Journal of Engineering and Sustainable Development

المجلد 22، العدد2 (الجزء-3)، آذار2018

ISSN 2520-0917

10.31272/jeasd.2018.2.33

EXPERIMENTAL STUDY ON THERMAL PERFORMANCE OF GLAZED ROOF WITH PHASE CHANGE MATERIALS AS AN APPLICATION OF ENERGY CONSERVATION IN RESIDENTIAL BUILDINGS

Dr. Hayder Mohammad Jaffal[1], *Dr. Tawfeeq Wasmi Mohammed[2], Marwa Hamid Wasmi[3]

1) Assist Prof., Mechanical Engineering Department, Mustansiriyah University, Baghdad, Iraq.
2) Lecturer, Materials Engineering Department, Mustansiriyah University, Baghdad, Iraq.
3) Materials Engineering Department, Mustansiriyah University, Baghdad, Iraq.

Abstract: The majority of electric energy that supplied to a residential house is consumed by air-conditioning during both summer and winter. Thus it has a major impact on the greenhouse gases and climate. Thermal energy storage systems using phase change materials (PCMs) in building elements has become a reliable solution for energy saving. The present study assists for the utilization of PCMs in the roof of residential buildings to absorb the heat comes from solar radiation during the daytime and releasing it to the inside nightly. The building considerations as well as thermo-physical properties of PCMs have been taken and measured experimentally. Results have shown that these materials have a good potential for reducing energy demand and satisfy comfortable thermal conditions. The experimental data show that the indoor temperature increases by 4-7 ^{o}C in the winter compared to that measured in a traditional one. Furthermore, a simulation program depended on degree-days method explained that the energy consumption could be saved up to 70%. Thus PCMs could submit encouraging suggestions toward the sustainability.

Keywords: *PCMs, Heat storage, Energy saving, Solar energy, Sustainability*

دراسة تجريبية عن الأداء الحراري للسقوف المدمجة بالمواد متغيرة الطور كتطبيق لحفظ الطاقة في المباني السكنية

الخلاصة: تستهلك المباني السكنية معظم الطاقة الكهربائية التي يتم تجهيزها من خلال تكييف الهواء خلال الصيف والشتاء. وبالتالي فإن ذلك عامل مؤثر في زيادة انبعاثات الغازات الدفيئة. ان استخدام انظمة تخزين الطاقة الحرارية عن طريق المواد متغيرة الطور في البناء يعتبر حلا موثوقا لتوفير الطاقة. ان هذه الدراسة تحث على استخدام هذه المواد في سقوف المباني السكنية لأستيعاب الحرارة الناتجة من الإشعاع الشمسي خلال النهار وإطلاقها إلى الداخل ليلا لغرض التدفئة. تم اخذ اعتبارات المبنى وكذلك الخصائص الحرارية-الفيزيائية للمواد بنظر الاعتبار عند اجراء العمل التجريبي. وقد أظهرت النتائج أن هذه المواد لديها إمكانات جيدة للحد من الطلب على الطاقة وتلبية الظروف الحرارية المريحة خلال الشتاء. وتظهر البيانات التجريبية أن درجة الحرارة في الأماكن المغلقة المزودة بهذه المنظومة تزيد بنسبة 4-7 درجة مئوية بالمقارنة مع تلك التي تقاس في الانظمة التقليدية. وعلاوة على ذلك، فإن برنامج محاكاة يعتمد على طريقة (أيام-درجة حرارة) قد اعتمد لغرض ايجاد مقدار استهلاك الطاقة حيث بينت النتائج انه يمكن توفير ما يصل الى 70٪ من الطاقة المستخدمة، كما يمكن تقديم اقتراحات مشجعة نحو الاستدامة.

* tawfeeqwasmi@uomustansiriyah.eud.iq

1. Introduction

Air-condition units are responsible for the majority of electrical power consumption in buildings during both summer and winter. Phase change material (PCM), as a latent heat thermal storage material, has the potential to increase the thermal mass of the building without drastically affecting the current construction techniques [1, 2]. The use of PCM, due to its high heat capacity, has been the center of attention of many researchers. A considerable number of papers have been published on the application of PCM as passive system in building envelopes.

