AN- NAJAH NATIONAL UNIVERSITY

FACULTY OF ENGINEERING

CHEMICAL ENGINEERING DEPARTMENT

EXPERIMENTAL INVESTIGATION ON THE PERFORMANCE OF PHASE CHANGE MATERIAL (PCM) INCORPORATED WITH SOLAR WATER HEATING SYSTEM

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Dedication

We dedicate this project to our parents and friends for their inspiration. Thank you. Our love for you all can never be quantified. God bless you.

We also dedicate this work to our advisor Dr. Abdelrahim AbuSafa, for his knowledge, time and understanding.

Acknowledgment

We would like to express our deepest appreciation to all those who provided us the possibility to complete this report. A special gratitude we give to our final year project advisor, Dr Abdelrahim AbuSafa, whose contribution in stimulating suggestions and encouragement, helped us to coordinate my project especially in writing this report.

Moreover, it is our duty to thank Mr. Bashar Dwekat for his huge efforts during manufacturing the system.

Table of Contents:

List of Figures:

List of Tables:

Abstract

Solar energy appears to be the only veritable and viable alternative source of energy. It is inexhaustible, has no effect on the environment, and can be converted to many other forms of energy. Converting it to thermal energy in order to heat water is done with a solar water heating system. In Palestine there is a large dependence on SWH to heat water.

Thermal energy storage (TES) systems provide several alternatives for efficient energy use and conservation. Phase change materials (PCMs) for TES are materials supplying thermal regulation at particular phase change temperatures by absorbing and emitting the heat of the medium.

The main objective of this study is to, design and construct a new solar water heater tank, integrated with PCM storage in the aim of reduce the solar water heater tank size.

Solar water tank was manufactured with a capacity of 30 litters coupled with the Phase change material (PCM) tank. Charging and discharging process was simulated by using a variable power electric heater tank which, supply the power based on different solar irradiation along the year in Palestine.

PCM tank configuration shows a high heat transfer rate during charging periods which, all the PCM is undergoing melt at different power supplies and water flow rates. The hot water supply time was increased by 30% more than conventional system. Also, the system with PCM stores

3000 kilojoules of energy more than conventional. which used to supply approximately 25 litters of hot water.

Design constraints

Investigate the performance of phase change material within solar water heating system may be contain some constraints especially during system design.

Tank height and diameter assumption to be $H/D = 3$, (Hall, 2012).

Based on literature review, PCM/Solar water tank volume ratio must be above 30% and PCM tank should be in the upper half of the Solar water tank.

Based on domestic water consumption, water flow rate within a range of 0.25 – 0.3 L/min.

Power supplied to the electric heater are 500, 700 and 900 kWh to simulate different month values during the year such as (February, April and July).

Chapter One: **Introduction**

This era is called the Energy Era, for its a tremendous impact on the industrial and technological development nowadays. Moreover, the development and progress in various areas of life has become strongly linked to the energy and its different forms. Which has created international competition in finding and developing energy sources, especially as traditional sources of energy including oil and gas are about to run out besides their significant negative role in polluting the environment.

It is clear that the global trend is becoming more concerned with harnessing the renewable resources of nature in power generation such as geothermal, wind and solar energy, because they are permanent, environmentally friendly and brings great economic benefits.

In Palestine, people suffer from scarcity of energy resources for many reasons. Mainly because of the great population growth with bad economic situation, as well as weak infrastructure and Israeli occupational policies. Therefore, it is difficult to keep up with the energy race in the world that requires finding out different ways to improve energy sources in Palestine.

Renewable energy sources are available in Palestine but they are not exploited for the reasons mentioned above. Sun is one of the most important things that can be exploited in the energy sector. Solar and thermal energy in Palestine has a limited use but at the same time they are very important and essential to people, because it is used in water heating through solar water heaters (SWH) on the roofs of houses.

But what has been observed recently is that the use of solar water heaters has been declined significantly due to the large population growth and the consequent rise of residential buildings in narrow areas. Therefore, there is a lack of space for solar water heaters. These harms the policy of using thermal energy as one of the renewable forms of energy in Palestine then getting back to use the fuel, which means greater pollution and higher costs. The percentage of households using solar heaters was 62% in 2014 while it was 72% in 2001, which shows this significant decline. (Anon., 2014)

No one disagrees with the importance of solar energy. It is free, clean, valuable in addition it is one of the promising alternative option of energy sources. The use of heat storage systems can improve and enhance of the reliability and performance of thermal energy. Moreover, developing energy storage systems is important as finding new resources of energy. (Atul Sharma, 2009)

These days and with the huge industrial revolution, the need for energy has become very huge. At the same time, there are limited clean energy sources which requires finding ways and solutions to reduce these problems, what forced mankind to think in energy storage.

Energy storage is one of the best solutions to enhance the reliability and the performance of the energy sources, moreover the big role of energy storage in reducing the costs and pollution and also in the increasing of the efficiency, it also contributes significantly to reducing the gap between the demand and supply of energy.

Energy can be stored in several methods, thermal, biological, mechanical, magnetic and chemical energy storage. Chemical storage is the most efficient and effective way of storing energy in large quantities for long periods of time, batteries are among the most prominent examples used in daily life that fall under this type of storage. Energy can be stored mechanically as kinetic energy, potential energy, or as the compression energy in a gas. (Dincer, 2002)

Thermal energy storage (TES) systems gives the possibility of reuse the energy later by storing it in form of heat or cold under different conditions such as power and temperature, the complete storage cycle involves three steps: charge, storage, discharge. (Cabeza, 2015)

The most common form of (TES) is through changing the temperature of a certain substance (lowering or elevating) in addition to phase change of a certain substance, in the form of latent heat, sensible heat or chemical heat. (Cabeza, 2015)

The storage unit of thermal energy is one of the most important parameters in the solar water heaters (SWH) system, because there is a high probability that the radiation decreases from one period to another or that there is no radiation received as at night. Thermal energy storage as a form of latent heat has convenient and attractive features over the sensible heat because of its high density of storage in addition to isothermal nature of the process at melting temperature. Solid liquid phase change process is preferred due to the operating pressure in the system (it is lower than liquid-gas or solid-gas phase change). (Cabeza, 2015)

This study will mainly focus on the experimental investigation on the performance of phase change material (PCM) Incorporated solar water heating system.

Materials used to store thermal energy in the form of latent heat are called phase change materials (PCM). It is a substance with a high heat of fusion which melting and solidifying at a certain temperature, that is capable of storing and releasing large amounts of energy as latent heat as show in figure 1. Heat is absorbed or released when the material changes from solid to liquid and vice versa. (Alemrajabi, 2013)

There is wide range of applications in different fields which PCM can be used in it such as transportation of perishable foods and temperature sensitive pharmaceuticals, green houses, construction materials, air conditioning, house heating and warm water.

The main objectives of this study are:

- Design and construct a new solar water heater tank, integrated with PCM storage in the aim of reduce the solar water heater tank size
- Simulate the charging and discharging behavior of the constructed system using variable power electrical heater tank, coupled with the PCM storage tank.

Chapter Two: **Literature Review**

It is important to review the literatures that were performed on the using of phase change material in solar water heaters.

Mohammad. F. A (Fazilati, 2013) has been experimentally investigated the effects of using Phase Change Materials (PCM) as storage medium on the performance of a solar water heater as show in (figure 1)

Paraffin Wax as PCM was used which has approximate 55ºC melting point temperature, embedded into the storage tank by 180 spherical HDPE capsules with 38 mm diameter. A 380 mm long and 0.3 mm diameter copper wire was inserted in each capsule to avoid the effects of paraffin's low thermal conductivity. Moreover, a jacketed cylindrical horizontal tank with capacity of 9.5 L, 20 cm diameter and 32 cm length are used. Finally, the tank is thermally insulated with 50 mm thick glass wool.

The most important results can be summarized as the energy storage density, is enhanced in the system up to 39% moreover, the exergy efficiency is increased up to 16% by using PCM. Also, it is observed that using PCM in the tank increases the time of hot water supply at specified temperature by 25%.

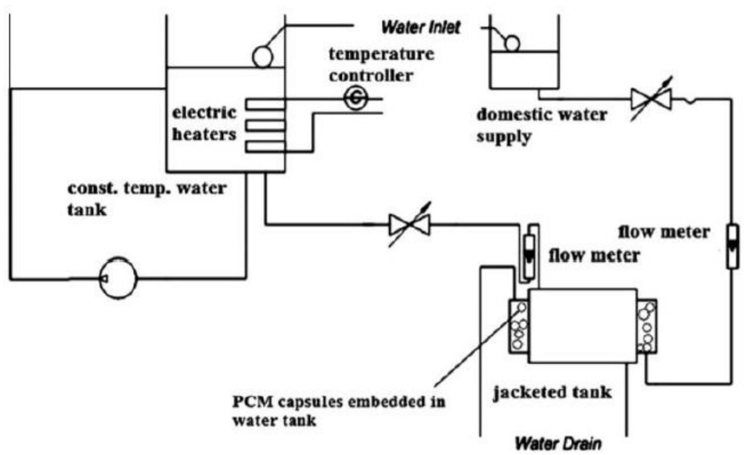

Figure 1:system diagram.

Mongibello and M. Atrigna, et al (Mongibello, 2017) designed a well-developed system for hot water storage system including a macro-encapsulated phase change material (PCM) as show in figure (2). A 1.27-meter cylinder tank was used with an internal diameter of 0.65 m and total capacity 420 litter, a 1" coiled-tube heat exchanger was also used with total heat exchange area of 1.9 m^2.

A 3 litters aluminum bottles was filled with bio-based pcm without any additives, which has a 58^{o}C melting point, each aluminum bottle contains 1.7 Kg of PCM.

the energy storage system has been charged for a period of six and half hours, with a constant water mass flow rate through the serpentine of 0.2 kg/s, and with an increment of the water temperature at the serpentine inflow section of 5°C/ (30 min). at the end of the period the water temperature reaches 85^{o}C with initial water temperate of 30^{o}C.

Two cases where tested in this work, water with PCM and water alone. And the results show that not all the PCM has undergone melting.

Figure 2:System and PCM inside tank

Pasam, Bhagya Lakshmi, et al (Bhagyalakshmi, 2018) have been experimentally investigated the effects of using Paraffin and Palmitic acid and the eutectic mixture in storage purpose in a cylinder shell type heat exchanger

A flat solar collector was used to heat up the water and stored it in the overhead tank, however the cylinder heat exchanger was filled with PCM by filling them in 16 cylinders made up from stainless steel are attached to a central cylinder as show in figure (3).

The HTF inlet temperature is maintained 75^{o}C and the solidification process carried out in three ways solidification by:

i) Hot water.

ii) Cold water

iii) Without water in the tank.

Results show that the eutectic PCM is able to store energy for a longer period of time than the base materials. These PCMs are suggested in solar water heating applications to store the solar hot water at higher temperatures twice that of the time of the ordinary unit.

Figure 3: System and PCM modules inside tank

Kailiang Huang. (Kailiang Huang, 2016), Have discussed enhancement of charging and discharging time for paraffin, inserting a high thermal conductivity material into the liquid PCM considerably, will increase the thermal conductivity hence decrease the time required for both charging and discharging. An experimental study has made by using float stones which mainly consist of SiO_2, CaO and MgO as show in (figure 4).

Three tests were performed. Micro structure observation which shows that the float stones were totally immersed by PCM and it can be assumed it’s a mixture of uniformity. Secondly, leakage tests which investigate cylinder fabricated from PET enclosed by ultrasonic welding can handle the PCM without leakage. Finally, it found that as diameter of the container decreased, time of melting decreased, as the surrounding temperature of the container increased, the time of melting decreased too. As a final point, third time of paraffin melting can be reduced by using float stones.

Three different Parameters were studied in this research:

1- Thermal conductivity (float stones and without)

2- Time of melting.

3- Surrounding temperature (three cases)

Figure 4: PCM with float stones.

Akgu¨n. (Akgu¨n, et al, 2007), Built an experimental setup system as show in (figure 5), to study the required time for charging and discharging of PCM, they used pure Paraffin as a heat storage and water as HTF. However, they used shell and tube configuration, where the HTF was in the tubes and PCM put in the inside the shell, in addition hot water bath as energy supply.

For charging, three different inlet temperature of HTF has studied 60, 65, 70, 75 C and varying the mass flowrate 4,6, 8 kg/min. An increasing in inlet temperature of HTF, results higher temperature gradient near HTF tube, this gradient decrease with increasing melting time. Moreover, increasing the enthalpy flow by increasing mass flow of HTF, shall decrease the melting time. For discharging, the inlet temperature of cold water remains constant during the solidification of paraffin, another discharging measurement has made with a different flowrate, as illustrated above increasing flow rate will enhance heat transfer.

Two Parameters were studied in this research:

1. Inlet temperature for HTF.

2. Mass flowrate for HTF.

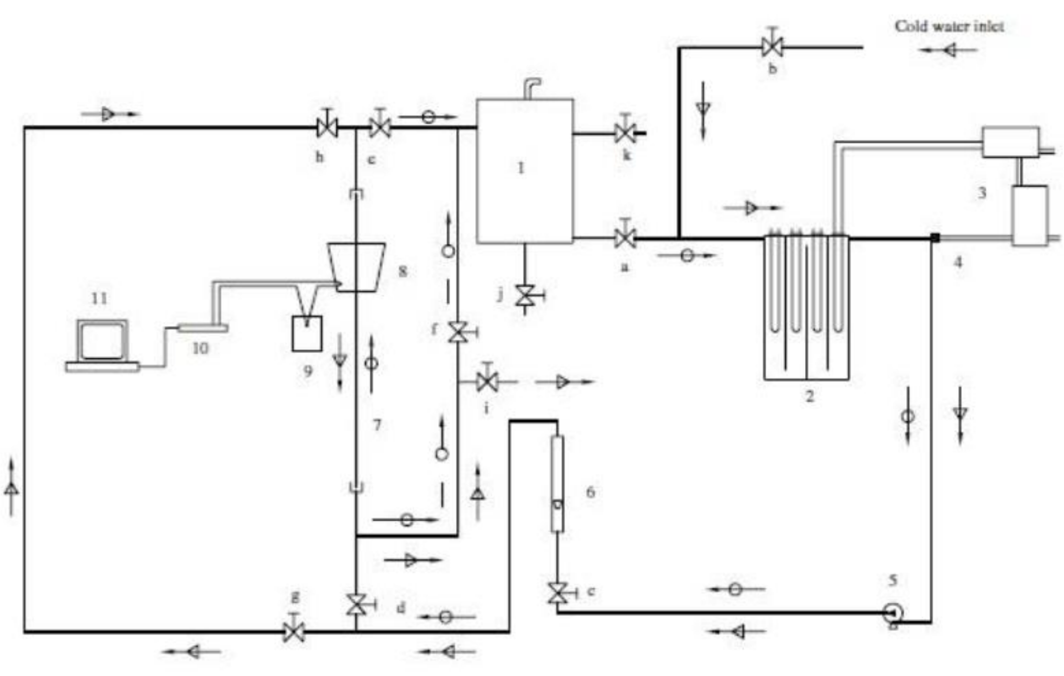

Figure 5: Schematic diagram.

