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EFFECTS OF PHASE CHANGE MATERIALS ON REDUCING ENERGY CONSUMPTION IN RESIDENTIAL BUILDINGS: CASE STUDY OF PARK VIEW APARTMENTS IN ERBIL CITY

Husein Ali Husein [1], Azad Hama [2], Younis Sarhang Jalal [2]

[1] *Department of Architecture, College of Engineering, Salahaddin University, Erbil, IRAQ.*
[2] *Department of Architecture, College of Engineering, Tishk International University, Erbil, IRAQ.*

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ABSTRACT

Smart construction materials have, over the years, received significant attention due to their inherent properties to respond to changes in their environments, for instance, temperature, light, pressure, and electric voltage. Phase Changing Materials (PCM) is a type of smart material that responds to changes in temperature conditions in their environment. As a result, they absorb and store large energy amounts during hot conditions and release it by melting at a predictable temperature. Based on this functionality, they are popularly employed in the thermal regulation of indoor environments in buildings. This research investigates the performance of phase-changing material (PCM) on reducing the energy consumption of Park View Apartments in Erbil, Iraq. Data was collected by simulating energy usage of the modeled apartment building in the Design-Builder application. Five different PCMs were used – Q21, Q23, Q25, Q27, and Q29 that were distinguished by their melting temperature indicated by their values (e.g. Q21 melted at 21°C). Four different thicknesses were also used, (M182 – 74.2mm, M91 – 37.1mm, M51 – 20.8mm, and M27 – 11.2mm). The obtained results showed that PCM with thickness 0.0742m and a melting temperature of 25°C generated the highest energy savings of 2.07%. Additionally, the material generated the most optimal results in heating applications while PCM M182 Q23 demonstrated better results in cooling applications. Directly, the findings suggest that the adoption of PCM is a tentative solution to reduce energy consumption levels in residential buildings in Iraq such as the Park View Apartments in Erbil where a hot and dry climate is experienced. In turn, this promotes the development of sustainable buildings.

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* Corresponding author (**H.A.Husein**) Tel:+9647504539436 Email : husein.ali@su.edu.krd

1. INTRODUCTION

In the current age, technology plays a fundamental role in leading innovation in nearly all sectors of the economy. One key application regards the development of new smart construction materials which unlike their predecessors, such as concrete, stone, and wood, are embedded with the ability to respond to changes in their environment in a beneficial manner (Mohamed, 2017). The researcher observes that smart materials can respond to changes in weather, such as winter or summer, temperature fluctuation in the environment or external pressure, and, as a result, ensure the needs of building occupants are met. A study by Abdullah and Al-Alwan (2019) has effectively categorized smart materials into three main categories: property-exchange, energy-exchange, and material-exchange.

As a result of their unique qualities, Borden and Meredith (2012) postulate that smart materials have been widely adopted in interior architecture due to the improved convenience they afford to the building occupants. Further, Mohamed (2017) reveals that smart materials used in buildings have immense potential in enhancing their designs as well as improving energy efficiency in terms of heating and cooling applications. This led to improving thermal comfort for building occupants.

Phase change materials (PCM) are a class of smart materials that are widely adopted as thermal regulators in buildings as they bridge the gap between the availability of energy and when it is needed for heating, cooling and improving the quality and comfort of both residential and commercial spaces (Harland, Mackay, & Vale, 2010). Further, Al-Baldawi (2015) reveals that PCM is effectively used in interior architecture as a thermal regulator through phase change wallboards. The researcher observes that PCM absorb, store, and release large amounts of energy through latent heat at predictable temperatures. As a result, they have been employed in walls and floors of buildings in different climates to help regulate internal temperature through the release of latent energy.

Figure 1: Erbil Citadel (UNESCO, 2014)

Ivarsson (2010) has observed that although Heating, Ventilation, and Air Conditioning (HVAC) systems are highly valuable in enhancing thermal comfort within buildings, they are, however, disadvantageous as they are attributed to 50% of the total energy consumed within buildings. Therefore, novel approaches to minimize energy consumption are highly sought to meet both the thermal comfort requirements in buildings and decrease energy usage (Addington & Schodek, 2012).

In the Middle East, in particular, HVAC systems are a necessity given the high temperatures experienced during summer conditions and low temperatures in winter. Subsequently, the use of PCM is investigated as a solution to the challenge.

