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Thermal Behavior of a PCM-Plywood Combination as Insulation for Buildings in a Hot Summer Condition

Aws Al-Akam[1*], Ahmed A. Abduljabbar[2], Ali Jaber Abdulhamed[1], Farooq H. Ali[3], Qusay Rasheed Al-Amir[4], Hameed K. Hamzah[3]

[1] Energy and Renewable Energy Engineering Department, Faculty of Engineering/AL-Mussayib, University of Babylon, Babylon 51001, Iraq
[2] Construction and Projects Department, Al Iraqia University, Baghdad 10011, Iraq
[3] Department of Mechanical Engineering, College of Engineering, University of Babylon, Babylon, 51001, Iraq
[4]Department of Air Conditioning and Refrigeration Techniques Engineering, Al-Mustaqbal University, Babylon 51001, Iraq

Corresponding Author Email: aws.al-akam@uobabylon.edu.iq

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ABSTRACT

Integrating innovative materials and technologies has become imperative in the quest to design energy-efficient and sustainable buildings. Among these, one of the promising solutions to improve indoor spaces' comfort conditions and energy efficiency is the Phase Change Materials (PCMs). The methodology experimentally explores the impact of combining plywood and paraffin wax as a PCM to improve indoor environments' thermal dynamics under Iraqi conditions. Two wooden boxes are used, with one having its wall stuffed with a PCM. A temperature analysis was made for the internal temperature of each box, walls' surfaces, and PCM temperature for seven days. The impact of the box arrangement on the temperature distribution was also considered. The result showed the temperature inside the modified box is lower than the conventional one by about 3.0 during the peak time from 08:00 hr. to 16:00 hr. The night cooling is slower for the box with the PCM than the conventional one. Having the modified and the non-modified box in arrangement improves the insulation of both of them. Moreover, the findings showed that there is no need for all the rooms to be modified for a building with many rooms. The correct position of the room based on the location of the building in the study area will be enough.

1. INTRODUCTION

Keeping the room or buildings in comfortable climate conditions in extremely hot and cold weather elevates the importance of having a method to reduce the power consumption required for this purpose. These methods usually rely on using different types of A/C units; however, these methods are expensive in terms of energy consumption and climate impact, with 45% of the energy consumption of the whole world [1]. Therefore, using PCM (Phase Change Materials) outfitted with the building's walls is a promising technique. The results from Dardouri et al. [2] showed that up to a 41.6% drop in the required energy for cooling or heating can be found based on the application of PCM. Several studies have dealt with this topic regarding its performance based on effective position, encapsulation area melting point, and thickness. Marin et al. [3] implemented a study on utilizing the Knauf comfort board, a type of phase change material, to regulate the indoor thermal conditions in lightweight buildings that can be easily moved. The researchers examined the effectiveness of this material under five different climate conditions: equatorial, arid, warm temperature, snowy, and polar. The numerical findings emphasized the capability of employing gypsum boards enhanced with PCMs in lightweight constructions to save energy in regions with warm climates. The results of the work by Souayfane et al. [4] showed that incorporating a Transparent Insulation Material with the PCM (TIM-PCM) on the southern side wall is more efficient than utilizing double-glazed windows in all examined climate conditions. In order to improve energy efficiency, PCM can also be placed on a brick wall's exterior face (at a different location relative to the brick and EPS). The southern wall has energy savings of up to 13.0% [5].

Moreover, the interaction between PCM and the utilized insulation within the brick walls enhanced the performance. Furthermore, integrating PCM into a concrete-based cool roof effectively offset winter drawbacks and decreased daily surface temperature fluctuations by as much as 5.40°C. In another study, the PCMs have functioned as thermal energy storage (TES) to cool buildings in arid climates [6]. Zeinelabdein et al. [6] used metallic elements filled with RT28HC PCM. Several geometrical arrangements and functional parameters have been evaluated.

Moreover, ANSYS Fluent software has been used to conduct a transient CFD simulation. The findings show that the cooling system based on the suggested arrangement saved about 67% of the cooling energy of the building's load in the warm season compared to traditional air-conditioning systems (A/C) in a dry-hot climate. Al-Yasiri and Szabó [7] conducted an experimental investigation on heat management and temperature regulation in a scaled-down room using paraffin wax. This includes the creation of two cubicles, one with a PCM-embedded roof and the other without PCM, and the analysis of their performance under non-ventilated conditions. The study focused on determining the hourly effectiveness of the PCM-integrated building. The results revealed the highest hourly temperature reduction of 9.1% and an hourly heat gain reduction of 16%. In contrast, the modified roof surface (with PCM) demonstrated the most significant temperature drop of 15.0% and a heat gain reduction of 35 %, respectively.

