Use of Phase Change Material in Residential Walls to Reduce Cooling Load

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Received on : 11/1/2011 **Accepted on : 29/3/2011**

Abstract.

This paper describes a numerical method for calculating the temperature distribution and latent heat storage (LHS) in the treated wall (TW) and non-treated wall (NTW). The developed method was assumed that the outer cement layer (Iraqi wall) enveloping the external wall of building and houses are contains paraffin wax as a phase change material (PCM). (25%) is the volume percentage of paraffin wax is mixed with cement which forming a treated layer. A comparison results between the (TW) and (NTW) has been done. The paper presents a simple calculation of case study for air-conditioning in two walls type of residential building. The outer solar air temperatures as function of day time are considered for a hot day in summer (July) for Baghdad city. The aim of this paper was to obtain physical validation of the numerical results produced from using developed FORTRAN program. This validation was obtained through a comparison of numerical solution of two different wall compositions exposed to the same external and internal load conditions. The calculations on transient heat transmissions across different walls were conducted. It was found that when using the (TW) with (PCM) produces lower surface and heat flux towards the cooling space with respect to (NTW).

Keywords: Phase Change Materials, Latent Heat Storage, Numerical Solution, Explicit Technique, Energy Storage.

1- Introduction.

In Iraq and Arab gulf countries the cooling of establishments building and residential houses contributes significantly to electrical consumption load. This demand of electricity occurs during the peak, which is approximately in the period of (12:00 pm to 4:00 pm). Due to difficulties of keeping or providing this demand, our work will shift some of the load away from the peak hours or reducing the electrical consumption in this period. The (PCM) is a substance which melts during the peak time of the day. (PCM) would absorb a percentage of the energy which would otherwise be transferred inside the building or houses. In our study the (PCM) is assumed to be casted with cement layer which forming a sub-layer under the external cement layer in Iraqi wall. This approach can be used in new houses constructions and old houses. Much works has been done in the study of the use of (PCM's) for thermal storage in new home constructions. M.Farid, A.Kudhair [1] which used different types of materials available as well as how they are currently being used and discussed in details. C.K.Halfored [2] a developing and simplified numerical model, which investigate a configuration product known as resistive-capacitive-resistive one dimension technique. In his technique explained how the ability to shift the peak of air conditioning load from using the (PCM). J.Kim, K. Darkwa [3] which discuses the development of model for a (PCM) that is integrated into building's drywall. In his work the simulation which is depend upon an implicit enthalpy solution. J. Blark, D. Heim [4] presented in his model a (PCM) embedded in gypsum wallboard and modifying software to represent the melting and refreezing of the material, also he treated his problem in one dimensional and the thermo-physical properties of (PCM) gypsum composite are considered homogeneous. A numerical method described by J.Rose, A. Lahme [5] for calculating the latent storage performance of building components containing (PCM) in order to evaluate the impact on heating and cooling demands. In our work the outer boundary condition represented by solar air temperatures are function of daily time which is taken from Amar K. [6], the numerical solution of one dimension energy equation through the wall is considered with constant properties of (PCM) through the solution from solid to liquid or vice versa. Our purpose of this work which developing a simplified numerical technique which investigate the ability of (PCM) in treated layer to shift the load beak due to the air conditioning through the summer away from electrical demand peak. (PCM) can store much amounts of thermal energy per unit mass than conventional building materials. This saving of energy as a latent heat not as sensible heat when its change from solid to liquid. (LHS) in a (PCM) is very attractive because of its high storage density with small temperature swing. It has been demonstrated that for the development of a latent heat storage system in a building fabric, the choice of PCM plays an important role in addition to heat transfer mechanism in the (PCM). Thermal energy storage in the walls, ceiling and floor of the buildings may be enhanced by encapsulating or embedding suitable (PCMs) within these surfaces. They can either capture solar energy directly or thermal energy through natural convection. Increasing the thermal storage capacity of building can increase human comfort by decreasing the frequency of internal air temperature swings so that indoor air temperature is closer to the desired temperature for a longer period of time. This system provides a valuable solution for correcting the difference between the supply and demand of energy. Many phase change materials has been studied and tested for different practical uses by many scientists. In an effort to avoid some of the problems inherent in inorganic PCM's, an interest has turned towards a new class of materials Christopher and Nicholas, Lane G. [7 and 8] low volatility, anhydrous organic substance such as paraffin, fatty acids and polyethylene glycol. These materials have strong advantages such as physical and chemical stability, good thermal behavior and adjustable transition zone. In building applications, only PCM's that have a phase change close to human comfort temperatures (20°C - 28°C) can be used as in R. Velraj [9]. Commercial PCM's have been developed by some of the manufactures listed in **table (1)** that are suitable for building applications. In 1983, Abhat [10] gave the general classification of energy storage material, and also by G.A. Lane [11, 12], Dinser and Rosen [13]. These papers gave the full detail like classification and characteristics of (PCM). B.Zalba [14] listed the properties of different PCM’s (Organic, Inorganic, Fatty acids) like density, specific heat, thermal conductivity and melting temperature. Some of the important properties required for PCM are

- High latent heat of fusion per unit mass, so that a lesser amount of material stores a given amount of energy.
- High specific heat that provides additional sensible heat storage effect and also avoid sub cooling.
- High thermal conductivity so that the temperature gradient required for charging the storage material is small
- High density, so that a smaller container volume holds the material

- A melting point in the desired operating temperature range.
- The phase change material should be non-poisonous, non-flammable and non-explosive.
- No chemical decomposition, so that the (LHTS) system life is assured.
- No corrosiveness to construction material
- PCM should exhibit little or no super cooling during freezing.