Erbil or Arbil is the capital of the Iraqi Kurdistan Regional Government (KRG) in Northern Iraq and one of the largest cities in the country (Gunter, 2019). As one of the oldest cities in the world, dating back to 2300 B.C., the Erbil Citadel has already been designated as one of UNESCO's world heritage sites (UNESCO, 2014). Figure 1 displays the Erbil Citadel.

Gunter (2019) also observes that Erbil city serves as an important trade center due to its high population of 1.5 to 2 million individuals. The city has also morphed into an Arabian tourism center, over the years, with contemporary architecture such as modern malls and shopping centers and many residential projects in different parts of the city. One of the contemporary buildings in Erbil is the Park View apartments illustrated in Figure 2.

Figure 2: Park View Apartments in Erbil (Baghy Shaqlawa, 2020)

This research focuses specifically on the Park View apartments in Erbil and the impact of utilizing phase change materials on the indoor comfort in the building. In, particular, the RT25HC type of PCM from Rubitherm GmbH is investigated. Features of the RTH25C material include high latent heat capacity levels at narrow ranges of temperature, unlimited lifetime, and supercooling effect. The material melts at 25°C, releasing 210 kJ/kg of heat.

Several researchers have examined the use of PCM RT25HC in enhancing the thermal comfort of indoor environments. Thus, this study is not unique but seeks to compare the findings obtained against similar studies. For instance, Meyer (2016) conducted an experiment where an air rig was encapsulated with RT25HC PCM plates and air blown from a fan through the duct. The ambient air temperature was recorded thereafter. Findings showed that the use of the PCM lowered the air temperature within the rig significantly. Chen at al. (2014) had also set up a similar experiment where an air rig was encapsulated with different aluminum plates, and the flow rate of the air was controlled within the rig. Results showed that setting the flow rate to 0.027, 0.061, and 0.075kg/sec led to the fluctuation of temperature by 2.9°C, 2.4°C, and 1.4°C respectively. The implication was that lower airflow rates led to higher cooling effects, respectively. Based on the positive findings, this research aims to compare the performance of the RT25HC PCM in the context of the Middle Eastern region.

2. RESEARCH NOVELTY

The novelty of the research stems from its focus on the use of Phase Change Materials (PCM) to save the energy consumption of Park View apartment buildings located in Iraq. Therefore, the study is unique in two ways; first, it investigates how the use of phase changing smart materials in the building can help improve the quality and comfort of indoor environments in Iraq given its long hot and dry summers and short winter climate. Second, the research is significant in that it demonstrates, through software simulation, how using smart materials can be an effective solution to promote energy efficiency in building apartments. The efficiency emerges from the release of energy during winter and the absorption of excess heat during the long and hot summers. To the best of the researcher's knowledge, this is the first study in Iraq that evaluates the use of PCM materials in apartment buildings to enhance their internal comfort as well as ensuring energy consumption remains at an affordable level.

3. LITERATURE REVIEW

The adoption of phase changing smart materials for thermal regulation applications in buildings has been examined by diverse researchers in various parts of the world. To begin with, Stropnik et al. (2019) observe that in the European Union, there is an urgent need to reduce energy use in the building sector as 40% of total energy use is attributed to buildings. To minimize energy consumption, the researchers advocated for the integration of retrofit with existing interconnected technological systems, particularly, implementing PCM materials into a building's storage tank. The research aimed to investigate whether PCM materials impacted the thermal energy storage of the tanks. Findings obtained showed that where the storage tank was fitted with PCM material, water at the desired temperature level could be supplied for a longer period. Directly, the study showed that PCM was effective in thermal energy storage applications where narrow temperature ranges when supplying and storing the thermal energy were preferred.

Da Cunha and de Aguiar (2019) further carried out a review examining the use of phase change materials in enhancing the energy efficiency of buildings. From the review article, findings showed that PCM materials operated on a principle whereby, they absorbed and stored energy when environmental temperatures increased by changing their state from solid to liquid.

On the contrary, however, a decrease in temperature led to the release of previously stored energy, leading to a change in state from liquid to solid. The review article further revealed that PCM materials are categorized into three based on their melting temperatures; the organic type that is either paraffinic or non-paraffinic, the inorganic type that includes hydrated and metal salts and the eutectic types that are comprised of a combination of the two. Key features of the PCM materials and their problems such as supercooling, low fire resistance, and phase separation were also outlined. Finally, approaches to integrate PCM materials in buildings such as encapsulation, immersion, shape stabilization, and direct incorporation were discussed.