Anter et al. [8] investigated experimentally and numerically using different thicknesses and types of PCM to increase the efficiency of a building in the summertime in Aswan, Egypt. The influences of PCM types and locations inside the wall and in different climates were examined. The results showed that RT-35HC presented the best performance, with optimal PCM location at 1.50 cm from both sides of the wall. The results indicated that this type of arrangement produced about a 66% reduction in the overall heat gain throughout the hot weather. Furthermore, Imafidon et al. [9], results demonstrated that integrating a honeycomb PCM into the walls of a retrofitted building in Ottawa, Canada, achieved a 41% and 96% reduction in heat gain and loss through the walls of the buildings on a typical summer day. Alam et al. [10] conducted simulations for six climate zones in eight cities in Australia using different phase transition temperature ranges (five ranges). It was absorbed that the local weather, PCM layer thickness, and surface area significantly impact PCM effectiveness. The incorporation of PCM led to an annual energy savings of 17-23% in the investigated house, except for hot and muggy places. Energy-saving increased for a particular thickness of PCM. Furthermore, with the increase in the surface area and a drop in the thickness of the PCM layer up to a certain point, the growth continues, and the potential begins to decline.

It was reported that the use of the PCM elements with doubled-layer provided lower energy consumption than the single-layer one, specifically in warm-arid regions [2]. This highlights the importance of the number of PCM layers, location, and thickness. Ait Laasri et al. [11] assessed seven different building envelope positions, each with PCM (Phase Change Material), in a semi-arid region, comparing them to a reference building without PCM. The findings demonstrated excellent indoor temperature steadiness during hot conditions when the PCM was positioned on all internal surfaces of the envelope, showing the highest decrease in indoor temperature fluctuations of about 110%.

In another work, the most effective way to use several PCM layers in the wall structure was determined using simulation in two cities' climates (Phuket, Thailand) [1]. It was established that PCM with a transition temperature of 25°C saves energy by 22% every year. Lee et al. [12] located PCM layers at different depths within the wall, numbered from 1.0 to 5.0 locations. Location 1.0 represented the closest position to the wallboard surface facing the hole, and subsequent depths were spaced at 1.27 cm intervals. The findings revealed a peak heat flux reduction of 51.3% for the southern wall and 29.7% for the western wall.

Yuan Zhang et al. used three wall configurations consisting of concrete blocks combined with powder of microparticle-based PCM and a paraffin-containing silica matrix [13]. The results revealed a thermal resistance of 1.0 $m^2 \cdot K \cdot W^{-1}$ or higher and a temperature variation of 5.0°C between the room's internal and external conditions. Kenzhekhanov et al. [14] used a laboratory setup with a lightweight concrete room model with walls integrated with PCM to quantify the impact of the PCM. It was recorded that the building combined with PCM exhibited improved performance regarding average temperature fluctuation reduction, especially during the warm season. Additionally, lower melting points PCMs proved to be most effective in the spring, while those with higher melting points demonstrated their optimal performance during the summer.

Farajollahi et al. [15] investigated numerically using COMSOL and Energy Plus software to explore the impact of integrating PCMs within the wall of the building on the energy necessary to maintain comfortable conditions within the building. The PCMs were positioned within one or two cavities in the wall, and the effect of the spacing between these chambers was examined. The outcomes indicated that the highest PCM melting occurred when the cavities were spaced 0.85 meters apart. Incorporating two cavities with PCM in the wall of the building led to about a 40% yearly decline in energy utilization and a 7.5% saving in yearly cooling needs. Kuczyński et al. [16] examined the performances of a PCM copolymer combination wallboard as insulation in a full-scale test room with control conditions. Three seasons were simulated and examined: summertime, wintertime, and a mid-season day. The findings showed that the internal temperature of the air inside the room with PCM is 4.2°C lower. Another assessment in eight separate cities (Abu-Dhabi, Dubai, Faisalabad, Mecca, Jodhpur, Nouakchott, Cairo, and Biskra) was performed using EnergyPlus and DesignBuilder [17]. Test data revealed that the best type of PCMs could decrease the temperature instabilities, with peak temperature reduction by 2.0°C. It was concluded that in desert climates, PCMs perform better when the melting point is high [17].