A PCM wall is capable of capturing a large proportion of the solar radiation incident on the walls or roof of a building. Because of the high thermal mass of PCM walls, they are capable of minimizing the effect of large fluctuations on the inside temperature of the building. They can be very effective in shifting the cooling load to off-peak electricity period.

Piia Lamberg [15] (PCM) can be impregnated into building materials such as outer cement sub layer as impregnated pellets. Paraffin wax because of its cheapness and ready availability, combined with its flexibly adjustable phase change temperature is seen as a particularly promising material for use in building components as PCM, M.Farid [1]. This paper attempts to analyses the information about application of (PCM) in the building walls for residential and commercial establishments.

2- Mathematical and Numerical Model.

Fig.(1) shows the traditional wall used in Iraq, the treated wall with (PCM) is split into four thermal zones. Each zone is having the same physical and thermal properties. All dimensions of wall layers are given in **Fig. (1)**.

The heat balance principle is adopted to investigate the transient thermal distribution by dividing the wall into sub-domains i.e. nodes. In each control volume the temperature is calculated as a function of the heat flux and the heat capacity of the material. The thermal conditions are taken as uniform throughout the control volume, this is reasonable approximation as long as control volume size are small enough.

The following assumptions are adopted in this work:

i. One dimensional transient heat conduction through the wall.
ii. The ambient temperature is a function of time.
iii. The thermophysical properties are constant.
iv. Outside and inside heat transfer coefficients are constant.
v. Radiation heat transfer with internal space is neglected.
vi. The internal space is constant temperature (26 C°).

2.1 Outer and Inner Boundaries.

The governing equation of heat transfer between the (n) layers of the wall is treated as one-dimension equation as in G.Myers and R. Canale[7 and 8],

$$\mathrm{k_n}\frac{\partial^2 \mathrm{T}}{\partial \mathrm{x}^2} = \mathrm{\rho_n C_n}\frac{\partial \mathrm{T}}{\partial \mathrm{t}} \tag{1}$$

Equation (1) can be used for treating the external and internal surfaces of the walls. The boundary conditions used are:

$$q_o(0,t) = -k\left.\frac{\partial T}{\partial x}\right|_{x=0} \quad \text{for } \mathrm{t} > 0 \tag{2}$$

$q_i(L,t) = -k \left.\frac{\partial T}{\partial x}\right|_{x=L}$ for $t > 0$

Since

$$q_o = h_o(T_{f1}(t) - T(0,t))$$

$$q_i = h_i(T_{f2} - T(L,t)) \quad (3)$$

An explicit numerical solution for an internal node is formulated by finite difference as given by [8]

$$T_i^{j+1} = T_i^j + \frac{k_n \Delta t}{\rho_n C_n (\Delta x)^2}(T_{i+1}^j - 2T_i^j + T_{i-1}^j) \quad (4)$$

For the outer and inner surfaces node temperatures (T_1 & T_N) are formulated from heat balance equation (1). The heat convected to element is equal to heat stored inside the element plus the heat conducted out from the element, the final equations of outer and inner surface temperature are.

$$T_1^{j+1} = 2F\left(T_2^j + R_o T_{f1}(t)\right) + (1 - 2FR_o - 2F)T_1^j \quad (5)$$

$$T_N^{j+1} = 2F\left(T_{N-1}^j - R_i T_{f2}\right) + (1 - 2FR_i - 2F)T_N^j \quad (6)$$

Where $F = \alpha\Delta t/\Delta x^2$, $R_o = h_o\Delta x/k$, $R_i = h_i\Delta x/k$.

2.2 Interface Boundaries.

To find the interface node temperature (T_I) between any two different material zones as shown in **Fig. (2)**. Two different material layers (n1 & n2) are taken and heat balance is adopted around control volume, its thickness $(\Delta x_{n1} + \Delta x_{n2}) / 2$. The stored heat ($q_s$) can be formulated as follows

$$q_s = \frac{\Delta x_{n1}}{2}\rho_{n1}C_{n1}\left(\frac{T_{n1}^{j+1} - T_{n1}^j}{\Delta t_{n1}}\right) + \frac{\Delta x_{n2}}{2}\rho_{n2}C_{n2}\left(\frac{T_{n2}^{j+1} - T_{n2}^j}{\Delta t_{n2}}\right) \quad (7)$$

By the same procedure as in surface boundaries, the temperatures (T_{n1} & T_{n2}) are the central temperatures at $(\Delta x/4)$ from the interface. The final formulated equation of interface temperature after simplifying the element thickness as follows,

$$T_I^{j+1} = \frac{1}{A1 + A2}\left[T_{I-1}^j + T_I^j(A1 + A2 * R - 1 - R)\right] + RT_{I+1}^j \quad (8)$$