The two relevant studies, Stropnik et al. (2019) demonstrated the practical use of PCM in enhancing the thermal properties of an underground water tank while Da Cunha and de Aguiar (2019) outlined the operational principles of PCM materials and other important concepts to better understand their performance. A separate study by Lee, Medina, Sun, and Jin (2018) further revealed that outfitting building walls with PCM materials improved their potential in saving energy and as a result, the thermal comfort of the buildings. However, an imminent challenge facing their adoption was that they required extra construction time to integrate the various layers involved. To tackle the challenge, Lee et al. (2018) advocated for the mixing of PCM with the insulation directly during the manufacturing process. Experimental tests conducted on walls enhanced with PCM showed that thermal performance improved significantly both in terms of daily and hourly peak heat flux reduction temperatures.

Chen et al. (2014) also examined the influence of embedding PCMs in metal foam to enhance their low thermal conductivity. The underlying argument for the research was that the low thermal conductivity of PCMs decreased their heat transfer rates and as a result, caused low energy utilization. Conversely, the metal foam was praised for its high thermal conductivity, strong mixing capabilities, and high porosity. The researchers embedded PCM onto aluminum, nickel, and copper foam and thereafter, examined the performance experimentally. Findings obtained showed that the embedding of the metal foam improved the heat transfer performance of PCM through suppressing natural convection and reducing convective heat transfer performance.

The analysis of the two studies (Chen et al., 2014; Lee et al., 2018) reveals that PCM qualities can be enhanced further by embedding them with metal foam or directly mixing them insulation materials during construction. In the two instances, the overall thermal performance of the PCM materials is observed to increase significantly. Eddhahak-Ouni, Drissi, Colin, Neji, and Care (2014) also investigated the impact of embedding Portland cement concretes with microencapsulated PCM materials. After performing several experimental tests, findings obtained showed that the heat storage capacity of the cement material was enhanced by adding PCM material.

Researchers Saxena, Rakshit, and Kaushik (2020) also investigated the impact of embedding bricks with PCM materials in an attempt to improve the passive conditioning of buildings. Experimental testing was thereafter undertaken during peak summer conditions when temperatures reached beyond 40°C during the day. Findings showed that a reduction of temperature ranging between 4 to 9.5°C was reported across the bricks that were embedded with PCM material in contrast to the ordinary bricks. Further heat reduction ranging between 40% and 60% during the day was also reported for the enhanced bricks. The findings resonated with previous research by Eddhahak-Ouni et al. (2014) which had shown that PCM in cementitious materials enhanced their thermal qualities. However, in the research by Saxena et al. (2020), bricks were considered as opposed to cement.

Based on the positive correlation observed between embedding PCM materials in construction materials and improving thermal performance, other researchers focused on identifying new methods to modify conventional materials with PCM. For instance, Ryms and Klugmann-Radziemska (2019) investigated three different approaches; adding microcapsule powder Micronal DS 5040X, adding it in liquid form as Rubitherm RT22, and as a porous aggregate using Rubitherm RT22. Findings obtained showed that incorporating PCM as an aggregate was the most advantageous approach as only a minimal amount of the material was incorporated into the construction materials to enhance their cooling abilities.

Yoo et al. (2019) further examined the thermal performance of biocomposites developed by combining PCM materials with coffee wastes. Findings showed that the use of bio-compatible PCM by-products not only led to enhanced thermal qualities but also, was environmentally friendly and sufficient for building applications. Jingchen et al. (2020) also evaluated the thermal qualities of biocomposites developed by combining PCM materials with fatty acids or wood flour. Findings obtained using thermogravimetric analysis, revealed that the composite material depicted excellent thermal characteristics.

3.1 LITERATURE GAP

From the analysis of the different studies reviewed in the previous section, it was apparent that PCM materials improve the thermal performance of buildings by absorbing heat during hot conditions and releasing it when temperatures fell. Da Cunha and de Aguiar (2019) argued that the inherent characteristics of the PCM materials were explained by the change in their states, whereby, they changed from liquid to solid during low temperatures and solid to liquid in hot conditions. Nonetheless, the various studies showed that adopting PCM materials in buildings improved the thermal performance of buildings by reducing heat loss during hot conditions and prolonging high temperatures in cold conditions.

