Engineering and Technology Journal
Journal homepage: engtechjournal.org

Analysis of Thermal and Insulation Performance of Double Glazed Window Doped With Paraffin Wax

Jalal M. Jalil[a], Salih M. Salih[b]*

[a] Electromechanical Eng. Dept., University of Technology, Baghdad Iraq. eme.uotechnology.edu.iq

[b] Electromechanical Eng. Dept., University of Technology, Baghdad Iraq.

*Corresponding author.

Submitted: 07/07/2019 Accepted: 01/08/2019 Published: 25/03/2020

K E Y W O R D S

Paraffin Wax, PCM, Thermal Performance, Finite Volume, Enthalpy Method

A B S T R A C T

In this paper, a numerical investigation has been performed to study the effect of varying the thermal properties of the paraffin wax on the performance of a double glazed window doped with it during the summer climate of Baghdad (33.3 °N, 44.4 °E). Using FORTRAN (f 90) constructed computer program, finite difference combined with the enthalpy method was utilized to deal with the conduction with phase change problems within the wax. Results obtained show that increasing the density, latent heat, and thickness of the paraffin wax PCM) would increase the temperature-time lag and reduce the temperature decrement factor of the double glazed window, and as a result, improve comparatively the performance of the unit. In contrast, changing the specific heat capacity of the paraffin wax is not a productive (inefficient) technique to develop the performance of the unit. Besides, the recommended thickness of the window (thickness of the PCM) under the ambient condition of Baghdad should be 20 mm or higher.

How to cite this article: J. M. Jalil and S. M. Salih, "Analysis of thermal and insulation performance of double glazed window doped with paraffin wax," *Engineering and Technology Journal*, Vol. 38, Part A, No. 03, pp. 383-393, 2020.
DOI: https://doi.org/10.30684/etj.v38i3A.448

Nomenclature:

A: Area (m^2)
a, b : Discretization equation coefficient
B: 'Bottom' neighbor of grid P
b: Control-volume face between P and B
Cp: Specific heat (kJ/kg °C)
Cp_l: Liquid phase's specific heat (kJ/kg °C)
Cp_s: Solid phase's specific heat (kJ/kg °C)
e: Control-volume face between P and E
E: 'East' neighbor of grid P
H: Enthalpy (kJ/kg)
i, j, k : Unit vector
k: Thermal conductivity (W/ m °C)

L: Latent heat (kJ/kg)
l: Liquid
N : 'North' neighbor of grid P
n : Control-volume face between P and N
P : Grid point
q : Heat generation (W/m^3)
$\bar{q}$: Average heat generation
S: 'South' neighbor of grid P
s: Control-volume face between P and S
s: Solid
T: Temperature (°C)
t: Time(s)
T: 'Top' neighbor of grid P
t: Control-volume face between P and T
Tm: Melting temperature (°C)
u, v, w : Velocity in x, y, z directions
V: Volume (m^3)
W: 'West' neighbor of grid P
w: Control-volume face between P and W
x, y, z : Cartesian coordinates(m)
ρ : Density (kg/m^3)
ΔT: Temperature range (°C)
Δx, Δy, Δz : Control volume's width in x, y, z directions
$\delta x, \delta y, \delta z$: The distance between two adjacent grid points in x, y, z direction
λ : Diffusion coefficient
Δ: Difference
∂ : Partial derivative

1. Introduction

The high level of temperature around the globe in the last decade led to reducing the thermal comfort and helped in creating a massive amount of heating load on the buildings. The researchers and developers around the world have studied the ways and ideas to overcome this problem. The transparent components are considered the vulnerable piece of the room which has a little thermal resistance, and capable of transmitting a large amount of solar radiation and temperature.
Significant efforts have been made to improve the performance of the transparent components in the aspect of thermal insulation, so a glazing technique has been a desirable approach to reduce the solar radiation and temperature transmitted to the room, also, increase the thermal comfort. A new idea of glazing system has taken some popularity nowadays, which is, filling the double glazed window with phase change materials (PCM). The phase change materials (PCM) are capable of absorbing and releasing a significant amount of heat within their phase change from solid-state to a liquid state and vice versa. So their chances of improving thermal comfort and reducing energy consumption are very high [1].
Ismail et al. [2] studied numerically and experimentally the thermal efficiency of two types of window, traditional and composite (filled with PCM or air). The experimental investigation was carried out employing spectrophotometry on both types. The reflectance test indicated that the reflectance of the single glass window was 12% to 13%; however, the reflectance of the window with PCM was 7 %. The present study's most important conclusion is that the principle of filling window glass with PCM is an effective approach thermally. Goia et al. [3] designed and built a test facility (glazing prototype) containing DGU_PCM (double glazed window with PCM) and DGU_GG (without PCM) and observed the performance of both of them within six months of the year focusing on the thermal comfort aspect and under real working condition. For the majority of the time, the DGU_PCM performance was much better; also, the merits of DGU_PCM will increase as the solar radiation increases; however, the interior surface temperature of DGU_PCM was greater than DGU_GG which is a promising feature in winter, but it must be avoided in summer. Gowreesunker et al. [4] analyzed numerically and experimentally the thermal and optical aspect of a double glazed unit with PCM compared to the usual double glazed unit. Both spectrophotometry and T-history principles were utilized to evaluate the optical and thermal properties, respectively. The acquired results illustrated that the transmittance during a fast phase change is unstable; on the other hand,