Where

$$A1 = \frac{\left[\frac{(\Delta x_{n1})^2}{\alpha_{n1}\Delta t_{n1}}\right]}{2} \quad (9)$$

$$A2 = \left\{\frac{\left[\frac{(\Delta x_{n2})^2}{\alpha_{n2}\Delta t_{n2}}\right]}{2}\right\} * \frac{k_{n2}}{k_{n1}} * \frac{\Delta x_{n1}}{\Delta x_{n2}} \quad (10)$$

$$R = \frac{k_{n2}}{k_{n1}} * \frac{\Delta x_{n1}}{\Delta x_{n2}} \tag{11}$$

The condition of convergence which must be satisfied is

$$\mathrm{A1} + \mathrm{A2} * \mathrm{R} - 1 - \mathrm{R} \geq 0 \tag{12}$$

2.3 Developing of PCM's for Cooling of Buildings.

The essential feature of (PCMs) is that they absorb energy as latent rather than sensible heat over a small range of temperatures around their melting point (fusion temperature), and hence exhibit no sensible temperature rise over this range. The PCM is distributed homogenously within the outer cement sub layer. The (PCM) absorbed energy from around system until all the (PCM) is melted in outer sub layer. If (λ) is the percentage volume of PCM in outer sub layer, the actual heat stored in control volume (I) can be given as:

$$Q_{act} = \lambda * \rho * H * \Delta x \tag{13}$$

The paraffin wax material used in sub layer is mixed at 25% volume percentage with cement. For solid PCM as homogenous distribution in treated cement layer, the energy Eq. 2 is given the following form

$$k_s \left(\frac{\partial^2 T_s}{\partial x^2}\right) = \rho_s C_s \left(\frac{\partial T_s}{\partial t}\right) \tag{14}$$

Where subscript (s) denotes the solid PCM. The energy balance for the solid-liquid interface in the melting process is given the form [8]

$$k_s \frac{\partial T_s}{\partial x_S} - k_l \frac{\partial T_s}{\partial x_S} = \rho_s L \frac{dS_x}{dt} \tag{15}$$

Where (S) is the solid-liquid phase change interface and L is the latent of the PCM fusion. In the solidification process the subscripts (l and s) are interchanged and the latent heat of fusion (L) is replaced with (-L) in Eq.(15), the temperatures of the solid and the liquid in (PCM) are equal in the solid-liquid interface, $T_s=T_l$.

To find out the behavior of the (PCM) during the melting and freezing process, Piia Lamberg [17] gives DSC-curve of the paraffin as shown in **Fig. (3)**. The paraffin material starts melting at (20-21C°) and the melting peak reaches at temperature (27.7 C°), the material at these temperatures is start for charging in case of melting and discharging in case of solidification. The (PCM) used in our calculation is technical grad paraffin. The material is both an ecologically and environmentally friendly material that utilizes processes between the solid and liquid phase change to store and release energy with small temperature rang. The material properties of the paraffin as (PCM) are presented in **table (2)**.

2.4 **Numerical Calculations.**

The calculations are done for the real conditions of a day time for the Bagdad city as given by Amar K. [6]. The assumptions made in Sec.2.1 are applied in our approach solution. **Table (3)** gives the properties of layers which are used in Iraqi wall as a (TW) under study. The numerical calculations are performed with developed FORTRAN program by using the melting temperature of paraffin wax as in **Fig. (3)**. The program was designed to simulate the outer condition and solve the heat conduction equations (4,5 and 6) through the treated and other wall layers simultaneously. When the temperature calculated (T_i^{j+1}) becomes above the melting temperature (T_m) in the treated cement layer the program directly switching to change the used properties in building material to the treated layer properties with (PCM). **Fig.(4)** shows the logic subroutine of calculating treated layer temperatures. Definitely this temperature depends on melting temperature (T_m) and the actual stored heat (Q_{act}) in the control volume of treated layer for a completely melted (PCM). The same simulation scenario is repeated for the case of frozen temperature of (PCM) in treated layer.

3. Results and Discussions.

The values of solar air temperatures are given by **Fig.(5)** which are represent the hottest day (21 July) in the Baghdad city. The values of solar air temperatures are reading from polynomial equations by program as the external load on the wall. This figure shows that, the highest temperature is in the west direction and then the higher load can be chosen and applied on the wall. Due to this reason the wall analysis is chosen in the west direction for approving the aim of this paper. In our calculations, we use a constant heat transfer coefficients for the outer and inner surface. The numerical values of these coefficients can be assumed as in [15] (h_o=25 W/m^2.C°) and (h_i=10 W/m^2.C°). From the **Fig.(6)** it clearly states the (TW) with (PCM) is better than (NTW). If the wall is treated with (PCM) it can reduce the transferred heat to the conditioned space about more than two-third than (NTW). A 66% reduction in heat transfer is obtained when using (TW) compared with (NTW). This reduction is directly proportional to the corresponding saving in the electrical power consumption from national electrical net to maintain the cooling space at (26°C). Definitely this reduction in heat flux in case of treated wall is due to stored heat inside the wall for a full day time.

Fig.(7) shows that, the stored heat flux in the (TW) is greater than the stored heat in (NTW). In the same figure, the time of store (charging time) is started at 11 A:M o'clock and reaches a maximum value (640 W/m^2) for treated wall at 15:25 P:M and continue until 22 P:M. This is due to the exits of (PCM) in cement layer and its changing from solid to liquid state with the same temperature and the heat is stored as latent heat rather than as sensible heat, therefore more energy added to the wall layer with same temperature. These fluxes of heat can be reflected on the behavior of internal surface temperature of the wall. **Fig.(8)** shows the internal surface temperature for two types of the wall, it's clear from this figure the internal surface temperature in case of treated wall with (PCM) is (3.25 C°) lower than the case without (PCM) with same boundary load conditions. Definitely this gain in reduction temperatures can be reflected on the internal air-conditioning load and therefore this load can be shifted away from the peak load of consummation on the network of electricity. M.ravikumar, PSS. Srinivasan [18] gives **Fig (9)** as the surface temperature at the bottom of the roof for three type of roof material. When compared the results produced from **Fig.(8)** with that in **Fig. (9)**, it's shown that the same prediction in differences between the (TW) and (NTW) in his work when compared with our work.

