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Performance of domestic solar heating system with thermal storage using phase change materials

Khaled A. Amer[1], Massuod Fakher[2], Suliman M. Ahmad[3], Mukhtar A. Irhouma[4], Salah Aldeen S. Altahbao[5], Elsadic Salim[6]

[1,2,3,4,5,6)] Department of Mechanical & Industrial Engineering, Faculty of Engineering Science and Technology, Sebha University, Brack-Libya

Abstract:
This present study discussed the concept of storing thermal energy by adding variable phase change materials that can help to maintain and increase energy efficiency. It can also help in maintaining the level of temperature in the hot water storage at a certain point and when it is unloading the stored energy. In this study PCMs with solid-solid and solid-liquid phase transition are discussed. Selection criterion for the chosen PCM is presented. Paraffin wax can be used for domestic solar heating systems for its appropriate thermal characteristic. The steps of volume calculation to maintain the thermal storage at a certain temperature have involved in this research, to give better understanding the design of PCMs thermal storage. Furthermore, a Fortran code has been created and attached here, in order to study the thermal performance of PCMs thermal storage. The obtained results show that increasing the volume of the PCMs in the storage leads to an increase the interval of the isothermal operation of the storage and increasing the charge and discharge time period.
***Keywords**: Thermal energy storage, phase change materials, sensible heat, latent heat, solar heating system, solar energy*

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I. INTRODUCTION

The global warming and climatic change are of concern to humanity. Greenhouse gas (GHG) emissions (especially CO_2) are the main cause of these phenomena. Most of GHGs are emitted from burning fossil fuels (coal, oil and natural gas) to produce energy [1,2]. In developing countries residential buildings play a pivotal role in increasing fossil fuel consumption, as it illustrated in Fig.1[3,4]. Buildings are responsible for 40% of the total world energy consumption and CO_2 emissions.

Many researches indicated that, renewable energies technologies have the potential to mitigate the pollution from conventional power plants and to provide solutions to the energy problems [5-8]. Therefore, it can replace the conventional power generation in the near future to stop the dangerous environmental degradation. Of course, economical and technical studies must be conducted to identify type or types (in case of hybrid systems) of renewable energy(s) available in a certain location in economic quantities, so that its use is competitive with other types of energies. Areas locate within the so-called "solar built" have preferred the solar thermal application (such Arabic countries [9,10].

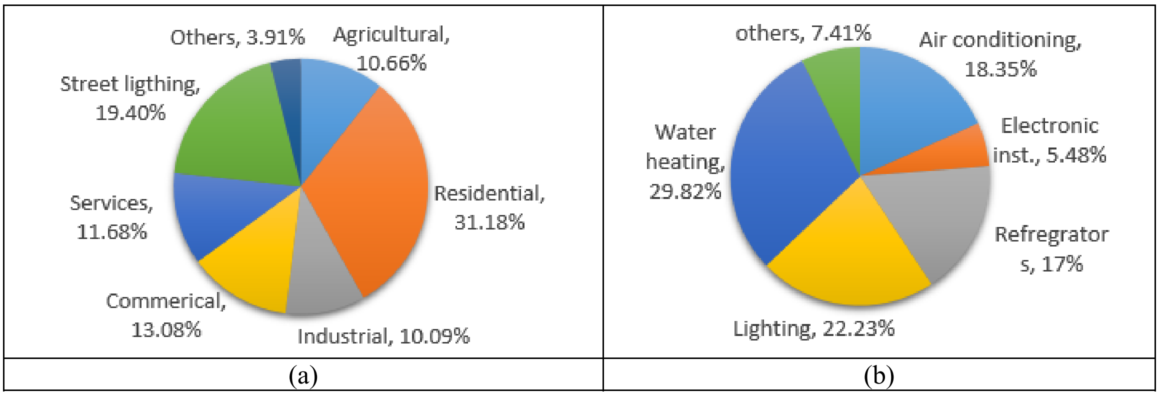

Fig. 1: Pie chart distribution of the electric load rating (a), and the domestic electricity consumption in Libya

One of the greatest challenges facing the solar energy is that it is an irregular source in terms of amount and continuity. So that there is a surplus of it in certain periods of time (day, summer) and a shortage in other periods (night, winter), which causes its less dependence as an energy source. The need for energy for many applications ranges from time to maximum to the lowest level, as does solar energy. However, there are no guarantees of a time mismatch between supply (solar energy) and demand (load). For example, we need hot water at night, and no solar energy at night. We also need a large amount of thermal energy to heat our homes in winter, while solar energy is not available in that amount in the winter season. For this reason, the to a thermal storage becomes essential and regardless this will raise the cost of the system [11]. Thermal energy storage (TES) is a technology that is used to balance the mismatch in demand and supply for heating and/or cooling. Solar thermal energy storage is used in many applications: buildings, concentrating solar power plants [12] and industrial processes [13].

