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Decrease of Electrical Consumption During Periods of Peak Load Into the National Grid by Improving Thermal Insulation of Buildings

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***Abstract*— Improving the thermal insulation of building envelope translates into reduced consumption of electrical energy used for air conditioning during the summer months, especially in hot regions such as region of Ouargla. In this paper a study of the thermal behavior and optimization by numerical simulation of a brick containing phase change material (PCM) is realized. Actual weather conditions of temperature and solar radiation in the region of Ouargla are used as boundary conditions. Several parameters affecting the efficiency of thermal insulation of brick as: the type of PCM, the geometry of the container of the PCM, the effect of surface / volume ratio and location of the PCM in the brick are optimized. The results show that the improved brick reduces 86.87% of the heat flux entering to the internal environment and therefore, the same portions of electrical energy used by air conditioning are reduced. Consequently the peak consumption of this energy into the national grid during periods of peak load is decrease.**

Keywords- Thermal insulation, Phase Change Material (PCM), building comfort, latent heat, bricks, hot and dry climates. Introduction (Heading 1)

Nomenclature:

CFD	Computational fluid dynamics
C_p	specific heat at constant pressure (kJ/kg °C)
H	length of the brick in the y direction (cm)
h	enthalpy of the material (kJ/kg)
h_{in}	convective heat transfer coefficient in indoor wall of brick (kW/m^2°C)
h_{out}	convective heat transfer coefficient in outdoor wall of brick (kW/m^2°C)
h_{ref}	reference enthalpy (kJ/kg)
HVAC	Heating, Ventilation and Air-Conditioning
k	thermal conductivity (kW/m°C)
L	length of the brick in the x direction (cm)
L_{fus}	latent heat of fusion (kJ/kg)
LHTES	Latent heat thermal energy storage
PCM	phase change material
S	heat generation (kW/m3)
T	temperature (K)
$T_{liquidus}$	melting temperature (K)
T_{ref}	reference temperature (K)
$T_{solidus}$	solidification or freezing temperature (K)
u_i	fluid velocity (m/s)
x_i	Cartesian coordinate
β	liquid fraction
μ	density (kg/m^3)

I. INTRODUCTION

It is very well known that specific climate regions in south Algeria are characterized by high temperatures during several months of the year and a very high energy consumption compared to other regions is noted (Table 1). This peculiarity is essentially due to the massive use of the air conditioning, i.e. heating, ventilation and air-conditioning (HVAC) [1].

TABLE 1. AVERAGE SPECIFIC ELECTRICITY CONSUMPTION BY CUSTOMER [1]

	Average specific consumption (kWh/customer) by Geographic Region	
Year	2008	2009
North	2545	2511
High plateau	2438	2463
South	3612	3799
Average specific consumption (kWh/customer)	2611	2623

Consequently, a good insulation of the building envelope will reduce the need of air conditioning. As a result, positive impacts include peak load shifting energy conservation and a reduction in peak demand for network line companies (Figure

1) as well as potential reduction in electricity consumption and savings for residential customers are expected.

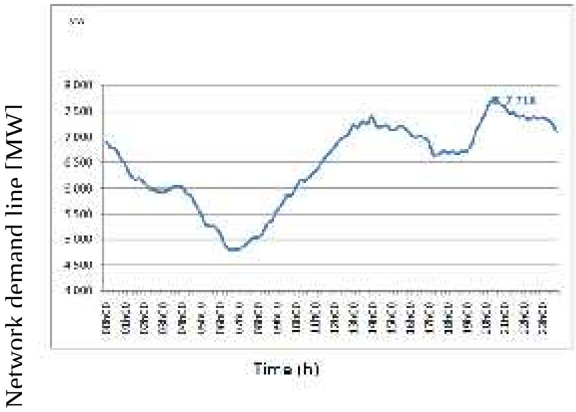


Figure. 1. Network demand line on the day of August 24th, 2010 ref [1]

Among the most recently used insulation methods, the insulation by latent heat is the most effective one. This later uses phase change materials (PCM) encapsulated in concrete, gypsum wallboard, ceiling and floor or placed directly in the form as plates by screwing or stapling of the building envelope [2-6]. On the other hand, the Latent Heat Thermal Energy Storage (LHTES) systems have many advantages due to their high-energy storage densities as compared to sensible heat storage techniques. The latent heat thermal energy storage materials or phase change materials (PCMs) absorb and release thermal energy as they will be solidified and melted at particular constant temperature known as phase change temperature [7].