Researches have shown that choosing the PCM melting temperature in different climate conditions is a key factor to improve the energy performance in buildings. Many methods have been researched for the PCM applied to the buildings, such as wallboards containing PCMs [3-6], PCMs filled into sandwich wall, concrete walls, concrete block and concrete floors [7-16], PCMs as insulating permeating into the building brick and furniture [17–21]. The roof is the main source of thermal loss in the building envelope. Therefore, one of the practices to enhance the thermal performance of roofs is to increase their thermal storage capacity using PCMs.

Several promising studies are taken place in the development of integration the PCM in the roof of the buildings. In a study carried out by Karthik M. [22] (2010) a Bio-PCM has used in the ceiling and the data were collected for two identical rooms with length, width and height as 4.8 m x 3.6 m x 2.4 m. The structures had enclosed attic space with R-19 fiberglass insulation between 24" ceiling. Standard BioPCM mat with a PCM density of 1 lb. per cubic foot was installed in the ceiling. In addition, BioPCM mat with a PCM density of 0.56 lbs. per cubic foot was installed in the walls. The data recorded at the experimental site included ambient temperature and indoor temperature. It was found that a Bio-PCM with a melting point from 23 to 27 °C led to maximum energy savings and is more suitable than other PCM temperature ranges for light weight building constructions.

The experimental setup showed maximum energy savings of about 30%, peak load shift for 1 hour and cost savings of about 30%. In a study, carried out by Mushtaq T. et al (2013) [23], the thermal performance of a PCM for energy conservation in residential Iraqi building is presented in an experimental set up consisting of two identical test rooms. The study has used integrated PCM-aluminum panel on the roof of the building with circulated water pipes. The study conduct that there is energy saving of het by 47 % compared to the roof without PCM panel.

An article published by Stéphane G. et al (2015) [24] presents a new configuration of using phase change material (PCM) in a complex roof on a dedicated test cell. The PCM is inserted into an enclosed air space between the corrugated iron and the plasterboard. The experimental device was set up for a tropical and humid climate. Test was also implemented in multi-zone building software in order to automatically determine the thermal indicator. The PCM melting point was around 23 ^{o}C. Results showed that the measured temperatures were more comfortable using the PCM’s. Furthermore, the phase change usually occurs close to 10:00 PM nightly and continuing for 2 hours of heat releasing which is efficient to keep the space warmer by at least 2 ^{o}C.

Furthermore, in a study carried out by Ayca T. et al (2015) [25] an experimental investigation and numerical analysis of a building has a flat roof that incorporates phase change material (PCM) as a layer have conducted. First, a planar surface area of 50 cm by 50 cm was constructed in laboratory conditions to be used in the experimental work. During the experiment, the temperature and the density have measured, as well as observation of the phase change interface. Then, to validate the experimental results, a computational fluid dynamics (CFD) model has simulated. The model is one-dimensional and is based on the first law of thermodynamics.

The thickness of the PCM inside the roof element was investigated in many run-times, where many PCM thicknesses varying between 1 and 5 cm were used. PCM thickness of 2 cm was found to be suitable for use in flat roofs in Istanbul. The influencing factors affecting on thermal behavior of different kinds of roofs with and without PCM in cold area of China have been explored numerically by Li Dong et al (2015) [26]. It is concluded that the PCM applied in the roof can decrease the building energy consumption and improve the thermal comfort. The results show that the PCM roofs effect on the temperature peak delay in the room 3 hours more than common roof. The thermal performances of PCM integrated roof used in a residential attic in Torino, Italy studied numerically by Hagar Elarga et al (2017) [27], The roof was divided into three portions, one, the bare roof, representing the reference case without PCMs, the other two integrating two PCM’s typologies with different melting/solidification temperatures range.

The results showed a reduction in the heat peak load between 13% and 59% depending on the PCM typology. Incorporating the PCM layer within the walls and the ceiling for the purpose of thermal insulation materials was investigated experimentally by Mushtaq I. Hasan et al (2018) [28]. The study focused on role of PCM on the thermal performance of Iraqi building using two identical rooms for comparison. The type of PCM used was paraffin wax with a melting point of 44 °C. Results obtained showed a reduction in the indoor temperature by 2 ^{o}C and reduction in air-conditioning load by 20 % as a maximum.

2. Experimental Rig

The aim of this study is to design an effective heating system depending on the using of phase change materials (PCMs) in the roof of the building. The reason of selecting the roof is due to the most exposed to sun, hence maximum efficiency of the system. The study performance is evaluated depending of the thermal analysis. The work has been done experimentally using a rig model built for that purpose in Baghdad (33^{o}.3, 44^{o}.4) at Al-Mustansiriyah University, Materials Engineering Department.

