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Numerical Analysis of the Passive Heating of Building integrated Phase Change Materials

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Abstract: In order to explore numerically the capability of solid-liquid phase change material (PCM) for heating indoor applications, melting of phase change material (PCM) was studied. The roof of the enclosure is filled with PCM (Hydrate salts PCM with melting temperature, $T_{melt} = T_{comfort}$ =22 °C) on which are inserted heat pipes coming from the solar collector (heat source). The room vertical walls are adiabatic. The power transferred from solar collector by water is fully dissipated in a PCM that filled a slab. The advantage of using this heating strategy is that the PCMs are able to store a high amount of heat generated by the solar collector and the sun rising on the slab without acting the HVAC system. Numerical investigations, based on a dynamic simulation, were conducted in order to analyze the thermal performance of the proposed system. It was found that, due to the PCM layer, there are less temperature fluctuations and comfortable leaving conditions are satisfied. The use of the HVACs systems will be remarkably reduced during January in Casablanca Morocco.
Key words: PCM, thermal comfort, heat storage, solar radiations, building.

1. Introduction

Due to the high cost of energy, the use of alternative heating system is important for a building to provide optimum inside conditions during winter months. The basic strategy of building passive heating system is to reduce the heat losses and at the same time to transfer excess heat during the day to heat storage. This heat is used during the night to satisfy the heating needs of the building. Thermal comfort of man comes mainly from space heating and heating hot water. In solar heating systems, water is still used for heat storage in liquid based systems, while a rock bed is used for air based systems. These units are capable of providing space heating during the day from the stored heat during the night; however, they are heavy and bulky in size. Several types of passive solar systems and techniques have been proposed and used by [1]. The most important existing building heating systems are: water storage, rock bed storage, ground air collector are also used for raising the greenhouse air temperature. Latent heat storage is one of the most efficient ways of storing thermal energy. Unlike the sensible heat storage method, the latent heat storage method provides much higher storage density, with a smaller temperature difference between storing and releasing heat. Phase Change Materials (PCM) have been considered for thermal energy storage in buildings since 1980. During the last 20 years, new PCM products to be used in buildings appeared in the market. In these products, PCM presents difficulties to be melted by direct solar radiation because of the poor heat conductivity of the PCM. On the other hand, the walls and ceilings of a building offer large areas for passive heat transfer within every zone of the building [2]. Implementing the PCM in gypsum boards, plaster, concrete or other wall covering materials, thermal energy storage becomes a part of the building structure, useful even for light-weight buildings. In the literature, development and testing were conducted for prototypes of PCM wallboard and PCM concrete systems, with particular interest in peak load shifting and solar energy utilization. Several researchers have investigated methods for impregnating gypsum wallboard and other architectural materials with PCM [3-5].

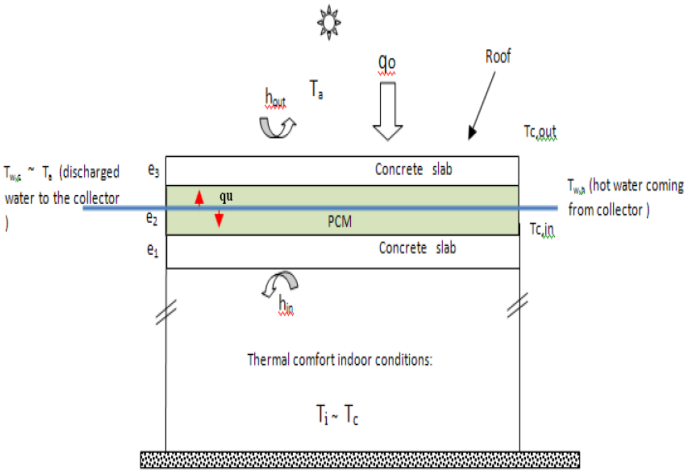

Figure 1: The physical model

k_b=1.5 W m^{-1} K^{-1}	ρ_b =2200.0 Kg m^{-3}	$c_{p,b}$=838 j kg^{-1} k^{-1}
$k_{m,l}$=1.1 W m^{-1} K^{-1}	$\rho_{m,s}$=1800 Kg m^{-3}	$c_{p,m}$ =2130 j kg^{-1} k^{-1}
$k_{m,s}$=1.1 W m^{-1} K^{-1}	$\rho_{m,l}$ =1460 J Kg^{-1} K^{-1}	e_3= 8 cm
T_f=22 ^{0}C	ΔH_f=1.7 10^5 J kg^{-1}	e_2 =2 cm
α_p=0.9	h_T =21 W m^{-2} K^{-1} h_i =5 W m^{-2} K^{-1}	e_1=20 cm