The performance of the PCM materials could be improved by either embedding them to metal foam (Chen et al., 2014), building bricks (Saxena et al., 2020), Portland cement (Eddhahak-Ouni et al., 2014) and organic waste (Yoo et al., 2019; Jingchen et al., 2020). However, what emerges from the analysis of the different studies is that very few studies are undertaken in the Middle Eastern region where climatic conditions lead to hot dry summers and cold winters. Therefore, this research aims to bridge this gap by investigating the performance of PCM materials on indoor thermal comfort in buildings in Iraq. Secondly, the analysis of the studies also showed that none of the researchers adopted software simulation methodology to investigate PCM materials. This study also utilizes Revit and SketchUp to model the buildings and Design-Builder to simulate energy flow both with and without the integration of PCM materials. This insight will be highly beneficial to both building owners in Iraq as well as stakeholders in the construction industry in the country. This research will spark more conversations on the need to integrate PCM in Iraqi buildings thereby, improving thermal comfort and saving more energy at a more affordable cost.

4. METHODOLOGY

This research is guided by a positivist philosophy and a deductive approach to theory development. Based on the positivist philosophy, the researcher aims to collect quantitative data through observation of phenomena in the real world using scientific techniques (Saunders, Lewis, & Thornhill, 2009). Likewise, the deductive approach implies that empirical observations will be collected to test the various prediction statements or hypotheses (Collins, 2010). The tested hypotheses are

H_1: Integration of PCM materials in Park View Apartments lowers the energy costs of cooling the building during the day.

H_2: Integration of PCM materials in Park View Apartments lowers energy costs of heating the building during the night and in the winter season.

To collect data, a case study research strategy will be adopted, whereby, the researcher seeks to gain an in-depth understanding of the impact of PCM on the quality of indoor thermal quality in the selected Park View apartments (Yin, 2014). With the case study approach, data will be collected through software simulation in two key processes.

The first process involves modeling a flat in the apartment buildings using SketchUp and Autodesk Revit software. The researcher selected the SketchUp application in the project based on its ease of use and handling, as well as its availability as it also includes a free version (SketchUp, 2020). Autodesk Revit was also adopted due to its advanced features and comprehensive workflows that suit the conceptualization of real-world building models (Autodesk, 2020). The two applications are also robust and provide a comprehensive database of models that can be reused in other related projects. In effect, this enabled the researcher to develop the 3D models of the apartments within a short time.

The second process involves the integration of the developed 3D models into Design Builder software in order to generate the technical data regarding the effect of PCM materials on the energy consumption levels in the buildings. The underlying factors motivating the adoption of the software application stem from its advanced features which facilitate the simulation of aspects such as energy and comfort (Design Builder, 2020). Additionally, the researcher is motivated to adopt the Design-Builder application due to its wide adoption by numerous researchers in assessing the impact of smart materials on building performance (Curpek & Hraska, 2016; Beltrán & Martínez, 2019).

Once the data is generated in the DesignBuilder application, the analysis will be conducted thereafter. The researcher will generate visual diagrams of the technical data to evaluate how the various variables interact with each other – the use of PCM materials and energy consumption levels in the building. The whole building was modeled in DesignBuilder v.6.1.4. A screenshot of the model of the building is shown in Figure 3.

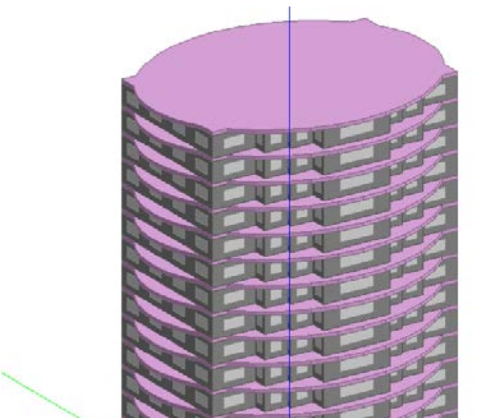

Figure 3: Design builder model of Park View Apartments

Considering that each floor of the building has the same distribution, building materials, surface floor area, and the activity is the same on each floor, only one floor was selected for analysis. The model of the floor that was used to obtain the results of the study is shown in Figure 4.

