve all these positives, and in the final stage of the design, this design proved its economic efficiency when it provided annual heating and cooling loads reductions of approximately 72% compared to the CM wall. In the last part of this research, the possibility of applying the proposed design to an external wall in the southern facade of a thermal insulated existing building was studied, The results of the M4 design proved its efficiency in improving the thermal conditions of the internal space and improving the level of satisfaction among users when compared to its original state.

Hence, we find that the possibility of applying seasonal heat storage is possible by applying a high-mass thermal wall and storing heat in materials with a high latent heat that enables it to absorb heat and store it for a long period. In return, this heat can be released on cold days.

Note that the application of M3-A can be applied as part of the external facade and is not necessarily on the entire building envelope and works on the trombe wall and solar chimney principles.

5.4 Limitations and Challenges

In this research, there are some limitations that may affect to the research results,

- One of the important limitation in this research that the research solution valid in the glazed façades (cladding system) buildings in Hebron - Palestine
- Another limitation is verifying the integration application on the eastern and western facades and compares its results with those of the southern facade.
- Another limitation is the lack of study of the structural system to verify the technical installation and verify the possibility of installing this model in buildings.

One the other hand, there's important challenge for examine the application of the model on the wall in terms of stability, economic issues and community awareness about the use of glass in facades.

5.5 Recommendation and Future Works

According to the research results, I recommend for using PCM and TIM for seasonal energy storage in the external wall construction to implement the PCM layer in the outer wall surface and the TIM in the inner wall surface; that will enhance the thermal storage and decrease the heat flow rate between inside and outside. On the other hand, this arrangement will save the buildings' energy consumption, thus, decreasing the buildings' heating and cooling loads. According to the orientation, the southern façade (most exposed to sunlight in winter) achieved satisfactory results in storing thermal energy seasonally in the exterior wall of the residential building in Hebron.

Based on the research results, I recommend future works to search about:

- Future studies on the application of PCM integration in other facades of local buildings.
- Future studies on including PCM integration in roofs for upper floors along with its integration in walls.

- Future studies on the use of PCM in windows and its integration with walls and roofs (for upper floors).

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