4. Conclusions.

The thermal heat storage with PCM was studded. The heat entering in to the cooling space was maximum with (NTW), because the thermal conductivity is high value. So almost all the heat entering the wall was transferred to the cooling space. The treated layer offers the resistance for the heat flow and heat transfer was reduced by (45%) for a total time of day. Also the treated layer is charging through the period of phase change with constant temperature until all the material becomes liquid, this will be delaying the heat input in to cooling space through the peak of electrical demand. An experimental model is the scope of future work.

5. References.

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6- Nomenclature.

Cp	specific heat, (J/ kg K)
h_0	wall outside heat transfer coefficient, (W/ mK)
h_i	wall inside heat transfer coefficient, (W/ mK)
H	enthalpy, (J)
k	heat conductivity (W/ m K)
L	latent heat of fusion, (J /kg)
q	heat flux in (W/m^2)
S	the location of the solid-liquid interface, (m)
t	time, (s)
T	temperature, (°C)
T_{f1}	temperature of cooling space, (°C)
T_{f2}	temperature of ambient, (°C)
x	direction

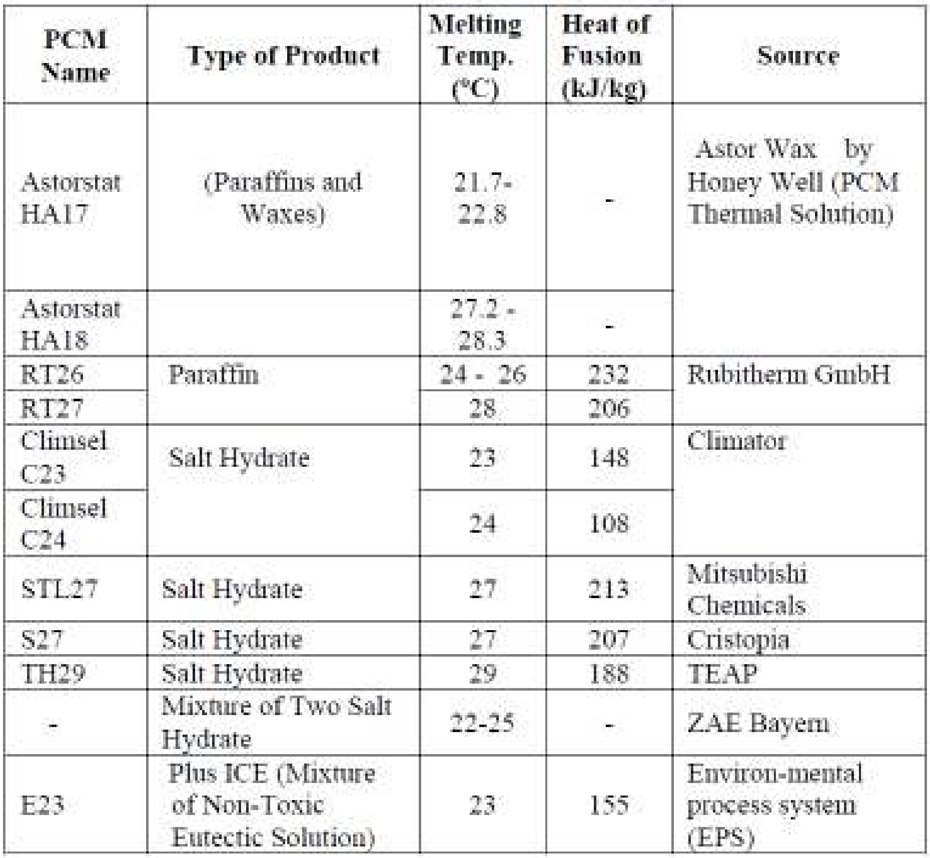
Greek.

ρ	Density, (kg/m^3)
λ	Volume percentage
Δ	Finite difference step
α	Thermal diffusivity (m^2/s)

Subscript:

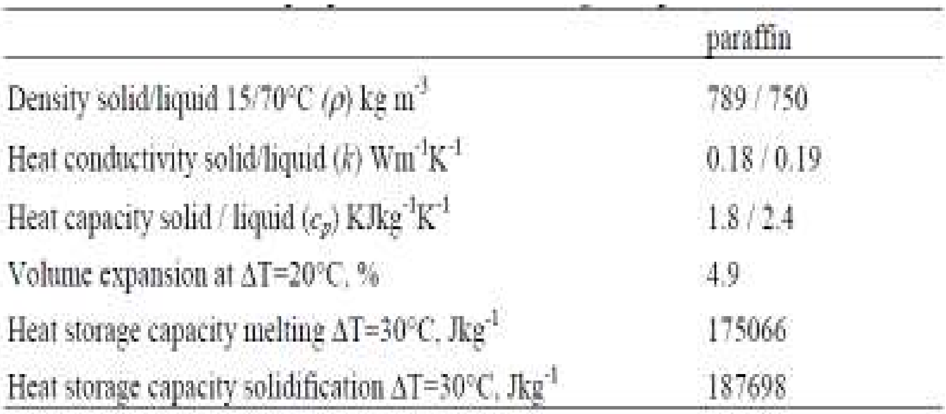
i	ith spatial step
j	jth time step
n	no. of layer
s	stored heat

Table 1: Phase change temperature and heat of fusion of typical commercial PCMs [9]