throughout solid and liquid phases, the visual transmittance rates are 40% and 90%, respectively. Also, during the phase change, the utilized PCM to fill the double glazed unit will enhance the thermal mass. Jin et al. [5] determined experimentally and numerically the optimum location of the "thin" PCM layer to be integrated into frame walls, in order to increase thermal mass and minimize peak heat fluxes through the wall. Based on the numerical results, the optimum location of this "thin" PCM layer can be determined, also found out that it was influenced by the environmental condition and the thermal properties of the PCM. Xie et al. [6] investigated numerically the transient heat transfer characteristics of combined multilayer thermal insulation materials combined with two types of PCM. Omari et al. [7] analyzed numerically the thermal conduct of composite material involving a micro-dispersed PCM in an insulating polymer matrix. To enhance the thermal insulating and gain of thermal inertia of a building envelope. Fiortti et al. [8] investigated experimentally and numerically a technology with the aim of enhancing the thermal performance of reefer container enclosure using phase change materials (PCM). An external PCM layer was inserted into an insulated sandwich panel in order to minimize and supplant the heat flux phase caused by external climatic conditions. With the purpose of validating the mathematical model, the calculation results were compared with the experimental readings, accomplishing high reliability (correlation coefficient equal to 0.95). Liu et al. [9] demonstrated the effect of semi-transparent property numerically, and zenith angle on the thermal performance of double glazed roof filled with PCM, the thickness of the PCM was studied. The obtained results have shown that the semi-transparent property, zenith angle, and the thickness of the PCM have an enormous influence on the performance of the double glazed roof. Li et al. [10] investigated numerically the thermal performance of the double glazed unit filled with PCM with different thermophysical parameters of PCM. The effects of thermal conductivity, density, specific heat capacity, latent heat, and melting temperature of the PCM were studied. The obtained results indicated that all of the mention properties affect the performance of the double glazed unit significantly. Li et al. [11] experimentally investigated the thermal behavior of triple –pane window (TW) + PCM and compared it with (TW) and (DW + PCM). The obtained results indicated that the inside surface temperature of the TW + PCM was lower than the DW+PCM and TW by 2.7 and 5.5 °C, respectively.

Consequently, minimize the heat entering the building by 16.6 % and 28% throughout the sunny summer day. Elarga et al. [12] investigated numerically and experimentally the performance of the PCM located in the roof of a residential attic in Torino, Italy. The roof was divided into three sections, the first one represents the reference roof (without PCM), and the other two were integrated with a PCM with different melting and freezing range. The obtained results have shown that the presence of PCM with different configuration brought down the interior surface temperature (2.2 and 8.2 °C) in the summertime. Furthermore, Derradji et al. [13] compared the thermal attitude of an office numerically with traditional walls with another office with walls integrated with a PCM in the location of Algiers (Algeria). The PCM in the second office minimized the indoor air temperature by 7 °C in the summer, also reduced the overheating, on the other hand, during the winter the office temperature will be increased by 3 to 4 °C. Hasan et al. [14] investigated the validation of installing layers of PCM as insulation Layers with different thickness located in walls and ceiling of a room located in Kut, Iraq. The acquired results have shown a considerable amount of reduction of indoor temperature and cooling load, which led to saving in electricity consumption. Liu et al. [15] developed a numerical model to determine the optical and thermal performance of glazed roof incorporate with PCM, besides the effect of air convection (h wind). PCM thicknesses and melting temperature were also studied in the northeast China climates. Four PCM thicknesses were selected 50, 20, 12, and 4 mm, also, two PCM melting ranges were proposed, 16-18 °C and 20-22 °C. The obtained results have shown that regarding the internal surface temperature of the glazed roof, the air convection influence should be considered; additionally, the recommended PCM thickness and melting temperature for the northeast China climates were 12-20 mm and 16-18 °C respectively.

The purpose of this paper is to investigate numerically the influence of varying thermal properties of the paraffin wax on the performance of a double glazed window filled with it under the hot environmental condition of Baghdad.

2. Mathematical and Physical Model

I. Geometrical characterization

Figure 1 Illustrates the detailed information of the double glazed window doped (filled) with PCM, which showcase the incident solar radiation and the portion of it that was transmitted to the room. Besides, heat transfer processes (thermal convection and radiation) occur on both of the interior and exterior boundary surfaces, respectively. Also, by means of conduction, convection, and radiation processes, the occupied (absorbed) heat will be transferred inward or outward. Figure 2 shows the (1m*1m*1m) numerical (model) room, which contains a 50 cm * 50 cm window in the south side of it. In addition, the simple cooling system was established on the west side of the room to prevent the overheating of the room. Also, the sun simulator system to simulate the radiation of the sun, which involves halogen lamps.