The phase change material introduced into the building envelopes absorbs a large amount of heat during the hot day time and fuses gradually in an isothermal way to prevent the entrance of heat inside housing environments. During the night time, the temperature decreases above the melting point of the PCM. This later releases heat into building envelope and becomes solid again so that it starts again the cycle of melting/solidification during the following hours.

In this context many research works have been done. Luisa F. Cabeza et al [8] has studied a new innovative concrete with phase change materials (PCM) on thermal aspects. The work consists on an experimental installation and the construction of two real size concrete cubicles in order to study the effect of the inclusion of this type of material at a melting point of 26° C and a phase change enthalpy of 110kJ/kg. The results of this study show that the energy storage in the walls by incorporating the PCMs and the comparison with conventional concrete without phase change materials leading to an improved thermal inertia as well as a lower inner temperatures. Also, Esam M. Alawadhi [9] studied the thermal analysis of building bricks containing phase change material (PCM) used in hot climates. The considered model consists on bricks with cylindrical holes filled with PCM. A parametric study was conducted to evaluate the effect of different conception parameters, such as the PCM’s quantity, the type, and the location in the brick. The results indicated that the heat flux at the indoor space can be reduced by 17.55% when three PCM cylinders were introduced and located at the centerline of the bricks. The increase of the PCMs quantity has a positive effect to reduce the heat gain through the bricks. A.Pasupathy et al [10] attempted to study the thermal performance of an inorganic eutectic PCM based on thermal storage system for thermal management in a residential building. The system has been analyzed theoretically and experimentally and a double layer PCM concept was studied in detail to realize the year thermal management around the year in a passive manner. It has been concluded that in order to reduce the internal oscillation air temperature and to be appropriated for all the seasons, for the purpose of narrowing indoor air temperature swing and to suit for all seasons, a double PCM layer incorporated in the roof is suggested and recommended. Ana Lazaro et al [11] presented an experimental setup for testing PCM–air real-scale heat exchangers and the results for two real-scale prototypes. The results showed that a heat exchanger using a PCM with lower thermal conductivity and lower total stored energy, adequately designed, has higher cooling power and can be applied for free-cooling. On the other hand, the thermal effectiveness of a building’s roof with phase change material (PCM) has been studied [12]. The considered model consisted on a concrete slab with vertical cone frustum holes filled with PCM. A parametric study was conducted to assess the effects of the cone frustum geometry, and the kind of PCM used. The results indicate that the heat flux at the indoor surface of the roof can be reduced up to 39% for a certain type of PCM and geometry of PCM cone frustum holes. Xing Jin et al [13] have studied the thermal performances of the double layer PCM floor, based on numerical model. The obtained results showed that the optimal melting temperatures for heating and cooling PCM are 38 °C and 18 °C respectively; and the optimal melting temperatures will vary with the change of the locations of the two PCM layers. Compared to the floor without PCM, the authors noted that the energy released by the floor with PCM in peak period will be increased by 41.1% and 37.9% during heating and cooling when the heat of fusion of PCM is 150 kJ/kg. S. Deng et al [14] studied two typical housing models; both are designed according to the real occupancy condition, the life schedule, the thermostats settings, etc., for the two cities; Shanghai (humid) and Madrid (dry). Indoor comfortable results show that the temperature comfort can be met for two models under Shanghai and Madrid’s weather. But humidity comfort demand need more customized energy concept’s design schemes for different weather, such as, dehumidification device for Shanghai or humidification device for Madrid. Calculation results shows that primary energy payback time of zero energy residential building in Madrid is 10.1 years and CO_2 equivalent saving is 74.4 ton during 50 years building lifetime. Waqar A et al [15] assessed the impact following application of using PCM in building material from an electricity demand side perspective they observed that energy conservation gains are sensitive to the minimum and maximum temperature during 24 h period. Further, application of PCM in building material and potential of saving electrical energy for air conditioning during summer has also been identified as a future assessment.

The purpose of our study is the optimization and the thermal analysis of an enhanced brick containing phase change material to isolate better the housing environment in the hot and dry regions. For this, two-dimensional numerical simulations were realized using the commercial software Fluent, to finally arrive at an optimal number, a type, and an arrangement of PCM in the brick.