PCM Name	Type of Product	Melting Temp. (°C)	Heat of Fusion (kJ/kg)	Source
Astorstat HA17	(Paraffins and Waxes)	21.7-22.8	-	Astor Wax by Honey Well (PCM Thermal Solution)
Astorstat HA18		27.2 - 28.3	-	
RT26	Paraffin	24 - 26	232	Rubitherm GmbH
RT27		28	206	
Climsel C23	Salt Hydrate	23	148	Climator
Climsel C24		24	108	
STL27	Salt Hydrate	27	213	Mitsubishi Chemicals
S27	Salt Hydrate	27	207	Cristopia
TH29	Salt Hydrate	29	188	TEAP
-	Mixture of Two Salt Hydrate	22-25	-	ZAE Bayern
E23	Plus ICE (Mixture of Non-Toxic Eutectic Solution)	23	155	Environ-mental process system (EPS)

Table 2: The material Properties of technical grade paraffin [15].



	paraffin
Density solid/liquid 15/70°C (ρ) kg m^{-3}	789 / 750
Heat conductivity solid/liquid (k) Wm^{-1}K^{-1}	0.18 / 0.19
Heat capacity solid / liquid (c_p) KJkg^{-1}K^{-1}	1.8 / 2.4
Volume expansion at ΔT=20°C, %	4.9
Heat storage capacity melting ΔT=30°C, Jkg^{-1}	175066
Heat storage capacity solidification ΔT=30°C, Jkg^{-1}	187698

Table (3): Material property data

Material	Density (kg/m^3)	Thermal Conductivity (W/mK)	Specific Heat (J/kgK)
Concrete	2100	1.16	920
Brick	2000	0.812	837.5
Gypsum	1280	0.464	1008
Treated layer (25%paraffin +75% concrete)	Solid: 1770	0.49	900
	Liquid: 1750	0.49	900