The model is located at the terrace floor with dimensions of 1m x 1m x 1m. The walls and the floor are constructed from 1 cm common MDF (medium density fiber) with 4 cm internal insulation by EPS (Expanded polystyrene). The insulated walls and floor have a U-value of 1.35 W/m^2 K and covered with Alu-foils to reflect the radiation inside and assure well mixing of indoor air. While the roof is totally exposed to sun and covered by 5 mm clear glass. Scheme of the rig is shown in Fig. 1.

The PCMs layer is located downward the glass by 10 cm. The PCM material that used was paraffin jelly (Vaseline) with the thermo-physical properties [29] listed in Table 1. This material has been collected locally, and packed into 25 pieces of PE clear bags. The dimensions of each PCM piece were 12 cm x 10 cm with 5-6 mm thickness. The PCMs pieces have arranged together in a net under the glass, as shown in Fig. 2.

There is a slot in the space between the glass and the PCMs layer in order to put an insulated fiber at sunset time (till sunrise time) to avoid heat loss to the outside. This mechanism (glazed roof, PCMs layer and insertable fiber in between) satisfies integrated and effective system with maximum heat storage as well as less heat losses. There is a hole of 9 cm^2 in the north façade (rear-side) in order to satisfy infiltration by 0.4 ACH in average, which is necessary to avoid condensation as well as to offer fresh air. The view of the experimental rig from outside is shown in Fig. 3.

The experimental data have been obtained during the sunny days of December 2017, where heating demand is required in the winter time in Iraq (mostly at night). The study served several instruments like: thermometer data logger (Lutron-Model TM-947SD) with temperature sensors (Type-K), as well as solar power meter (Lutron-Model SPM-1116SD). The sensors have set to measure the temperatures of: glass, PCMs, indoor air and outdoor air each 30 minutes during the entire day. The solar meter used to measure the maximum radiation each hour.