Table 1: Thermophysical properties and dimensions

2. Mathematical model

The composite wall described above is initially maintained at a uniform temperature '$Tc= T_f$'. The boundary condition on the outer surface of roof is considered due to the combined effect of radiation and convection. In order to consider the radiation effect, the average monthly solar radiation heat for every 1-h in Casablanca city, Morocco is used (see Fig. 2).

For natural convection, the heat transfer coefficients (h_T) and (h_i) on the outer and inner surfaces of the concrete slab are considered and taken into account in the present research work. See Table 1 [9].

To model the solar collector combined with slab filled PCM, some assumptions were adopted. Heat transfer by conduction in the composite wall is one-dimensional and edge effects are neglected; The thermal conductivity of concrete is assumed to be constant; The PCM is homogeneous and isotropic, the effect of convection is neglected in the PCM; The interfacial resistances between the different layers of the slab are neglected. The water is used as heat transfer fluid. In solar collector, heat transfer is one-dimensional, and the sky is considered as black body at T_{sky}.

Solar collector heat balance:

$$A\,G^{a}_{g,s} = Q_u + Q_p \;,\; Q_u = A_c\left[G^{a}_{g,s} - U_L(T_p - T_a)\right] \tag{1}$$

where $AG^{a}_{g,s}$ and Q_p are the rate of heat flow absorbed and solar collector heat lost, respectively.

The global heat loss coefficient U_L was calculated iteratively based on the glass and absorber temperatures. The energy transferred to the water $q_u = \pi D_i h_{cf}\left(T_b - T_f\right)$, where h_{cf} is the convective heat transfer factor calculated using internal flow correlations [7]. Di is the solar collector internal tubes diameter.

The energy q_u is fully absorbed by the PCM layer. Thus, the temperatures of the water in inlet and outlet are respectively $T_{fi} = T_f$ ($T_{fo} > T_{fi}$).

The conductance factor F_R represents the ratio of power actually recovered and the power that would be obtained if the water temperature was equal to the water inlet temperature, the energy transferred to the water in the solar collector, the average temperature of the fluid can be expressed respectively as:

$$F_R = \dot{m}c_p(1 - e^{-AU_L F/\dot{m}c_p})/AU_L \;,\; q_u = AF_R\left[S - U_L\left(T_{fi} - T_a\right)\right] ,\; \bar{T}_f = T_{fi} + \frac{q_u(1-F_R)}{AU_L F_R} \tag{2}$$

where F denotes the absorber tubes efficiency.

The transient energy's equation in the composite floor (concrete PCM) is written, using the enthalpy method [6]:

$$\rho c_p \frac{\partial T}{\partial t} = \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) - \rho\lambda\frac{\partial f}{\partial t} \tag{3}$$

The second term is a source term which takes into account of the latent heat associated with the phase change; the value of λ is equal to the latent heat of melting ΔH_f in the layer of PCM. It is zero for layers e1 and e3. The term volumetric liquid fraction f is given by: f=1 for $T>T_f$, f=0 for $T<T_f$ and $0<f<1$ when $T=T_f$.

The slab is subject to the following boundary conditions:

$$x = e_1 + e_2 + e_3 \quad , \quad k_b \left.\frac{\partial T}{\partial x}\right|_x = h_{out}(T_a - T_x) + \alpha_b q_o + q_u \tag{4}$$

q_u is the heat carried by the water coming from the solar collector given above. It should be noticed that the function of the solar collector is to extend virtually the surface of exchange between the slab and the ambient; Thus, q_u, is injected in the boundary conditions of the present (1D) model.