Nallusamy. (Nallusamy& al, 2007), Have investigated experimentally sensible and latent heat storage system as shown in (figure 6), by using paraffin as PCM inserting it in a 43 L TES as 50 % volume. In fact, 264 capsules fabricated from HDPE have used to enhance heat transfer between Paraffin and HTF. Charging and discharging time measured when using a Hot Water Bath and Solar collector, and different inlet HTF temperature in different flow rate. Temperature PCM and HTF inside LHS set as 32 ^oC in the beginning in each experiment.

- Charging: Until thermal equilibrium between temperature of PCM and HTF

a) Constant inlet Temperature form hot water bath storage $T_{f.i}$:

i) $T_{f.i}$ = 66 ^oC, Charging time = 220 min.

ii) $T_{f.i}$ = 70 ^oC, charging time = 160 min.

b) Flat plate solar collector, varying $T_{f.i}$:

i) Charging time 240 min

Eventually, increasing inlet temperature shall decrease charging time. However, using solar collector well significantly increase charging time, due to gradual increase in temperature.

Effect of changing mass flow rate from 2 to 6 L/min, charging time has decreased 14% when constant inlet temperature. While in varying inlet temperature it has large effect, 26 % of charging time has decreased.

- Discharging time measured in two methods Batch wise and Continuous,

Batch wise: In the case of batch wise discharging process a certain quantity of hot water is withdrawn from the storage tank and mixed with cold water to obtain 20 L hot water at average temperature of 45 °C.

Then the storage tank is again filled with cold water of quantity equal to the amount of water withdrawn. Now the temperature of HTF (water) in the tank increases by gaining heat from PCM capsules and after a retention period of 10 min, another batch of hot water is withdrawn and mixed with cold water. The batch wise discharging process is continued until the PCM temperature reaches 45 °C.

i) 6 Batches of 20 L of hot water at average temperature 45 °C in period of 60 min.

Continuous discharging process: the HTF outlet temperature decreases continuously with time.

i) Around 90 min period of discharging time.

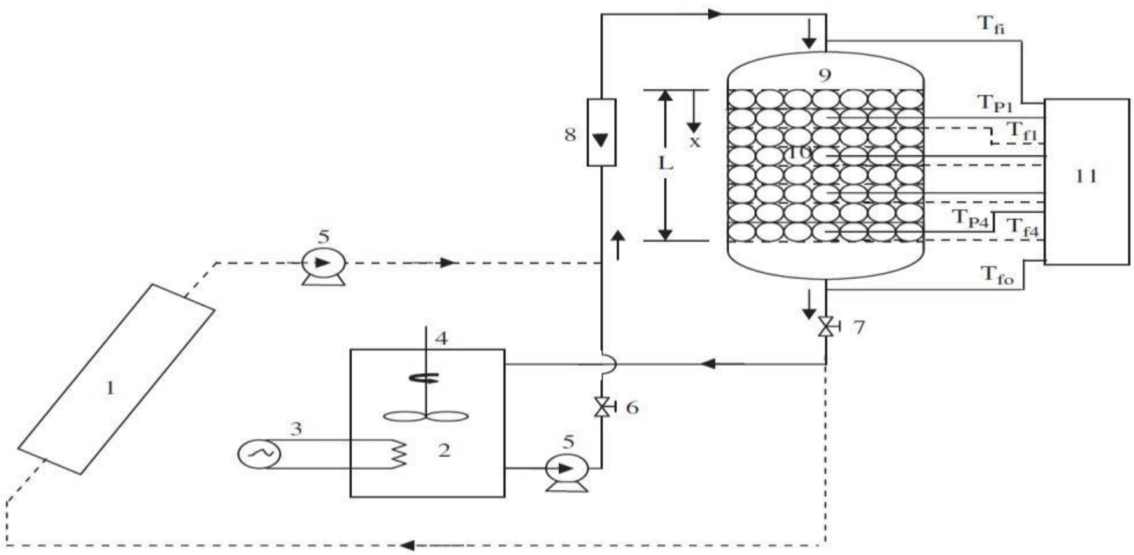

Figure 6: Schematic of experimental setup

1: Solar flat plate collector; 2: Pump; 3 & 4: Flow control valves; 5: Flow meter; 6: TES tank;

7: PCM capsules; 8: Temperature indicator; Tp&Tf: Temperature sensors (RTDs).

Summary

At the end of this chapter, a summary table was prepared to compare the Literature reviews as in (Table 1 and 2)

Table 1:Design Parameters Summary

Author	Tank volume [L]	Tank Height [m]	Tank Diameter [m]	PCM material	PCM Melting [C]	PCM vol%
(Nallusamy& al, 2007)	43	0.46	0.36	Paraffin	60	50%
(Akgu¨n& al, 2007)	3.272	0.465	0.09467	Paraffin	44.23	50%
(Mongibello, 2017)	420	1.27	0.65	Paraffin	58	Undefined
(Bhagyalakshmi, 2018)	63	0.5	0.4	Eutectic mixture	56	25%
(Fazilati, 2013)	9.5	0.032	0.02	Paraffin	55	55%

Table 2: Configuration Summary

Author	Configuration	Studied Parameters	results
(Nallusamy& et al, 2007)	264 HDPE capsules, in eight rows along tank height	Charging and discharging time in different HTF temperature and flow rate	Increasing inlet temperature of HTF from 66 to 70 [C], decreasing charging time from 220 [min] to 160 [min]. At solar collector usage charging time was 240 [min]
(Akgu¨n& al, 2007)	Shell and tube, tube made using copper. Whereas the outer shell made from stainless	1.Inlet temperature of HTF 2. Mass flowrate of HTF	higher temperature gradient near HTF tube increasing the enthalpy flow
(Kailiang Huang, 2016)	Capsulated tubes fabricated using PET. Moreover, immersing float stones inside liquid PCM	Thermal conductivity Time of melting Surrounding Temperature Diameter of the container	diameter of the container decreased; time of melting decreased
(Mongibello, 2017)	aluminum bottle contains 1.7 Kg of PCM in the top of tank	effects of the presence of the PCM inside hot storage tank	not all the PCM has undergone melting
(Bhagyalakshmi, 2018)	16 cylinders each of 75mm diameter and 120mm of height are attached to a central cylinder of 100mm diameter and 400mm height	study the type of solidification during PCM discharging	It is concluded that the eutectic PCM is able to store energy for a longer period of time than the base materials
(Fazilati, 2013)	180 spherical HDPE capsules embedded into the storage tank	effects of using (PCM) as storage medium on the performance of a solar water heater	increases the time of hot water supply at specified temperature by 25%.

Analysis of solar irradiation in Palestine:

Palestinian areas can be classified into three irradiation areas as follows in figure (7):

General irradiation map of Palestine:

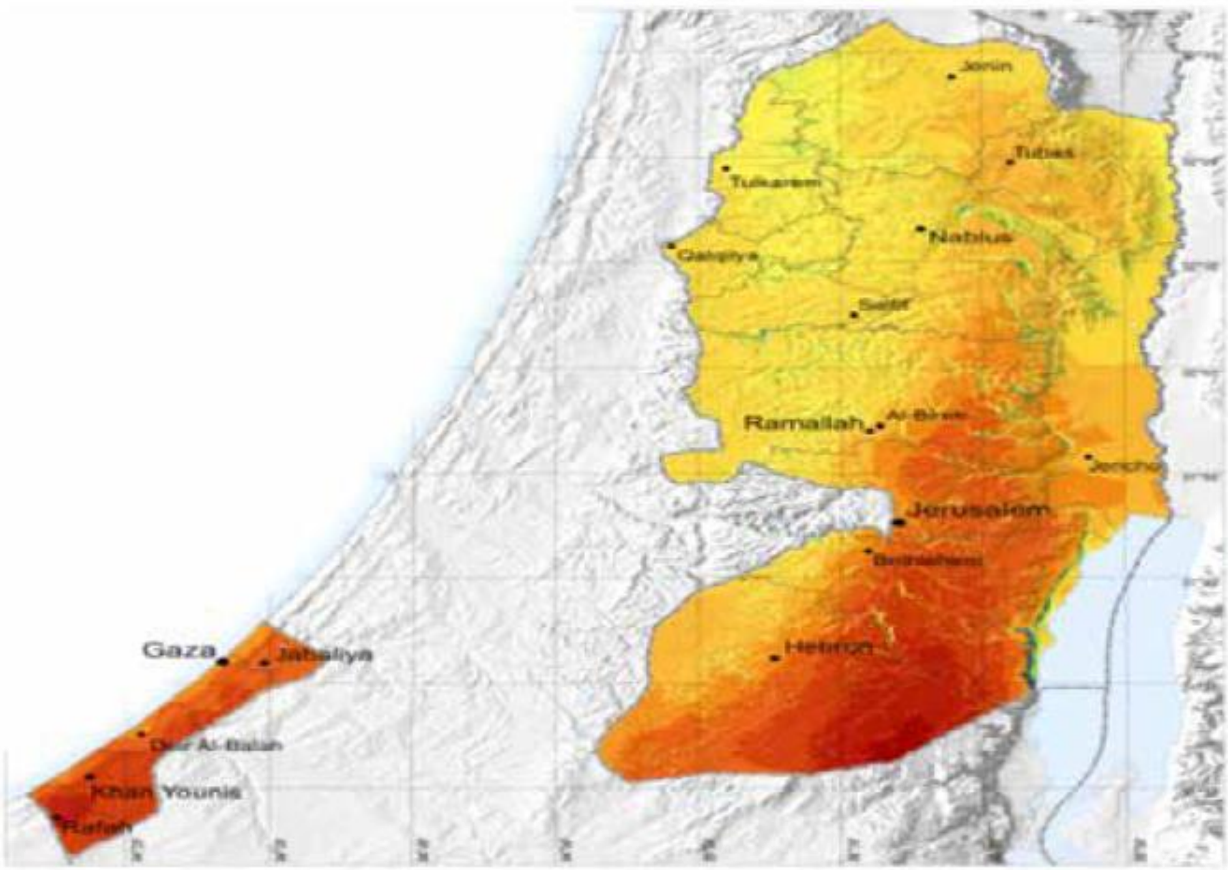

Figure 7: Average Global Tilted Irradiation of Palestine.

- Areas with highest irradiation: areas colored in red with radiation above 2300 kwh/m^2 are covering middle and south areas. For basic purposes those are hilly and coastal areas in Ramallah, Jerusalem, Bethlehem, Hebron and all Gaza strip governorates. (Solar Energy Production in Palestine)

- Areas with medium irradiation: areas colored in brown with radiation between 2200-2300 kwh/m^2 that are covering mainly Jordan valley and northern hilly areas in Palestine. Those areas are Jericho and southern part of the Jordan valley, in addition to Tubas governorate and some other areas in the northern middle part of the West Bank. (Solar Energy Production in Palestine)
- Area with low irradiation: areas colored in yellow with radiation less than 2200 kwh/m^2 are covering the most areas of West Bank north. It includes Tulkarem, Qalqilya and Jenin and other rural areas in the western side of the West Bank. (Solar Energy Production in Palestine)

According to this study of the existing solar irradiation data, the average solar irradiation in Palestine is given 5.4 kWh/m^2.day. In some areas the maximum irradiation reaches 8.5 kWh/m^2.day in June while the minimum goes down in December and reaches 2.8 kWh/m^2.day. (Ghanem, 2016)

Chapter Three: **Energy storage**

The world nowadays facing a rapid growing problem in the consumption of non-renewable energy, because of harmful emissions and its effect on environment and it was necessary to look forward another method for reducing this problem. From that point of view the energy storage is one of the solutions to reduce these emissions as possible.

Energy storage plays an important role in the future of renewable energy for the following reasons (Holla, 2015)

1. It helps the electrical grids to be more stable and flexible, so that any surge in peak demand can be addressed effectively and more efficiently, thereby allowing balance in supply and demand of energy.
2. It assists in managing excess energy generated for a later use.
3. It minimizes renewable energy curtailment, thereby increasing the return on investment of renewable energy generation.
4. It reduces the use of fossil-fuels.
5. It facilitates in maintaining power quality.
6. It defers or eliminates the need for additional generation or transmission infrastructure.

Energy can be stored with in many techniques:

1- Magnetic
2- Biological
3- Mechanical
4- Chemical
5- Thermal

Magnetic Energy Storage:

Energy storage is very important for electricity as it improves the way electricity is generated, delivered and consumed. With a big challenge in balancing the power supply need with the demand instantaneously within milliseconds. Which makes power networks more efficient and convinced.