In view of the distribution of electricity and energy consumption in Libya as shown in Fig.1, it finds that about 30% of the energy is consumed in heating water and therefore, that efforts are directed to reduce this percentage by using solar systems to heat water, as that Libya locates within the solar belt. The daily total of solar radiation is about 7.1 kWh / m² / day on the coast and about 8.1 kWh / m² / day on the southern regions [14].

Several efforts have been made to improve the thermal performance of solar thermal heating systems, for example the solar energy heating and cooling program funded by the International Energy Agency and the thermal analysis of such systems is included in most books on solar energy [9,14]. However, the use of (PCM) in thermal tanks is still limited to large tanks that are used in electricity generation [11].

The aim of this research is to outline the initial steps in the development of a domestic hot water solar heating with thermal storage system using PCMs, with emphasis on the numerical and experimental studies used to access the phase change and thermal behavior of the selected PCM, this through discussion the following topics:
1. Thermal analysis of the thermal storage.
2. Determine the size of PCMs required for the system
3. Set the tank temperatures in the charging and discharging periods.

II. ENERGY STORAGE

In energy systems, energy storages have crucial role to play as to ensure the supply on demand, to improve the performance and reliability and to conserve energy [16]. There are many forms of energy that can be stored include mechanical, electrical, chemical and thermal [17]:

- Mechanical energy storage: e.g. flywheel, pumped hydropower storage (PHS), and compressed air energy storage (CAES)
- Electrical energy storage: e.g. battery etc.
- Thermal energy storage: e.g. sensible heat, latent heat storage.
- Chemical energy storage: e.g. Hydrogen storage

The choice of storage method depends on the nature of the process. For example, the process of heating water, storing energy as heat. There are two methods of storing thermal energy, as sensible heat or as latent heat.
The main characteristics of thermal energy storage systems are[18]:

- Capacity per unit volume of the tank
- Operating temperature range is the temperature at which heat is added or withdrawn to or from the tank
- Addition and withdrawal temperature difference accompanying operating conditions
- Temperature is included in the tank
- The energy needed to add or withdraw heat to and from the tank
- Methods of controlling thermal loss from the tank
- The cost

In this research we considered the latent thermal storage

2.1 Sensible heat storage:

In sensible heat, heat energy is stored by raising the temperature of the material, liquid or solid. The Quantity of thermal energy storage depends upon, temperature difference, specific heat capacity of medium and the amount of storage material used. Therefore, the amount of heat energy stored is in the form of sensible heat from the following equation:

$$Q = \int_{T_i}^{T_f} m\, Cp\, dT \qquad (1)$$

Integrating eq. (1) yields to:

$$Q = m\, Cp\, (T_f - T_i) \qquad (2)$$

Where Q is the amount of sensible heat that stored in or withdraw out from the thermal storage in (kJ),

m is the mass of the material (kg), Cp is material heat capacity (kJ/kg.K), T_f and T_i are final and initial temperatures (ºC) respectively.

2.2 Latent heat storage:
The latent heat is defined as the amount of heat needed to convert a unit of mass from astate to another state at a constant temperature (saturationtemperature). The unit measured in the international sentence is Joules (Joules / kilograms).
In Latent heat storages (LHS), thermal energy is stored on the account of heat absorbed or released during phase changeof the storage material. The storage capacity of the LHS with solid to liquid phase change is given by:

$$Q = \int_{T_i}^{T_m} (m\, Cp)_{sol}\, dT + m\, L_m + \int_{T_m}^{T_f} (m\, Cp)_{liq}\, dT \qquad (3)$$

Or;

$$Q = (m\, Cp\,)_{sol}(T_m - T_i) + m\, L_m + (m\, Cp\,)_{liq}(T_f - T_m) \qquad (4)$$

Where: the subscript *sol* refers to solid phase and *liq* refers to liquid phase.
T_m: is the melting point of the variable phase material (ºC).
T_i: starting temperature of the material transition (ºC)
L_m: fusion latent heat (kJ/kg)
T_f: final temperature (ºC)

2.3 Phase Change Materials (PCMs):

The use of PCMs has recently gained more interest and importance in the PV solar panels [19], energy devices [21], buildings [21], etc. The theories, design and analysis of PCMs to store latent heat have been explored thoroughly in many literature [22].

Some of the classifications, types and methods will be discussed as follows. Based on their phase change, PCMs can be classified into four different types: solid-solid, solid-liquid, solid-gas and liquid-gas. Of these four types, solid-liquid PCMs are the most suitable for storing thermal energy, and they can be found as organic PCMs, inorganic PCMs and eutectics, as seen in Fig.2 [23,24].