II. MODEL AND ANALYSIS

Figure. 2 shows the different geometries of the PCM container in a brick of dimensions: 48cm x 30cm x 25cm. The radius of the cylindrical hole containing the PCM (Figure.1.e) is equal to 3 cm, which means that the volume of the cylinder is equal to 706.86 cm 3. Four other geometry, in addition to the cylinder have been studied, they have the same volume of the cylinder. Varying the ratio L1/L2 makes change the type of geometry of the container from rectangle (parallelepiped) for L1/L2 = 1 to a triangle (Tetrahedron) for L1/L2 = 0. The height of the containers "b" remains constant for the four geometries, it's equal to 6 cm. The outdoor surface of the wall is simultaneously subjected to a time dependent solar radiation and forced convection boundary (h_{out} = 20 w/m²°C). The total rate of the heat transfer between the air and the outside wall of the brick is determined by adding the convection and solar radiation components [16]. The indoor wall is subjected to a time independent free convection boundary condition (h_{in} = 10 w/m²°C) of which the temperature of the air contacts with the inner face of brick must satisfy the conditions of comfort. It's necessary to note that based on the adaptive thermal comfort principle, the occupants of the buildings in dry and hot climatic conditions feel comfortable even at higher temperature up to 30◦C [17, 18]. In this study we imposed an internal temperature equal to 27°C.

Before arriving at the final geometry of the enhanced brick we made several simulations of different geometries and it by changing every time the type, the position and the surface/volume ratio of holes containing the PCM. In every case studied, only a portion of the wall is considered in the analysis because there is symmetry in the problem.

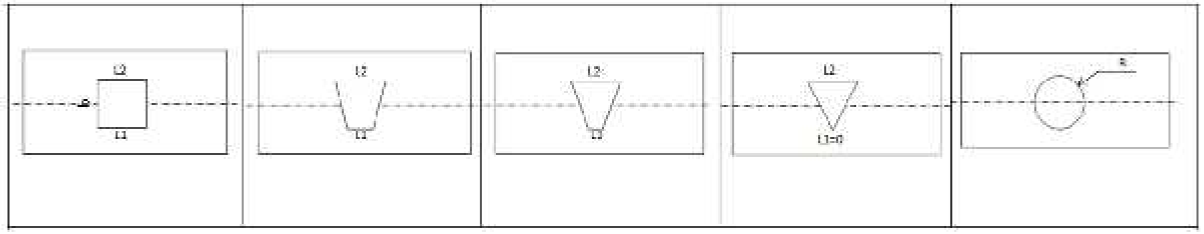


Figure. 2: Geometry of the brick containing PCM in different form of containers

A. Site description

The temperature measurements and the solar radiation are carried out for the month of July in Ouargla town, in the southern region of Algeria and presented on figure 3. This region is located at latitude of 31.56° N, longitude of 5.24° E, and with an altitude of 139 m above sea level. In fact, Ouargla is characterized by a hot and dry climate. In summer, the hottest months are July and August with a maximum temperature ranging between 47 °C and 52 °C and a minimum temperature ranging between 26 °C and 27 °C. The diurnal air temperature swing during July reaches 20 °C. In July, the air is dry with humidity at a minimum of 14.1% and reaching a daily lowest percentage of approximately 6%. The prevailing winds in Ouargla are northern ones (NE-NW), and an excessively hot dry and dusty southern wind from the desert blows frequently during the hot season.

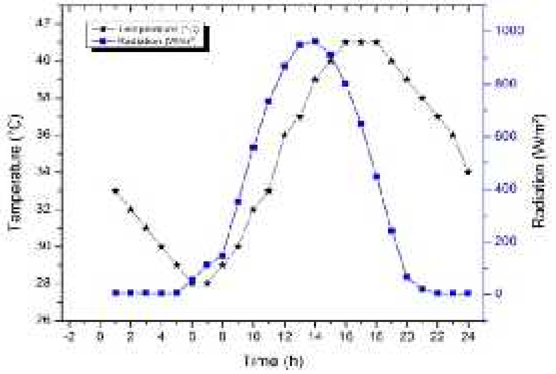


Figure. 3. Ambient temperature measurements and solar radiation for the month of July in Ouargla town

