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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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.

I. ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS

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) 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) 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)

II. STUDY AREA

A. 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). 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.

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). According to

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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)

B. *Sample Selection Criteria*

The selected sample was a type of common residential building design located in Hebron-Palestine.

Building description: a living room (18 m2 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 II-A**Error! Reference source not found.**).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.

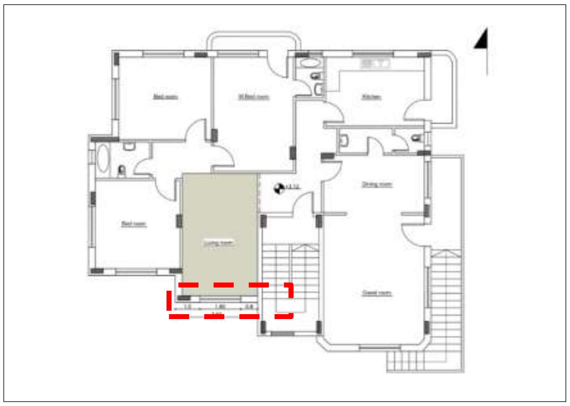

Figure II-A: the selected building plan, the south façade bordered by red line and the targeted room is highlighted

C. *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.

III. Thermal Insulation Materials (TIMs)

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)

A. *TIM selection*

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. (Huang et al., 2020)

Due to its positive properties in density, thermal conductivity, lifetime and cost; the expanded polystyrene EPS was chosen. Some variables have been fixed as shown in the Table I below.

Table I: the constant values in calculations

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

To calculate the thickness of the EPS it's depending on its properties; and by fixing some variables in across sectional wall (Figure III-A), such as the assumption of external temperature (20 C) and sectional area ($20cm^2$),through mathematical equations (Eq. 1and Eq. 2) the R-value, U-value, q, power losses and discharging time were calculated.

Based on the relationship curve between Q and thickness, the appropriate thickness was between 3-5 cm. Accordingly, the insulation thickness was fixed at 3 cm as shown in (Figure III-B).

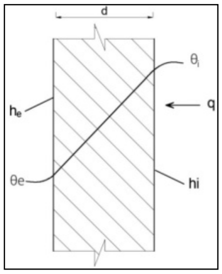

Figure III-A: cross sectional wall

$$\mathrm{U_{total}} = \frac{1}{\mathrm{R_{total}}} = \frac{1}{\left(\frac{1}{\mathrm{h_i}}\right) + \Sigma\left(\frac{\mathrm{d_i}}{\lambda_\mathrm{i}}\right) + \left(\frac{1}{\mathrm{h_e}}\right)} \qquad \text{Eq. 1}$$

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

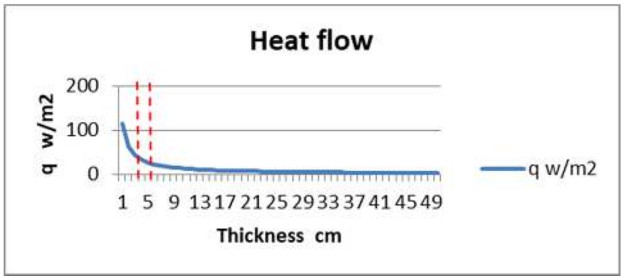

Figure III-B:the relation between thickness and heat flow

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

IV. PHASE CHANGE MATERIALS (PCM)

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) (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. 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)
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. (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. (Boemi, Irulegi and Santamouris, 2015) Storage periods range from short-term daily storage to long-term storage, usually between seasons (called seasonal storage).

A. Long-Term (seasonal TES) PCM selection

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. 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. In terms of cost, the cost comparison for both types showed that salt hydrates are the more cost effective option than paraffins. (Hirschey et al., 2018) 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.

The design was proposed based on the common case of the construction system in Palestine (Figure IV-A), 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 (Figure IV-B).