Magnetic traditional storage systems store energy within capacitors, but nowadays superconducting magnetic energy storage (SMES, which can storage, bulk amount of electrical power in superconducting coil. The stored energy is in the form of a DC magnetic field. The unique properties with SMES system are the high efficiency (> 90%) and the fast response (<100ms). (Kumar, 2015)

The major components of the Superconducting Magnetic Energy Storage (SMES) System are: (Holla, 2015)

- Large superconducting coil,
- Power conversion system
- Cryogenic refrigerator and a vacuum insulated vessel. As show in (figure 8)

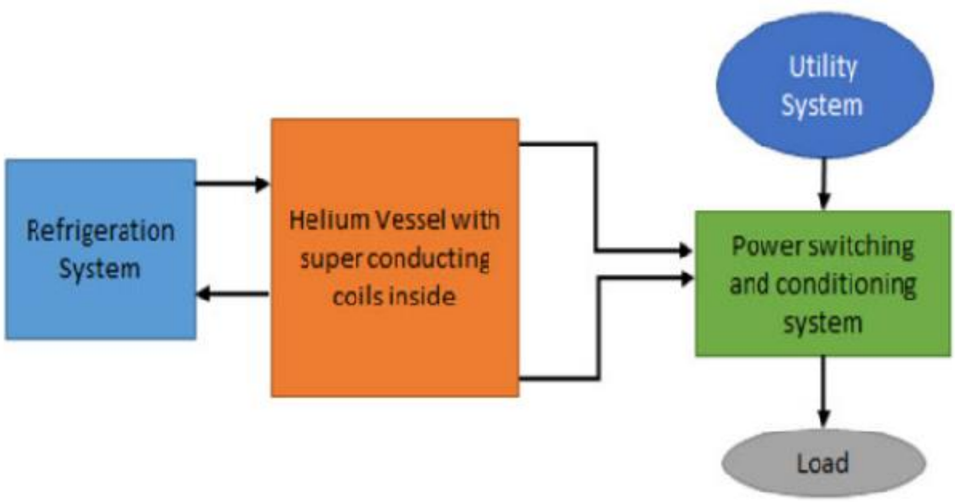

Figure 8: SMES System

The storage unit could be charged during off-peak hours, with the electricity discharged back to the grid at a later time to meet peaking needs.

Chemical Energy Storage

Chemical storage (CS) is the most efficient and effective way of storing energy in large quantities for long periods of time, batteries are among the most prominent examples used in daily life that fall under this type of storage. battery's is frequently referred to as electrochemical energy because chemical reactions in the battery are caused by electrical energy and subsequently produce electrical energy.

One of the strategic elements for chemical energy storage is interfacial catalysis, regardless if it occurs in batteries, electrolyzes, photochemical devices or solar refineries. All chemical processes are subjected to the concept of thermodynamics and kinetics. Otherwise thermodynamic cannot be change its possible to change kinetics by catalysis. (Schlogl, 2016)

Hydrogen and synthetic natural gas (SNG) are second strategy for (CS). Hydrogen which can be produced electrochemically by the electrolysis of water or thermochemically by direct chemical reactions in multistage processes. Hydrogen could be used in generating heat through direct burning or generate electricity through using fuel cell. (Rosen, 2011.)

The overall efficiency of hydrogen and SNG is low compared to storage technologies such as batteries.

Biological energy storage

Strictly speaking, "biological energy" ought to refer to the chemical potentials produced and consumed by the myriad and interwoven reactions that take place within the compartments of living matter. But these processes are perhaps better known, collectively, as metabolism. (group, 2005)

Living organisms use two major types of energy storage. Energy-rich molecules such as glycogen store energy in the form of covalent chemical bonds. Cells synthesize such molecules and store them for later release of the energy.

The second major form of biological energy storage is electrochemical and takes the form of gradients of charged ions across cell membranes. (Anon., 2017)

Mechanical storage

Valuable items will be stored if they are easily available but not needed at the moment. Mechanical energy is such a valuable item and should be stored whenever it is available but not consumed.

To store the excess mechanical or electrical energy as kinetic energy in flywheels, potential energy in water or compression energy in air, to use it at high demand time as mechanical or electrical energy has great importance for the civilized world mainly because of irregularities of demand or supply. (Gőğűş, 2009)

There are three main mechanical storage types: hydro storage, compressed-air storage, and flywheels.

Pumped storage (Hydro):

Today mostly used and largest capacity systems are for storage of electricity in pumped hydro power plants because of its simple work principle. Water from a lower reservoir or lake is pumped up to a reservoir hundreds meter higher, at the next day when the demand is high electrical power is produced by letting the water flow down through the hydraulic turbines as show in (figure 9**).** The pumped water storage plant has a low efficiency, which is about 50 %. Due to the losses happened while water pumped uphill and also while the water flows down**.** (Gőğűş, 2009)

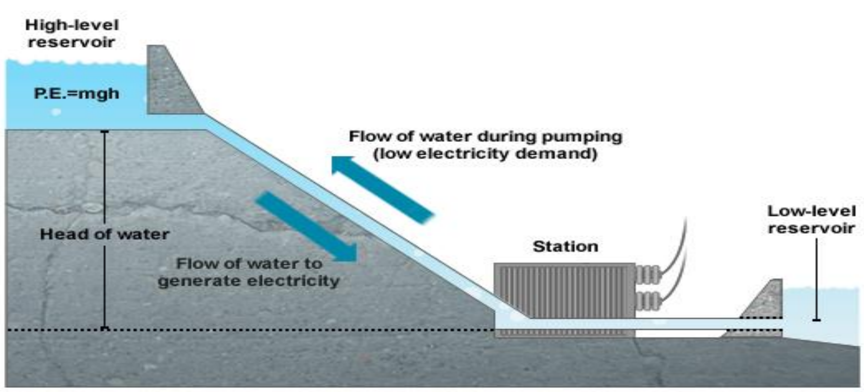

Figure 9: Pumped Hydroelectric Storage

Compressed air energy storage

these systems are essentially gas turbine power plants with an additional cavern to store the compressed air. The vessels or pipes usually being underground or above-ground as shown in the (figure 10).

During the off-peak hours or at night, air is compressed into this cavern at a pressure 40 to 80 bar and used next day to run the gas turbine during the peak hours. They have the advantage to increase total installed power by less investment in comparison to pumped hydro power plants. However, they depend on liquid or gas fossil fuel. Furthermore, geological conditions to create a cavern are not satisfied at most places. (Gőğűş, 2009)

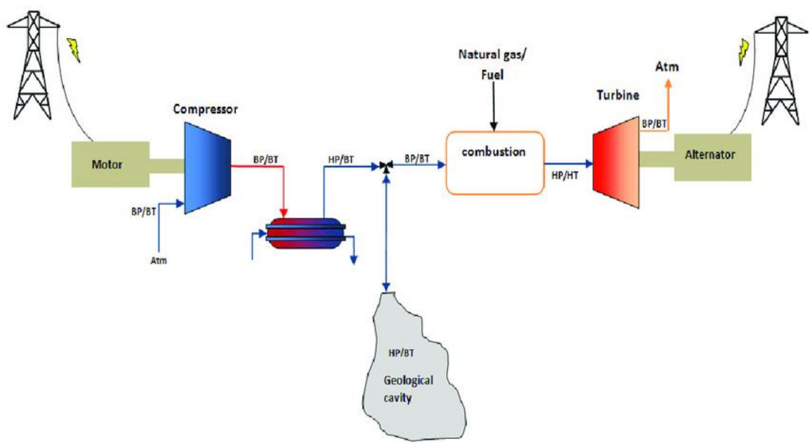

Figure 10:Compressed air energy storage

Flywheel energy storage

For medium and small-scale mechanical energy storage flywheels are very suitable. It uses electric energy as input which is stored in the form of rotational kinetic energy in an accelerated rotor, and can be called up instantaneously.

The advantages of this system are the cycle stability and long life, little maintenance, high power density and the use of environmentally inert material and are applied as spinning reserve at a power rate 1.6 MW and 5 kWh energy capacity (Gőğűş, 2009) (Lemelson, 1981)

The most important characteristics of mechanical energy storage systems are their capacity [kWh; MWh or MJ, GJ] and their delivery power [kW; MW]. In comparing different types of storage methods, the energy storage density is an important parameter. (Gőğűş, 2009)

Thermal energy storage:

As renewables gain a greater foothold in the energy system, the importance of energy storage is going to increase in kind. With the ongoing gradual shift away from traditional baseload energy sources, the development of efficient energy storage systems is imperative.

Thermal energy storage (TES) has been developing for around 25 years. This technology stocks thermal energy by heating or cooling a storage medium so that the stored energy can be used at a later time for heating and cooling applications and power generation. It can reduce or eliminate the cause of peak electric power loads.

Thermal energy used specially in systems that have high thermal energy consumption, and their demand may vary during any given day with lowering the CO_2 emissions.

There are three mainly types of TES systems; Sensible heat, Latent heat and thermo-chemical heat storage.

Sensible heat storage is the most common method and has been employed for hundreds of years as hot water tanks. Sensible heat storage simply means changing the temperature of storage medium. The storage medium is most commonly water but rock, sand, clay and earth can also all be used. (Barbour, 2013)

Heat transferred to the storage medium leads to a temperature increase of the storage medium as shown in (Figure 11)

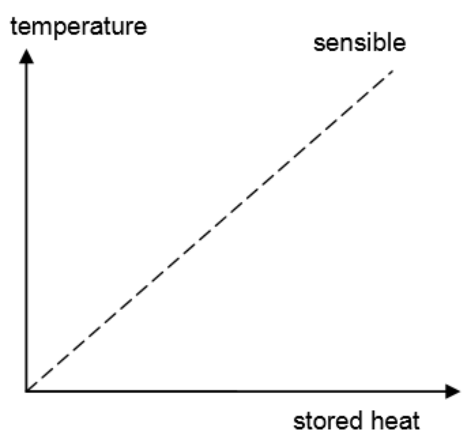

Figure 11: Heat storage as sensible heat

Latent heat energy storage involves the storage of energy in Phase-Change Materials (PCM's). Thermal energy is stored and released with changes in the materials phase. The most common phase change to exploit is the solid-liquid transition, as the liquid –gas transition is impractical and solid-solid (crystalline structure) transitions usually have too low an energy density to be useful. When a PCM is heated initially it behaves like sensible heat energy storage and the materials temperature is increased. However, once the transition temperature is reached the material will continue to absorb heat at a constant temperature while it changes state. This heat absorbed at constant temperature is known as the latent heat of the transition as show in (figure 12). To retrieve the energy the PCM can be changed back from the liquid to the solid phase and the energy stored as latent heat is released. (Barbour, 2013)

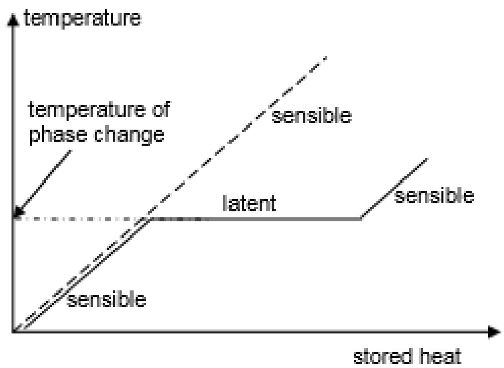

Figure 12:Latent heat storage for solid –liquid phase change

Thermochemical heat energy storage involves storing heat energy in chemical bonds. A reversible chemical reaction which absorbs heat is used to absorb the heat energy that is to be stored. This reaction can then be reversed to release the stored heat. The most common reactions used for this process is the hydration of salts. The energy storage is based on the release of the heat of hydration. Hence, a salt hydrate storage system is charged by the endothermic thermal dehydration of the respective higher hydrated salt. (Barbour, 2013)

Chapter Four: **Solar energy**

The sun supplies the majority of the energy available on the Earth. Lack of sun can easily end life. Without the Sun, the Earth's temperature will drop suddenly and Earth will be cold and dark, so no plant life and no human on earth will exist.

Wind power, hydropower, biomass and all fossil fuels produce from the sun, solar energy derivation have certain advantages such as storage and transportation of energy. So, energy plays a significant role in economic and social development, and constitutes a major threat to the environment and sustainable development. Rapid technological developments, improvement in standards of living, and increased population density have increased the interests to use the Renewable energy resources. (Juaidi, 2016)

Palestine with its climatic nature have a potential solar energy about 3000 sunshine hours per year and high annual average of solar radiation amounting to 5.4 kW h/m^2/day on horizontal surface (Juaidi, 2016). These values show the efficiency of utilization solar energy in solar water heaters (SWH) in Palestine; due to the high number in solar radiation and sunshine hours. **As shown in (figure 13) 65% of water heating depend on solar energy.**

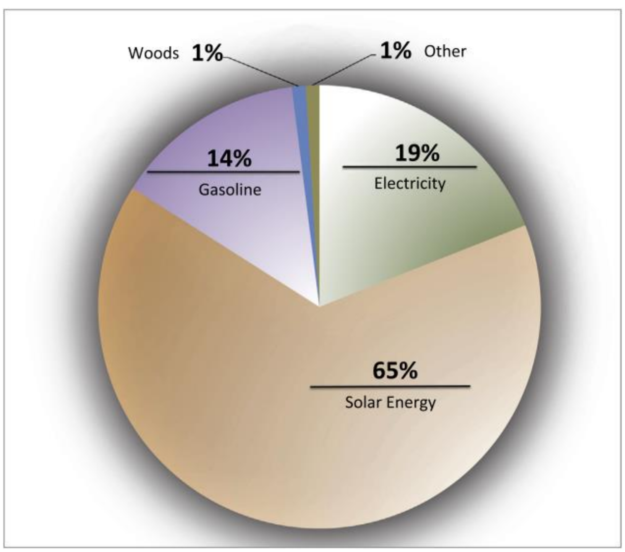

Figure 13:Distribution of energy consumption for water heating, 2013.

Due to the highly dependent on solar energy for water heating, it's necessary to improve new technology for energy storage, such as using PCM to **reduce the occupied area and the volume of the hot water storage tank**.

5.1 Domestic Solar Water Heater

Because of 65% of water heated depend on solar energy and the Geographic nature of Palestine which the sunshine hours per year is relatively high, using domestic solar water heater system is effective.

A domestic solar hot water system can be a cost-effective way to reduce energy costs from gas, electric, or propane sources. The instillation cost for solar hot water system will cost more than a conventional water heating system. The overall cost is determined by its size and complexity. (Colorado, 2011)

There is two classification of solar water heaters, Active and passive systems. **Passive systems** have no electrical pumps. They rely upon convection to circulate hot water through the collector and storage tank. Hot water is either stored in the collector itself or transferred to a storage tank. There are two basic types of passive systems:

Thermosyphon systems as show in (figure14), water flows through the system when warmwater rises as cooler water sinks. The collector must be installed below the storage tank so that warm water will rise into the tank. These systems are reliable. They are usually more expensive than integral collector-storage passive systems.