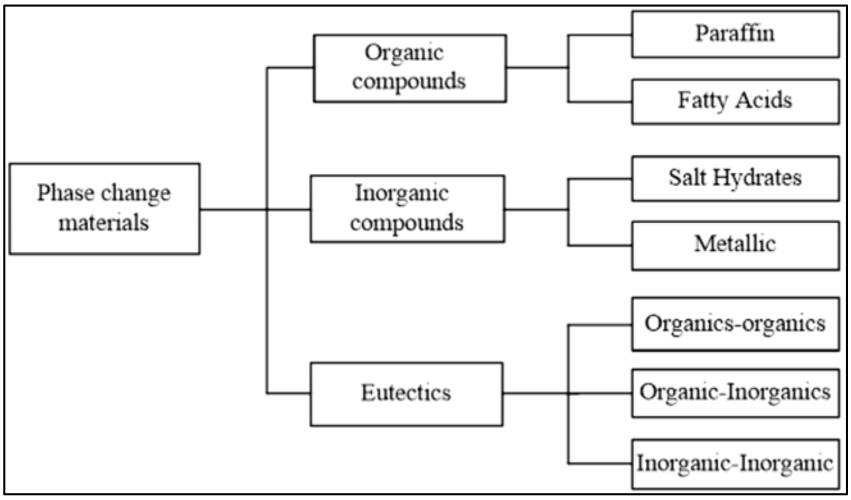

Fig. 2: Classification of PCMs

Paraffin wax qualifies as a PCM because it can be used over a wide range of temperatures and it has reasonably high heat of fusion. Paraffin wax can also undergo freezing without experiencing super cooling. Hence, technical grade paraffin wax is the most cost effective, feasible and widely used PCM. There are several studies on this topic [25,26]. Fatty acids are organic compounds characterized by $CH_3(CH_2)_{2n}COOH$ with a higher heat of fusion value compared to paraffin wax. Fatty acids have the ability to reproduce melting and freezing with little or no super cooling. One thing that prohibits the application of fatty acids is their cost, which can be 2.0 to 2.5 times higher than the cost of paraffin wax [25]. Salt hydrates commonly have a chemical formula of M_nH_2O, where M is an inorganic compound and this inorganic compound is important in storing heat due to its high density of volumetric latent heat storage [27]. Metals have not been a serious candidate for PCM because of their heaviness. However, when volume is taken into account, metals are likely contenders because of their high thermal

conductivities and high latent heat of fusion per unit volume [28]. Physical properties including Melting point and latent heat of fusion of paraffin's and non-paraffin's PCMs are tabulated in [25]. The PCM to be used in the design of thermal-storage systems should passes desirable thermophysical, kinetics and chemical properties which are as follows [25]:
1. Thermal properties: suitable phase-transition temperature, high latent heat of transition, and good heat transfer.
2. Physical properties: favourable phase equilibrium, high density, small volume change, and low vapor pressure.
3. Kinetic properties: no super cooling, and sufficient crystallization rate.
4. Chemical properties: long-term chemical stability, compatibility with materials of construction, no toxicity, and no fire hazard.
5. Economics: abundant, available, and cost effective.
Among all PCMs paraffin's (wax materials) can be selected for solar heating systems for the following advantages:

- Non-toxic
- Does not cause rust
- Good thermal conductivity
- Great latent heat
- low price
- It has no bad smell
- High ignition point

III. THERMAL ANALYSIS

3.1 Solar thermal storage system:
Fig.3 shows the solar thermal tank system and the system consists of:
Water tanker tubes
A solar collector to heat water by energy coming from the sun, and the maximum temperature of water in the solar collector is at midday
Water pump on request
A heat exchanger that heats the water in the tank through the solar collector
The thermal tank works to collect water from the solar collectors
Extra heater
The tank is considered one of the most important elements in the system because it works to store energy when the supply increases (i.e. not using water coming directly from the complex) and supply it to the load when the demand increases.