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 cross sectional wall, conceptual heat flow models (Figure IV-C and Figure IV-D) and walls' description model has been studied, analyzed and simulate the heat loss, heat gain and thermal comfort in summer and winter seasons. The base model and the developed scenario were as followed:

The studied base model (CM) is 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 as show in (Figure IV-A). As for the developed model (M3), 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, as shown in (Figure IV-B)

By Low-E glass, 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. (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. 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%.

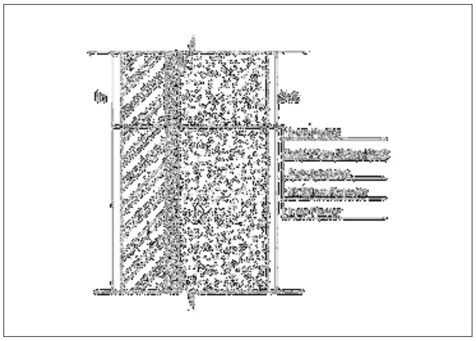

Figure IV-A: Base model cross sectional

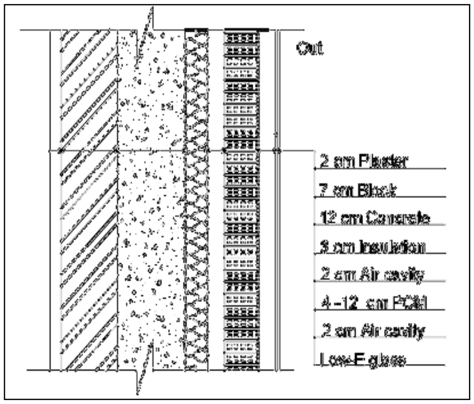

Figure IV-B: M3 cross sectional wall

A. 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, as shown in (Figure IV-C and Figure IV-D).

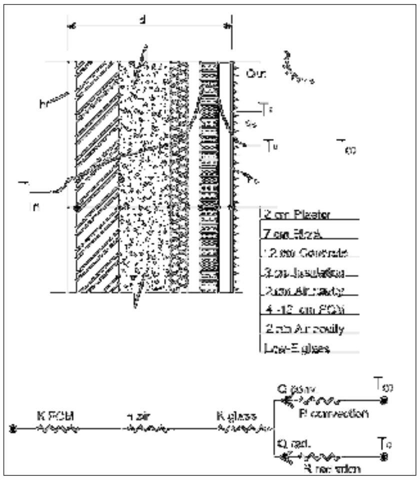

Figure IV-C: Charging model

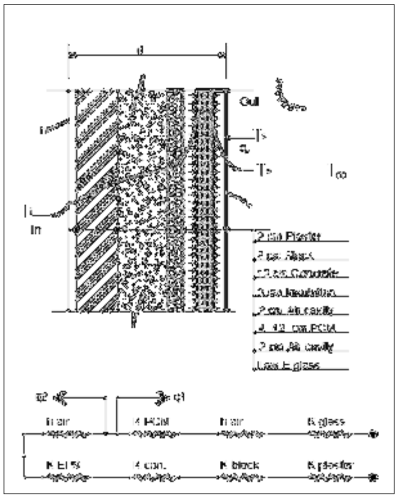

Figure IV-D: Discharging model

V. 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. The model 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 with the common wall.

A. Thermal energy calculations

To calculate the energy losses (q losses) during the day, the procedure was according to the walls' materials conductivity (Table II) and the heat flow directions, as shown in (Figure V-A).

Table II: 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

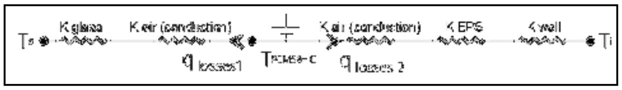

Figure V-A: M3 heat flow direction

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%.

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.

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,

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 V-B).