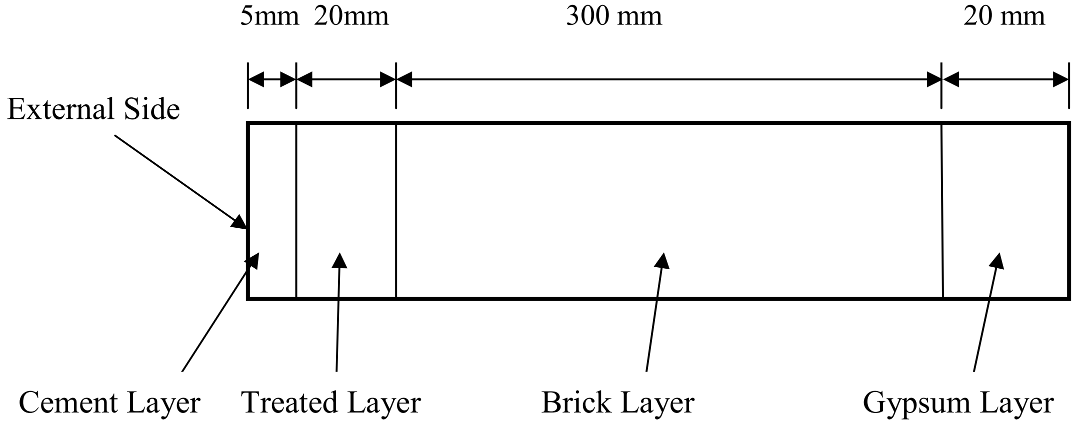


Figure (1) Iraqi wall geometry

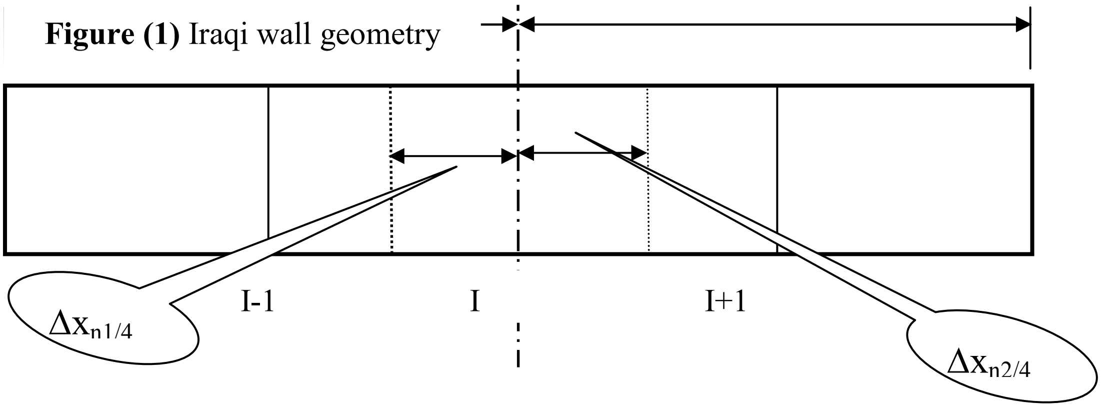


Figure (2) Interface control volume of two different layers

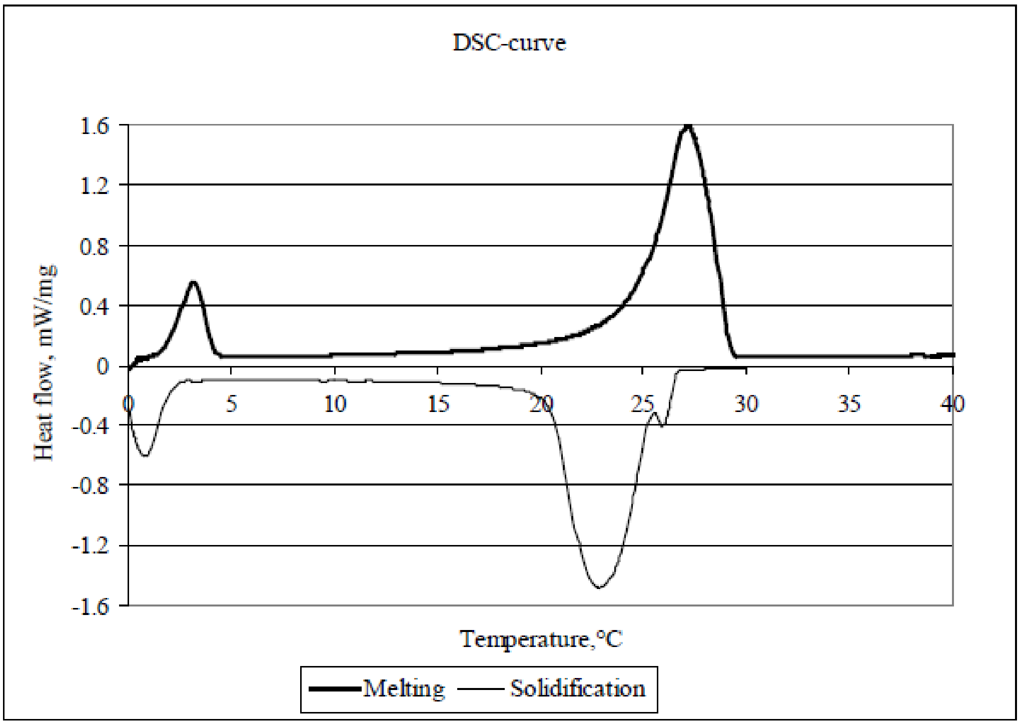


Figure (3) The DSC- curve of the paraffin [17]