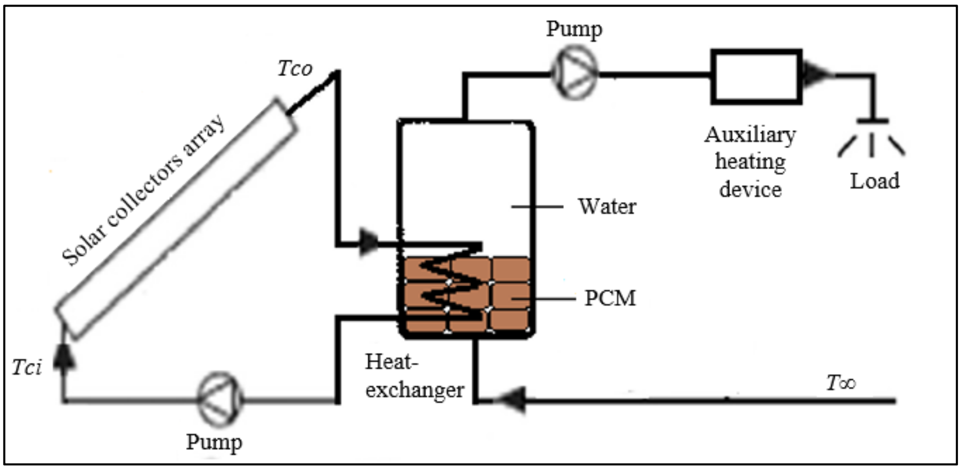

Fig. 3: Typical solar heating system with PCM thermal storage

3.2. Energy Balance of water storage with PCM:
Fig.4 demonstrates the energy balance of the storage. Using the first law of thermodynamics, the equilibrium can be formulated in the following image.

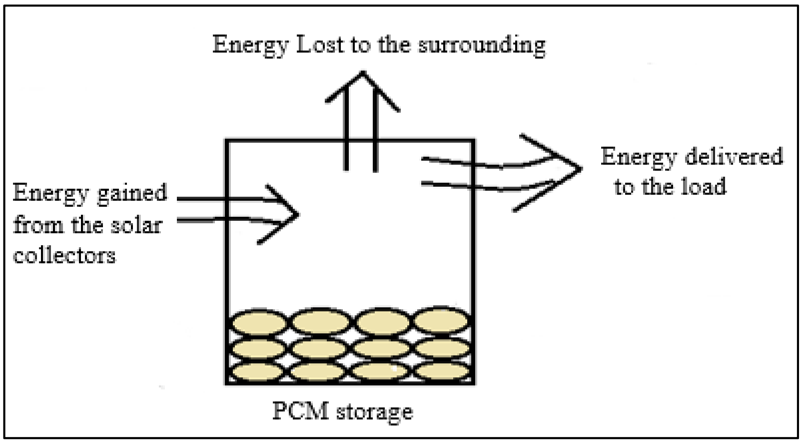

Fig. 4: Thermal equilibrium of the storage tank

The energy balance of the system yields to [29]:

$$Q_{solar} = Q_{loss} + Q_{load} + \Delta\dot{E} \quad (5)$$

Where: $Q_{solar}$is the energy coming from the solar collector (J), Q_{loss} is the energy lost to the surrounding, Q_{load} is the energy delivered to the load, and $\Delta\dot{E}$ is the change of the internal energy of the storage.

Fig. 5 illustrates a complete storage process, that includes three cycles: Charging, storing and discharging cycles. In practical some of these steps might occur in the same time. During the charging cycle, the thermal storage received energy from the solar collector's array. Now if the income temperature is smaller than the melting temperature of the PCM, the temperature of the PCM is increased (Mode I). If the income fluid temperature is greater than the melting temperature of the PCM in the storage, the PCM undergoes to a phase change from solid to liquid state. During this process the PCM absorbs a certain amount of thermal energy, known as the melting enthalpy (Mode II). The main character of this stage that is the temperature of the storage remains at a constant level. If the amount of income heat is enough to molten all the mass of PCM and the temperature is still greater than the melting-point the PCM undergoes through a sensible heat again (mode III). This stage is not desirable in a good design latent thermal storage. Accordingly, the charging cycle must be stopped at the mode II.

When the energy is drained from the thermal storage, the discharging stage begins, which is generally the opposite of the charging stage (mode IV). However, there is a natural phenomenon that must be stopped, and it is the phenomenon of recrystallization (hysteresis phenomena) (see Fig. 6).PCM needs a temperature that is less than its melting point to one or two degrees to return to the crystal and then the latent heat to solidify and thus the temperature of the material rises again to the melting temperature and the process continues until all the potential energy of the hardening of the material is depleted, then all the material becomes solid and then moves The process to the perceived heat again.