B. Numerical method analysis

The numerical simulation analysis is carried out by a commercial code Fluent. An interval size of 0.1cm for quadrilateral cells was found to be sufficient to resolve the details of the temperature fields based on comparison of the liquid fraction for various grid densities. The Second Order Upwind differencing scheme was used for solving the energy equations. The User Defined Function UDF is used to introduce the boundary condition of the outer wall of the brick which is a time dependent solar radiation and forced convection boundary. The thermophysical properties of the PCMs and brick used in this article are shown in Table 2. The model of enthalpy-porosity used to solve the problems of solidification and melting in Fluent has been validated previously by several studies [19-21]. The mathematical equation that governs the physical phenomenon of melting/solidification in the PCM is modeled as given below:

$$\frac{\partial(\rho h)}{\partial t} + \frac{\partial(\rho u_i h)}{\partial x_i} = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) + S \qquad (1)$$

Where h is the enthalpy, T is the temperature, ρ is the density, u_i is the fluid velocity component, x_i is a Cartesian coordinate, and S is the source term.

The enthalpy of the material is computed as the sum of the sensible enthalpy and the latent heat:

$$h = h_{ref} + \int_{T_{ref}}^{T} C_p\,dT + \beta L_{fus} \qquad (2)$$

Where h_{ref} is the reference enthalpy at the reference temperature T_{ref} and C_p is the specific heat, L_{fus} is the latent-heat of fusion.

The liquid fraction, β, can be defined as:

$$\beta = 0 \quad \text{if} \quad T < T_{solidus}$$

$$\beta = 1 \quad \text{if} \quad T > T_{liquidus}$$

$$\beta = \frac{T - T_{solidus}}{T_{liquidus} - T_{solidus}} \quad \text{if} \quad T_{solidus} < T < T_{liquidus} \qquad (3)$$

The following assumptions are made for the CFD *(Computational fluid dynamics*) analysis:

(i) No heat generation occurs (S = 0).

(ii) The thermal expansion of PCM and brick is not considered.

(iii) The density and thermal conductivity of the PCM are considered to be constant for solid and liquid phase. Average value is assumed during phase change [21].

(iv) The natural convection of liquid PCM is not accounted in the computations. However All particles have permanent zero velocity $(u_i = 0)$.

Then equation (1) can be simplified as follows

$$\left[\rho C_p + \frac{\rho L_{fus}}{T_{liquidus} - T_{solidus}}\right]\frac{\partial T}{\partial t} = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) \qquad (4)$$

TABLE 2: THERMOPHYSICAL PROPERTIES OF PCMS AND BRICK [9, 22]

Compound	**Melting temp, T_m (°C)**	**Heat of fusion, L_{fus} (kJ kg^{-1})**	**Specific heat capacity, Cp (kJ kg^{-1} K^{-1})**	**Thermal conductivity, k (Wm^{-1} K^{-1})**	**Density, ρ(kg m^{-3})**
Brick	-	-	0.84	0.7	1600
P116-Wax	47	225.0	2.4 (solid), 1.9 (liquid)	0.24 (solid), 0.24 (liquid)	830 (solid), 773 (liquid)
n-Eicosane	37	241.0	2.01 (solid), 2.04 (liquid)	0.15 (solid), 0.15 (liquid)	778 (solid), 856 (liquid)
Paraffin wax	32	251	1.92(solid) 3.26(liquid)	0.514 (solid) 0.224 (liquid)	830
$CaCl_2.6H_2O$	29.9	187	2.2 (liquid) 1.4 (solid)	0.53 (liquid) 1.09 (solid)	1530 (liquid) 1710 (solid)
n-Octadecane	27.7	243.5	2.66 (liquid) 2.14 (solid)	0.148 (liquid) 0.190 (solid)	785 (liquid) 865 (solid)

III. RESULTS AND DISCUSSION:

3.1Choice of the PCM type

For a container of cylindrical geometry in the center of the brick we compared five types of PCM, for different melting temperature (see Table .2). The heat flow in (W / m²) entering in the indoor environment through the brick in 24 hours is shown in Figure.4. The results show that CaCl2 6H2O with of melting temperature 29.9 ° C gives the best insulation. The melting of this latter during the hottest hours of the day prevents a large quantity of heat to pass through the brick wall and consequently reduces the temperature of the inner surface of the brick. For both liquid and solid phases CaCl2 6H2O is a good insulator. Brick containing this type of PCM retains its insulating capabilities without phase change.