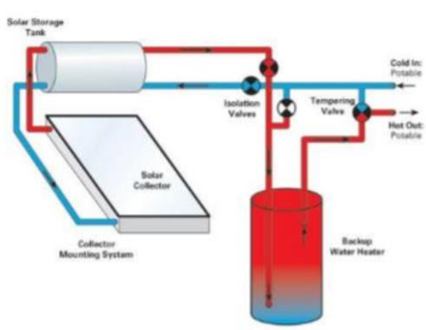

Figure 14:Thermosyphon system

5.2 Types of collector

Flat-plate collectors as show in (figure 15) are the most common collector type used in domestic water heating systems. They consist basically of an insulated metal box with a glazed glass cover and a dark-colored absorber plate. (Colorado, 2011)

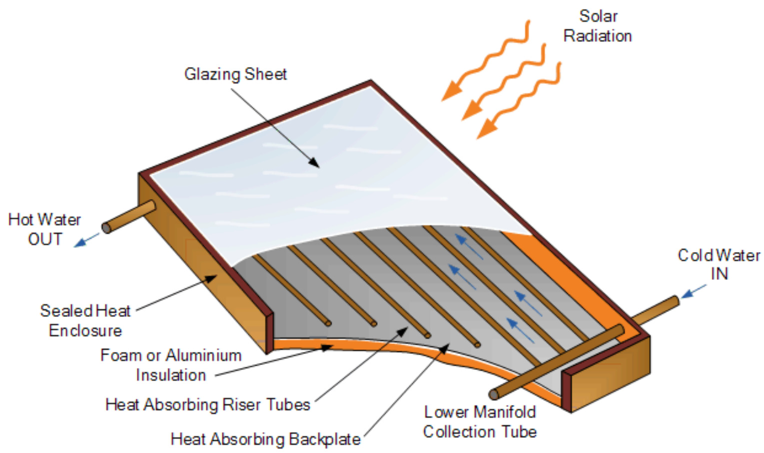

Figure 15: Flat-plate solar collector

Evacuated tube collector, it could achieve extremely high temperatures (170°F to 350°F) which makes them more appropriate for industrial and commercial cooling applications (Colorado, 2011). consists of a number of rows of parallel transparent glass tubes connected to a header pipe and which are used in place of the blackened heat absorbing plate. An evacuated tube collector is sealed in a vacuum that minimizes heat loss and helps absorb solar energy under cloudy conditions. as show in (figure 16)

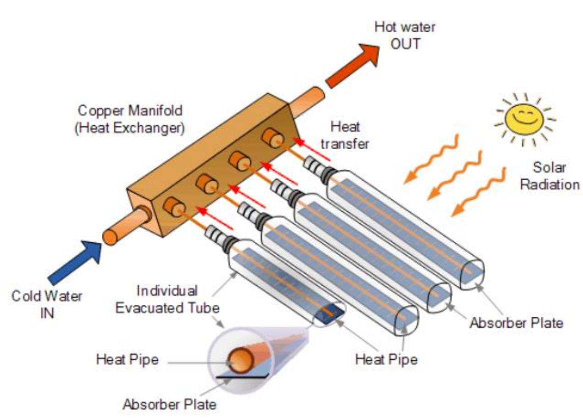

Figure 16: Evacuated tube collectors.

5.3 Energy Efficiency and Load Factors

Energy efficiency is one of the important factors to categorized in Domestic water heating (DWH). These relative efficiencies are then used as guidelines for current manufacturing water heaters. (C. Aguilar, 2005)

Overall efficiency of DWH could be determine by solar energy factor (SEF) and solar fraction (SF). Solar energy factor is defined as the energy delivered by the system divided by the electrical or gas energy put into the system. The higher the number, the more energy efficient. Systems with solar energy factors of 2 or 3 are the most common.

The solar fraction is the amount of energy provided by the domestic solar heaters divided by the total energy required. The higher the solar fraction, the greater the solar contribution to water heating, which reduces the energy required by the backup water heater. Typical solar factors are 0.5–0.75. (saver, 2006)

Size and overall cost of solar water heating system must take in consideration while choosing the system with the energy efficiency.

Chapter Five: **Phase change material**

Phase change materials (PCM) are "latent" thermal storage materials. They use chemical bonds to store and release heat. The thermal energy transfer occurs when a material changes from a solid to a liquid or from a liquid to a solid. This is called a change in state or "phase." Initially, these solid-liquid PCM perform like conventional storage materials; their temperature rises as they absorb solar heat. Unlike conventional heat storage materials, when PCM reach the temperature at which they change phase (their melting point), they absorb large amounts of heat without getting hotter. When the ambient temperature in the space around the PCM material drops, it solidifies, releasing its stored latent heat. PCM absorb and emit heat while maintaining a nearly constant temperature.

Application of PCMs in thermal energy storage systems:

1. Cooling of heat and electrical engines.
2. Cooling: food, wine, milk products (absorbing peaks in demand), greenhouses
3. Heating and hot water: using off-peak rates
4. Safety: temperature level maintenance in rooms with computers or electrical/electronic appliances
5. Thermal comfort in vehicles
6. Thermal protection of electronic devices
7. Thermal storage of solar energy

The inclusion of a PCM module in water tanks for domestic hot-water supply is a very promising technology. It would allow having hot-water for longer periods of time even without exterior energy supply. Furthermore, smaller temperature changes between storing and releasing energy, or to use smaller tanks for the same purpose. Indeed, many Properties need to be studied to choose the suitable PCM. (Chen, 2009)

The following phase change material (PCM) requirements should be taking in consideration:

Physical requirements, regarding the storage and release of heat as show in (table 3):

Table 3: the Advantges for the Physical requirements

Physical requirements	**Advantages**
Suitable phase change temperature	To assure storage and release of heat in an application with given temperatures for heat source and heat sink.
Large phase change enthalpy	To achieve high storage density compared to sensible heat storage.
Reproducible phase change, also called cycling stability	To use the storage material as many times for storage and release of heat as required by an application
Small supercooling degree	To assure that melting and solidification can proceed in a narrow temperature range.
Good thermal conductivity	To be able to store or release the latent heat in a given volume of the storage material in a short time

Technical requirements, regarding the construction of storage as show in (table 4):

Table 4 : the Advantges for the technical requirements

Technical requirements	**Advantages**
Low vapor pressure	To reduce requirements of mechanical stability and tightness on a vessel containing the PCM.
Small volume change	To reduce requirements of mechanical stability on a vessel containing the PCM.
Chemical stability of the PCM	To assure long lifetime of the PCM if it is exposed to higher temperatures, radiation, gases.
Compatibility of the PCM with other materials	To assure long lifetime of the vessel that contains the PCM,
Safety constraints	The construction of a storage can be restricted by laws that require the use of non-toxic, non-flammable materials

Economic requirements, regarding the development of a marketable product as show in (table 5)**:**

Table 5: the Advantges for the economic requirements

Economic requirements	**Advantages**
Low price	To be competitive with other options for heat and cold storage
Good recyclability	For environmental and economic reasons

PCM material types:

There are a large number of organic, inorganic and eutectic materials, which can be identified as PCM from the point of view of melting temperature and latent heat of fusion.

As no single material can have all the required properties for an ideal thermal storage media, one has to use the available materials and tries to make up for the poor physical property by an adequate system design. For example, metallic fins can be used to increase the thermal conductivity of PCMs, super cooling may be suppressed by introducing a nucleating agent in the storage material and incongruent melting can be inhibited by use of suitable thickness.

Materials that have been studied during the last 40 years are hydrated salts, paraffin waxes, fatty acids and eutectics of organic and non-organic compounds. Depending on the applications, the first criteria for PCMs should be their melting temperature.

Materials that melt below 15 ˚C are used for storing cooled air in air-conditioning applications, while materials that melt above 90 ˚C are used for absorption refrigeration. All other materials that melt between these two temperatures can be applied in solar heating and for heat load leveling applications. (Kalnæs, 2015)

There are two main groups of PCMs, paraffins and salt hydrates. Paraffins have an excellent stability concerning the thermal cycling, i.e. a very high number of phase changes can be performed without a change of the material’s characteristics. On the other hand, the drawback of their usage come in a form of their flammability and their relatively low melting enthalpy and density compared to salt hydrates. Salt hydrates tend to corrode and don’t have a large the cycling stability, unless certain conditions are met.

Another drawback of salt hydrate is sub- cooling. That means that the material does not crystallize at the melting temperature, but at a lower temperature. The sub- cooling can be reduced by adding so called nucleators into the PCM. (Murat Kenisarin, 2007).

Table 6 and 7 show the Merits and demerits about the three type of PCM.

Table 6 : Merits of three PCM types

Merits		
Organic	In-Organic	Eutectics
Availability in a large temperature range	High volumetric latent heat storage capacity	Eutectics have sharp melting point similar to pure substance
Freeze without much super cooling	Low cost and easy availability	Volumetric storage density is slightly above organic compounds
Ability to melt congruently	Sharp melting point	
Self-nucleating properties	High thermal conductivity	
Compatibility with conventional material of construction	High heat of fusion	
No segregation	Low volume change	
Chemically stable	Non-flammable	
High heat of fusion		
Safe and non-reactive		
Recyclable		

Table 7: Dmerits of three PCM types

Demerits		
Organic	In-Organic	Eutectics
Low thermal conductivity in their solid state. High heat transfer rates are required during the freezing cycle	Change of volume is very high	Only limited data is available on thermo physical properties as the use of these materials are very new to thermal storage application
Volumetric latent heat storage capacity is low	Super cooling is major problem in solid-liquid transition	
Flammable. This can be easily alleviated by a proper container	Nucleating agents are needed and they often become imperative after repeated cycling	

PCM configuration:

To reach the highest using of PCM storage density and efficiency, configuration of PCM and the way it's installed should be considered. Many different ways for PCM installing has studied, the following describe a few methods for PCM configuration:

- Encapsulating:

Encapsulation is a process of covering the PCM (that forms the core part of the encapsulated PCM) with a suitable coating or shell material. A primary purpose of encapsulation is holding the liquid and/or solid phase of the PCM and keeping it isolated from the surrounding. This ensures correct composition of the PCM that would have otherwise changed due to mixing of the PCM with the surrounding fluid.

Other advantages of encapsulation:

1. Involve reduction in reaction of PCM with the surrounding
2. Flexibility in frequent phase change processes
3. An increase in heat transfer rate and enhancement in thermal and mechanical stability of the PCM
4. Improve the compatibility of hazardous PCMs that cannot be directly used or immersed in certain applications such as blood transport, food storage, building cooling/ heating, etc. (Pasupathya, 2006)

Based on size, encapsulated PCM can be classified as follows:

1. macro (above 1 mm)
2. micro (0–1000 miro meter)
3. nano (0–1000 nm)

- Rectangular container

Melting of phase change materials in rectangular enclosures has received great attention due to its wide-ranging engineering applications in such fields as casting, metallurgy and thermal energy storage.

(PRAKASH, 1985) Has discussed using PCM in a rectangular box as shown in (figure 17)

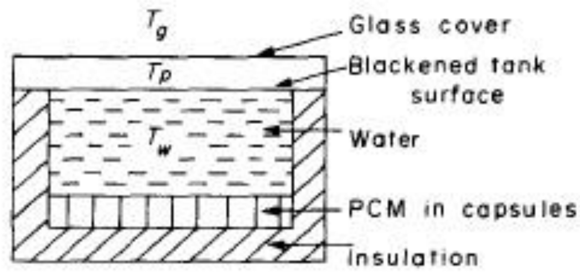

Figure 17: Using PCM in rectangular shape

- Spherical capsules

Placing the phase change material in spherical capsules, different arrangements could be considered. (Nallusamy, 2006) Has placed PCM capsules along the tank storage figure (18) shows how PCM installed.

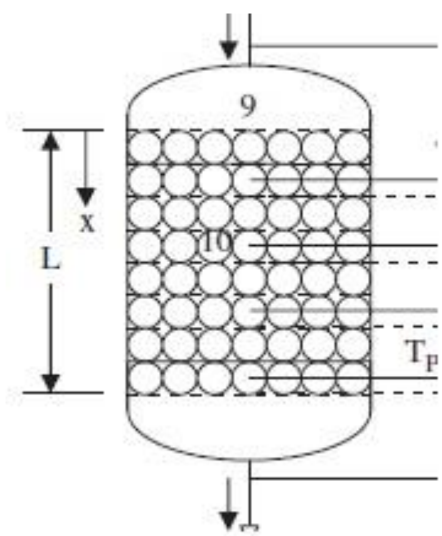

Figure 18: Capsulated PCM along the storage tank

Another arrangement was studied by (BAJNÓCZY, 1999) that used PCM capsules at the top of the cylinder tank, to utilize the hot water at the top as show in (figure 19).

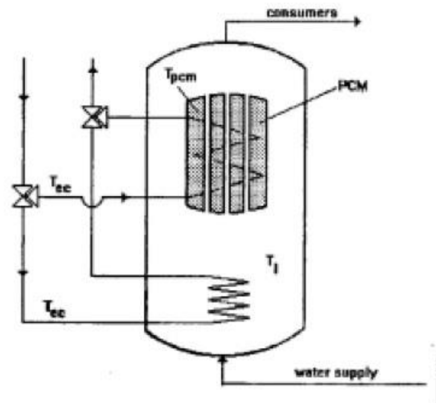

Figure 19: phase change material placed at the top of the thermal energy storage tank

- Cylindrical tubes:

Another way to use PCM as heat storage, inserted in a heat exchanger. Indeed, different configuration can be used, two concentric tubes, multi tubes in a one shell and multi tube passes or shell. As conventional shell and tubes heat exchanger, many parameters can be studied to perform the best configuration as show in (figure 20). (Ronny Hendra et al, 2005), (Mithat Akgüna, Orhan Aydına and Kamil Kaygusuzb, 2007)

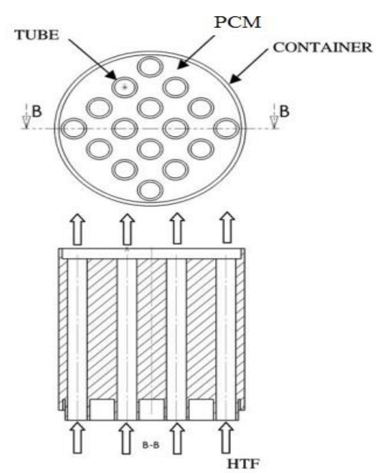

Figure 20: Using multi tubes for PCM storing

Storage material could be stored in vertical cylindrical tubes, where the heat transfer fluid transfer between the tubes. (GHONEIM, 1989) Studied that configuration as show in (figure 21).