II. Numerical formulations

The numerical model comprises two parts. The first part is the main program for the room in which Navier Stokes equations were solved based on finite volume, and the second part is the subroutine for the double glazed window in which the energy equation was solved. The aim is to calculate the temperature distribution within the window and across the room.
The assumption that has been made under the numerical solution.

1- 3-D conservation equations.
2- Steady-state incompressible flow.
3- 3-D conduction heat transfer within the glass and PCM
4- Across the room, the natural flow of air has been considered laminar according to Grashof number value.
5- At the average temperature, all properties were estimated.
6- No body forces (neglected).

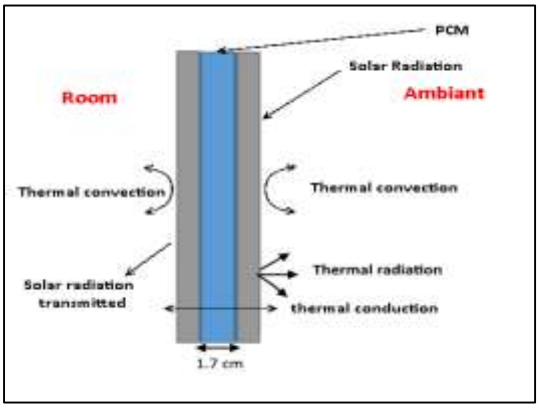


Figure 1: Double glazed window filled with paraffin wax

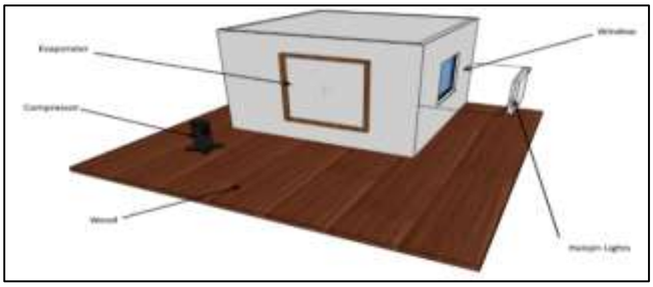


Figure 2: Numerical (model) room

II. Room

For the room, the finite volume has been used to solve the 3-D Laminar Cartesian Coordinates Navier Stokes equations, i.e., Continuity, momentum, and energy. The 3D laminar Navier Stokes equations for the natural convection are:

1-Continuity Equation:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z} \qquad (1)$$

2-Momentum Equation:
x-direction (u-Momentum)
$$\frac{\partial}{\partial x}(uu)+\frac{\partial}{\partial y}(uv)+\frac{\partial y}{\partial z}(uw)=-\frac{1}{\rho}\frac{\partial P}{\partial x}+v\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \quad (2)$$
y-direction (v-Momentum)
$$\frac{\partial}{\partial x}(vu)+\frac{\partial}{\partial y}(vv)+\frac{\partial}{\partial z}(vw)=-\frac{1}{\rho}\frac{\partial P}{\partial y}+v\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right)+\beta g(T-T_W) \quad (3)$$
z-direction (w-Momentum)
$$\frac{\partial}{\partial x}(uw)+\frac{\partial}{\partial y}(vw)+\frac{\partial}{\partial z}(ww)=-\frac{1}{\rho}\frac{\partial P}{\partial z}+v\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right) \quad (4)$$

3-Energy Equation
$$\frac{\partial}{\partial x}(uT)+\frac{\partial}{\partial y}(vT)+\frac{\partial}{\partial z}(wT)=\frac{k}{\rho C_p}\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \quad (5)$$

III. Double glazed window

Stefan problems were used to represent the heat conduction problems with phase change. This issue is addressed utilizing the enthalpy transforming method; this method was offered to transform the energy equation into a non-linear equation with a singular dependent variable enthalpy (H). The benefit of the enthalpy method is that it can solve the problem when it's formulated in a fixed region. Besides the temperature, this mythology deals with enthalpy as a subordinate variable; additionally, it separates the energy equation for a combination of equations that include both temperature and enthalpy. This analysis's assumptions are:
1. No viscous dissipation.
2. No radiation and convection terms.
3. For each phase, the specific heat is constant, and the phase change takes place at a particular temperature.
The analysis of the model in 3-D is regards Cao [17].
The energy equation is:
$$\frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k\frac{\partial T}{\partial z}\right)+\overline{q}\ =\rho\frac{\partial H}{\partial t} \quad (6)$$
In addition, the state equation:
$$\frac{dH}{dT}=C_P \quad (7)$$
The phase change happened at a certain temperature [18],
$$T=\begin{cases} T_m+{H}/{C_{ps}} & H\le 0 \quad (Soild\ phase) \\ T_m & 0<H<L \quad (Phase\ change) \\ T_m+{(H-L)}/{C_{pl}} & H\ge L \quad (Liquid\ phase)\end{cases} \quad (8)$$
For the prior relation, H is equal to zero and it was picked out according to the phase change material (PCM) in their solid state to temperature T_m.
$$a_pH_p=a_NH_N+a_SH_S+a_EH_E+a_WH_W+a_TH_T+a_BH_B+b \quad (9)$$