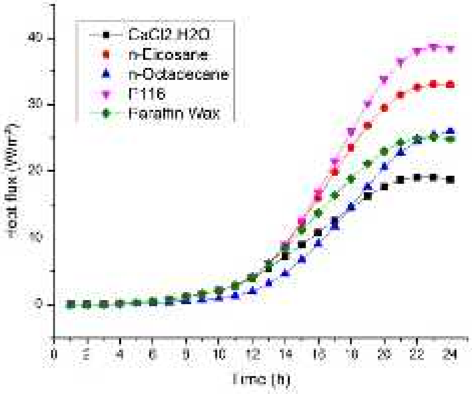


Figure. 4 The effect of different types of PCM on thermal insulation of a brick

3.2 Effect of geometry container of PCM

The figure.5 shows the variation of heat flux entering through a hollow brick of different geometries in the center, filled with CaCl2 6H2O. A cylindrical cavity (circle) is compared with other geometries (isosceles trapezoid) whose length ratio L1/L2 varied from 1, 0.5, 0.25, and 0. The results show that the cavity of a ratio L1/L2 = 0.25 gives the best insulation. The reduction of the total flux in 24 hours compared to a brick without PCM for this geometry is 53.33% (see figure.6), by against it is 50.35% for a circle (cylinder) and 52.92%, 50.91%, 49.89 % for the length ratios L1/L2 = 0, 0.5 and 1 respectively.

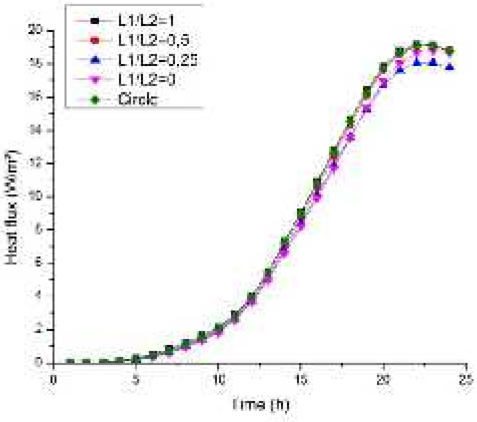


Figure. 5 Heat flux entering the internal environment for different geometries of the container of PCM

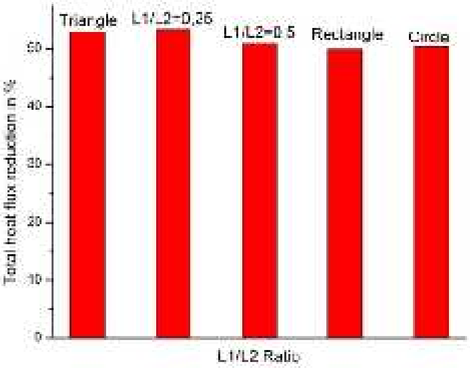


Figure. 6 Reduced heat flux compared to a brick without PCM

3.3 Effect of surface/volume ratio on the insulation of the Brick

The surface / volume ratio is very important or not that improves heat transfer [23]. The increased surface contact between the PCM and brick promotes heat transfer will consequently reduces the time of phase change. A fast phase change from solid to liquid state, hanging the hot hours of the day makes the PCM inactive during a significant time and does not allow efficient insulation (PCM is already in liquid form in early day, although the temperature outside always increases). On the other hand, if the time of phase change is much more important because of the reduced exchange surface, melting of PCM will never be complete and a quantity of PCM remains inactive in the solid state. A combination of the exchange surface and the amount of PCM defined by the volume of the container (surface / volume ratio) is very important to maximize the thermal insulation of the brick with the use of a minimal amount of PCM, which optimizes the cost of the brick improved. To increase the surface / volume ratio in the brick we multiplied the number of cavities by keeping the same total volume of the MCP introduced into the brick. The table 3 shows the studied cases.