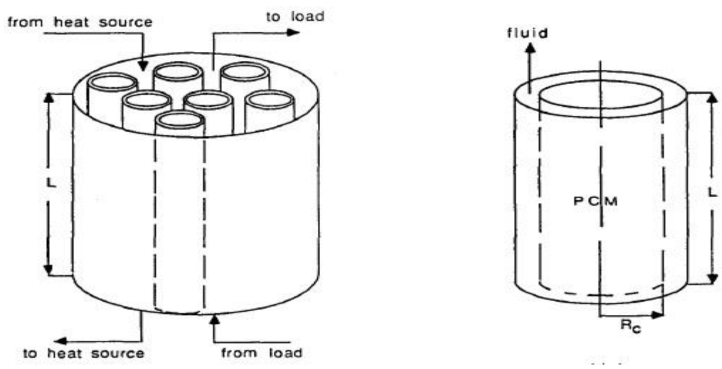

Figure 21: PCM placed in vertical cylindricals in a packed vessel

Heat transfer enhancement techniques for the PCM based applications. It was reported that the heat transfer can be enhanced by the following ways:

1. Using fin configuration.
2. Inserting a high thermal conductivity metal matrix into a PCM.
3. Dispersing the PCM with high thermal conductivity particles.
4. By micro-encapsulation of the PCMs.
5. Using multi tubes.

Chapter Six: **Methodology**

Thermal energy storage has always been one of the most critical components in residential solar water heating applications. Solar radiation is a time-dependent energy source with an intermittent character. The heating demands of a residential house are also time dependent. However, the energy source and the demands of a house (or building) in general, do not match each other, especially in solar water heating applications. The peak solar radiation occurs near noon, but the peak heating demand is in the late evening or early morning when solar radiation is not available. (Atul Sharma, C. R. Chen).

Thermal energy storage provides a reservoir of energy to adjust this mismatch and to meet the energy needs at all times. It is used as a bridge to cross the gap between the energy source, the sun, the application and buildings. So, thermal energy storage is essential in the solar heating system.

Therefore, in this study, an attempt has been taken to summarize the investigation of the solar water heating system incorporating with Phase Change Materials (PCMs).

Thus, the scope of this work is to Investigate the Performance of PCM -Incorporated Solar Water Heating System experimentally, improve the performance of SWH and storing energy as much as possible, with focusing at specific parameters such as charging and discharging behaver, amount of PCM and the geometry of SWT.

After reviewing and studying many researches related to the subject as shown in the literature, a new design was adopted that takes into account all of the advantages that have emerged in the studied designs and avoids a lot of their disadvantages.

Household water consumption and water temperature must be suitable for each type of uses so that this design simulates the reality. The figure below shows the daily hot water demand for domestic use. The consumption peak time starts at 7 am and finish at 12 am as show in (figure 22). The consumption from midnight until the morning is neglectable. (Balalta Deema, 2017)

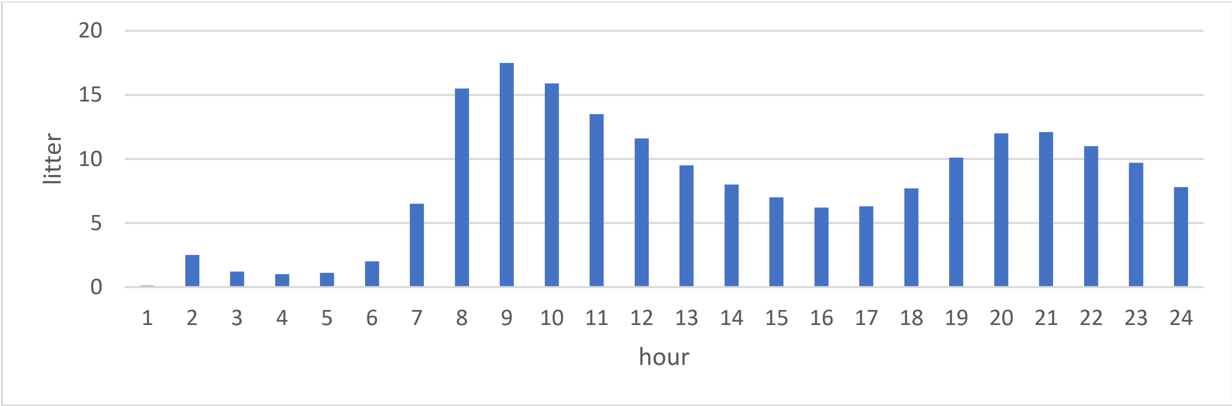

Figure 22: Daily load profile of the domestic hot water system.

The daily hot water consumption for domestic hot water system is very important parameter to determine a sensible heat needed to heat water, also the temperature of the hot water load temperature. Table (8) shows the required temperature for the domestic application, as the water temperature differs according to the application. (Engineers, Domestic Hot Water Systems, 2015)

Table 8: The water temperature for different applications.

Application	**Temperature (ºC)**
Sink, Hand washing	40
Showers	43
Dish washing and laundry	48-60
Therapeutic baths	53

Experimental Setup:

- **PCM selection:**

PCMs which are suitable as energy storage material can be categorized in two groups of organic and inorganic compounds. From the inorganic category, crystalline salt and from the organic category, paraffin is the most popular compounds. As regards to continuous phase change in its working period, PCMs must have certain properties such as congruent melting, unchanged thermal properties during phase change, compatibility, availability, low price, high thermal conductivity, and high relative latent heat. (Fazilati, 2013)

Paraffin is a hydrocarbon. Usually commercial paraffin changes phase over a temperature range, however pure paraffin has a shorter melting range. Paraffin has almost all desired properties, except low thermal conductivity as show in table (9), which makes it a suitable PCM for storage systems. (Fazilati, 2013)

Paraffin wax physical properties

Table 9: Paraffin wax physical properties.

Melting temperature (^oC)	55
Latent heat of fusion (kJ/kg])	190
Solid density (kg/m^3)	910
Liquid density (kg/m^3)	790
Thermal conductivity (W/m. ^oC)	0.21
Solid specific heat (kJ/kg. ^oC)	2
Liquid specific heat (kJ/kg. ^oC)	2.15

- **Design of pilot system:**

This system consists mainly of many interconnected units to achieve experimental study that simulates the practical reality of the solar heating system. A hot water storage tank containing the PCM in a suitable configuration, electric heater instead of the solar collectors, as well as pipes linking between the different parts of the system, thermocouples to measure the temperatures at different positions and finally different types of fittings.

The following figures are showing the system with its main parts:

Figure 23: the experimental system

Figure 24: Control Panel.

As figures (24, 25) shows:

Five temperature recorders with their thermocouples distributed in different location as follows:

T1: temperature of cold-water which entries to the heater from the storage tank.

T2: temperature of hot-water which exits from the heater to the storage tank.

T3: temperature of PCM.

T4: temperature of the cold-water which entries to the storage tank from supplier.

T5: temperature of the hot water which exits from the storage tank to the usage.

Moreover, a solid-state relay with potentiometer is used to control the power supplied to the electric heater, so, it could simulate the solar radiation for the flat collectors.

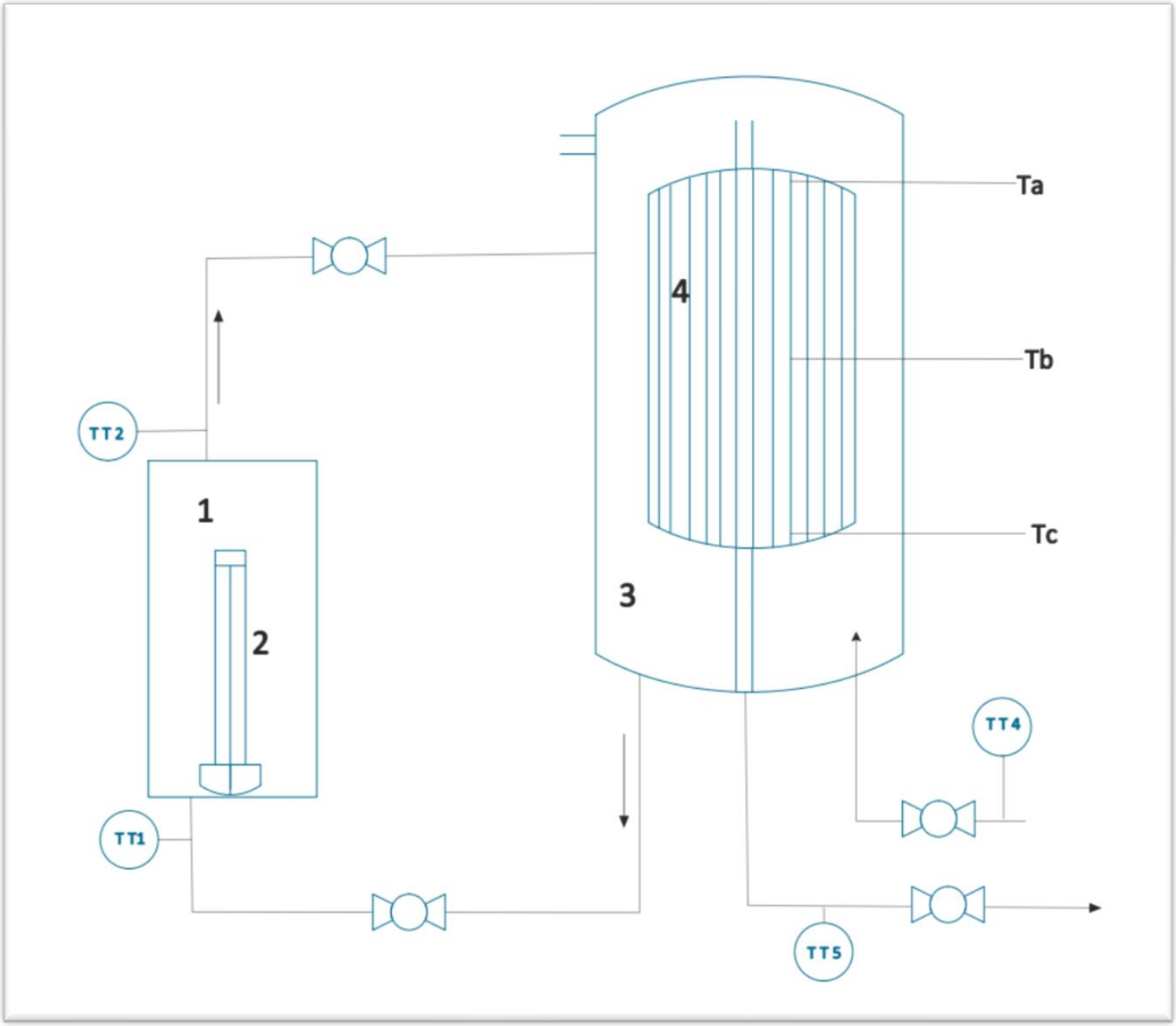

Figure 25: schematic diagram of the system.

Figure (25) show a Schematic diagram for the system

Ta: Water temperature ^{o}C, at the surface of the TES tank.

Tb: Water temperature ^{o}C, at 28 cm below the surface.

Tc: Water temperature ^{o}C, at 55 cm below the surface

1: Heater Tank   2: Electric Heater

3: Solar water storage tank 4: PCM storage tank

- **Design of the storage tank:**

The storage capacity of the tank is decided to be about 30L, with 0.25m and 0.75m of diameter (D) and height (H) respectively, depending on the assumption of H = 3D. (Hall, 2012)

A pipe with 2 cm diameter has placed in the middle of the tank starts from bottom of tank up to the highest point possible to withdraw hot water while cold water enters from the bottom by a separate entrance. Moreover, there is a horizontal pipe (nozzle) with 2 cm diameter in the upper side of the tank opposite to the highest point of hot water inside the tank to withdraw hot water instead of the previous pipe which passes through cold water, what causes loses of the heat of hot water.

This tank is insulated with 10 cm of polyurethane on the entire perimeter of the tank.

- **PCM configuration in the tank:**

Based on the literature review, there has been a lot of research with a different PCM configurations. In this work, a new design has been adopted that takes into consideration all of the advantages that have emerged and avoids a lot of its problems. This new design will be discussed in detail as follow:

The design of the new configuration:

The configuration of PCM in the tank is considered one of the most important parameters that affect the heat transfer rate, density of the energy and efficiency of the system. In this work, it is adopted a new configuration of PCM based on getting highest heat transfer rate and volume fraction of PCM in the tank.

In general, this configuration is in form of a hollow cylinder to contain the PCM, with length of 40 cm and diameter of 23 cm, contains 26 vertical holes regularly distributed with a diameter of 2 cm on the same length of the cylinder in addition to another vertical hole with diameter of 5.5 cm located in the center of the cylinder to allow the passage of hot water pipe from the top the storage tank. 10 kg of paraffin wax is added into this cylinder.

This configuration of PCM has some distinct advantages. The main advantages are providing large heat transfer area, preventing of the PCMs reactivity towards the outside environment and controlling the changes in volume of the storage materials as phase change occurs.

Also, it acts simultaneously as a storage unit and the diverging agent for water inflow to and outflow from the tank; the storage water in the tank should pass through the space between the configuration and the tank. In addition, the holes in the configuration to increase heat transfer rate.