Furthermore, the findings showed that electricity demand declined by 8.7% in summer and 45.7 % in winter. Zhu et al. [13] used EPS panels stuffed with PCM for a 12.0 cm^3 cubic box. The impact of orientation and thickness was investigated. The simulation results stated that a layer of the PCM with 5.0 mm thickness located on the internal surface was recommended. Different thicknesses of PCMs (melting point of 25°C) used in the wallboards were studied by Sajjadian et al. [18]. The thickness ranged from 12 mm to 60 mm with a 12 mm step in contact with an air gap were examined. The simulation results stated that the air gap provides airflow for PCM boards and an additional insulation layer for the building. Furthermore, cooling energy savings of up to 128.1 kWh in warm weather in London were registered.

Alam et al. [10] performed simulations using Bio-PCM has six various melting ranges: 18-22°C, 9-23°C, 20-24°C, 21-25°C, 22-26°C and 23-27°C. The data revealed that the effect of the melting point on energy saving was reduced when the PCM's melting point dropped outside the controllable range for the specific city. Five types of PCM have been examined in four hot regions and four cold districts by Soleiman Dehkordi et al. [19] and Li [20] in a local building. Using a mathematical model, the calculations show that the most significant annual energy-saving for hot areas was obtained for PCM (with a Solidus Temperature of 22°C and Liquidus Temperature of 24°C). The maximum energy saving in these regions was 19-30 $kWhm^{-2}$. On the other hand, Khan et al. [21]

reported that using PCM with melting change from 24 to 26°C in buildings reduced power utilization in a hot season by 13.7%, while in winter, it was reduced by 32.7%. One of the solutions proposed by Ji and Li [22] is to adjust the solar absorptance of TC-PCM systems to improve the performance of phase change cycles in PCMs, resulting in reduced energy consumption for both cooling and heating. The findings also indicate that the TC-PCM system greatly impacted energy savings in all provinces in summertime and wintertime regions by about 10.2% [22]. Adilkhanova et al. [23] investigated the impact of implementing various PCMs on a building model representing a residential living area, with occupancy times set from 00:00 to 08:00 hrs. and 18:00 to 24:00 hr. The phase transition temperature range for the phase change was 24°C to 28°C; 26°C to 30°C; 28°C to 32°C; and 30°C to 34°C. On Kazakhstan's landmass, there are five different climate zones. The simulation results showed that adopting PCM layouts in conjunction with ventilation can increase the thermal performance of the thermal comfort conditions during the hotter seasons. Using PCM with a melting temperature of 21°C has preferred heating energy savings, while PCM with 29°C melting temperature has better cooling energy savings as reported by Dardouri et al. [2]. An advanced nanoparticle improved PCM (nano-PCM) was developed by Biswas et al. [24]. The PCM is supported by expanded graphite nanosheets and tested experimentally and numerically. The results showed a reduction in heat transfer by 23%, and the power required to cool the space reduced by 21%. 26 et al. [25] investigated the applicability of a phase change material (PCM)-based radiant floor cooling system. The data from the simulation revealed that the proposed PCM-based radiant floor combined with the cooling system and night ventilation accomplished a thermal comfort cycle of up to 68.5% a year.

The above-presented work covered a wide range of cases that used various types of PCM and studied the influence of the installation locations to identify the best performance that can be produced from this method. However, very few studies covered the use of PCM in the Iraqi climate and the impact of the combination of plywood sheets and the PCM combination on the room climate. The thermal conductivity of the wood is relatively low and decreases with the reduction in density [26]. Moreover, the impact of night cooling was not covered extensively, and the results could help future studies on how to invest it in improving the performance of PCM. The current work will experimentally evaluate the impact of different simplified room configurations with and without PCM stuffed in the wooden walls and how each room affects the other. The results will reveal how beneficial the combination of wood and PCM is as insulation in the building. Moreover, it will ease the judgment on whether it is necessary to use insulation for all the walls of the rooms inside the buildings.

2. EXPERIMENTAL SETUP

2.1 Fabricated wooden box

Dimensionally similar cubes were built with 0.5 m×0.5 m ×0.5 m dimensions for comparison. Plywood sheets were used as a building material, Figure 1. One of the boxes' walls was filled with Paraffin wax (melting temperature 40-44°C) [7], Figure 1, and the other was left without wax to initiate the comparison. The test was performed under the climate conditions of Iraq, Babil governorate, and the City of Hilla (32.47 °N, 44.42 °E). The cubes were placed over the rooftop of a building installed in a location with an assurance that they receive solar irradiance from early morning to sunset. The cubes are mounted so each wall faces one of the coordinates, Figure 1.