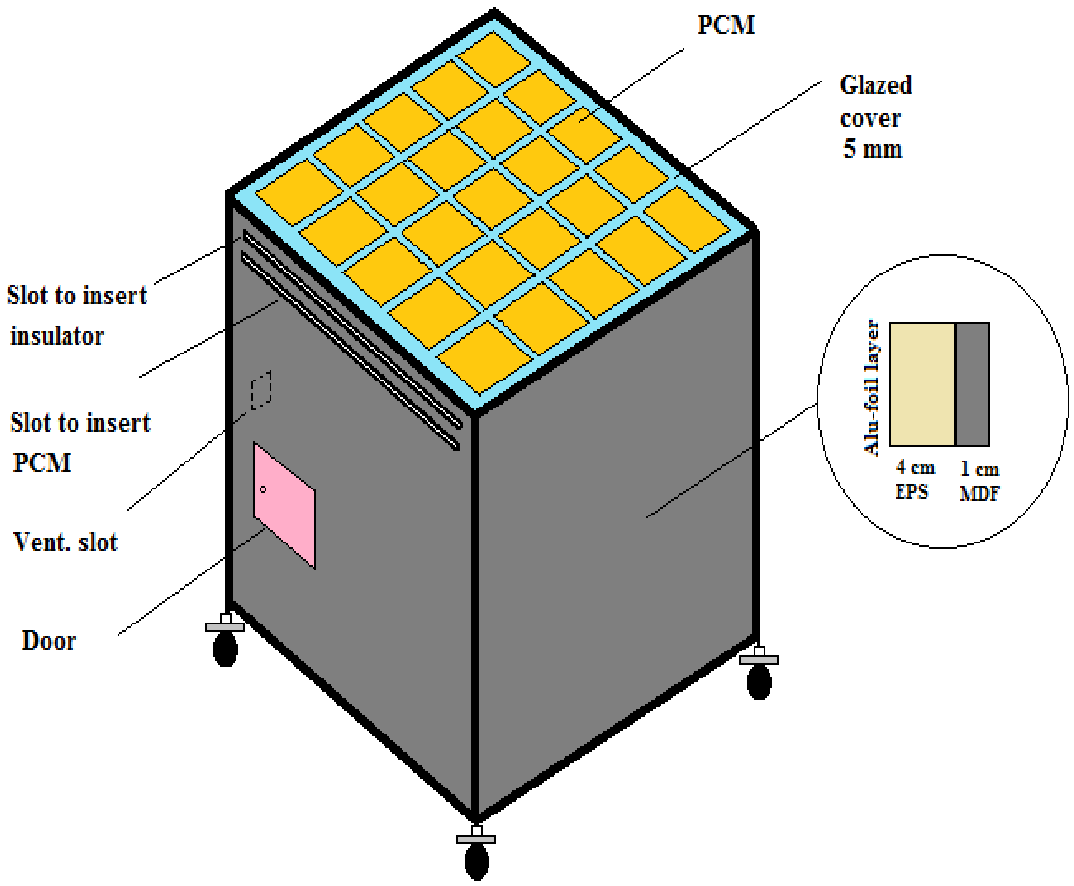

Figure 1. Scheme explaining the features of the model

Figure 2. Photo of PCMs pieces arranged in a net under the glass

Figure 3. Photo of the experimental rig

Table 1. Thermo-physical properties of PCM used in the study [29]

Name of PCM: Paraffin jelly (Vaseline)
Density: 950 kg/m^3
Melting point: 38 ^{o}C
Specific heat of solid: 2100 J/kg.K
Specific heat of liquid: 2500 J/kg.K
Heat of fusion: 170 kJ/kg
Thermal conductivity: 0.3 W/m.K
Total weight: 1.6 kg

3. Results and Discussions

The study includes in-site measurements on the model built for the purpose of reducing the heating demand by using the PCMs. In December, the ambient temperature almost swings between 10-25 ^{o}C on sunny days with daytime duration of 10 hours and maximum solar radiation up to 700 W/m^{2}. In order to evaluate the performance of PCM in heat storage, the PCM layer was installed in many days and removed in other days. Samples of readings are selected to analyze in this study.

For the case of with-PCM, Fig. 4, 5 and 6 show the variation of outdoor temperature, indoor temperature, PCM temperature and glass temperature for the entire days of 18 Dec, 19 Dec and 20 Dec respectively. The outdoor temperatures were swinging from 11 °C (at 7:00 AM) to 25 °C (at 2:00 PM) with solar radiation up to 700 W/m^{2}. The average indoor temperature with PCM was 28 °C with maximum value of 39 °C at 3:00 PM and minimum value of 16 ^{o}C at 7:00 AM. The indoor temperature at the night was decreasing from 27-16 ^{o}C with an average of 18 ^{o}C. Furthermore, the PCM temperature was swinging between 17-40 ^{o}C and phase change (melting) usually occurs in the period between 12:00 PM-3:00 PM.

For the case of without-PCM, Fig. 7, 8 and 9 show the variation of outdoor temperature, indoor temperature and glass temperature for the entire days of 24 Dec, 25 Dec and 26 Dec respectively. The outdoor temperatures were swinging from 10 °C (at 7:00 AM) to 24 °C (at 2:00 PM) with solar radiation up to 650 W/m^{2}. The average indoor temperature without PCM was 23 °C with maximum value of 34 °C at 2:00 PM and minimum value of 11 ^{o}C at 7:00 AM. The indoor temperature at the night was decreasing from 20-11 ^{o}C with an average of 14 ^{o}C.

The results of comparison of data between with and without PCM cases, show that the increasing of indoor temperature due to the using of PCM is about 4-7 ^{o}C most of the time. Also, the results showed that the PCMs can maintain indoor temperature above 20 ^{o}C for 11 hours daily, while for the case of without-PCM it was only for 8 hours daily.

Based on these results it could estimate the heating load for the sample days to show the energy saving thus the performance of PCM. A simulation program depended on degree-days method is established and the results of calculation are shown in Table 2 for base temperature of 20 ^{o}C. The results explained that the energy consumption for the model with PCM was 114 kJ/m^{2} daily as an average. On the other hand, the energy consumption for the model without PCM was 386 kJ/m^{2} daily as an average. So, it could say that the using of PCM saved the energy by 70%.

It is important to mention here that some discrepancies could be found in the experimental data due to many reasons like: sensitivity of K-Type sensors, rate of ventilation in real conditions, solar intensity rate, other ambient conditions as well as the differences in the properties of the materials used.