The values of coefficients are:
$$a_p=a_N+a_S+a_E+a_W+a_T+a_B$$
$$a_E=\frac{\Delta t}{\rho\Delta V}\frac{\lambda_E A_x}{\delta x_e},a_W=\frac{\Delta t}{\rho\Delta V}\frac{\lambda_W A_x}{\delta x_w},a_N=\frac{\Delta t}{\rho\Delta V}\frac{\lambda_N A_y}{\delta y_n},a_S=\frac{\Delta t}{\rho\Delta V}\frac{\lambda_S A_y}{\delta y_s},a_T=\frac{\Delta t}{\rho\Delta V}\frac{\lambda_T A_z}{\delta z_t},\ a_B=\frac{\Delta t}{\rho\Delta V}\frac{\lambda_B A_z}{\delta z_b} \quad (10)$$
Where, $A_x=\Delta y\Delta z, A_y=\Delta x\Delta z, A_z=\Delta x\Delta y, \Delta V=\Delta x\Delta y\Delta z$
And,
$$b=-[a_N+a_S+a_E+a_W+a_T+a_B-1]H_p^o+b_NS_N+b_SS_S+b_ES_E+b_WS_W+b_TS_T+b_BS_B-b_pS_P+\frac{dt}{\rho} \quad (11)$$
Also,
$$\mathrm{b_p=b_E+b_W+b_S+b_N+b_T+b_B}$$
Where,
$$b_E=\frac{\Delta t}{\rho\Delta V}\frac{A_x}{\delta x_e},b_W=\frac{\Delta t}{\rho\Delta V}\frac{A_x}{\delta x_w},b_N=\frac{\Delta t}{\rho\Delta V}\frac{A_y}{\delta y_n},b_S=\frac{\Delta t}{\rho\Delta V}\frac{A_y}{\delta y_s} \quad (12)$$

The last methodology is similar to solid and liquid regions.
In this work, temperature time lag ($\varnothing_{pcm}$) and temperature decrement factor (d_{pcm}) were used to evaluate the performance of the double glazed window [15].

$$\varnothing_{pcm} = \tau_{g,\,max} - \tau_{a,\,max} \tag{13}$$

$$d_{pcm} = \frac{T_{pcm,max} - T_{pcm,min}}{T_{a,max} - T_{a,min}} \tag{14}$$

Where, $\tau_{g,\,max}$ is the time required for the internal surface temperature of the glazed to reach the maximum point and $\tau_{a,\,max}$ is the time required for the ambient (outdoor) temperature glazed to reach the maximum point (both of them starting from the morning). Besides, ($T_{pcm,max}$) and ($T_{pcm,min}$) are the maximum and minimum internal surface temperature of the double glazed unit respectively, on the other hand, ($T_{a,max}$) and ($T_{a,min}$) are the maximum and minimum ambient temperature where the maximum and minimum ambient temperature was 50°C and 33°C respectively (during week 25) as shown in Figure 3.

IV. Boundary conditions

The boundary conditions of the system, which consists of a double glazed window and room are shown in Figure 4.

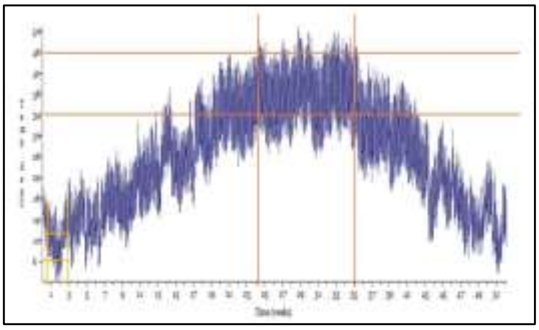


Figure 3: Temperature levels for Baghdad in 2018

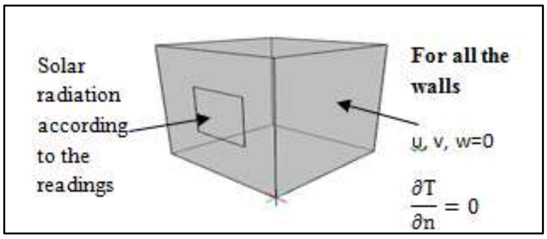


Figure 4: Boundary condition applied on both (room and window)