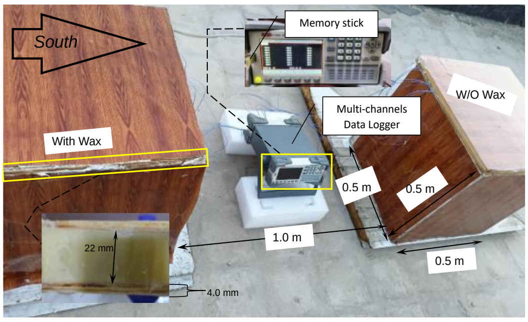

Figure 1. Experimental setup

2.2 Measuring tools

A temperature data logger with 24 channels (Uni-T UT 3224 model) was used to collect the data from several K-type thermocouples attached to different locations inside the cubes and over the walls (Figure 2). The solar irradiance measurement was conducted using a 1.0-2000 w/m^2 solar power meter. The wind speed was measured using (UNI-T UT 363 BT) model anemometer (Figure 3), with a speed range from 0-30 m/s. The data collection period was extended for seven days in arrow for 24 hrs. each day.

Based on the tool's user handbook, the accuracy of the measurements taken for the current study was provided. The measurement error for the solar power meter is 10% for each reading. The data logger reported instability of 0.1°C or less. The anemometer's error is estimated at 5.0%.

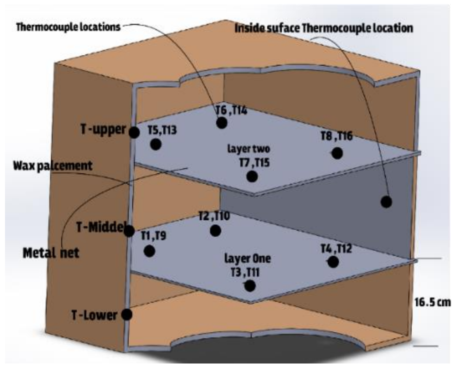

Figure 2. Sketch of the box showing the locations of the thermocouple's placement

(a)Temperature data logger with 24 channels (Uni-T UT 3224 model) (b) Solar power meter (c) (UNI-T UT 363 BT) model anemometer

Figure 3. Measuring tools

2.3 Experimental design

The tests included measuring two layers with four thermocouples inside each box (Figure 3). Moreover, the ambient temperature measurements were also considered. Seven tests were performed to have a clear vision of how the PCM, and the wooden box would perform during the warm days and to capture the impact of the day heating and night cooling (Table 1).

Table 1. Cases and the parameters measured with time for each box

Case#	Days	Time (hr)	Parameters
1	Seven days	00:00 to 24:00	T_{ave}, $T_{surf.}$, T_{wax}
2		00:00 to 24:00	T_{ave}, $T_{surf.}$, T_{wax}
3		00:00 to 24:00	T_{ave}, $T_{surf.}$, T_{wax}

Afterwards, the location of the boxes with respect to each other was changed to explore their effect on each other; this simulates two neighbouring rooms in a building considering the sun's location on them (Figure 4). The temperature inside the room over each suggested layer location was measured along with the contact wall surface temperature (Table 2).

Table 2. Cases and the parameters measured with box location analysis

Case#	Location	Time (hr)	Parameters
1	P1	01:00 to 20:00	T_{ave},T_{surf}.
2	P2	01:00 to 20:00	T_{ave}, $T_{surf.}$
3	P3	01:00 to 20:00	T_{ave}, $T_{surf.}$

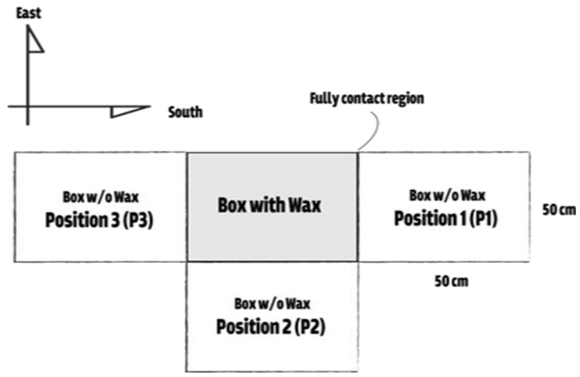

Figure 4. Location of the box (w/o wax) relative to the box with wax

3. RESULTS AND DISCUSSION

3.1 Internal temperature behavior

The time change of the internal temperature of each box is averaged and presented in Figure 5. The collected data over the specified period showed that the inside temperature of the modified wall box was below the conventional box temperature from 9:45 to about 14:00 hr. (Figure 5). In contrast, this period extends to 15:00 hr. as the ambient temperature reduces (Figure 6).