TABLE. 3 STUDIED CASES OF DIFFERENT SURFACE/VOLUME RATIO

Number of bricks cavity (figure. 1.c)	**L1 in cm**	**L2 in cm**	**L1/ L2**	**Total heat exchange surface cavities in cm²**	**Total volume of the cavity containing PCM in cm^3**	**Surf/Volu ratio cm^{-1}**
1	1,88	7,54	0,25	136,14	706,86	0,19
2	0,94	3,77	0,25	204,49	706,86	0,29
3	0,63	2,51	0,25	275,20	706,86	0,39
4	0,47	1,88	0,25	346,54	706,86	0,49

Figure. 7 shows the variation of the flux over time for four surface / volume ratios which are: 0.19 cm^{-1} for 1 PCM, 0.29 cm^{-1} for 2 PCM, 0.39 cm^{-1} for 3 PCM and 0.49 cm^{-1} for 4 PCM . The results show that the flow through the brick containing CaCl2 6H2O in hollow shape of an isosceles trapezoid whose report of its two bases is L1/L2 = 0.25 is minimum when the surface / volume ratio is equal to 0.39 cm^{-1}, which corresponds to insert the PCM in three holes in the brick. A maximum reduction of 81.11% of the total flux entering the indoor environment compared to a brick without PCM is noted for this configuration (see Figure. 8). For the same surface / volume ratio (0.39 cm^{-1}) the cylindrical configuration of the container of PCM reduce 74.93% the total flow, more unless the isosceles trapezium of a portion of 6.18%. It should be noted that the efficiency of a brick with four PCM is important, it reduces the total flux for 24 hours up to 80.63%.

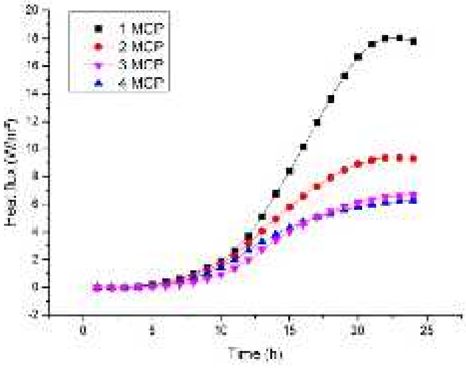


Figure. 7 Effects of surface / volume ratio on the heat flux entering through the brick for L1/L2 = 0.25

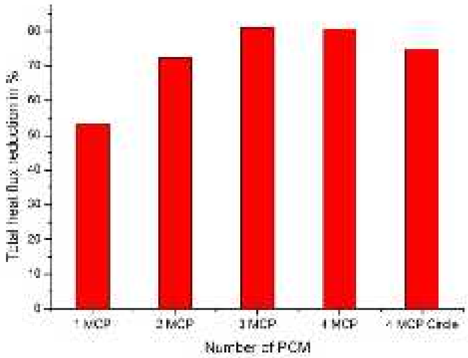


Figure. 8 reduction in the total heat flux entering through the brick improved compared to a brick without PCM (L1/L2 = 0.25)

3.4 Position effect of the PCM

The effect of PCM position on the thermal insulation of the brick is studied for 3 and 4 PCM which the surface / volume ratio is respectively 0.39 and 0.49 cm-1. Arrangements H/2, H/4 and 3H/4 of holes containing CaCl2 6H2O near the outside interface of the brick have a significant effect on reducing the total flow through the brick. Position H / 4 (shown by solid lines in Figure. 9) for a surface / volume ratio equal to 0.49 cm^{-1} (4 PCM) gives the best thermal insulation of 86.87% compared to a brick without PCM (see Figure. 10 and 11).

Figure. 12 show a comparison of the variation in 24 hours of the average temperature on the internal wall between:

- optimized brick: brick containing of the CaCl2 6H2O in 4 hollows of a shape of an isosceles trapeze whose report of its two bases is L1 / L2 = 0.25, arranged to H/4 far from the outside wall

- brick containing CaCl2 6H2O in 4 hollows of cylinder shape, arranged to H/4 far from the outside wall
- brick without MCP

While the brick with cylindrical hollows decreases the temperature of the internal wall of 3.1°C relative to a brick without PCM, the optimized brick decreases this temperature of 3.68°C. The maximal temperature which is equal to 27.46°C of the inside of the brick optimized last one day during the hot summer months, guarantee a comfortable indoor habitats and consequently, the consumption of the energy used by the air conditioning is minimal.