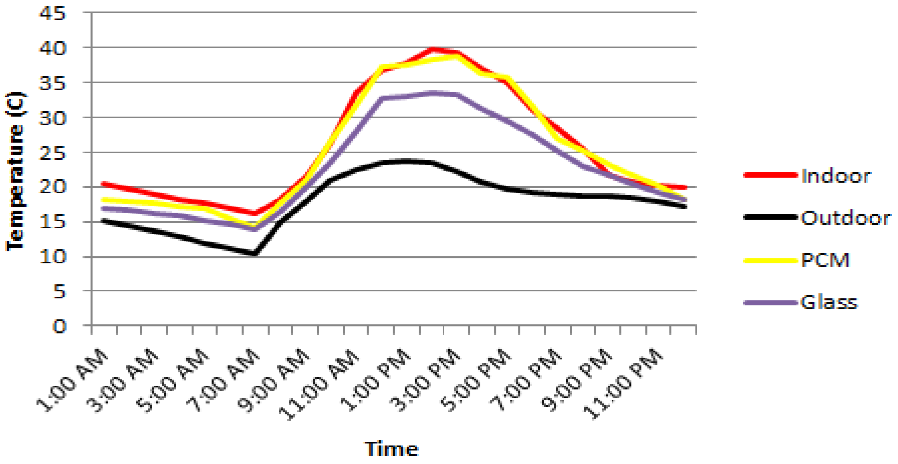

Figure 4. Experimental data on 18 Dec 2017 (Max Rad=650 W/m^2)

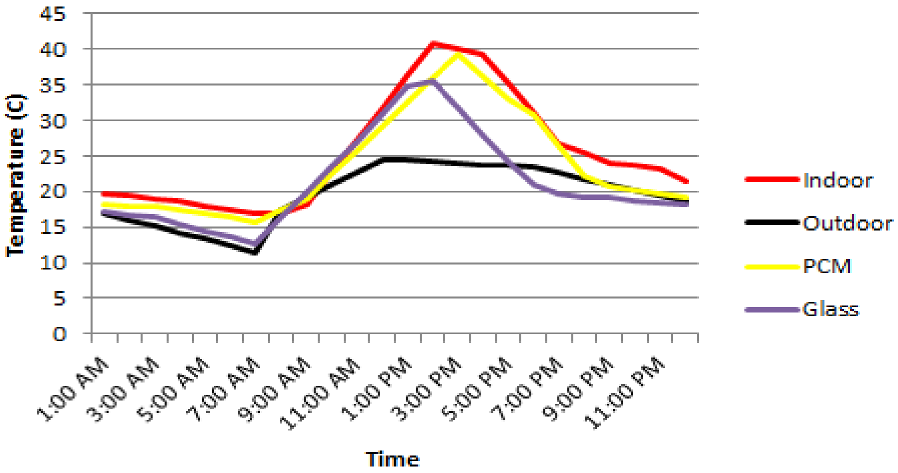

Figure 5. Experimental data on 19 Dec 2017 (Max Rad=650 W/m^2)

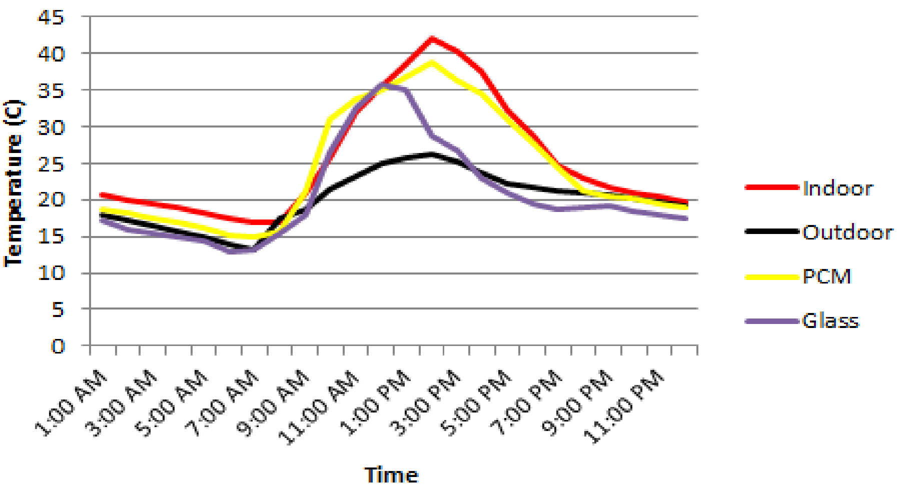

Figure 6. Experimental data on 20 Dec 2017 (Max Rad=700 W/m^2)