The single-day period can be divided into three regions: Region A (from 01:00 to 08:00 a.m.), Region B (from 8:00 to 15:40 hr.), and Region C (from 15:40 hr. to 24:00 hr.). For region A, both boxes have internal temperatures lower than the ambient temperature, Figure 5, with the lowest recorded temperature of the wooden box without PCM. This region has similar behaviour for all seven test days, Figure 6. In region B, representing the active working hours during the day in Iraq, the box modified with PCM has the lowest recorded temperature by about 1.5°C compared to the conventional box, Figure 5, with solar irradiance range of 628 w/m^2 at 8:00 am to 642 w/m^2 at 16:00 hr. In this region, the temperature of the outside conditions is lower than the temperature inside both boxes; this is attributed to the thermal storing effect of the closed space, which can be tackled by ventilation.

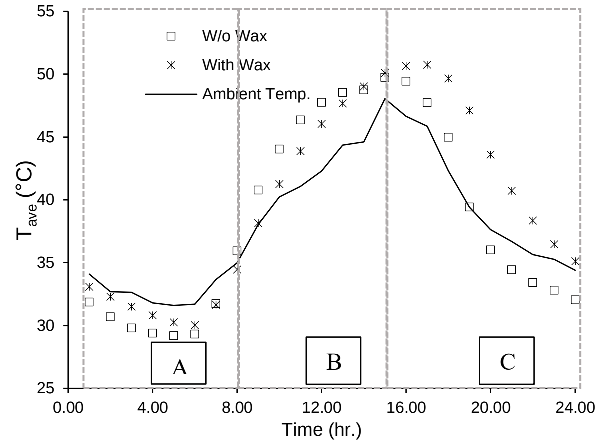

Figure 5. Comparison of the temperature behavior inside the boxes and the ambient temperature for the 12 Aug testing day

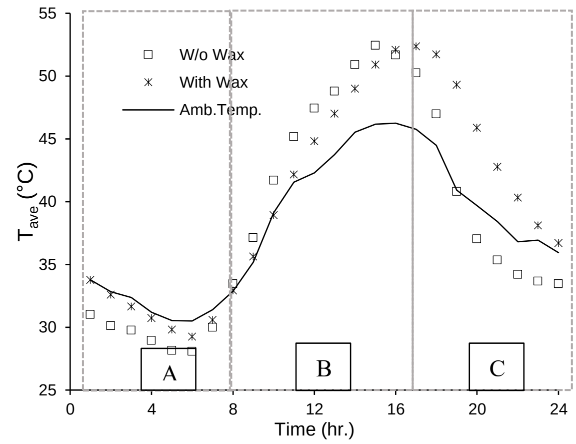

Figure 6. Comparison of the temperature behaviour inside the boxes and the ambient temperature for the 13 Aug testing day

When the period of region C starts, the night cooling effect begins in Figures 5-6. The temperature inside booth boxes starts to fall. The box without PCM embedded with the wall loses the temperature faster than the box with the PCM for all the test days (Figures 5 and 6). This is expected to be due to the role of the PCM in storing the heat and losing it slowly. This behavior made the box without the PCM have an inside temperature lower than ambient and the modified box temperature after 20:00 hr. for all days (Figures 5 and 6). It is worth mentioning the period of each region shifts to the right as the ambient temperature reduces, as seen in the comparison between Figures 5 and 6. It is worth mentioning that the wind speed range during the test day was from 0.0 m/s to 2.0 m/s.

The temperature variation ($\Delta T=T_{ave(w)}-T_{ave(wo)}$) for the two days of measurement is represented in Figure 7. It can be noted that from 01:00 am to about 07:00, the boxes are still losing the heat they received the day before. Therefore, the box's temperature with the stuffed wall is higher than the baseline. Afterwards, the temperature inside the box with PCM stays lower than the box without PCM until about 15:30, when the night cooling (starts after 16:00 hr) effect on the baseline box is more noticeable due to the heat-storing characteristics of the PCM. Night cooling could be of use in cold areas as rooms will keep much of the gained heat during the day. The behaviour applies for both days of the test with slight timing changes.