3. Validation of the Numerical Model

A room with the dimensions of 1m*1m*1m was manufactured. The walls and ceiling were made of PVC sandwich panel (10 cm thickness) containing a window in the south side of it with the dimensions of 50*50 cm; in addition, the ground was made of wood with a thickness of 2 cm. as shown in Figure 5. Also, the solar radiation of the sun was simulated by using 4 halogen lamps, which placed 70 cm away from the window. A controlling system was successfully set up to simulate the solar radiation and light of the sun during day time (13 to 14 hours of day time) by means of Arduino Uno, diac, triac, and sets of relays and variable resistances.
The numerical model is validated by means of this experimental room, under the environmental condition of Baghdad (extremely hot summer) in 25/6/2018. Incident solar radiation is shown in Figure 6.
Figure 7 spectacles the comparison between the experimental and numerical results regarding the interior surface temperature of the double glazed window (filled with PCM) and the indoor temperature of the room. Which displays a mean bias error (MBE) of 1.88 and 0.2, respectively. Consequently, a quite good agreement between them.

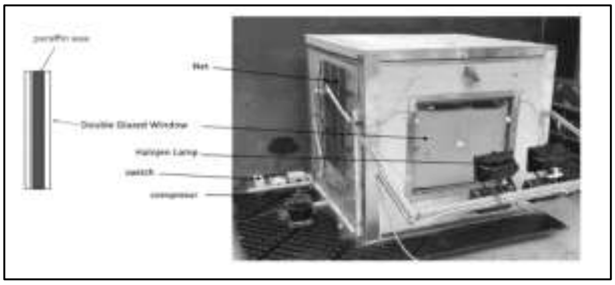


Figure 5: Experimental room

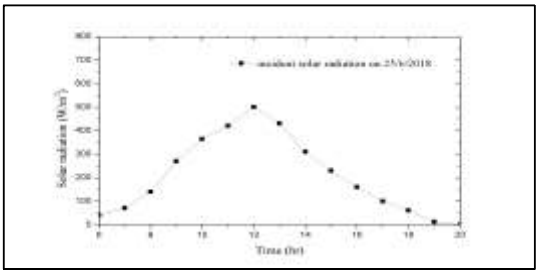
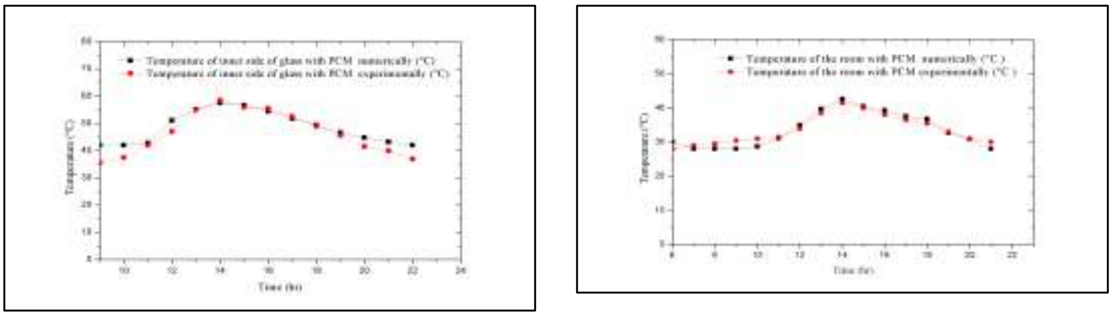


Figure 6: Solar radiation recorded on 25/6/2018



a b

Figure 7: Comparison between experimental and numerical results (a) Internal surface temperature of the double glazed window (b) Room temperature

4. Results and Discussion

In this simulating work, a constructed FORTRAN program was utilized. The original thicknesses of the PCM and the glass are 17 mm and 6 mm, respectively, and the recorded incident solar radiation on the 25th of June in 2018 is shown in Figure 6. Furthermore, Table 1 listed the thermal properties of the materials, which involve the melting temperature of the paraffin wax (around 40 °C), which is utterly convenient and close to the average ambient temperature of Baghdad's summer period.

I. Effect of varying the density

For determining the effect of varying the density of paraffin wax on the performance of the double glazed window filled with it (paraffin wax), five different PCM's densities were investigated 650, 880, 1250, 1500, and 1800 Kg/m^3, simultaneously, leaving the remaining thermal properties (listed in Table 1) unchanged. Figure 8 shows the numerical internal façade temperature of the double glazed window with various PCM's densities. When the PCM's density is 650, 880, 1250, 1250, and 1500, the temperature decrement factor and temperature time lag were, 1.3 and 1.5 h, 1.2 and 2.5 h, 1 and 2.5 h, 0.8, and 3 h, 0.6 and 3.5 h, respectively. This process reveals that increasing the density of the paraffin wax, decreases the temperature decrement factor and increases the temperature-time lag; moreover, the density of the PCM is very influential regarding the temperature decrement factor. The reason for this attitude is that increasing the density means adding more amount of PCM, which increases thermal resistance and reduces temperature transmitted. Worth noting that the density plays a great role in determining the PCM's liquid phase period, which affects directly the solar energy transmitted to the room because increasing the density of the PCM would shorten the liquid phase period and ultimately, reduces solar energy transmitted.