The indoor boundary condition, at x = 0, and the equality of heat flow and temperatures at the different interfaces are:

$$k_b \left.\frac{\partial T}{\partial x}\right|_x = h_i(T_c - T_x) \qquad k_+ \left.\frac{\partial T}{\partial x}\right|_{x_+} = k_- \left.\frac{\partial T}{\partial x}\right|_{x_-} \;,\; T_+ = T_- \tag{5}$$

At interfaces 'i', between two different materials ('+'/'-'), the properties are estimated using the harmonic means method[8] and the thermo-physical properties of the PCM are evaluated as follows:

$$k_i = \frac{k_+ k_-(\delta_+ + \delta_-)}{k_+\delta_- + k_-\delta_+}, \quad k_m = f\,k_{m,l} + (1-f)k_{m,s} \;,\; \left(\rho c_p\right)_m = f\left(\rho c_p\right)_{m,l} + (1-f)\left(\rho c_p\right)_{m,s} \tag{6}$$

where δ+ is the distance between the interface and the first node of the material '+', and δ- is the distance between the interface and the first node within the material '-'. The obtained system of equations is integrated numerically on a mesh using control volume method [8].

3. Results and discussions

Figure-2 shows the evolution of the ambient temperature T_a during January in Casablanca-Morocco. The ambient temperature varies between a maximum of 23°C (the day of January, 24th), and a minimum of 2°C (the night of January, 04th). The variation of the ambient temperature Ta undergoes a rapid rise due to the sunrise. This oscillation phenomenon (increase followed by a decrease) is due the alternating day/night every 24 hours. The minimum temperatures are obtained during the first 20 days, and then increased to the maximum value toward the end of the month. On average, temperatures range between 7°C to 16°C during the month.

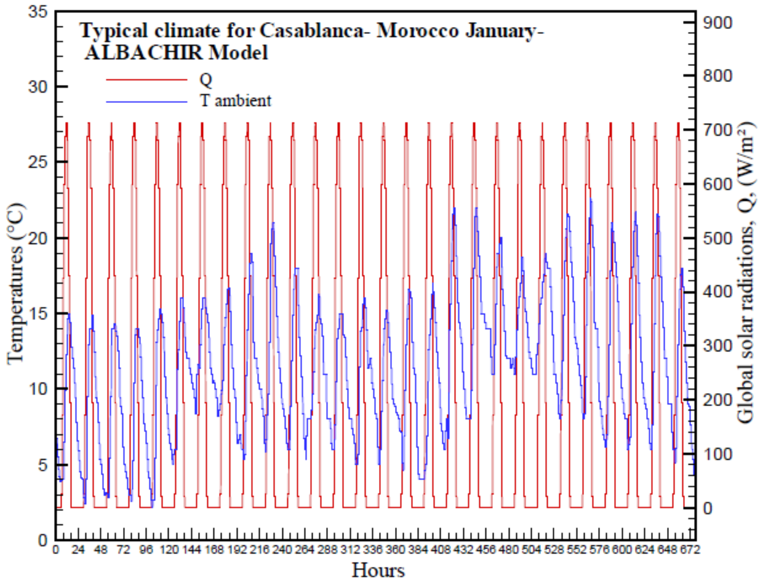

Figure 2: Typical climate for Casablanca-Morocco January

Figure-2 shows also the evolution of the global power of solar radiation incident during the month of January on a horizontal slab. The radiation is zero during the first 6 hours and increases with the sunrise which causes the increase in the ambient temperature between 6 am and 13 am, (solar noon). Radiation reaches its maximum value (720 W/m²) between solar noon and 15 hours, and falls to its minimum value 0 W/m² at 18 hours which present the sunset and therefore the cancellation of solar radiations. This power remains zero during the night. It undergoes a further increase in the days following. This behaviour is periodic with a period of 24 hours.