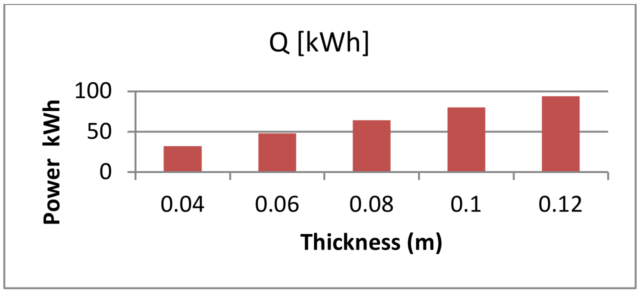

Figure V-B:Maximum energy capacity in PCM in related to its thickness

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.

B. Wavelength data

Based on the black body diagram, all energy less than 4.7 will be allowed to pass through the glass (Figure V-C). Since the PCM temperature is 58 °C = 331.15 K, based on the (
Figure V-D:The variation of the blackbody emissive power with wavelength for several temperatures.(Wujek and Dagostino, 2010)
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. The energy is trapped inside because the base wavelength founded by the (
Figure V-D:The variation of the blackbody emissive power with wavelength for several temperatures.(Wujek and Dagostino, 2010)
) =10μm and this wavelength is more than the allowable wavelength that can be passes through the selected glass.

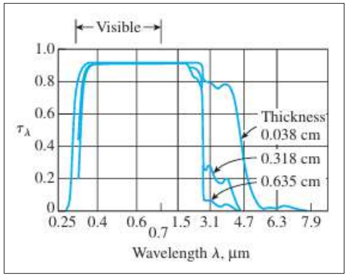

Figure V-C:The selected lowE glass wavelength diagram for different thicknesses,(Hoffman, no date)

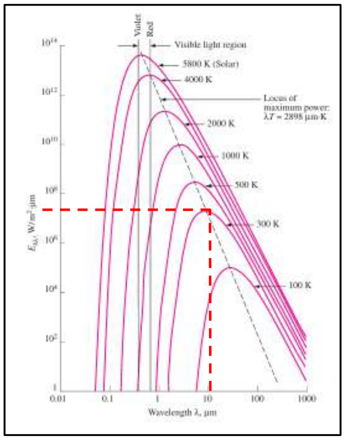

Figure V-D:The variation of the blackbody emissive power with wavelength for several temperatures.(Wujek and Dagostino, 2010)

VI. RESULTS

A. Thermal energy storage

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.

The amount of energy stored in the PCM, the amount of energy losses and the total energy results were as in (Figure VI-A). Thermal storage in M3 was high, 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.

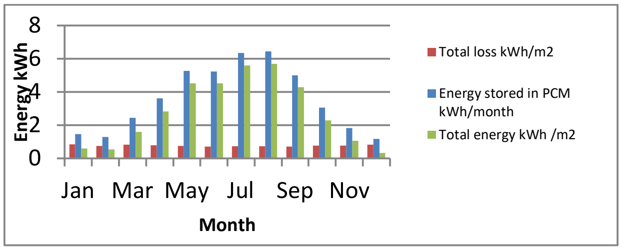

Figure VI-A: PCM energy results in M3

B. Indoor Air Temperature

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

C. 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 compared these values whith the CMs' values, the results showed that the CM is a bad case in achieving thermal comfort for occupancy in summer (Figure VI-B) and winter (Figure VI-C), 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.

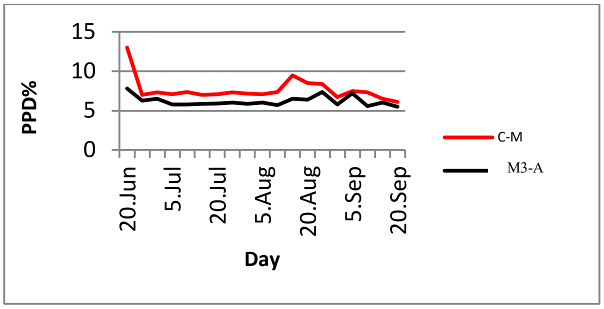

Figure VI-B: PPD% for M3 in summer.