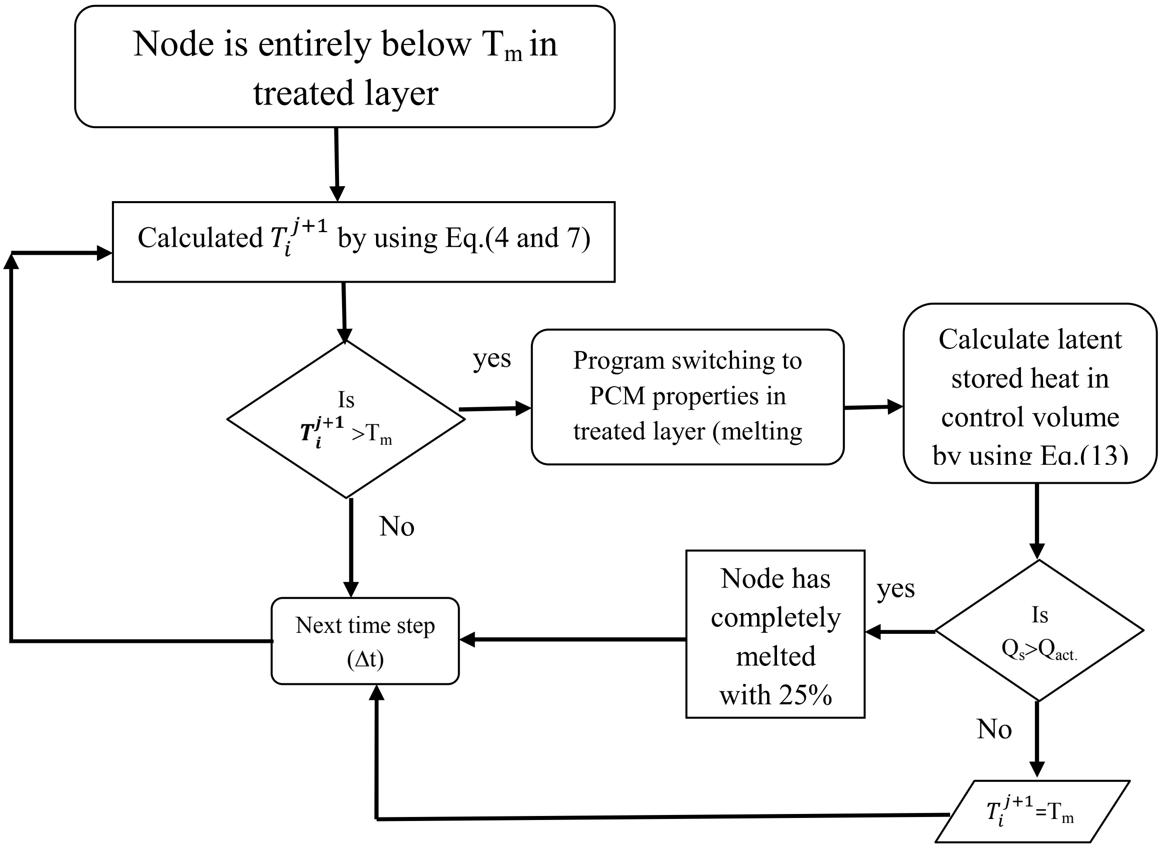


Figure (4) Logic subroutine for calculating temperature in PCM layer

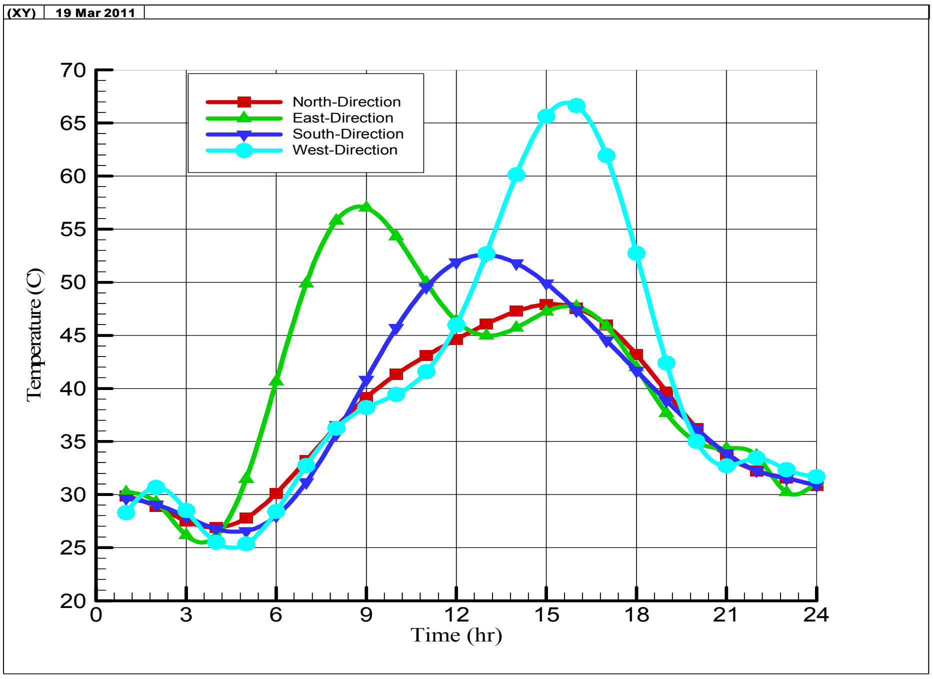


Figure (5): Weather data for Baghdad city during july [6]

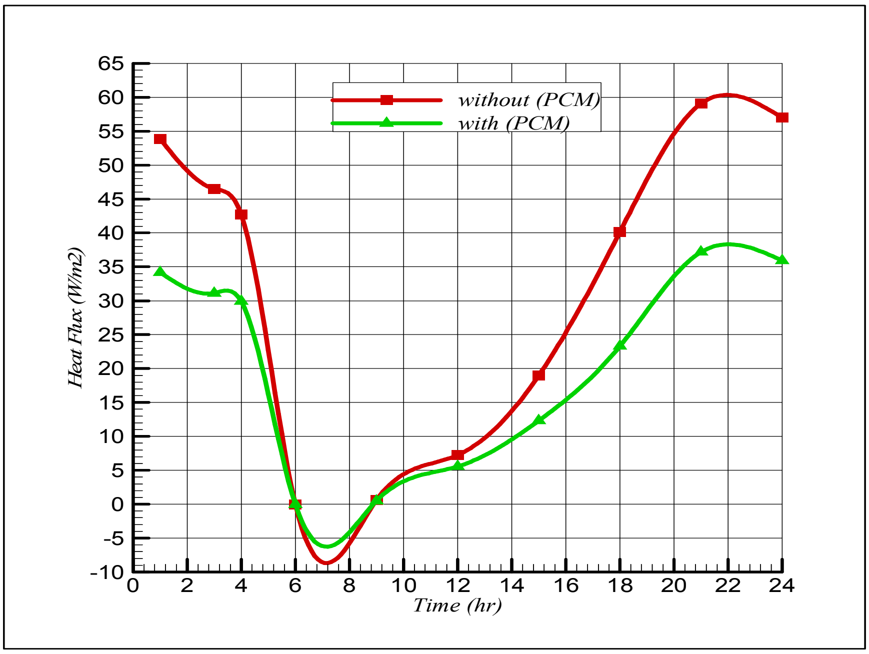


Figure (6): heat flux entered to the conditioned space.

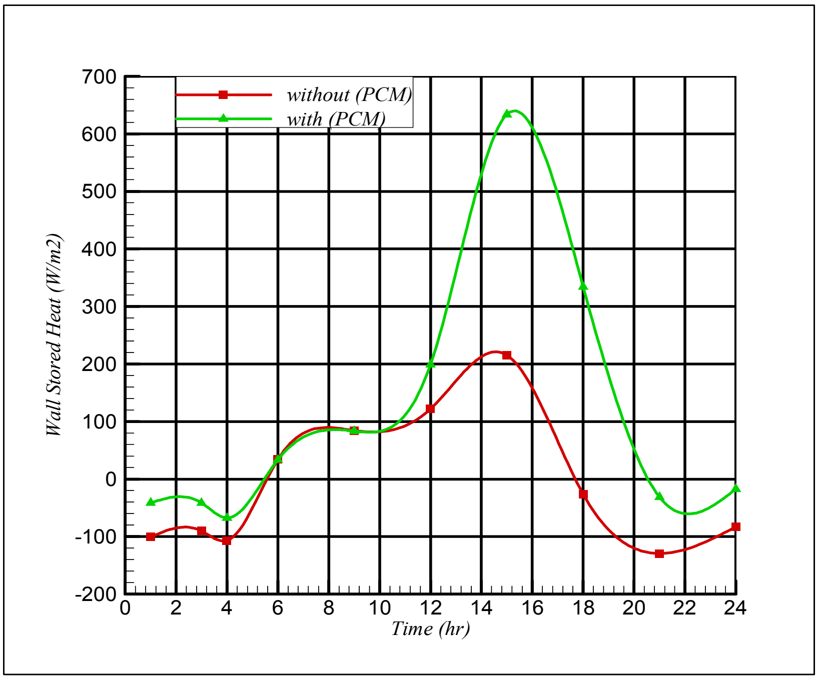


Figure (7): Stored heat flux in the two different walls.