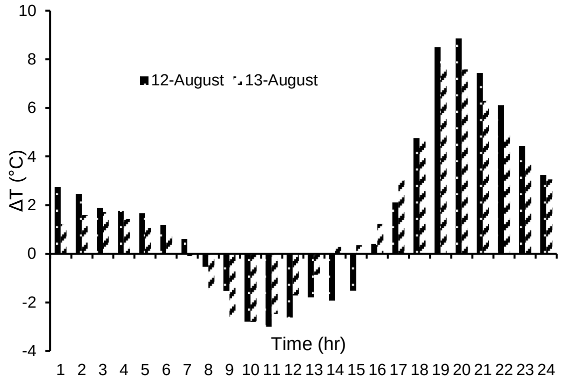

Figure 7. Temperature difference between the modified walls box and the baseline with time and testing days

The Maximum temperature reduction was recorded to be about 6.5% at 10:00 am and a minimum decrease of 0.3% during test day of 12th of August. Moreover, approximately a 6.7 % temperature decrease was recorded during the test day of 13th of August. These rates are compared with the most recent and related work of Al-Yasiri and Szabó [7], who recorded a 9.1% reduction.

3.2 Wall temperature examination

Three days of measurement were made for the wall temperature for the inside and the outside surface for the southern wall only, Figures 8 and 9. Generally, the behavior of the temperature of the interior surface of the wall is similar to the internal temperature for both boxes. Figures 8 and 9 show that in Region A, the temperature of the outer surface is lower than the ambient temperature for both boxes; this can be attributed to the wood's slow absorption of the heat. At region B, the external surface temperature of the wall for the conventional box is higher than the box with the PCM, which is attributed to the impact of the PCM in absorbing the heat and reducing the thermal conductivity of the wall. This is also supported by comparing the inner surface temperature for both boxes (Figure 8 and 9). Both figures (representing different test days) have the same behavior, except the ambient temperature is higher in 17-Aug, reaching 49°C (Figure 8).

The wax temperature inside the wall was measured using three vertically changed locations, Figure 10. From 8:00 a.m. to 10:00 a.m., the temperature of the wax is lower than the ambient temperature for all three locations by about 1.2°C. After that, the wax starts to absorb heat, so its temperature increases and becomes higher than the ambient temperature by a maximum difference of about 12°C at 17:00 hr. for the middle sensor location, Figure 9. The difference in temperature for the three selected locations showed an irregular pattern, especially during the heating times of the day from (8:00 a.m. to 19:00 hr.). This refers to the irregular phase change along the wall. At some locations, the PCM reached the melting point before the other, which could lead to the movement of the melted wax inside the wall, as the liquid wax goes down and contributes to melting the solid part of the PCM. At 17:00 hr., the temperature is almost equalized for the three locations, Figure 10, because all the wax transfers melted. During the cooling time, the upper layers of wax will cool faster than the lower part, which is expected as the melted wax tends to stay at the lower wall.

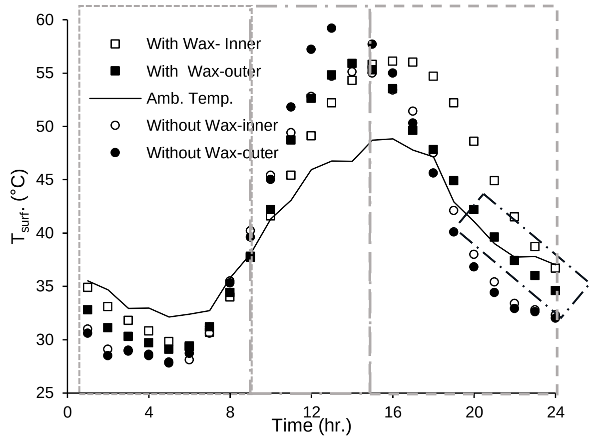

Figure 8. Comparison of the surface temperature over the southern wall of both boxes, measured on the 16th of August