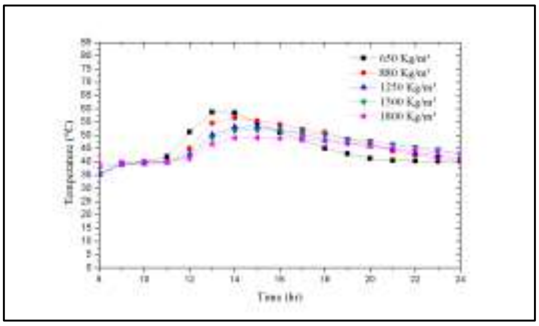


Figure 8: Internal surface temperature of the double glazed window with different PCM densities

II. Effect of varying the specific heat

In order to investigate the effect of changing the specific heat capacity of the paraffin wax on the performance of the glazed window filled with it, five different specific heat capacities were investigated, 1000, 1400, 1800, 2200 and 2600 J/Kg.K, at the same time, leaving the other thermal properties of the PCM unchanged. Figure 9 displays the numerical internal surface temperature of the double glazed window with various PCM's specific heat capacities. When the PCM's specific heat capacity is 1000, 1400, 1800, 2200 and 2600 J/Kg.K, the temperature decrement factor and temperature time lag were, 1.4 and 1 h, 1.3 and 1.5 h, 1.2 and 2.5 h, 1.1 and 2.5 h, 1 and 3 h, respectively. This process demonstrates that increasing the specific heat capacity of the paraffin wax decreases the temperature decrement factor and increases the temperature-time lag. However, the influence of the PCM's specific heat capacity on temperature decrement factor is relatively low when the C_p (paraffin wax) is < 1800 J/Kg.K. As a result, increasing (or controlling) the PCM's specific heat capacity is not an ideal approach to optimize the performance of the double glazed window.

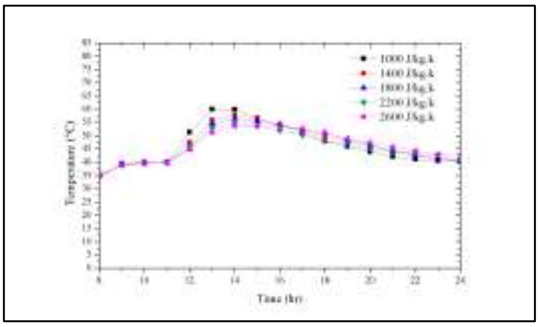


Figure 9: Internal surface temperature of the glazed window with various PCM specific heat capacities

Table 1: Thermal properties of materials

Material	Melting temp. (°C)	Density ($kg.m^{-3}$) solid	liquid	Thermal condu. ($W.m^{-1}.K^{-1}$)	Specific heat ($J.kg^{-1}.K^{-1}$)	Latent heat ($kJ.kg^{-1}$)
Glass	--	2500	--	0.96	840	--
Paraffin wax [20]	40	880	760	0.13	1800	174.12

III. Effect of varying the latent heat

For determining the influence of varying the fusion enthalpy of paraffin wax on the performance of the double glazed window filled with it (paraffin wax), five different PCM's latent heats were investigated 120, 150, 174, 200 and 250 KJ/Kg, while, leaving the remaining thermal properties unchanged. Figure 10. shows the numerical internal surface temperature of the double glazed window with various PCM's latent heats. When the PCM's latent heat is 120, 150, 174, 200 and 250 KJ/Kg, the temperature decrement factor and temperature time lag were, 1.6 and 1.5 h, 1.3 and 2 h, 1.2 and 2.5 h, 0.9 and 3 h, 0.2 and 3.5 h, respectively. This process indicates that increasing the latent heat of the paraffin wax decreases the temperature decrement factor and increases the temperature-time lag. Furthermore, increasing the latent heat of the PCM above < 174 KJ/Kg leads to better results regarding to the temperature decrement factor. As a result, increasing PCM’s latent heat is a beneficial and influential approach to develop the performance of the double glazed window.