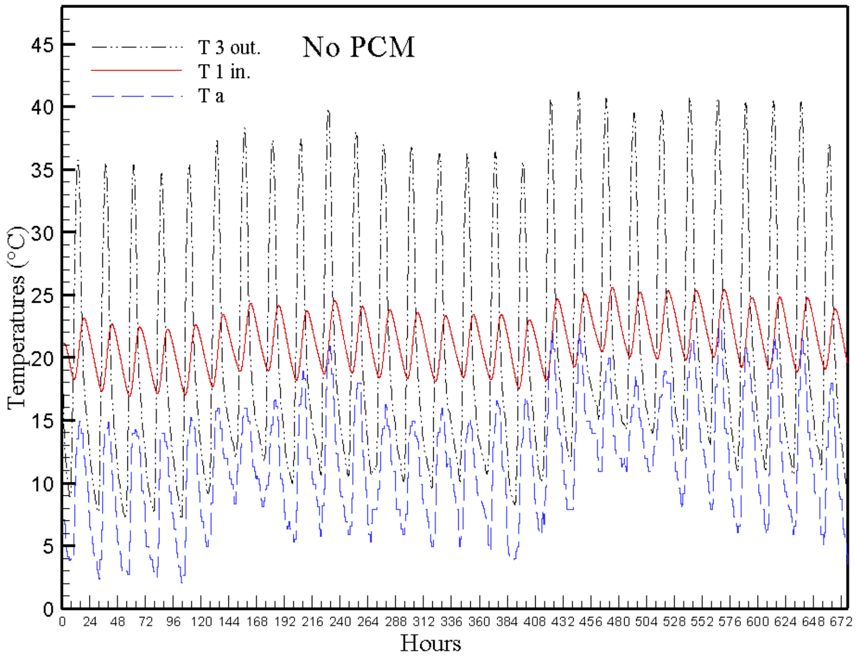

Figure-3 Time evolution of the average temperature of the different layers of an ordinary concrete roof (without PCM)

Figure-3 shows the time evolution of the average temperature of the different layers of an ordinary concrete roof (without PCM) during January in Casablanca- Morocco. The analysis such figure show that the ambient temperature decreases and subsequently a decrease in the temperatures of the outer and inner faces of the slab. Between 6 am and solar noon (13h), solar radiations cause an increase in ambient temperature. The outside temperature and the inner temperature increase with a delay due to the inertia of the concrete. The day/night causes increase/decrease of the ambient temperature. These variations influence the temperature of the exterior and interior floor. The ambient temperature varies between 02°C and 23°C. Fluctuations range of the outside temperature situates between 7°C and 41°C. The temperature of the inner face varies between 17°C and 25°C. This fluctuation is harmful and crates non-comfort conditions for the occupants of the building. So it is necessary to operate the HVACs system during the January in Casablanca- Morocco.