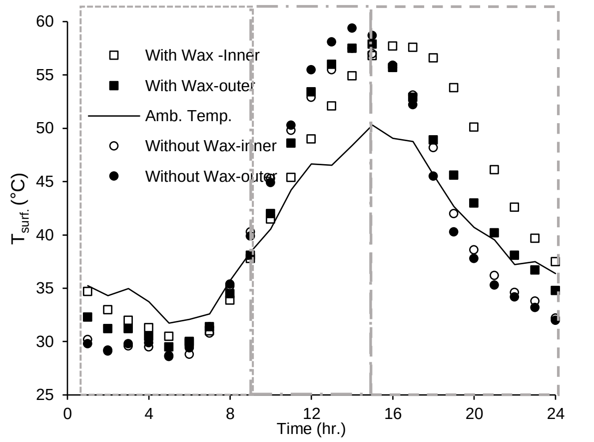

Figure 9. Comparison of the surface temperature over the southern wall of both boxes, measured on the 17th of August

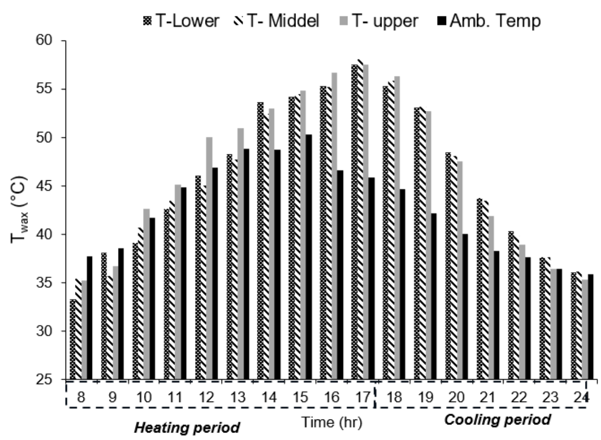

Figure 10. The wax temperature inside the southern wall at three locations, measured on the 17th of August

3.3 Boxes arrangement impact

The location of the boxes to each other was examined for various arrangements, as shown in Figure 4. Three days of data collection are presented for the temperature inside of each box and the contact wall inner temperatures. For the position (P1), both boxes made contact through the southern wall, and the average temperature (T_{ave}) inside showed almost similar behavior when there was no contact, Figure 11. However, it was noted that the average temperature is as low as the ambient temperature, Figures 11-13, which is not the case for standalone boxes, Figures 5 and 6. This is attributed to the conventional boxes' impact as an additional insulation layer for one of the walls. The worst position is present by position P2 (when the traditional box is in contact with the modified wall box through the western side); the temperature inside the box with wax became higher than the ambient and the conventional box temperature at 15:00 hr. earlier than the other cases, Figure 12. As the ambient temperature levels become lower than 48°C, the box with wax has a higher temperature from 1:00 to 5:00 hr., Figures 12 and 13 as compared with Figure 11. It also noted that the internal temperature of both boxes stays lower than the ambient temperature for longer (1:00 to 13:00 hours, Figure 10) compared to standalone boxes, Figures 5 and 6. This behavior is supported by Figures 14-16; the surface temperature is kept lower than the ambient temperature. After 14:00 hrs, it exceeds the environmental temperature; however, the box's temperature with the wax-modified walls is still lower than the conventional one. This concludes that applying the Plywood-PCM walls improved the comfort temperature and became better for the combined rooms inside the building. Also, there is no need for all the rooms' walls to be modified with PCM; having two contact rooms with and without PCM could produce good results.

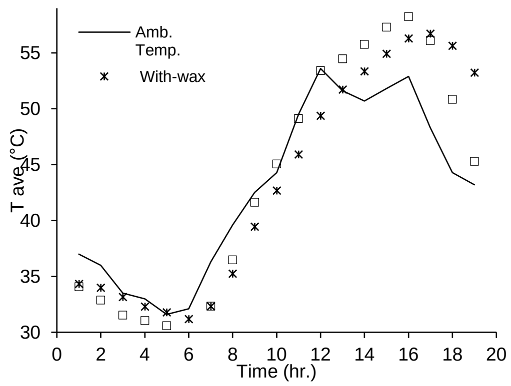

Figure 11. Temperature behavior inside the boxes and the ambient temperature for P1

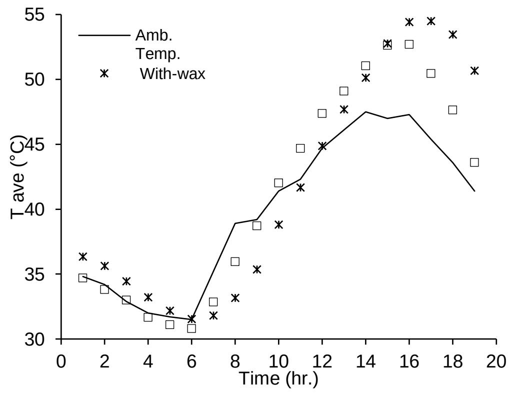

Figure 12. Temperature behavior inside the boxes and the ambient temperature for P2