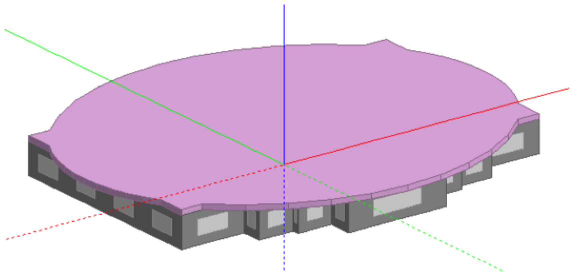

Figure 4: Model of the floor that was used to obtain the results of the simulations.

5. RESULTS AND DISCUSSION

Five different PCMs were used in the simulations, each one with different melting temperatures (Q21, Q23, Q25, Q27, Q29 – the melting temperature of 21°C, 23°C, 25°C, 27°C, and 29°C, respectively). For each case, four different thicknesses were considered (M182 – thickness of 74.2mm, M91 – thickness of 37.1 mm, M51 – thickness of 20.8 mm, and M27 – thickness of 11.2mm). The combination of the previous parameters resulted in 20 different variations of PCM walls that are summarized in Table 1. For comparison, the heating and cooling energy consumption of the building without PCM is also included. As can be seen from the results, the use of an M182Q25 PCM resulted in the highest energy savings of 2.07%. The reason for the relatively low energy savings could be related to the fact that strategies for completing the melting/freezing cycles of the PCM were not implemented. This type of strategy could include the opening of windows at night to use night cool air to solidify the PCM, the circulation of mechanical ventilation air, or the circulation of cool water through the PCM. Table 1 shows the simulation data with different variations.

Table 1: Energy consumption comparison

	Cooling [kWh]	Heating [kWh]	Total HVAC [kWh]	Total Energy Savings [%]
M182Q23	43864.6494	29350.79	73215.4394	1.97%
M182Q25	43675.09	29461.21	73136.3	2.07%
M182Q21	43912.17	29420.98	73333.15	1.81%
M182Q27	43901.6	29705.12	73606.72	1.44%
M91Q25	43986.48	29736.23	73722.71	1.29%
M91Q23	44107.84	29650.46	73758.3	1.24%
M182Q29	44113.18	29689.46	73802.64	1.18%
M91Q21	44132.14	29726.93	73859.07	1.11%
M91Q27	44132.4	29888.01	74020.41	0.89%
M51Q25	44212.95	29847.83	74060.78	0.84%
M51Q23	44295.24	29773.42	74068.66	0.82%
M51Q21	44308.18	29833.56	74141.74	0.73%
M91Q29	44309.88	29877.25	74187.13	0.67%
M51Q27	44304.48	29952.57	74257.05	0.57%
M27Q25	44392.31	29915.44	74307.75	0.50%
M27Q23	44444.93	29862.94	74307.87	0.50%
M27Q21	44451.61	29900.91	74352.52	0.44%
M51Q29	44460.92	29944.86	74405.78	0.37%
M27Q27	44439.27	29982.06	74421.33	0.35%
M27Q29	44543.26	29977.36	74520.62	0.22%
Baseline (no PCM)	44677.02	30007.47	74684.49	0.00%

An important aspect to notice from the results that the optimum PCM for reducing cooling energy consumption is not the same as the PCM that is optimum for reducing heating energy consumption. For cooling, an M182Q25 PCM is the optimum solution while for heating, an M182Q25 PCM is the optimum solution.

The main reason for the reduction of heating and cooling energy is related to the reduction of heating and cooling loads as shown in Figures 5 and 6. The peak heating load of the building without PCM is 5060.623 W, while the peak heating load of the building with PCM is 4973.929 W. Similarly, the peak cooling load of the building without PCM is 48065.33 W, while the peak cooling load of the building with PCM is 23494.94 W. This is an indication that the walls of the PCM building can absorb some of the heat gains during the occupancy period and release them during unoccupied periods, which is evidenced in Figure 7 that shows that during occupied periods, the temperature of the exterior walls with PCM is lower than the baseline case, while during unoccupied periods, the walls with PCM are higher.