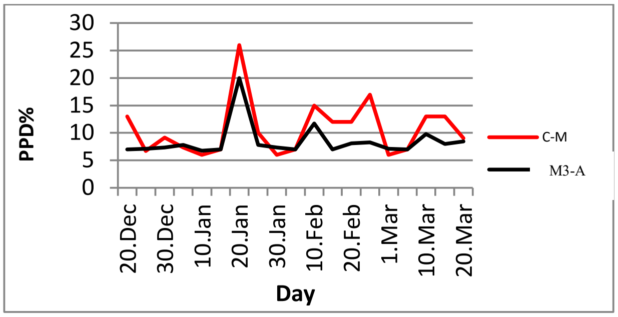

Figure VI-C: PPD% for M3 in winter

D. Heating and Cooling Loads

In this section, the DB results of heating and cooling loads in winter and summer respectively were studied and analyzed, and comparing it with the heating and cooling loads results for the base model CM. The results of the heating loads in winter indicate that PCM-TIM integration model was outperformed of CM significantly, as for the M3-A result, the heating loads were decreased significantly when compared to CM results, as for the cooling loads in summer; the results indicate that PCM-TIM integration model was outperformed of the CM significantly when compared to each other, shown in (Figure VI-D).

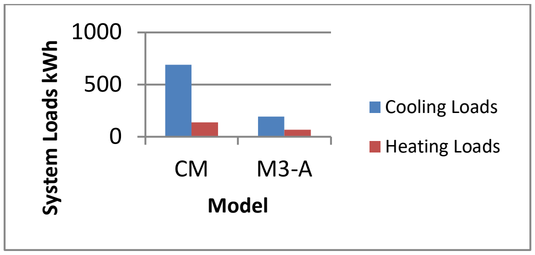

Figure VI-D: Heating and cooling loads in CM and M3

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. 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 a good 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.

E. Heat Flow Simulation results

For the M3-A, 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 VI-E, and Figure VI-F).

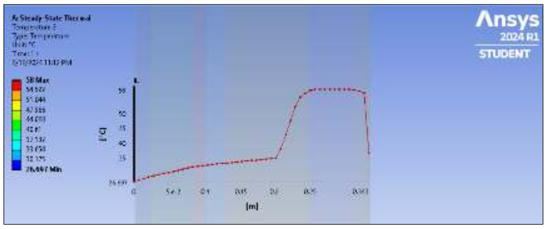

Figure VI-E: Heat flow temperature diagram for M3-A in a summer day

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.

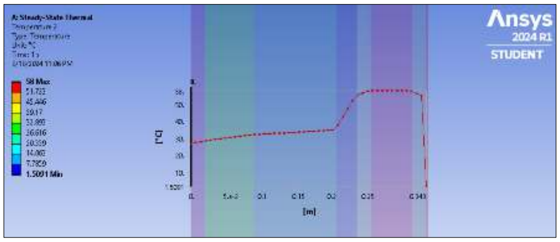

Figure VI-F: Heat flow temperature diagram for M3-A in a winter day

In winter heat flow simulation, 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 VI-G)

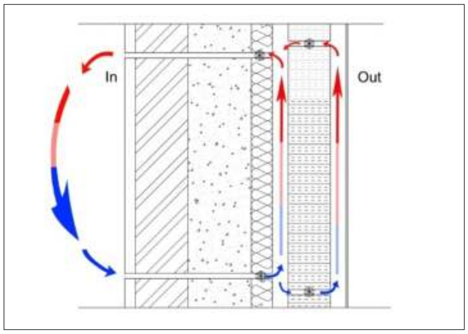

Figure VI-G: air circulation in M-3

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.

VII. CONCLUSION

A. Indoor Air Temperature

In conclusion, after comparing the proposed model with the CM, and after analyzing the results, it was found that M3-A outperformed of CM 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.

For the indoor thermal comfort, and when comparing with the CM, the results showed that the CM is a bad case in achieving thermal comfort for occupancy in summer and winter, 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.

B. Heating and Cooling Loads

In general, as expected, when comparing heating and cooling loads with the CM, the M3-A results were the better 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.

VIII. 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, all the proposed cases were better than the CM case, 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.

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