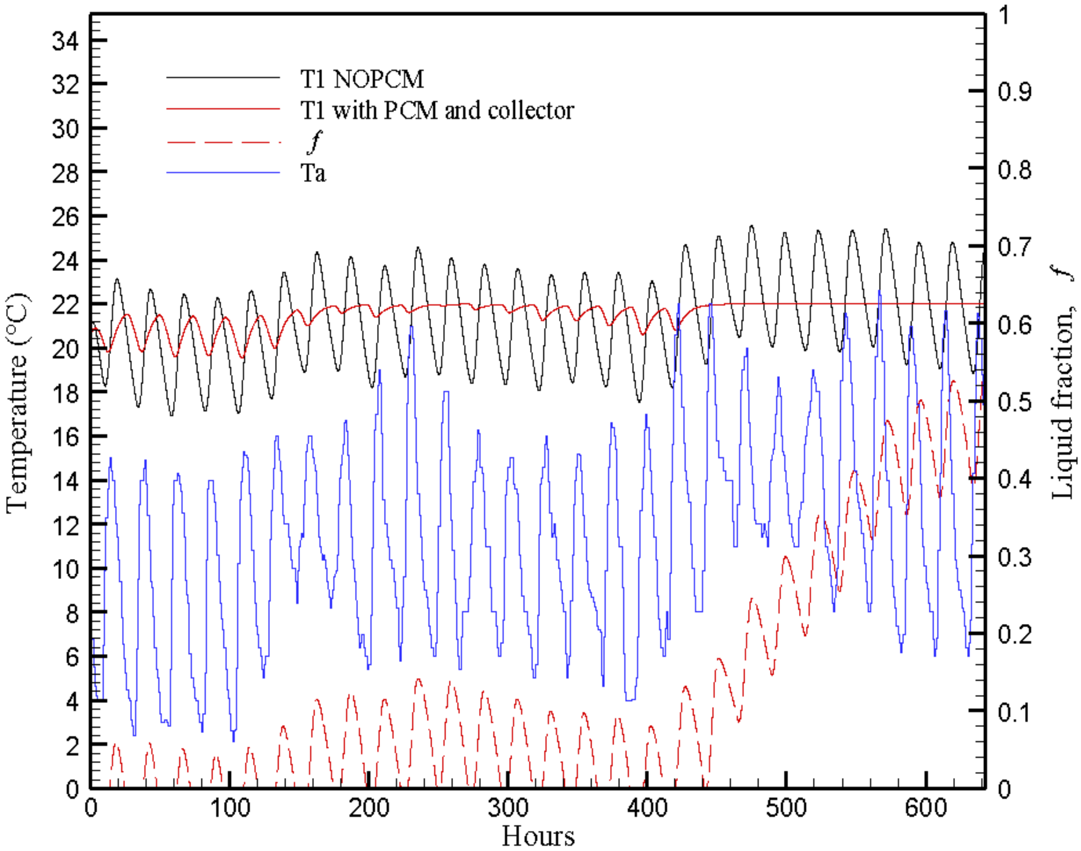

Figure 4: Time response to the internal faces of a slab without PCM and a slab encapsulating PCM with heat pipes

Figure 4 shows the time response to the internal faces of a slab without PCM, a slab encapsulating PCM (PCM: hydrate Salt CaCl2-6H2O, see Table 1) with heat pipes coming from a solar collector in Casablanca- Morocco, January. Analysis of this figure show that between 0 and 6 hours, the ambient temperature is decreasing due to the complete absence of sunlight causing the decrease in temperature of the outside floor, which in turn influences the inside temperature (decrease of T_{in} of 21.2°C to 20°C for PCM and PCM with heat pipes, where a decrease of 21.2°C to 18.4°C for an ordinary concrete slab). Between 8:00 and solar noon, the ambient temperature increases from 4°C to 15°C due to solar radiations. The temperature of the interior slab increases from 18.4°C to 23.2°C, from 20°C to 21.6°C and from 20°C to 21.6°C respectively for an ordinary concrete wall, a wall encapsulating PCM and a wall encapsulating PCM with heat pipes coming from the solar collector; the PCM layer receives a heat flux which increases the temperature of PCM to the melting temperature T_f=22°C and a first layer of the liquid phase appears (volumetric liquid fraction *f* increases from 0 to 0.06 for PCM with heat pipes and from 0 to 0.03 for PCM). The presence of the heat pipes increases the heat transfer, and hence, increases of the liquid fraction. Note that, the ambient temperature is lower than that of interior slabs, and this difference is due to the energy stored by sensible heat in the inner layer of the concrete slab. The ambient temperature decreases after passing through a maximum value obtained during the day thereby causing the fall of the outside and inside slab temperatures with a delay due to the thermal inertia of concrete (with PCM and heat pipes). The day/night allows for an increase/decrease in ambient temperature and the temperature of the interior floor (concrete with PCM and heat pipes) which varies between a minimum of 18.6°C and maximum of 21.2°C during the first 440 hours. PCM undergoes solidification and successive melting with a volumetric liquid fraction *f* variation between 0 and 0.14. The fluctuation range of the slab temperature (concrete with PCM and heat pipes) decreases with the increasing of the PCM liquid fraction (development of the latent heat of melting). After t=448 hours (19 January), it is clear that the temperature of the inside of the slab remains constant to 22°C. The liquid fraction is always positive $0.1<f<0.54$ for a concrete slab encapsulating PCM with heat pipes coming from a solar collector, which means that the melting front never reaches the inner layer and therefore we have always PCM liquid at T=22°C in contact with the internal layer of the slab which explains the constancy of observed temperature of this layer. The energy storage by latent heat of melting in the slab encapsulating PCM with heat pipes coming from a solar collector maintains the temperature of the inner face of the floor substantially constant at 22°C (days and nights). The slab encapsulating PCM with heat pipes coming from the solar collector achieves more efficient in thermal insulation and increases the thermal efficiency of the local during the coldest period of the year.