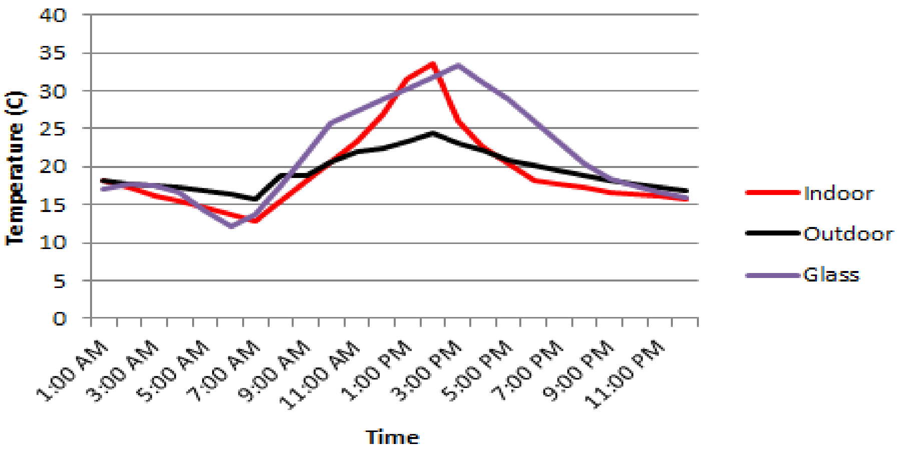

Figure 7. Experimental data on 24 Dec 2017 (Max Rad=650 W/m^2)

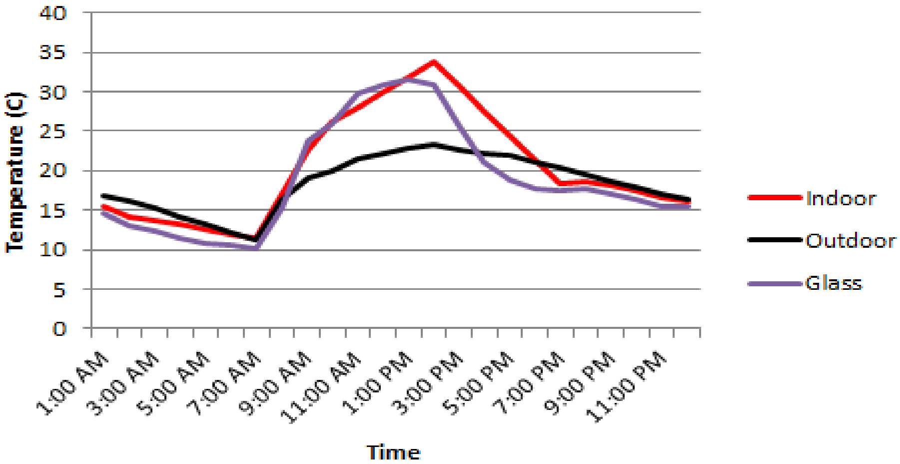

Figure 8. Experimental data on 25 Dec 2017 (Max Rad=650 W/m^2)

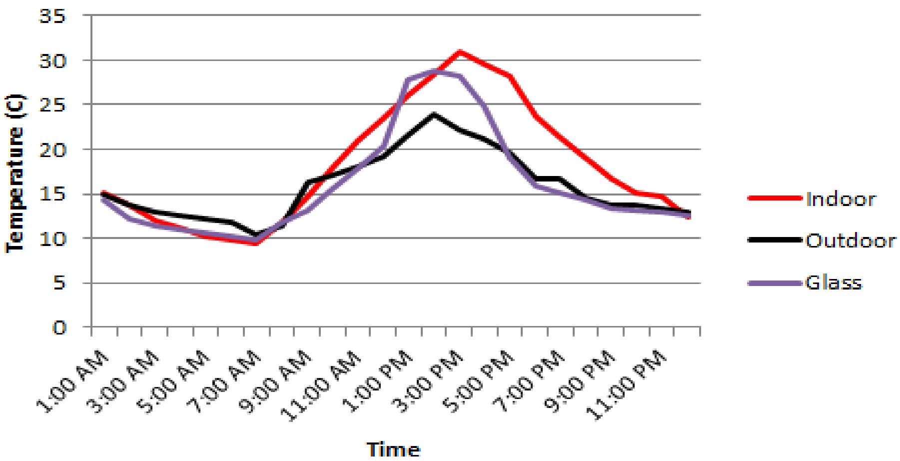

Figure 9. Experimental data on 26 Dec 2017 (Max Rad=600 W/m^2)