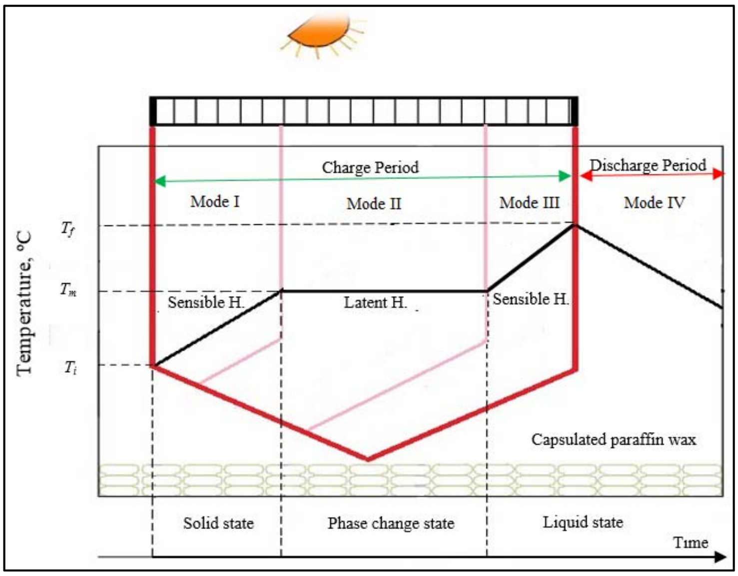

Fig. 5: Demonstration of behavior of the PCM material

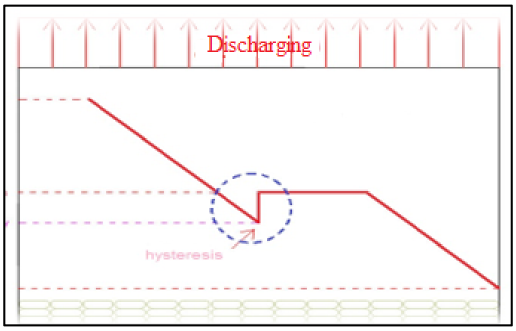

Fig. 6: Hysteresis phenomena

Thus, the equation of the amount of heat energy in the thermal storage is as follows:

$$Q_{in} = Q_{mode\ I} + Q_{mode\ II} + +Q_{mode\ III} \quad (6)$$

$$Q_{mode\ I} = [(\rho V Cp)_{water} + (\rho V Cp)_{wax,sol.}](T_m - T_i) \quad (7)$$

$$Q_{mode\ II} = \rho V L_m|_{wax} \quad (8)$$

$$Q_{mode\ III} = [(\rho V Cp)_{water} + (\rho V Cp)_{wax,liq.}](T_f - T_m) \quad (9)$$

$(\boldsymbol{\rho}\mathbf{v})_{water:}$: Volume and density of water, respectively
$(\boldsymbol{\rho}\mathbf{v})_{wax}$:The size and density of the wax respectively
$(\mathbf{c_p})_{water}$:Specific water temperature (kJ / kg. K)
$(\mathbf{c_p})_{wax}$:Specific wax temperature (kJ / kg. K)
$\mathbf{L_m}$:Latent fusion temperature (kJ / kg) (kJ / kg)

3.3. Calculation of PCM volume:

PCM is chosen based on the required temperatures in the tank, and the paraffin wax are suitable for heating domestic water, because its melting points range from 50 to 76 ºC. Physical properties of one of the components of paraffin wax that are available or suitable for use in the solar thermal systems used for domestic purposes are tabulated in Table 1.

Table 1: Thermal properties of paraffin wax [20]

Property	Value
The molting temperature	60ºC
The specific heat of the solid state	2.95kJ / kg. K
The specific heat of the liquid state	2.51kJ / kg. K
The density of the solid case	818kg / m3
The density of the liquid case	760kg / m3
Thermal conductivity of solid state	0.24w / m. K
Thermal conductivity of the liquid state	0.24w/m.K
The latent heat of fusion	244kJ/kg

The well designed thermal storage where the PCM must absorb all the energy entering the storage in the second stage (the melting stage) and not reach the third stage. Therefore, eq. (6) can be rewritten in the following form:

$$Q_{in} = [(\rho V Cp)_{water} + (\rho V Cp)_{wax,sol.}](T_m - T_i) + (\rho V\ L)_{wax} \quad (10)$$

Therefore, if the volume of the tank is $0.3m^3$ and Q_{in} 35.64 MJ calculated from previous research
Where Q_{in} is the amount of heat energy coming from the solar collector
ΔT: temperature difference of 10 ºC
We substitute the volume of water with the formula, $V_{water} = (0.3 - V_{PCM})$
We will get the size of the PCM material :$V_{PCM} = 0.137m^3$

3.4. Dynamic modelling of the storage with PCM

The unsteady state energy balance of the water thermal storage with PCM yields to:

$$Q_{solar}^{t} = Q_{Loss}^{t} + Q_{Load}^{t} + [(\rho VCp)_{water}^{t} + (\rho VCp)_{wax}^{t}]\frac{\left(T_m{}^{t+\Delta t} - T_i{}^{t}\right)}{\Delta t} \qquad (11)$$

Where Δt is the time interval which is taken 3600 sec.

IV. RESULTS AND DISCUSSION

A comprehensive FORTRAN code has been written in order to study the effect of volume of the PCM on the dynamic thermal behavior of the water storage tank, the program code is attached in appendix. The obtained results have been plotted graphically by mains of Excel program.

The presented here results are obtained for the given data in table 1, also one can find the input data from the code attached down in the appendix.