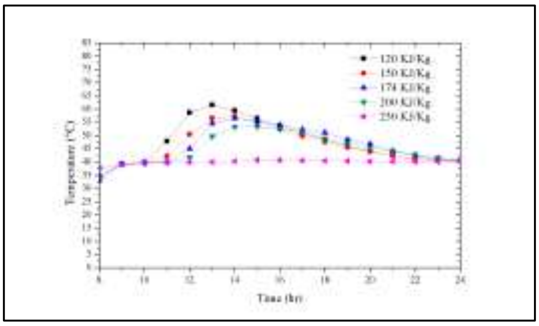


Figure 10: Internal surface temperature of the double glazed window with different PCM latent heats

IV. Effect of varying the thickness of the PCM

In order to investigate the effect of changing the thickness of the paraffin wax on the performance of the double glazed window filled with it, five different thicknesses of the wax were investigated, 10, 15, 17, 20, and 25 mm, in addition, leaving the thermal properties of the PCM listed in Table 1 unchanged (all of them). Figure 11 displays the numerical internal surface temperature of the double glazed window with different thicknesses. When the thickness is 10, 15, 17, 20 and 25 mm, the temperature decrement factor and temperature time lag were 1.7 and 1.5 h, 1.4 and 2.5 h, 1.2 and 2.5 h, 1 and 3 h, 0.5 and 3.5 h, respectively. This process indicates that increasing the thickness of the paraffin wax (and the window), decreases the temperature decrement factor and increases the temperature-time lag. Moreover, changing the thickness of the double glazed window (also the thickness of the PCM) plays a significant role in determining its thermal performance. Consequently, results obtained show that for the environmental condition of Baghdad (summer period), the recommended thickness of the window should be 20 mm or higher (for the tested period, which is the month of June). However, increasing the thickness of the window should not be random because increasing the thickness means adding more amount of wax, which leads to a higher amount of heat that would be discharged within the re-solidification phase (discharge phase), which may affect negatively. Therefore, there is an optimum thickness (of the window), which leads to a better(ideal) performance.

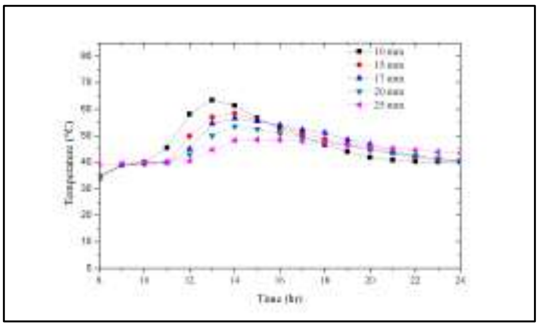


Figure 11: Internal surface temperature of the double glazed window with different PCM thicknesses

V. Effect of varying the melting temperature

For determining the effect of varying the melting temperature of paraffin wax on the performance of the double glazed window filled with it (paraffin wax), four different PCM’s melting temperatures were investigated 38, 40, 42, and 44 °C, while, leaving the remaining thermal properties unchanged. Figure 12 shows the numerical internal façade temperature of the double glazed window with various PCM’s melting temperatures. When the PCM’s melting temperature is 38, 40, 42 and 44 °C, the temperature decrement factor and temperature time lag were 1.25 and 1.5 h, 1.26 and 2 h, 1.3 and 1.5 h, 1.3 and 2.5 h, respectively. Which indicates that the temperature decrement factor increases as the melting temperature of the PCM increases. On the other hand, the influence of changing the melting point of the PCM on the temperature-time lag is not consistent, also, when it is above 40 °C the temperature decrement factor is > 1.1. Ultimately, managing the melting point of the PCM is a significant method to enhance the performance of the double glazed window. In addition, the melting temperature should be matched with both outdoor and indoor temperatures.

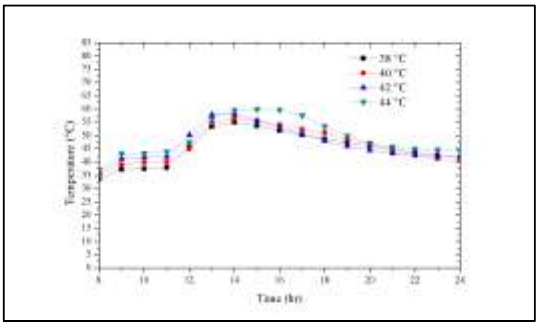


Figure 12: Internal surface temperature of the double glazed window with different PCM melting temperatures

5. Conclusions

1- Increase the density of the PCM from 650 g/m^3 to 1800 g/m^3 would increases the temperature-time lag from 1.5 h to 3.5 h, in addition, reduces temperature decrement factor from 1.3 to 0.6, which leads to conclude that, increasing the density (or picking the proper density) of the PCM is very beneficial and valid approach to develop the performance of the glazed unit.
2- Increasing the PCM's specific heat capacity is not a helpful technique to improve the performance of the double glazed window, because the influence of specific heat capacity on the temperature decrement factor is not powerful. (d_{pcm}) is 1.4, 1.3, 1.2, 1.1, and 1 when the Cp of the PCM was 1000, 1400, 1800, 2200, and 2600 J/Kg.K.
3- Temperature decrement factor and temperature time lag were, 1.6 and 1.5h when the latent heat value was 120 KJ/Kg, also, 0.2 and 3.5 h when the latent heat was 250 KJ/Kg, which states that increasing the PCM's latent heat is very useful and would give a quite optimistic results.
4- Increasing the thickness of the double glazed window (i.e., the thickness of the PCM filled the window) would decrease the internal surface temperature, also, reduces the temperature decrement factor remarkably. In addition, increases the lag time. The recommended thickness of the double glazed window filled with paraffin wax (PCM) should be 20 mm or higher, for the tested period.
5- The melting point of the PCM should be close or matched with environmental temperature and indoor temperature in order to have improved performance of the double glazed window.