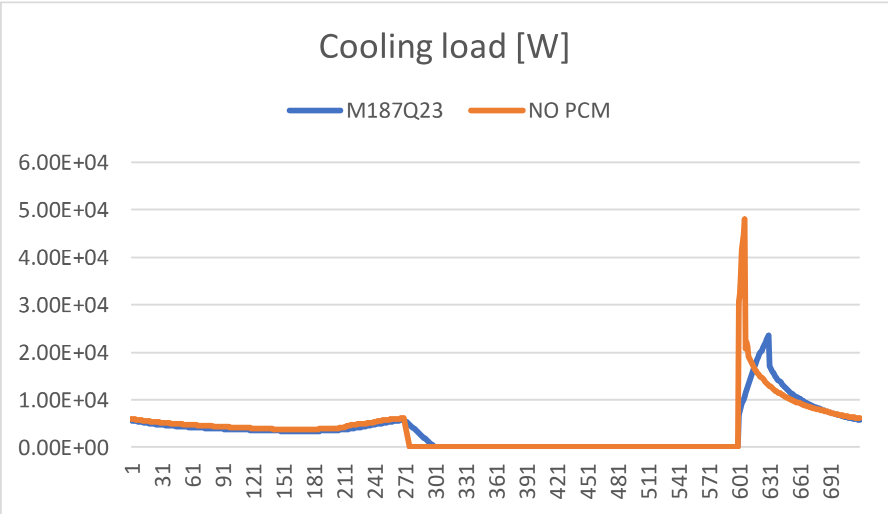

Figure 5. Comparison of the cooling load of the building with (M182Q23) and without PCM.

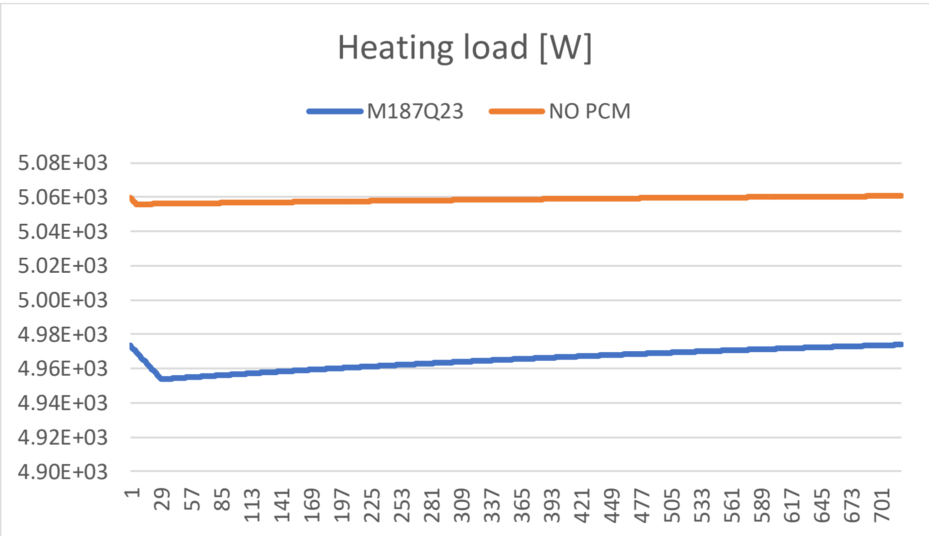

Figure 6. Comparison of the heating load of the building with (M182Q23) and without PCM.