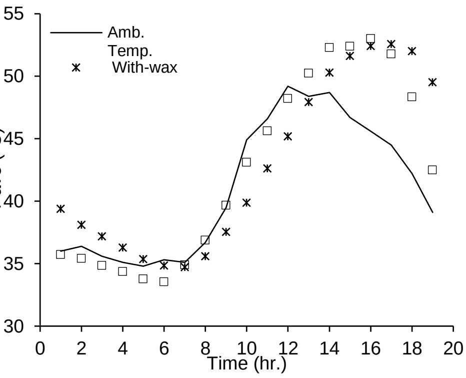

Figure 13. Temperature behavior inside the boxes and the ambient temperature for P2

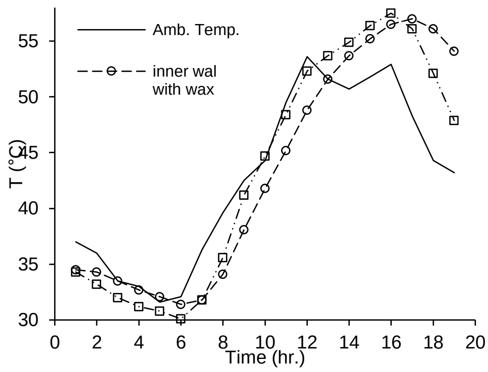

Figure 14. Comparison of the surface temperature over the inner side of the contact wall of both boxes for P1

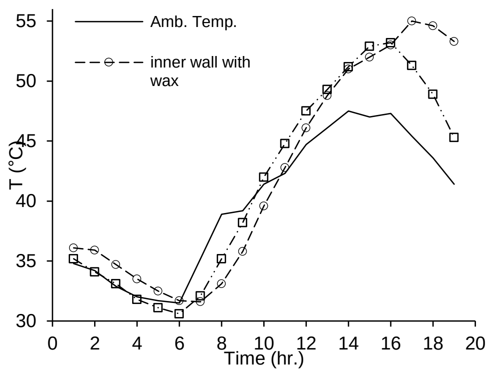

Figure 15. Comparison of the surface temperature over the inner side of the contact wall of both boxes for P2

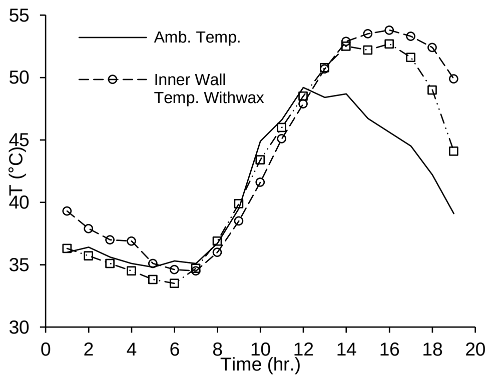

Figure 16. Comparison of the surface temperature over the inner side of the contact wall of both boxes for P3

4. CONCLUSIONS

Thermal analyses were made to use the combination of plywood and a PCM as a suggested insulation for building walls. The study was performed in two stages: standalone and arranged boxes. The temperature inside the boxes, the walls, and the PCM were measured for seven days. The results showed the temperature inside the modified box is lower than the conventional one by about 3.0°C during the peak time (from 8:00 a.m. to 04:00 p.m.). The night cooling is slower for the box with the PCM than the conventional one. Having the modified and the non-modified box in arrangement improves the insulation of both of them. There is no need for all the rooms to be insulated for a building with many rooms. The correct position of the room based on the location of the building in the area of study will be enough. The suggested combination of wood and paraffin wax is promising insulation. During hot hours in Iraq during the day, the insulation showed a reduction in the temperature. Night cooling could be of use in cold weather regions. Considering the findings of this work, implementing the current insulation in a building would be a future task. Furthermore, doing CFD analysis and widening the range of the controlling parameters is also promising work.

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NOMENCLATURE

Amb	Ambient
P	Position
PCM	Phase change Matrial
T	Temperature, ℃
W/O	Without
W	With
CFD	Computational Fluid Dynamics

Subscripts

ave	average
Surf.	Surface