References

[1] L. Socaciu, A. Pleşa, P. Ungureşan and O. Giurgiu, "Review on phase change materials for building applications," *Leonardo Electronic Journal of Practices and Technologies* 25, pp. 179-194, 2014.

[2] K. A. R. Ismail and J. R. Henrıquez, "Parametric study on composite and PCM glass systems," *Energy conversion and management*, 43.7, pp. 973-993, 2002

[3] F. Goia, M. Perino and V. Serra, "Improving thermal comfort conditions by means of PCM glazing systems," *Energy and Buildings* 60, pp. 442-452, 2013.

[4] B. L. Gowreesunker, S. B. Stankovic, S. A. Tassou and P. A. Kyriacou, "Experimental and numerical investigations of the optical and thermal aspects of a PCM-glazed unit," *Energy and Buildings*, 61 pp. 239-249, 2013.

[5] X. Jin, M. A. Medina and X. Zhang, "Numerical analysis for the optimal location of a thin PCM layer in frame walls," *Applied Thermal Engineering,* 103, pp. 1057-1063, 2016.

[6] T. Xie, Y. He and Z. Tong, "Analysis of insulation performance of multilayer thermal insulation doped with phase change material," *International Journal of Heat and Mass Transfer*, 102, pp. 934-943, 2016.

[7] K. El Omari, Y. L. Guer and P. Bruel, "Analysis of micro-dispersed PCM-composite boards behavior in a building's wall for different seasons," *Journal of Building Engineering,* 7, pp. 361-371, 2016.

[8] R. Fioretti, P. Principi and B. Copertaro, “A refrigerated container envelope with a PCM (Phase Change Material) layer: Experimental and theoretical investigation in a representative town in Central Italy,” *Energy conversion and management*, 122, pp. 131-141, 2016.

[9] C. Liu, Y. Zhou, D. Li, F. Meng, Y. Zheng and X. Liu, “Numerical analysis on thermal performance of a PCM-filled double glazing roof,” *Energy and Buildings*, 125, pp. 267-275, 2016.

[10] D. Li, Z. Li, Y. Zheng, C. Liu, A. K. Hussein and X. Liu, “Thermal performance of a PCM-filled double-glazing unit with different thermophysical parameters of PCM,” *Solar Energy*, 133, pp. 207-220, 2016.

[11] S. Li, G. Sun, K. Zou and X. Zhang, “Experimental research on the dynamic thermal performance of a novel triple-pane building window filled with PCM,” *Sustainable cities and society,* 27, pp. 15-22, 2016.

[12] H. Elarga, S. Fantucci, V. Serra, R. Zecchin and E. Benini, “Experimental and numerical analyses on thermal performance of different typologies of PCMs integrated in the roof space,” *Energy and Buildings*, 150, pp. 546-557, 2017.

[13] L. Derradji, F. B. Errebai and M. Amara, “Effect of PCM in Improving the Thermal Comfort in Buildings,” *Energy Procedia*, 107, pp. 157-161, 2017

[14] M. I. Hasan, H. O. Basher and A. O. Shdhan, “Experimental investigation of phase change materials for insulation of residential buildings,” *Sustainable cities and society*, 36, pp. 42-58, 2018.

[15] C. Liu, Y. Wu, J. Bian, D. Li and X. Liu, “Influence of PCM design parameters on thermal and optical performance of multi-layer glazed roof,” *Applied energy*, 212, pp. 151-161, 2018.

[16] A. R. Abdulmunem and J. M. Jalil, “Indoor investigation and numerical analysis of PV cells temperature regulation using coupled PCM/Fins,” *International Journal of Heat and Technology*, Vol. 36, No 4, December, pp. 121-1222, 2018.

[17] Y. Cao, A. Faghri and W. S. Chang, “A numerical analysis of Stefan problems for generalized multi-dimensional phase-change structures using the enthalpy transforming model,” *International journal of heat and mass transfer*, 32.7, pp. 1289-1298, 1989.

[18] T. Norton, A. Delgado, E. Hogan, P. Grace and D. Sun, “Simulation of high pressure freezing processes by enthalpy method,” Journal *of food engineering*, *91*(2), pp. 260-268, 2009.

[19] S. H. Cho and J. E. Sunderland, “Heat-conduction problems with melting or freezing,” *Journal of Heat Transfer,* 91.3, pp. 421-426, 1969.

[20] I. Dinçer, A. Midilli and H. Kucuk, eds, “*Progress in Sustainable Energy Technologies,” Vol II: Creating Sustainable Development*, Vol. 2. Springer, 2014.