The decision to put the shell which contains PCM in the upper part of the tank came from the point of exploiting as much heat as possible in the system in order to melt PCM, because the hot water in the tank is at the top due to its density which is less than the density of cold water located below the tank.

- **Material of construction:**

Material selection and compatibility between construction material and working fluids are important issues, in particular with regard to corrosion and operation at elevated temperature.

While choosing materials of construction some requirement should be considered e.g.: low cost, light weight, high thermal conductivity to enhance and allow heat transfer between water and PCM.

Galvanized-steel was chosen for the storage tank construction due to its strength, corrosion resistance and low cost.

Furthermore, Stainless-steel was found that is the preferable choice for the construction of the inside configuration which provide good heat transfer rate that cover all the needed requirements due to its properties as corrosion resistance, light weight, low cost and good thermal conductivity which will assist in solving the problem of low thermal conductivity of the paraffin wax. (Coulson & Richardson's, 2005)

Experimental Procedures:

Several tests have been carried out based on two main parameters which are the consumed energy by the heater in water heating and the flow rate of water.

Based on the previously studied researches and the average daily consumption of hot water, it was decided to adopt basic range of the water flow rate simulate daily domestic usage rate, so that experiments were conducted based on it, which is (0.25 - 0.3) L/min.

As for the supplied energy to the electric heater, values that have been adopted are simulating the amount of collected solar energy by the solar collectors in Palestine throughout the year. Based on a study carried out in 2016 (Solar Energy Production in Palestine), the highest amount of collected energy was in the summer in the month of July which equal to 8.5 kWh/m^2. day, which approx. equal to 0.944 kWh/m^2. hr. In contrast, the lowest amount of collected energy was in the summer in the month of December which approx. equal to 2.8 kWh/m^2. day, which equal to 0.311 kWh/m^2. hr. Taking into account that the number of hours of sun brightness is 9 hours per day.

Based on the above, the energy values of 0.5, 0.7 and 0.9 kWh/m^2. hr have been adopted for carrying out the tests.

Tests carried out are classified into two categories as batchwise and continuous conditions, which will be explained in details as follow:

- **Batchwise Tests:**

Batchwise means there is no cold-water flow into the system or hot water flow out of the system until the end of the test, so the water in the tank is still in a circle loop by convection of density difference between the hot water and cold water through the heater.

This test simulates the state of absence of any use of hot water during the day with heating process.

Batchwise tests are divided into two types:

Batchwise tests with PCM: Includes two stags as follow:

The first stage (Charging condition): operating the electric heater on 0.5, 0.7 and 0.9 kWh in three separate experiments and recording the temperature differences along the time of the PCM and the top water (the water that will be withdrawn to use).

Moreover, checking whether there is complete melting of the PCM or not. The charging period ends in the event of full melting of the PCM or the passage of nine hours maximum.

The second stage (Discharging): turning the heater off and starting an inlet flow rate of cold water of (0.25 – 0.3) L/min. recording the temperature differences along the time of the PCM and the top water (the water that will be withdrawn to use). The discharging stage ends in the event of full solidification of the PCM which mean the temperature of the top water equal to the temperature of the inlet cold water.

Batchwise tests without PCM: Includes two stages of (charging and discharging) that are quite similar to the previous test but here without any PCM presence.

After the completion of the previous two tests it is very important to make a detailed comparison between the results of the two tests which should show the importance and usefulness of having the PCM in the tank on the absence of the PCM.

- **Continuous Tests:**

Continuous case means there is cold-water flow into the system and hot water flow out of the system until the end of the test, In conjunction with the circulation by convection of density difference between the hot water and cold water through the heater.

This test simulates the use of hot water during the day or night, the use during the day with heating process is called charging period while the use during the night with no heating source is called Discharging period.

Continuous tests are divided into two types:

Continuous tests with PCM: Includes two stags as follow:

The first stage (Charging condition): operating the electric heater on 0.5, 0.7 and 0.9 kWh in conjunction with inlet cold water flow rate within a range of 0.25 - 0.3 L/min in three separate experiments and recording the temperature differences along the time of the PCM and the top water (the water that will be withdrawn to use). Moreover, checking whether there is complete melting of the PCM or not. The charging period ends in case of fully melting of the PCM or the passage of nine hours maximum.

The second stage (Discharging): cutting the power source, on the other, hand keeping the inlet flow rate of cold water at (0.25 – 0.3) L/min. measuring the temperature differences along the time of the PCM and the top water (the water that will be withdrawn to use). The discharging stage ends in the event of full solidification of the PCM which mean the temperature of the top water equal to the temperature of the inlet cold water.

continuous tests without PCM: Includes two stages of (charging and discharging) that are quite similar to the previous test but here without any PCM presence.

After the completion of the previous two tests it is very important to make a detailed comparison between the results of the two tests which should show the importance and usefulness of having the PCM in the tank on the absence of the PCM.

Chapter Seven: **Results and Discussion**

Based on the methodology the tests were carried out by changing parameters, the obtained data will be analyzed and discussed in the next section. Moreover, a comparison with similar studies in the literature will be performed.

7.1 Charging:

Charging process divided to batchwise and continuous system, energy supplied using a heater with an adjustable power.

1. Effect of heater power:

a. 500 watt:

Fig 26 describes the PCM behavior during charging, the test occurred under an ambient temperature of 16 C and PCM initial temperature 19 C. Sensible and latent heat stored as follow: 195 min for increasing PCM temperature to its melting point, 115 min as latent heat period and 90 min to ensure completely melting of PCM the temperature increased to 72 C.

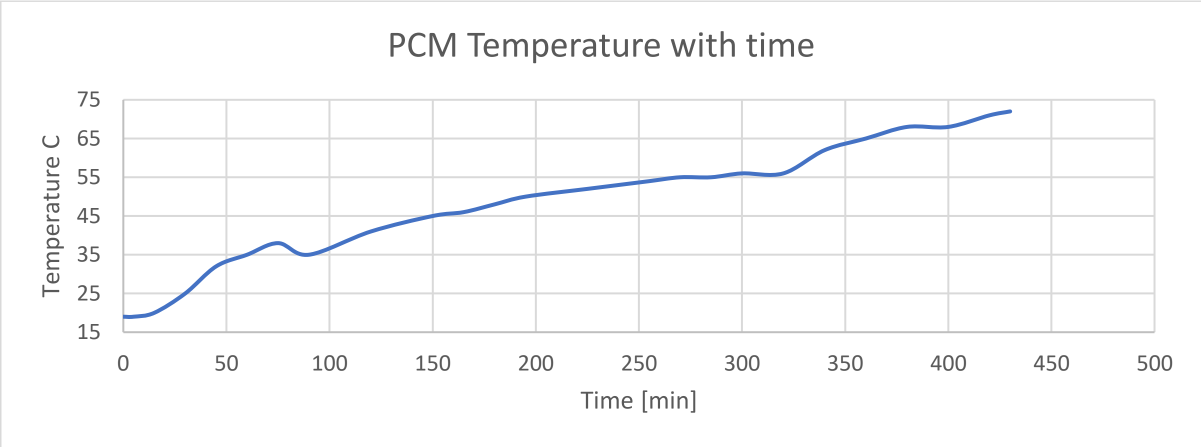

Figure 26 PCM Temperature during charging at 500 watt in Batchwise system.

Fig 27 represents a comparison between water temperature in the two different systems with and without PCM using batchwise process, inlet power of 500 watt and nearly the same water initial temperature. Water temperature increases gradually with time for both systems at the same period, in the system with PCM more energy supplied because of the combined heat (sensible and latent) that goes to the PCM.

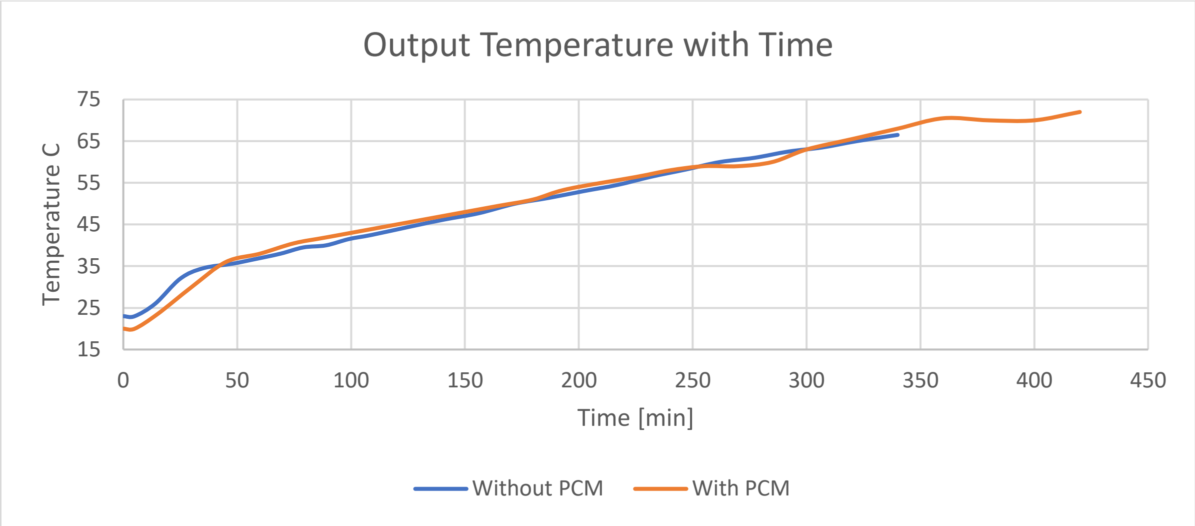

Figure 27 Water Output Temperature during charging at 500 Watt in Batchwise with and without PCM

b. 700 Watt:

In the batchwise system Fig 28 shows PCM behavior during charging process, sensible and latent heat storage for PCM. 320 min to increase PCM temperature from 21 to 72 C, divided as sensible heat storage from 21 to 52 C during 170 min, latent heat during 100 min and 50 min to ensure completely melting of PCM.

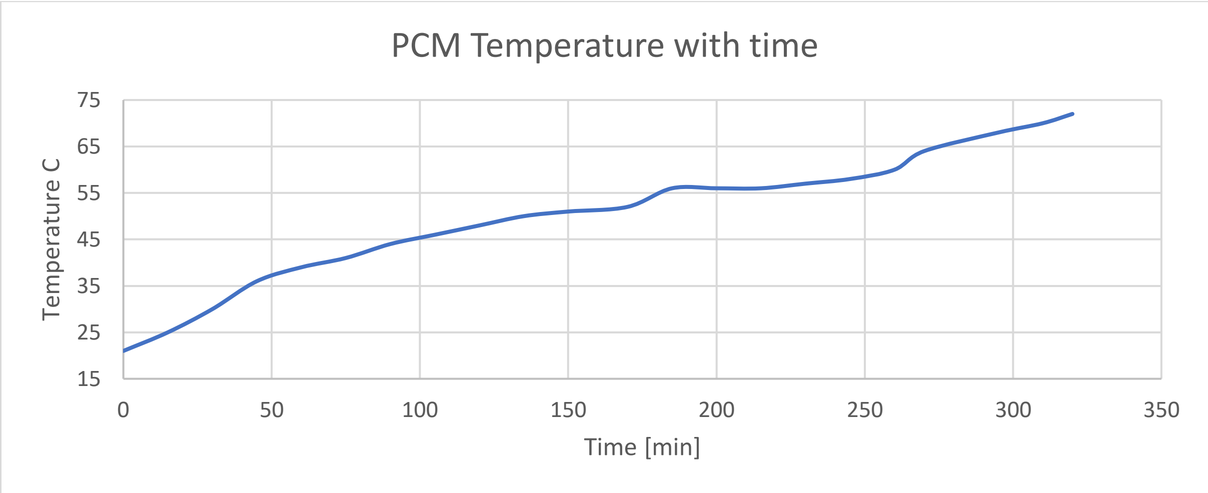

Figure 28 PCM Temperature during charging at 700 watt in Batchwise system.

Where Fig 29 shows PCM behavior in the continuous system, as water inlet flowrate is 0.27 l/min, PCM starts melting after 225 min, latent heat stored during 180 min and charging continued until PCM reached 73 C. To illustrate, 525 min needed to raise PCM temperature from 20 to 73 C in the continuous system.

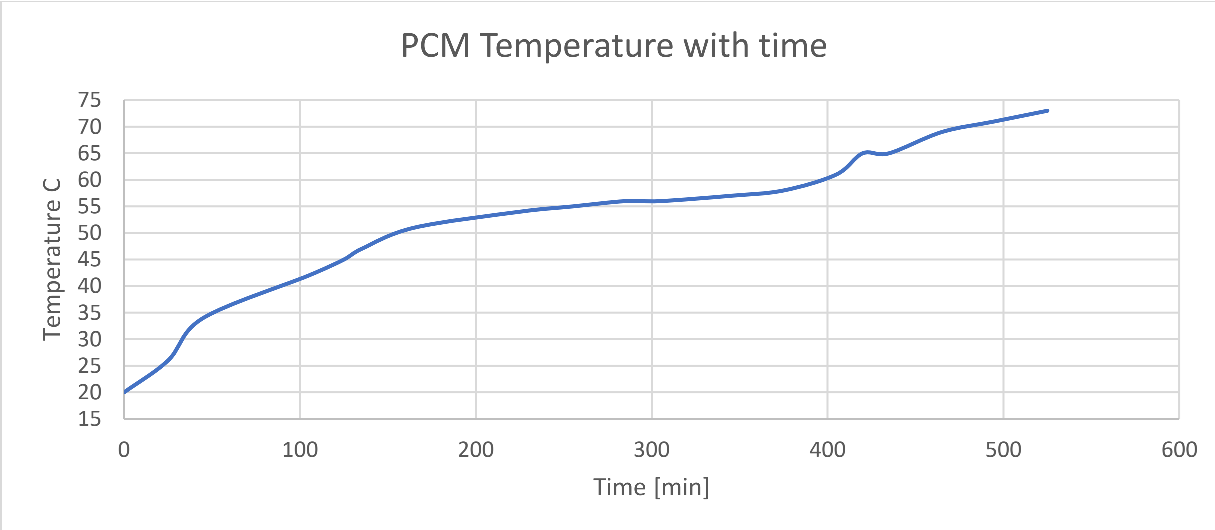

Figure 29 PCM Temperature during charging at 700 watt in Continuous system.