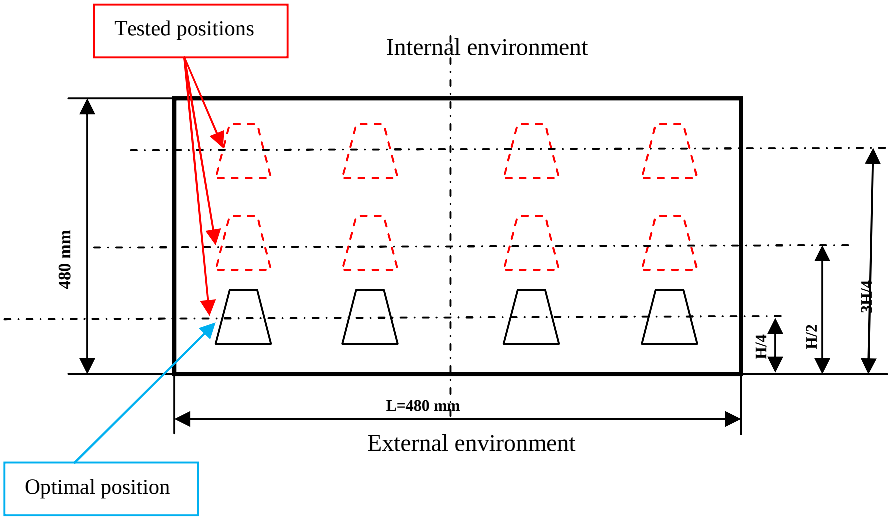


Figure. 9 Position of the holes containing the PCM in the brick

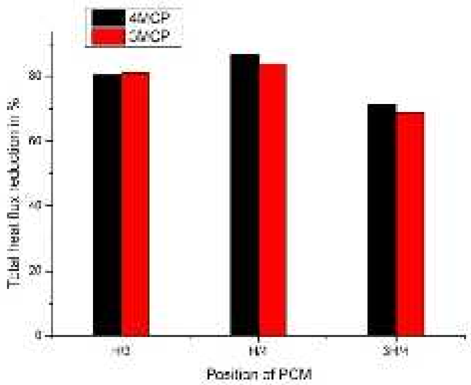


Figure. 10 position Effect of the PCM in the brick for 3 and 4 holes

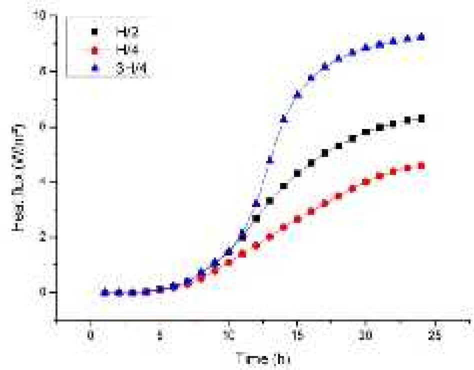


Figure.11 **Change in average flow through the inner surface of a brick containing CaCl2 H2O in four holes for three positions: H/4, H/2 and 3H/4**