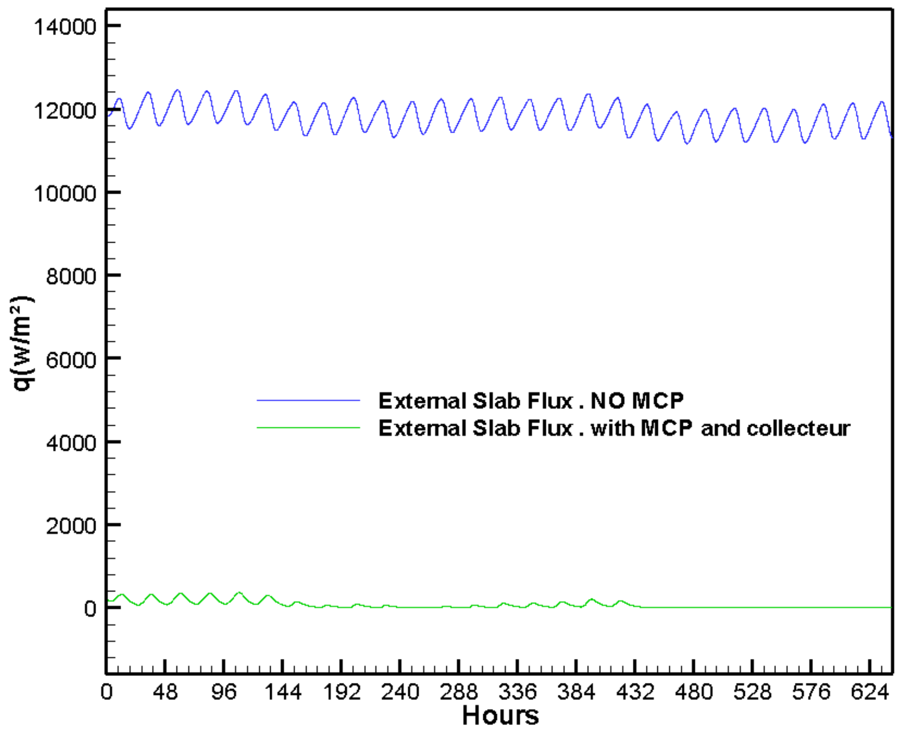

Figure-5: Evolution of the interior flux for a concrete slab, slab encapsulating PCM and a slab encapsulating PCM with heat pipes coming from a solar collector for January

Figure-5 shows the evolution of the rate of heat flow for a concrete slab, slab encapsulating PCM and a slab encapsulating PCM with heat pipes coming from a solar collector for the month of January in Casablanca-Morocco. The day/night allows for an increase/decrease in the inside rate of heat flow which varies between 11600 W/m^2 to 12400 W/m^2, 0 W/m^2 to 500 W/m^2 and between 0 W/m^2 to 400 W/m^2 respectively for a concrete slab, slab encapsulating PCM and a slab encapsulating PCM with heat pipes coming from a solar collector during the first 168 hours. The rate of heat flow of the inside of the slab encapsulating PCM with heat pipes coming from a solar collector stars decreasing and after t=432 hours, the inside rate of heat flow remains constant to zero. The PCM store the energy in latent heat form and transfers it to the internal wall which explains the small change in the internal rate of heat flow compared to the internal rate of heat flow of a wall without PCM. Complete melting of the PCM leads to the comfort temperature where the stability of the rate of heat flow to the zero.

Figure-6 shows the typical evolution of the useful power and the outlet temperature of the solar collector during one day of January. The useful power decreases during the first 6 hours and an increase begins with the sunrise which causes the increase in the outlet temperature between 6 am and 13 am, solar noon. Power reaches its maximum value 150 W/m² between solar noon and 15 hours, it underwent a rapid decline to its minimum value 0 W/m² to 18 hours which present the sunset and therefore the cancellation of power. The same for the outlet temperature which reaches its maximum value 115°C between solar noon and 15 hours than it underwent a rapid decline to its minimum value 0°C. The evolutions of useful power and the outlet temperature of the solar collector are periodic with a period of 24 hours. The outlet temperature of the fluid depends primarily on the useful power and the conductance factor. In fact, the increase and decrease of the useful power lead the increase and decrease of the outlet temperature. The useful power decreases from 8 W/m² to 4 W/m² and the outlet temperature remains constant to zero during the first 6 hours. An increase begins with the sunrise which causes the increase in the outlet temperature between 6 am and 13 am, solar noon. The useful power reaches its maximum value 154 W/m² between 11:00 and 14 hours, it underwent a rapid decline to its minimum value 0 W/m² to 18 hours which present the sunset and therefore the cancellation of power. The same, the outlet temperature reaches its maximum value 115°C between 11:00 and 14 hours than it underwent a rapid decline to its minimum value 0°C to 17 hours. The outlet temperature of the fluid depends primarily on the useful power and the conductance factor. In fact, the increase and decrease of the useful power lead the increase and decrease of the outlet temperature.