On the other hand, Water temperature compared for both systems with PCM and without PCM. In the batchwise process fig 30, time need to heat water from 30 C to 73 C is 285 and 300 min without PCM and with PCM respectively. Nearly it's almost the same period, but it should be take in our consideration in without PCM case amount of heated water is 40 L where with PCM its 35 L the difference in water volume regard to PCM volume tank and material as discussed previously.

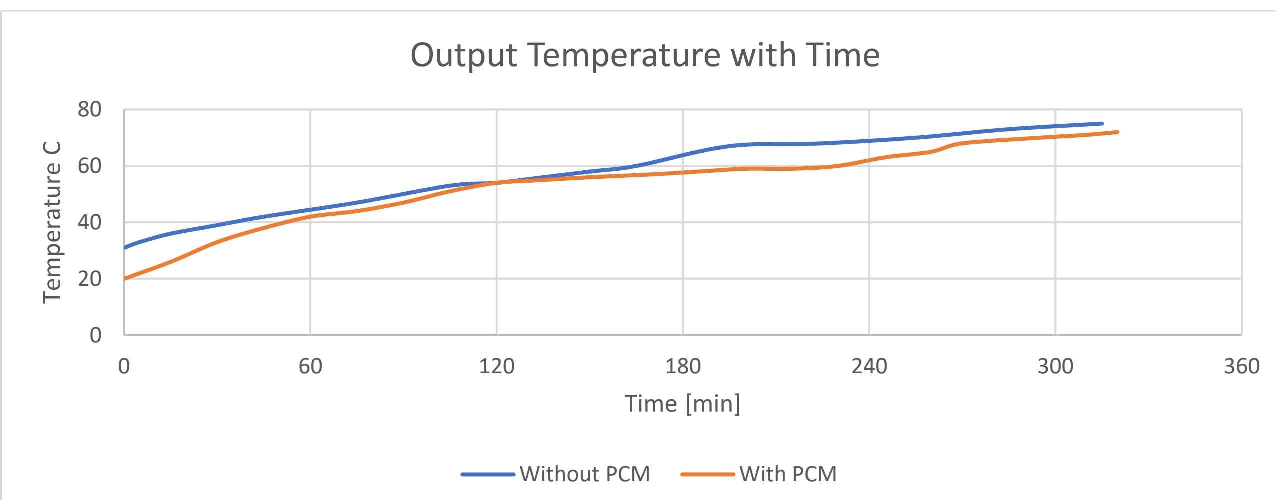

Figure 30 Water Output Temperature during charging at 700 Watt in Batchwise with and without PCM

While, in the continuous process water output temperature was as follow fig 31:

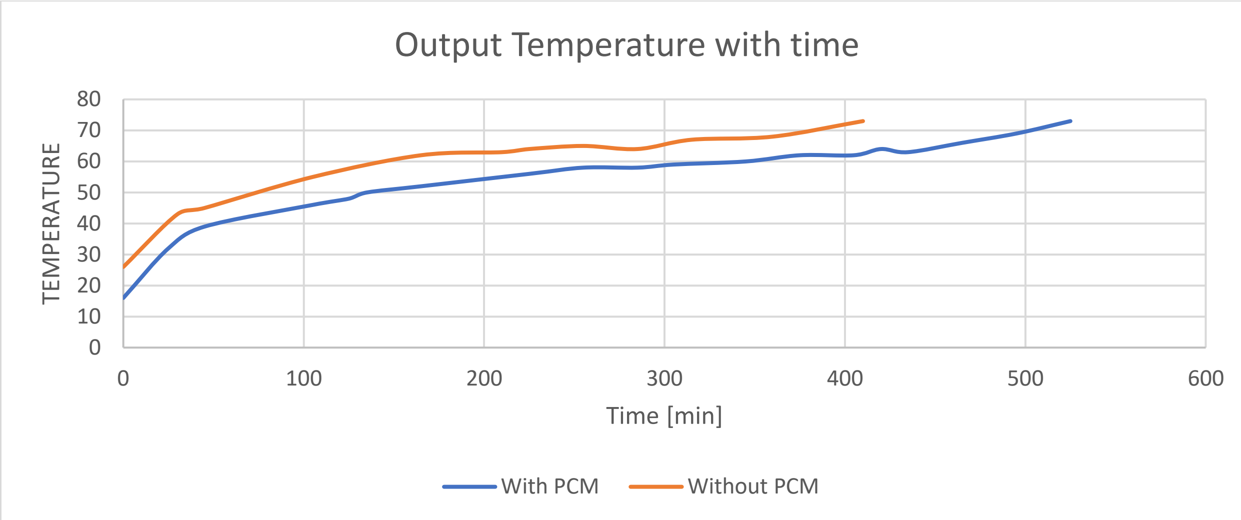

Figure 31 Water Output Temperature during charging at 700 Watt in Continuous with and without PCM

Water heated from 30 C to 73 C with a period of 410 and 525 min for Without PCM and with PCM respectively, compared with the batchwise at the same amount of heat and temperature difference its about 1.5 time without PCM case and 1.75 time with PCM case. Not forgetting water inlet at 20 C with a constant flowrate of 0.28 l/min.

c. 900 Watt:

When adjusting the heater power on 900 watt and comparing the batchwise with continuous system, Fig 32 resresents the relation between PCM temperature with time in the batchwise process, it could be noticed that PCM reaching melting point after 125 min, latent heat stored during 85 min following that heating the liquid PCM to 71 C. The charging process took 240 min to ensure completely melting of PCM.

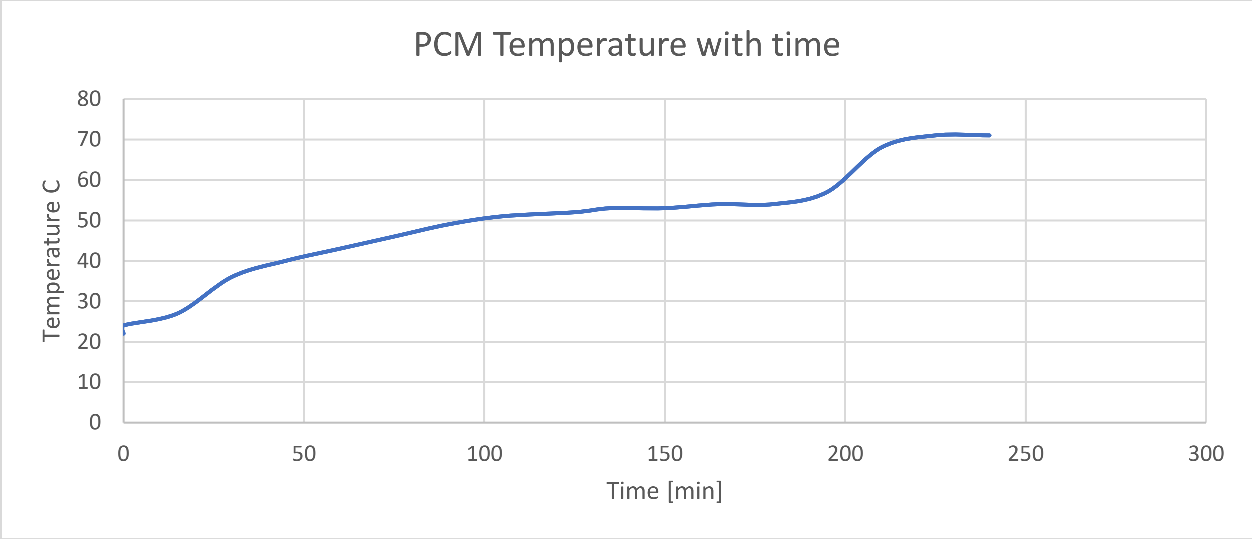

Figure 32 PCM Temperature during charging at 900 watt in Batchwise system.

While in the continuous process fig 33, PCM behavior was as follow: 145 min PCM charging as sensible heat to reach the melting point, after that a period of 120 min as latent heat storage continued by heating PCM to 72 C. This process took 415 min of charging with continuous flow of water as 0.27 l/min with temperature of 20 C.

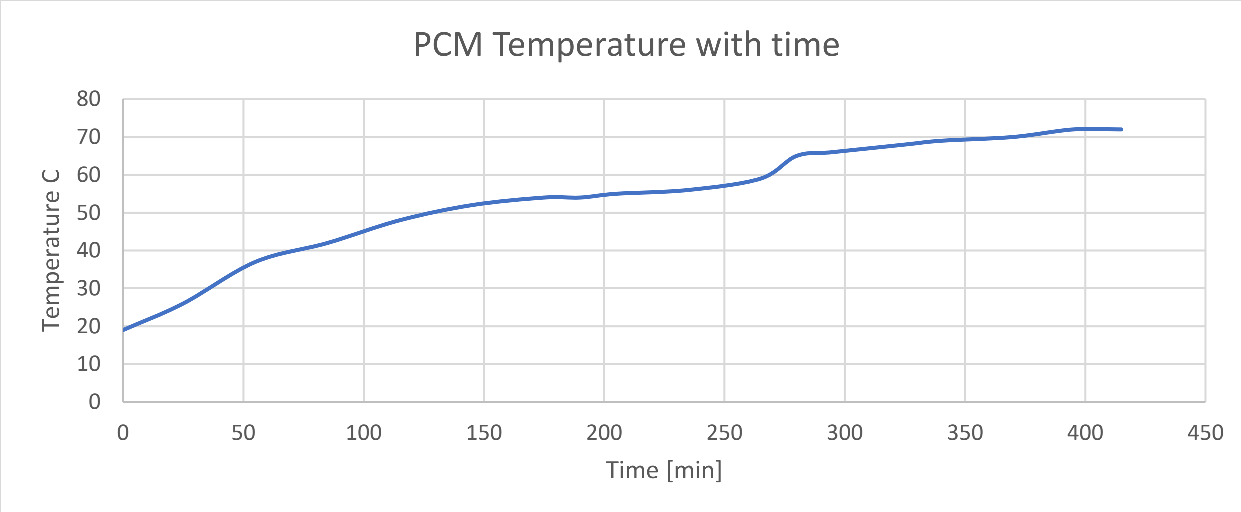

Figure 33 PCM Temperature during charging at 900 watt in Continuous system.

The test complete to study the effect of using PCM in the batchwise and continuous process on water outlet temperature, Fig 34 shows a comparsion between water temperature for batchwise process. Without PCM water heated from 30 C to 74 C during 180 min while with PCM at the same temperature difference it took 210 min; as discussed previously some heat transfer to the PCM as energy storage.

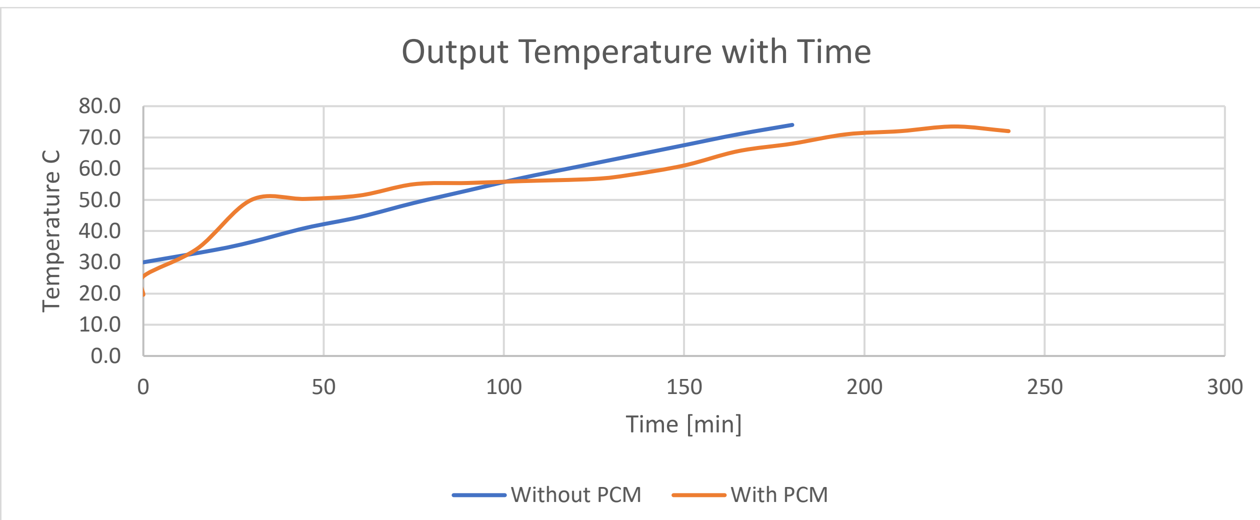

Figure 34 Water Output Temperature during charging at 900 Watt in Batchwise with and without PCM

In the continuous process Fig 35 represents water temperature with time for both systems with and without PCM. As energy supplied to the system by adjusting the heater on 900 watt, water temperature increased from 25 C to 73 C during 415 min without using PCM. However, the same period took to increase water temperature from 15 C to 73 C with PCM.