Table 2. Heating load for selected sample days

Date	Load with PCM (kJ/m^2)	Load without PCM (kJ/m^2)
18 Dec	128	-
19 Dec	98	-
20 Dec	116	-
24 Dec	-	335
25 Dec	-	376
26 Dec	-	449
Avg.	114	386

$$Energy\ saving = \frac{\text{Load without PCM} - \text{Load with PCM}}{\text{Load without PCM}} = 70\ \%$$

4. Conclusions

The recent study submit a design for an effective heating system depending on the using of phase change materials (PCMs) as integrating layer in the roof of the building. The study performance is evaluated depending of the thermal analysis of the experimental data. Results have shown that these materials have a good potential for reducing energy demand and satisfy comfortable thermal conditions. The indoor temperature for the model with PCM has and average value of 18 ^oC at night hence an increasing by 4-7 ^oC comparing to that measured for the model without PCM. Furthermore, a simulation program depended on degree-days method explained that the energy consumption for the model with PCM has an average value of 114 kJ/m^2 , hence a reduction of 70 % comparing to that calculated for the model without PCM. Hence, the PCM technology has significant advantages for residential buildings in terms of energy saving and reducing the discomfort hours. Besides that, the using of PCM adds thermal stability to the elements of building.

Acknowledgement

Authors are grateful to all support given by Faculty of Engineering, Mustansiriyah University, Iraq.

5. References

1. Barilelo Nghana and Fitsum Tariku (2016), "*Phase Change Material's (PCM) Impacts on the Energy Performance and Thermal Comfort of Buildings in a Mild Climate*", Building and Environment, Vol. 99, pp (211-238).
2. Mohammad Saffari, Alvaro de Gracia, Cèsar Fernández and Luisa F. Cabeza (2017), "*Simulation-based optimization of PCM melting temperature to improve the energy performance in buildings*", Applied Energy, Vol. 202, pp (420-434).
3. Alvarode Graciaa and Luisa F.Cabeza (2015), "*Phase change materials and thermal energy storage for buildings*", Energy and Buildings, Vol. 103, pp (414-419).
4. Murat Kenisarin and Khamid Mahkamov (2016), "*Passive thermal control in residential buildings using phase change materials*", Renewable and Sustainable Energy Reviews , Vol. 103, pp (371-398).