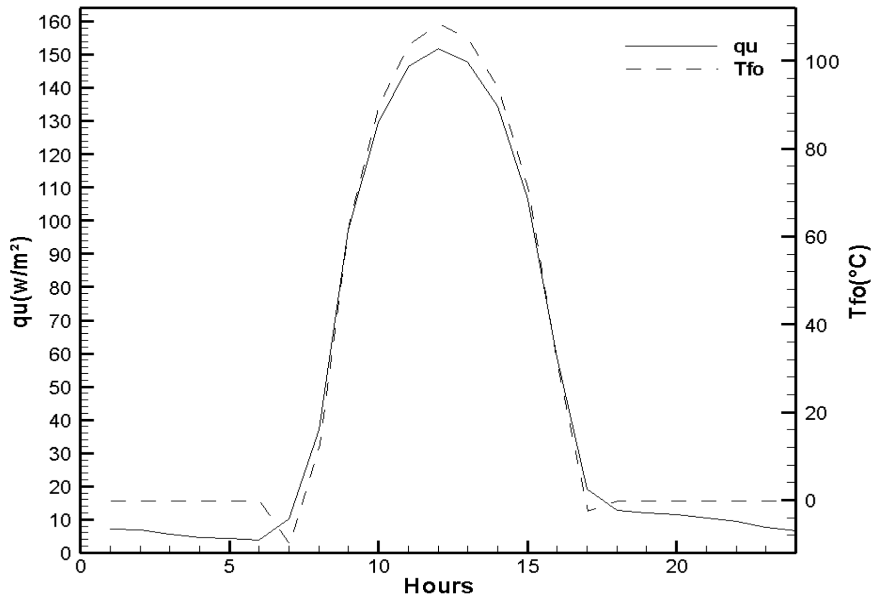

Figure-6: Evolution of the useful power and the outlet temperature of the solar collector

4. Conclusion

In this study numerical investigations, based on a dynamic simulation, were conducted in order to analyze the thermal performance of the Building integrated Phase Change Materials results shows that:

- Inside temperature fluctuates between 16 °C and 25 °C in case of the slab without PCM layer.

- In case of the slab without PCM layer, more than 12 kW are removed from the house due to the thermal gradients between the external slab and the ambient during the colder mount (January)in Casablanca- Morocco. Indoor temperature fluctuations create uncomfortable leaving conditions, so the use of the HVACs systems is necessary.

-During the first week of January the ambient temperature falls down to 4 °C during the night, and increases up to 16 °C during a day. This behavior causes only a weaken decrease and increase in the inside slab temperature from 22 °C to 20 °C. Melt fraction *f* growth between 0 % to 10 % due to the combination of solar collector (q_u), ambient heat convection and solar radiation (Q_{max} = 700 W/m²).

- Latent heat storage aids the slab to stabilize its temperature and the inside temperature fluctuations disappears after the first week and practically no heat is lost from the house to the exterior during the colder mount in Casablanca- Morocco. and there are less temperature fluctuations and comfortable leaving conditions are satisfied. The use of the HVACs systems will be remarkably reduced during January in Casablanca Morocco due to the PCM layer.

-Note that that temperature inside the room, Ti, is assumed constant and equal to the PCM melting temperature. Thus, the analysis is restricted to the influence of the ceiling energy storage system on temporal changes of Ti – temperature of the ceiling internal surface. The mathematical model should be extended to the 2 D case by including heat transfer through the room air to study fluctuations of Ti.

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