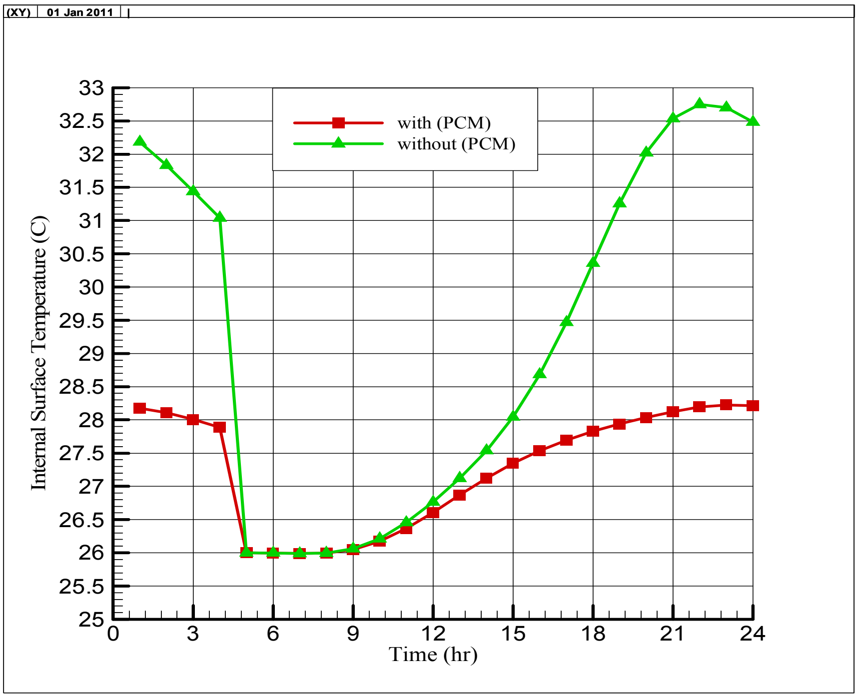
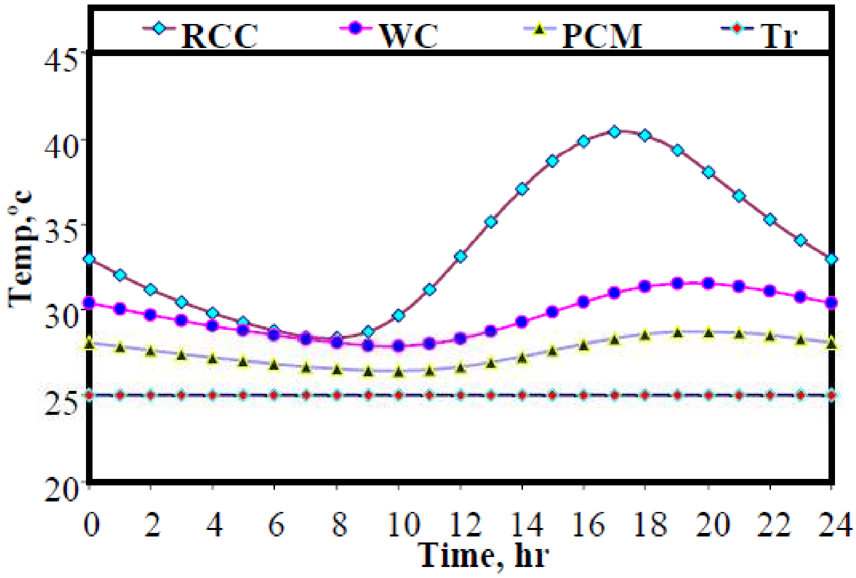


Figure (8): Internal surface wall temperature for the two different walls



RCC = Temperature of concrete roof.
WC = Temperature of RCC roof covered with withering course.
PCM = Temperature of RCC covered with mixing layer of (PCM&WC)
Tr = Room temperature.

Figure (9): Roof bottom surface temperature [18]

أستخدام مواد متغيرة الطور في الجدران لتقليل حمل التبريد

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الخلاصة

توضح الدراسة البحثية التي أجريت على جدار معامل بمادة متغيرة الطور (شمع البرافين) بنسبة حجمية ٢٥% مع جدار تقليدي من خلال الحل العددي بأن الجدار المعامل يقوم بخزن كمية أكبر من الحرارة داخله في الطبقة المعاملة بعد تعرضهما الى نفس الظروف المحيطة. علما بأن درجة حرارة الهواء الشمسية لمدينة بغداد أخذت لأحر يوم في تموز وبالأتجاه الغربي. وبما أن الطبقة المعاملة هي أقرب الى السطح الخارجي، فأت كمية التفريغ الى المحيط الخارجي هي أكبركما أثبتته الدراسة ان كمية الحرارة المنبعثة من السطح الداخلي للجدار المعامل هي أقل من كمية الحرارة المنبعثة من الجدار القليدي الى المحيط المراد تبريده. كذلك درجة حرارة السطح الداخلي للجدار المعامل هي أقل من درجة حرارة الجدار التقليدي. وعليه يمكن الأستفادة من المواد متغيرة الطور بعد أضافتها بنسب معينة الى مواد البناء وذلك بتقليل الأنبعاث الحراري الى المحيط المراد تبريده ومن ثم تقليل حمل التبريد في فترة الطلب القصوى وبذلك تقليل الحمل المسلط على شبكة الكهرباء الوطنية او تحريك الحمل الأقصى على الشبكة الوطنية الى غير وقته الذي يحدث في فترة الذروى عند أستخدام هذه المواد في البيوت السكنية والمباني الحكومية علما بأنة بالأمكان تطبيقها على البيوت الحديثة والقديمة وهي أمينة الأستخدام.

الكلمات الدالة: مواد متغيرة الطور، حرارة الخزن الكامنة، الحل العددي، الحل الصريح، خزن الطاقة