In Fig. 7 a comparison of simulation of heating water tank is done for several ratios of PCM volume ranges from 0% (absence of PCM) t0 100% (only PCM presented)

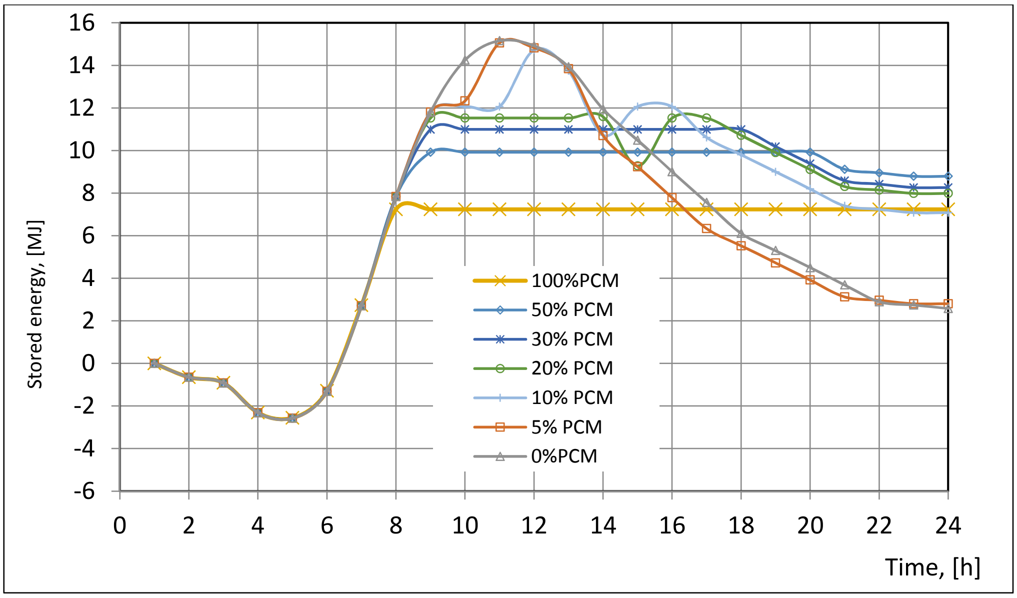

Fig. 7: A comparison of energy stored for several ratios of PCM volume

Fig. 7 illustrates the relationship between the heat stored in the water storage tank as a function of time for various volume ratios of PCM. Increasing the volume of PCM leads to a decrease in the amount of energy stored in the water storage tank, this is because the product of (ρVCp) of the PCM is less than the value for the water. Also it is clearly depicted in Fig.7 that increasing PCM volume leads to an increase in the charging and discharging periods. The optimum size of the PCM is determined according to the tank temperature should not exceed its melting temperature. It can be determined directly so that the thermal load on the tank does not exceed the latent heat area, which in this case is just over 20%.

Fig. 8 shows hourly water temperature in the hot water storage tank in terms of various ratios of the PCM volume occupied the storage to the storage tank volume.

As is evident from Fig.8, increasing the PCM volume leads to more water temperature stability in the tank. The simulation results show that, he temperature of water in the tank is dropping down due to heat losses to the ambient for 0% PCM volume faster than in case of PCM presenting.

The simulation starts at 1:00 am with initial water temperature 50ºC, the water temperature is decreasing due to energy losses with the surrounding and reaching to minimum temperature. The solar collectors start providing the storage tank with solar gained energy at 6:00 am causing an increase in (water and PCM) temperatures this so until the temperature reaches 60ºC (The melting point of the PCM), at this temperature the PCM starting melt causing an isothermal situation in the tank (constant temperature). This situation is clear in Fig. 8 when PCM is presenting, the situation is different when no PCM, the water temperature continuing to rise. This stage called charging stage. The length of this stage is extremely dependent on the PCM volume, more PCM volume leads to more stability period in the tank. Then, the water temperature dropped down during the energy extraction to the load and energy losses to the surrounding.