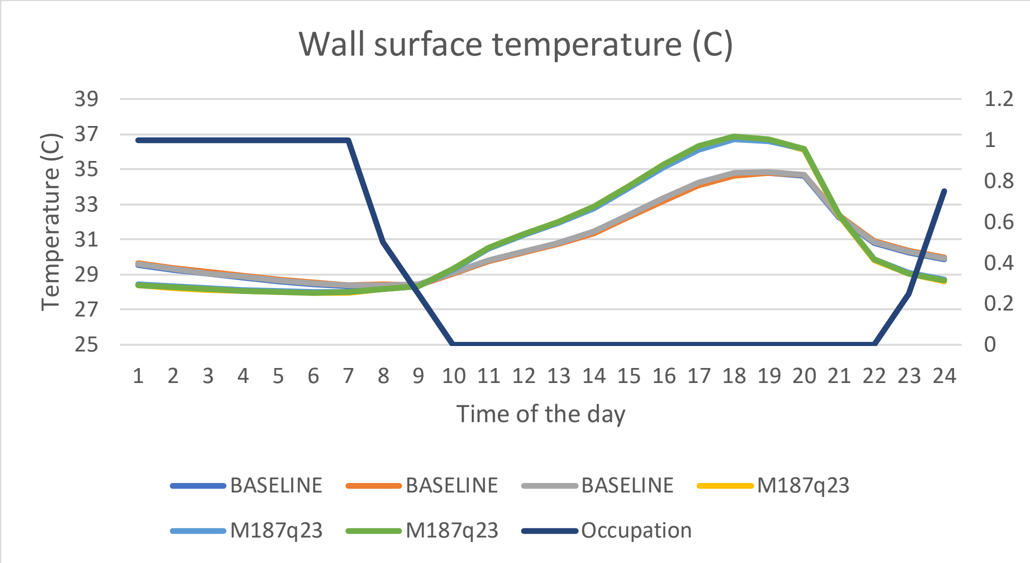

Figure 7. Comparison of the temperature of the inside face of exterior walls of the bedrooms of the building (simulation during the summer design day).

As shown in Figure 8, the temperature of the analyzed zone in the building during occupied periods is the same in both cases, which is expected as the cooling system maintains the desired thermal conditions (cooling setpoint of 26°C) regardless of the presence of the PCM.

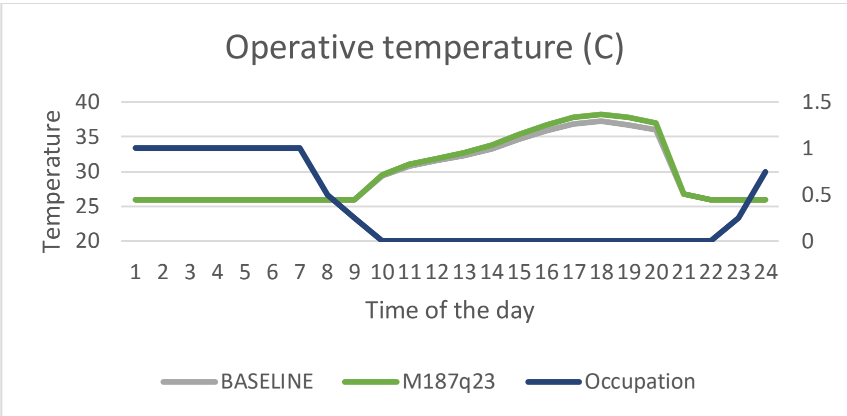

Figure 8. Comparison of operative temperatures inside the bedrooms of the building (simulation during the summer design day).

6. CONCLUSION

This research aimed to investigate the impact of using PCM materials in a reduction of energy consumption in the selected case study residential building – Park View Apartments in Erbil, Iraq. Based on the evaluation of the simulation results, findings showed that the PCM M182 (0.0742m thickness) and a melting temperature of 25°C led to the highest energy cost savings on cooling while PCM M182 with a melting temperature of 23°C generated the optimal results in heating. For two cases, the results showed that PCM material outperformed baseline scenarios.

Subsequently, based on the positive performance of PCM in both heating and cooling applications, the research recommends its adoption as a strategy to minimize energy consumption in residential buildings in Erbil, Iraq. Given the hot and dry climate experienced in Iraq, PCM usage is anticipated to improve thermal comfort in residential buildings through cooling hot temperatures during the day and enhancing heating at night when cooler temperatures are experienced. Directly, this leads to savings on energy costs incurred in heating and cooling buildings and as a result, contributes to the development of more economically and socially sustainable buildings.

7. DATA AND MATERIAL AVAILABILITY

Information can be made available by contacting the corresponding author.

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Dr. Husein Ali Husein is an Assistant Professor of Architectural Engineering and competence of Architectural Technology, Department of Architecture, Salahaddin University -Erbil. He gained a B.Sc. degree in Architectural Engineering from the University of Technology- Baghdad, an M.Sc. degree in Architectural Engineering and Public Building Design from TU-Berlin, and a Ph.D. degree in Architectural Technology from the University of Sulaimania.

Dr.Azad Hama Ahmed is an Assistant Professor, Architecture Engineering Department at the American University of Duhok in Kurdistan. He received his BA and a Master in Architecture and a PhD from the University IUAV of Venice, Italy, where he became a Lecturer during 1995-1998, whilst carrying out his post-doctoral research.

Younis Sarhang Jalal is an M.Sc. student in Interior Architecture Program at Tishk International University. He received a B.Sc. degree in Architecture Engineering from Cihan University. He is the owner and chief architect of Variable Architects Company.