5. MuratKenisarin and KhamidMahkamov (2017), "*Experimental study on thermal performance of phase change material passive and active combined using for building application in winter*", Applied Energy, Vol. 206, pp (293-302).
6. Kong, Chengqiang Yao, Pengfei Jie, Yun Liu, Chengying Qi and Xian Rong (2017), "*Development and thermal performance of an expanded perlite-basedphase change material wallboard for passive cooling in building*", Energy and Buildings, Vol. 152, pp (547-557).
7. Yusuf Ali Kara (2016), "*Diurnal performance analysis of phase change material walls*", Applied Thermal Engineering, Vol. 102, pp (1-8).
8. Subbiah M. (2017), "*Analysis of Solar Heat Gains and Environmental Impact of the Phase Change Material (PCM) Wall* ", Innovative Energy & Research, Vol. 6, pp (1-6).
9. Chenglong Luo , Lijie Xu, Jie Ji, , Mengyin Liao, Dan Sun (2017), "*Experimental study of a modified solar phase change material storage wall system*", Energy, Vol. 128, pp (224-231).
10. Lidia Navarro, Alvaro de Gracia, Albert Castell, Servando Álvarez, Luisa F.Cabeza (2014), "*Design of a prefabricated concrete slab with PCM inside the hollows*", Energy Procedia, Vol. 57, pp (2324-2332).
11. Ahmad Hasan, Khaled A. Al-Sallal, Hamza Alnoman, Yasir Rashid and Shaimaa Abdelbaqi (2016), "*Effect of Phase Change Materials (PCMs) Integrated into a Concrete Block on Heat Gain Prevention in a Hot Climate*", Sustainability, Vol. 8, pp (1-14).
12. Jianli Li, Ping Xue, Hong He, Wenying Ding, Jinmin Han (2009), "*Preparation and application effects of a novel form-stable phase change material as the thermal storage layer of an electric floor heating system*", Energy and Buildings, Vol. 41, pp (871-880).
13. Entrop A.G , Brouwers H.J.H, Reinders A.H.M.E (2011), "*Experimental research on the use of micro-encapsulated Phase Change Materials to store solar energy in concrete floors and to save energy in Dutch houses*", Solar Energy, Vol. 85, pp (1007-1029).
14. Xing Jin and Xiaosong Zhang (2011), "*Thermal analysis of a double layer phase change material floor*", Applied Thermal Engineering, Vol. 31, pp (1576-1581).
15. Hyun Bae Kim, Masayuki Mae, Youngjin Choi and Takeshi Kiyota (2017), "*Experimental analysis of thermal performance in buildings with shape stabilized phase change materials*", Energy and Buildings, Vol. 152, pp (524-533).
16. Esam M. Alawadhi (2008), "*Thermal analysis of a building brick containing phase change material*", Energy and Buildings , Vol. 40, pp (531-557).
17. Xiangfei Kong, Shilei Lu, Jingyu Huang, Zhe Cai, Shasha Wei (2013), "*Experimental research on the use of phase change materials in perforated brick rooms for cooling storage*", Energy and Buildings , Vol. 62, pp (597-604).
18. Xu Wang, Hang Yu, Lu Li, Mei Zhao (2016), "*Experimental assessment on the use of phase change materials (PCMs)-bricks in the exterior wall of a full-scale room*", Energy Conversion and Management , Vol. 120, pp (81-89).

19. Karunesh Kant, A. Shukla, Atul Sharma (2017), "*Heat transfer studies of building brick containing phase change materials*", Solar Energy, Vol. 155, pp (1233-1242).
20. Lu Li, Hang Yu, Rui Liu (2017), "*Research on composite-phase change materials (PCMs)-bricks in the west 1 wall of room-scale cubicle: mid-season and summer day cases*", Building and Environment, Vol. 123, pp (494-503).
21. Hicham Johra, Per Heiselberg (2016), "*Influence of internal thermal mass on the indoor thermal dynamics and integration of phase change materials in furniture for building energy storage: A review*", Renewable and Sustainable Energy Reviews, Vol. 69, pp (19-3).
22. Karthik M. (2010), "*Application of phase change material in buildings: field data vs. EnergyPlus simulation*", Master thesis submitted to Arizona State University.
23. Mushtaq T. H, Ahmed Q. M, Hasanain M.H. (2013), "*Experimental and numerical study of thermal performance of a building roof including phase change material (PCM) for thermal management"*, Global Advanced Research Journal of Engineering, Technology and Innovation, Vol. 2(8), pp. (231-242).
24. Stéphane G., Frédéric M., Dimitri B., Bruno M., Harry B. (2015), "*Experimental investigation on a complex roof incorporating phase change materia*l", Energy and Buildings, Elsevier, 108, pp (36-43).
25. Ayca T., Tahsin B. and Cengiz S. (2015), "*An experimental and numerical investigation on the use of phase change materials in building elements: The case of a flat roof in Istanbul*", Energy and Buildings 102, pp (91–104).
26. Li Dong, Zheng Yumeng, Liu Changyu and Wu Guozhong (2015), "*Numerical analysis on thermal performance of roof contained PCM of a single residential building*", Energy Conversion and Management 100, pp (147–156).
27. Hagar Elarga, Stefano Fantucci, Valentina Serra, Roberto Zecchin and Ernesto Benini (2017), "*Experimental and numerical analyses on thermal performance of different typologies of PCMs integrated in the roof space*", Energy and Building.
28. Mushtaq I. Hasana, Hadi O. Basher and Ahmed O. Shdhan (2018), "*Experimental investigation of phase change materials for insulation of residential buildings*", Sustainable Cities and Society 36, pp (42–58).
29. IPCS-INCHEM, 2017"*Chemical Safety Information from Intergovernmental Organizations, Properties of Petroleum Jelly (Vaseline)*", CAS #: 8009-03-8, www.inchem.org, accessed on 12/11/2017