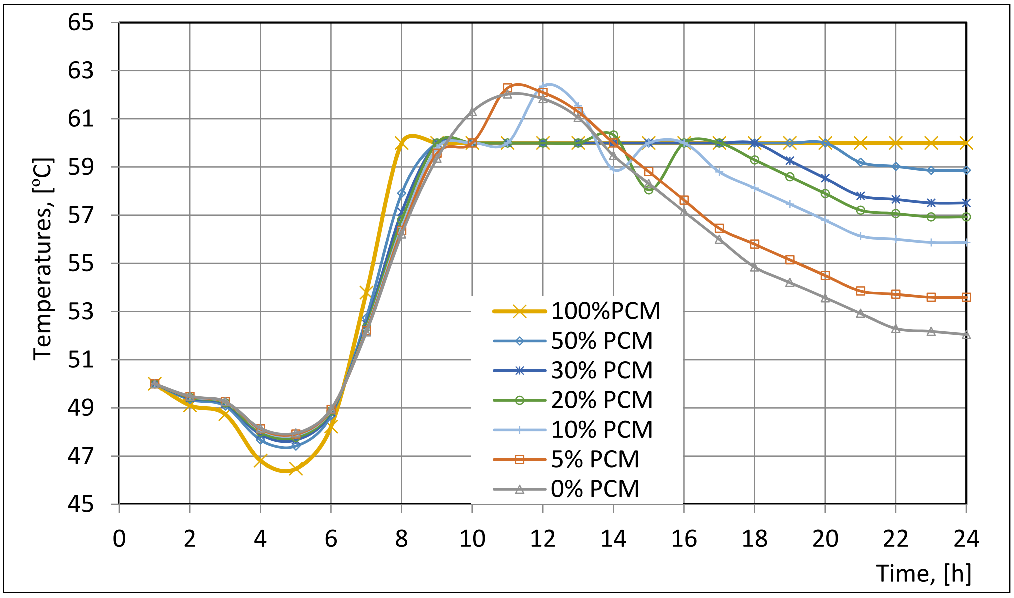

Fig. 8: The hourly water temperature in the storage as a function of the ratio of PCM volume to the tank volume.

Fig.9 shows the relationship between the heat capacity of the heat tank as a function of the temperature of the tank material. As shown in the figure, water at a certain temperature has a greater storage capacity than all, and the reason for this is because the specific density and heat of water is greater than that of paraffin wax used in the tank. However, wax stores the first "physical" energy and the second "latent" energy. The wax is distinguished from the water in the potential energy storage area, i.e. at the temperature difference of the tank at 1 degree, 1 kg of water will store 4200 J/kg. K while for the wax, the stored energy will be 244,000 J/kg.K.

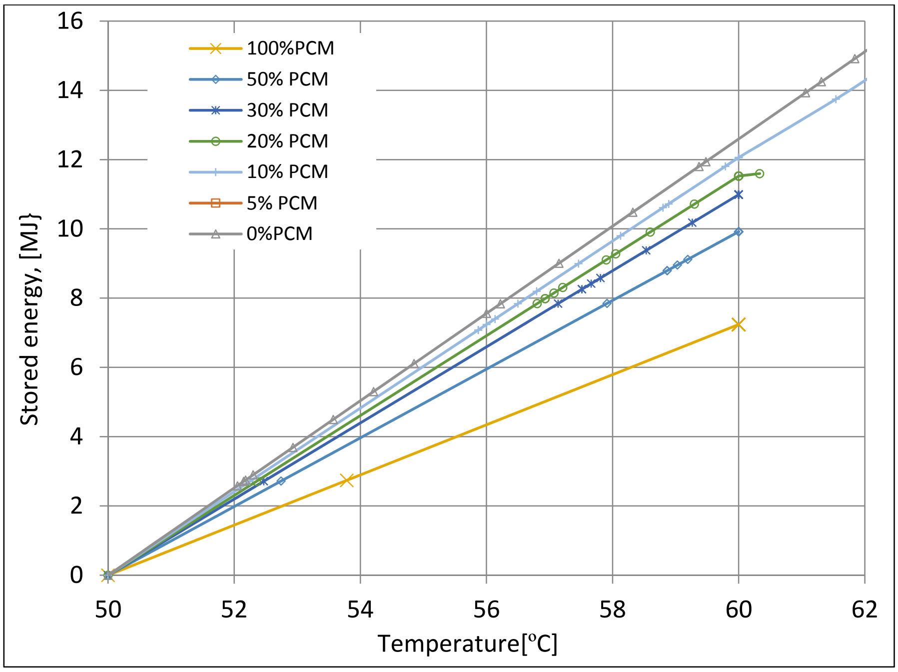

Fig. 9: The relationship between the storage capacity of the tank and the tank temperature

Because the amount of heat stored with water and PCM storage tank is not significantly greater than the amount of heat stored in the ordinary water storage tank, the advantage of PCM in these systems has to be questioned, especially considering the increase in volume, as well as relatively high costs of PCM. However, in Fig. 8 the increasing in the constant temperature period may be considered as an advantage of PCM and compensate the reduction in energy stored quantity and the increase in volume and capital cost of the system.

V. CONCLUSIONS:

The results obtained in this research encourage the use of PCMs in the field of solar domestic water heating supply systems. In general, the use of PCMs will reduce the temperature of the water in the storage, this leads to: increases the effectiveness of solar energy systems, as the heat exchange between the solar collectors and the thermal storage will take place under a higher temperature difference than in the absence of the PCM in the thermal storage. Reducing the heat losses to the surrounding due to the small temperature difference between the water temperature and the ambient temperature. The speed of charging is greater for the case of tank with water and PCM. This paper shows that, when used in adequate quantity and temperature range, PCMs can help improve thermal energy system.