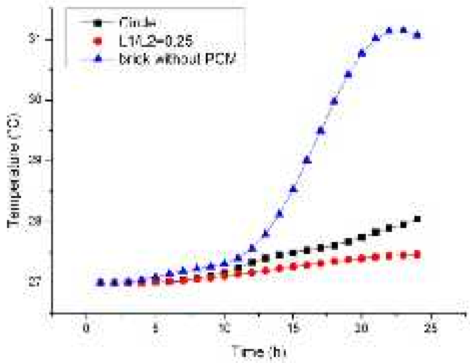
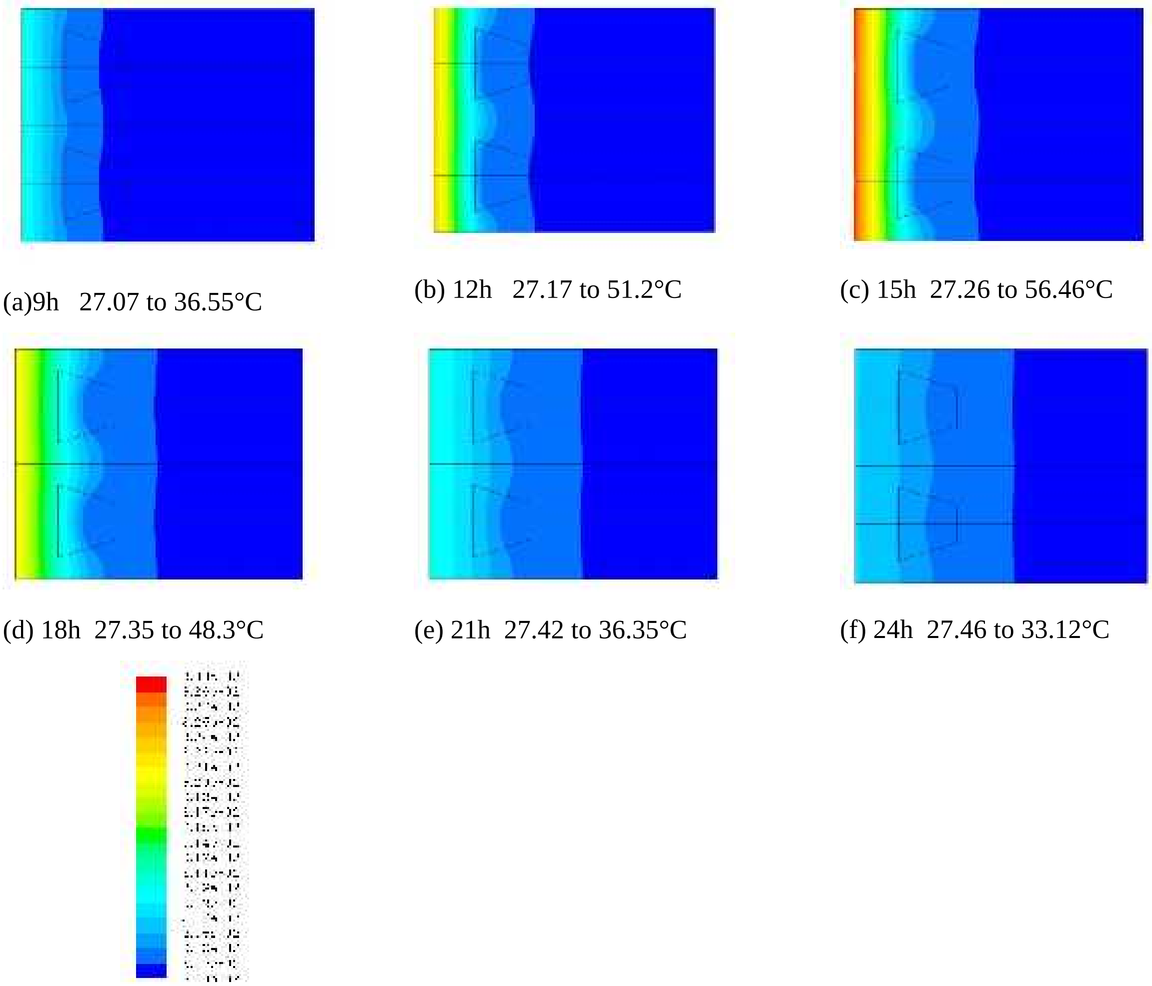


Figure.12 **Changes in the average temperature on the inner wall of the brick optimized (4 holes filled with CaCl2 6H2O arranged to H/4 near the outer wall)**

3.5 Temperature distribution for the enhanced brick

Figure. 13 show the distribution of the temperature during hours: 9, 12, 15, 18 and 21 hours in the interior of a brick with four isosceles trapezoid hollow, whose report of its two bases is L1/L2=0.25, arranged at H/4 near the outer surface of the brick. The right side in the figure represents the outer face, the left face is the part inside and both faces; superior and inferior are axes of symmetry. From the results we see that the hollow filled with PCM brake the increase and the penetration of temperature in the internal environment. This point is clearer in Figures b, c and d for the time 12h, 15h, and 18h respectively, when temperature outside reaches its maximum values.



(a)9h 27.07 to 36.55°C

(b) 12h 27.17 to 51.2°C

(c) 15h 27.26 to 56.46°C

(d) 18h 27.35 to 48.3°C

(e) 21h 27.42 to 36.35°C

(f) 24h 27.46 to 33.12°C

Figure. 13 isothermal contours of the enhanced brick during time (a) 9h, (b) 12h, (c) 15h, (d) 18h et (e) 21h

IV. CONCLUSION

A study of the thermal behavior and optimization by numerical simulation of a brick containing phase change material (PCM) is performed. Actual weather conditions; temperature and solar radiation in the region of Ouargla are used as boundary conditions. Several parameters affecting the efficiency of thermal insulation of this brick as; the type of PCM, the geometry of the container of the PCM, the effect of surface / volume ratio and location of the PCM in the brick are optimized. The results show that the improved brick reduces the temperature of the inner wall of 3.68 °C and reduces 86.87% of the heat flux entering to the internal environment. Therefore the same portions of electrical energy used by air conditioning are reduced and the peak consumption of this energy into the national grid during periods of peak load is decrease.

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