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Appendix: FORTRAN Code

```
$debug
PROGRAM PCM
        IMPLICIT NONE
        REAL,DIMENSION(24)::Tamb,Qsolar,Qload,Qloss,Ts,Tw,Tss,Qs
   !Properties of the PCM "Paraffine Wax"
        REAL::CpL,Cps,Rol,Ros,Tmelt,Lfusion,Cpw,Row,Tsubcooling
        DATA CpL,Cps,Rol,Ros,Tmelt,Lfusion,Tsubcooling/2510,2950,760,818,60,244000,1 /
  !Properties of Water
        DATA Cpw,Row/4200,1000/
        REAL::Vw,Vpcm,Vwater,V,x
        REAL::UA,Ti
        REAL::SUMQs,Q
        INTEGER::I,Time
        OPEN(unit=11,file="PCM.in")
        OPEN(unit=12,file="PCM.out")
        READ(11,*)V,Vwater
        READ(11,*)Ti,UA
        Vw=V*Vwater
        Vpcm=V-Vw
        WRITE(12,*)"water volume=",Vw*1000 ,Vwater,"%","   PCM volume=",Vpcm*1000, 1-Vwater"%",
        WRITE(12,*)"water mass=",Vw*Row,"PCM mass=",Vpcm*Ros
        DO I=1,24
        READ(11,*)Tamb(I),Qsolar(I),Qload(I)
        ENDDO
        Ts(1)=Ti
        Tw(1)=Ti
        DO I=1,23
        Qloss(I)=UA*(Tw(I)-Tamb(I))*3600/1000000
        Tw(I+1)=Tw(I)+1E06*(Qsolar(I)-Qload(I)-Qloss(I))/(V*Row*Cpw)
        ENDDO
        DO I=1,23
        Qloss(I)=UA*(Ts(I)-Tamb(I))*3600/1000000
        Ts(I+1)=Ts(I)+1E06*(Qsolar(I)-Qload(I)-Qloss(I))/(Vw*Row*Cpw+Vpcm*Ros*Cps)
        enddo
        WRITE(12,200)
        DO I=1,24
        Tss(I)=Ts(I)
        WRITE(12,201)Tamb(I),Qsolar(I),Qload(I),Qloss(I),Tw(I)
        ENDDO
        IF(Vpcm>0)THEN
        SUMQs=0
        WRITE (12,202)
        ELSE
        GOTO 100
        ENDIF
        DO I=1,24
        IF(Ts(I)>Tmelt)THEN
        Time=I
        GOTO 51
        ENDIF
        ENDDO
        GOTO 100
51      CONTINUE
        x=0
        DO I=Time,24
        IF(Ts(I)>Tmelt)THEN
        Qs(I)=(Vw*Row*Cpw+Vpcm*Rol*Cpl)*(Ts(I)-Tmelt)/1E+06
        SUMQs=SUMQs+Qs(I)
```

```
        IF(SUMQs<=Vpcm*Rol*Lfusion*1E-06)THEN
        Tss(I)=Tmelt
        Q=SUMQs
         ELSE
        Tss(I)=Ts(I)
        ENDIF
        ELSE
        Q=Q-(Vw*Row*Cpw+Vpcm*Rol*Cpl)*(Tmelt-Ts(I))*1E-06
        IF(Q>0)THEN
        x=x+1
        Tss(I)=Tmelt
        if(x==1.and.Tss(I-1)>60)Tss(I)=Ts(i)-Tsubcooling
        ELSE
        Tss(I)=Tss(I-1)+1E06*(Qsolar(I)-Qload(I)-Qloss(I))/(Vw*Row*Cpw+Vpcm*Ros*Cps)
        ENDIF
        ENDIF
        ENDDO
        WRITE(*,*)SUMQs,Vpcm*Rol*Lfusion*1E-06
        DO I=1,24
        if(Tss(I)>60)then
        Qs(I)=(Vw*Row*Cpw+Vpcm*Rol*Cpl)*(Tss(I)-Ti)/1E+ 6
        else
        Qs(I)=(Vw*Row*Cpw+Vpcm*Ros*Cps)*(Tss(I)-Ti)/1E+06
        endif
        WRITE(12,203)I,Ts(I),Tss(I),Qs(I)
        ENDDO
200     FORMAT("Tamb,[C]     Qslar,[MJ]      Qload,[MJ]     Qloss,[MJ]     Tstorage,[C]")
201     FORMAT(2X,F4.1,7X,F7.4,10X,F7.4,9X,F7.4,9X,F5.2)
202     FORMAT("Time,[h] ,Ts,[C]      Tss,[C]     Qs,[MJ]  ")
203     FORMAT(2X,I2,7X,F7.4,10X,F7.4,9X,F10.4)
100     END
```

Khaled A. Amer, et. al. “Performance of domestic solar heating system with thermal storage using phase change materials." *International Journal of Engineering Research And Development*, vol. 16(9), 2020, pp 01-11.