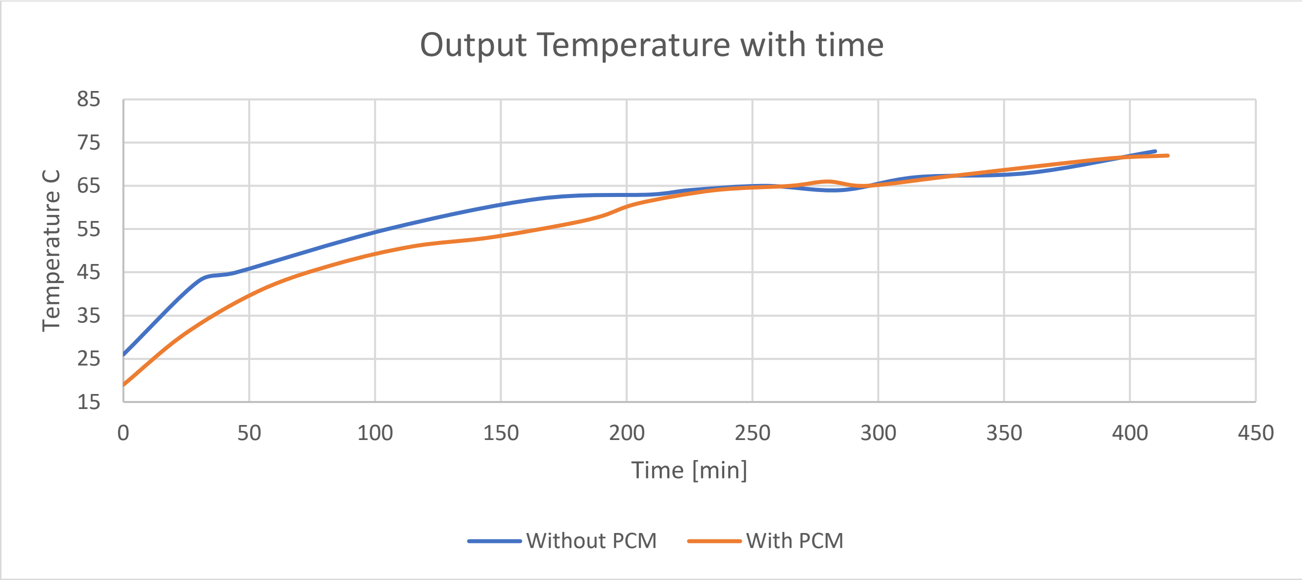

Figure 35 Water Output Temperature during charging at 900 Watt in Continuous with and without PCM

6.2 Discharging:

PCM behavior and water outlet temperature have been studied during discharging process (heat recovery), effect of flowrate, nozzle location and comparative study between both systems without PCM and with PCM are presented.

During discharging a continuous flow of water with a range of 0.27- 0.3 l/min, temperature equals to 20 C. Fig 36 and 37 represents PCM behavior and water outlet temperature, respectively. At the beginning of discharging heat released as sensible heat until the transition phase, 120 min took as sensible heat for the liquid PCM. After that a negligible change in PCM temperature during latent heat released, notice that in this period water outlet temperature drop slower than the first stage, 160 min as transition period for PCM. When PCM returned to the solid phase, heat continued to release to water as an overall time of 300 min, the system stopped till water temperature reached 40 C. comparing the water temperature without PCM and with PCM it can be noticed that 90 min time increase when using PCM, that equals to 3200 kJ which is 27 L of water.

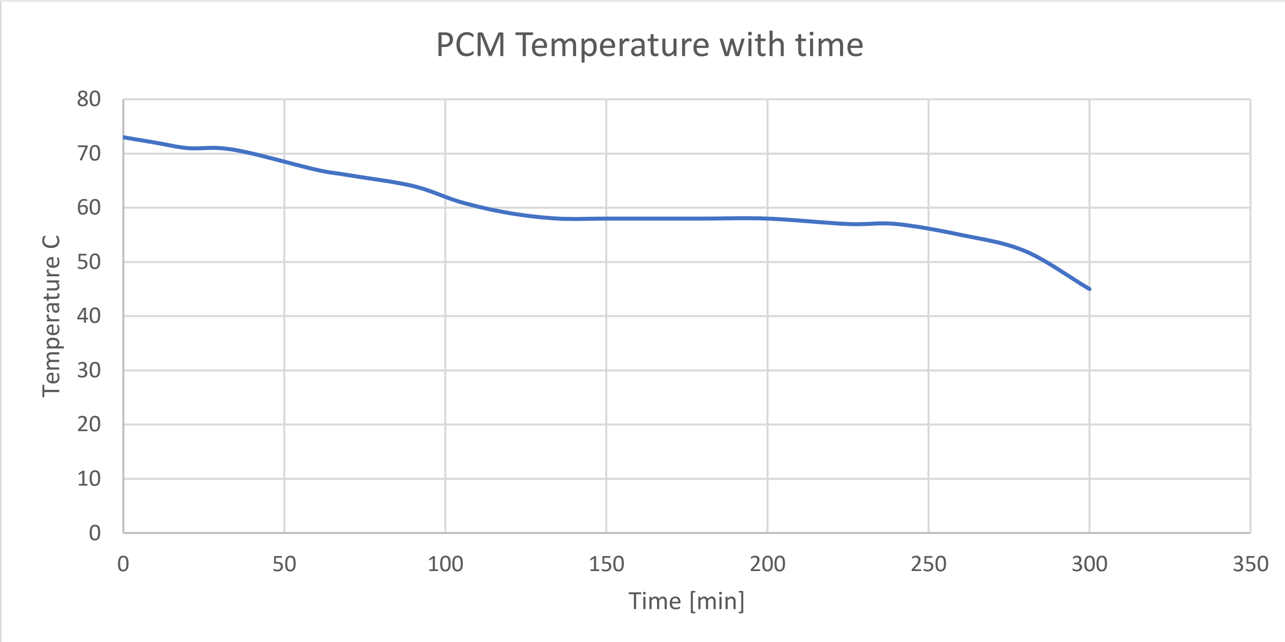

Figure 36 PCM Temperature during discharging Continuous system.

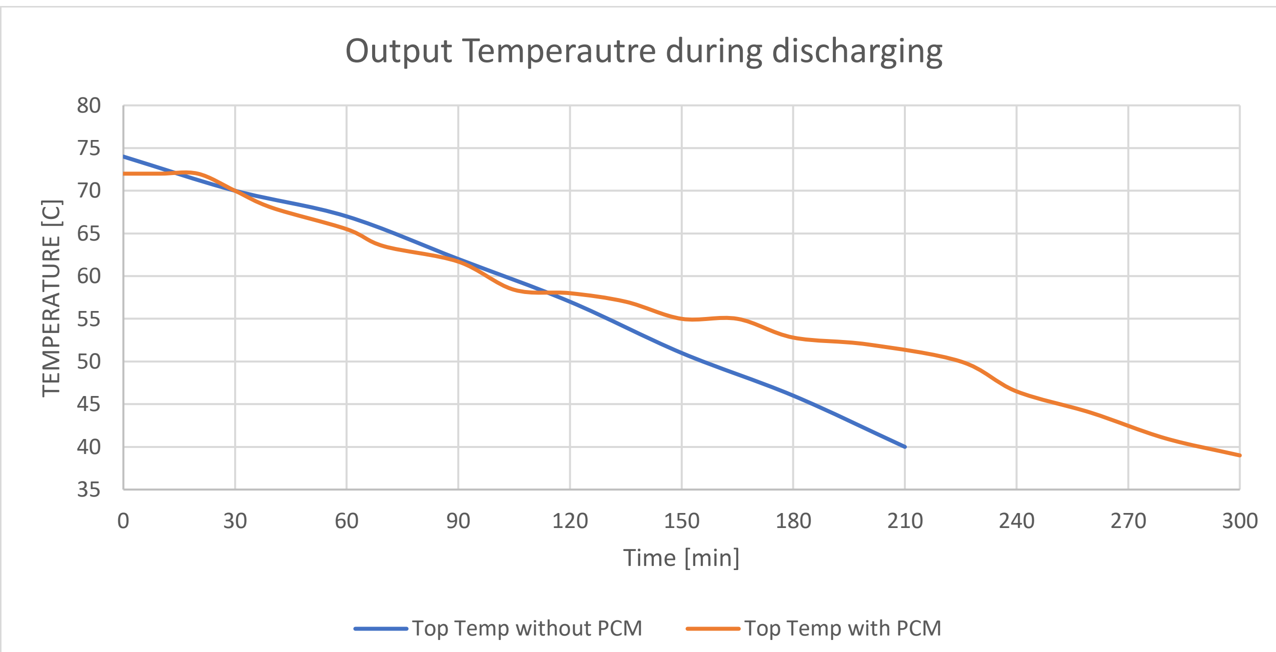

Figure 37 Water outlet Temperature during discharging Continuous system.

Temperature profiles along the TES tank:

Water temperatures along storage tank were measured during charging and discharging process, theoretically there is different layers along the storage tank due to water density difference. Figure (38) below represents the temperature variation of water inside the storage tank during continues discharging period with PCM.

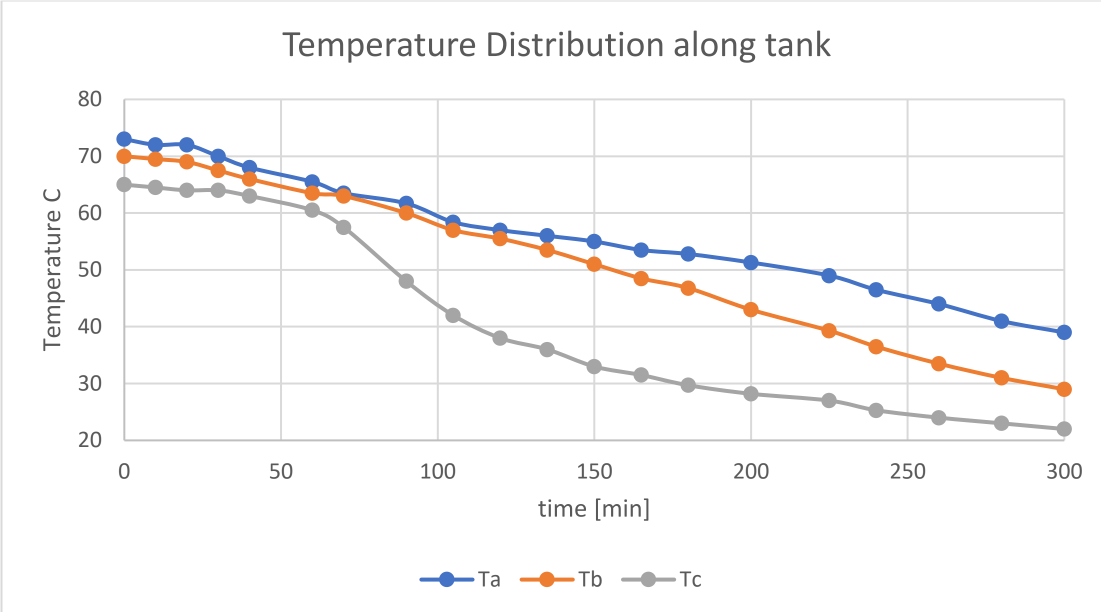

Figure 38: Temperature Distribution along tank at discharging period with PCM

Ta:Water temperature ^{o}C, at the surface of the TES tank.

Tb: Water temperature ^{o}C, at 28 cm below the surface.

Tc: Water temperature^{o}C, at 55 cm below the surface.

Review figure (25), (flow diagram) for more details.

It's observed from the figure that at the beginning of discharging, sensible heat released from PCM, at that time there is uniformity in temperature at the top, middle and bottom. But when latent heat released to water (after 70 min of discharging began), most of the released heat goes to the top. Moreover, cold water at 22 ^{o}C enters the storage from the bottom, not forgotten that hot water density lower than cold water so the top temperature will remain high, that is PCM storage recommended to be in the top half of TES tank. It's also observed that top temperature decreases 5 ^{o}C each 60 min until all the PCM solidified, where bottom temperature decreased 5^{o}C During the first 60 min but after 120 min it decreases around 30 ^{o}C, 60 min after that another 8 ^{o}C temperature decrease until it reaches water inlet temperature which is 22 ^{o}C.

Effect of nozzle position for hot water withdrawn:

In general, hot water supplied to domestic usage from TES tank by inserting a pipe inside the tank to withdraws water from the top section to the usage. Hot water supplied by two ways in this project, water withdrawn by the inserted pipe and water withdrawn from a nozzle at top of TES tank as shown in figure (25).

Figure (39) below represents two comparison studies for water withdrawn to the usage.

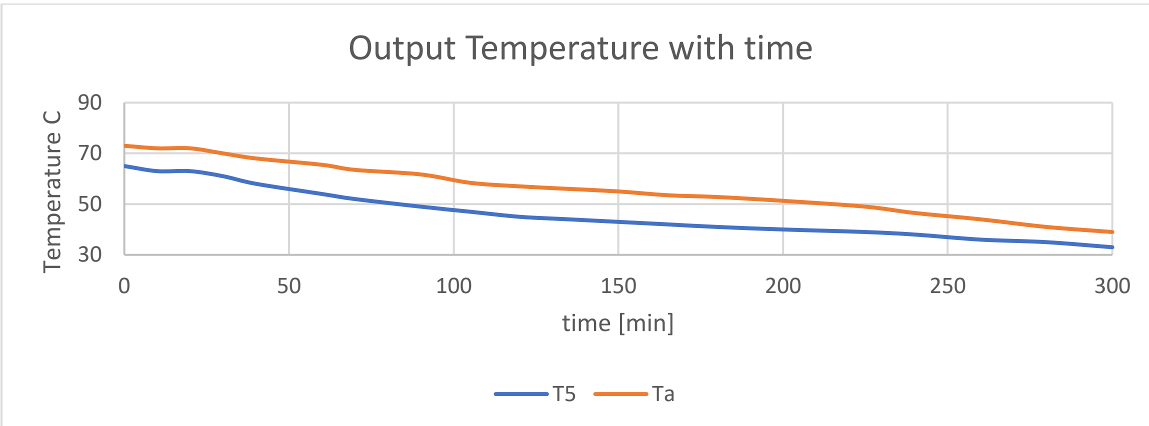

Figure 39: Effect of nozzle position for hot water withdrawn.

Review figure (25)flow diagram for Ta and T5.

Its observed from the figure (39), that T5 is lower than Ta during discharging because of, water from the inserted pipe is passing throw the storage tank. due to, the density difference and low water flowrate; cold water will be at the lower half which will cause heat losses and decreasing for the output water temperature.

Effect of flowrate on PCM behavior and water outlet temperature:

Figure (40) below represents water flowrate effect on output water temperature during continuous discharging process, it’s observed that whenever the flowrate increase, the output temperature will decrease faster due to the large cold water input the system.

At 0.45 L/min flow rate, it took 155 minutes for the output water temperature to decrease from 74 to 39 C, and 300 minutes at 0.27 L/min water flow rate to lose its energy at the same temperature range.

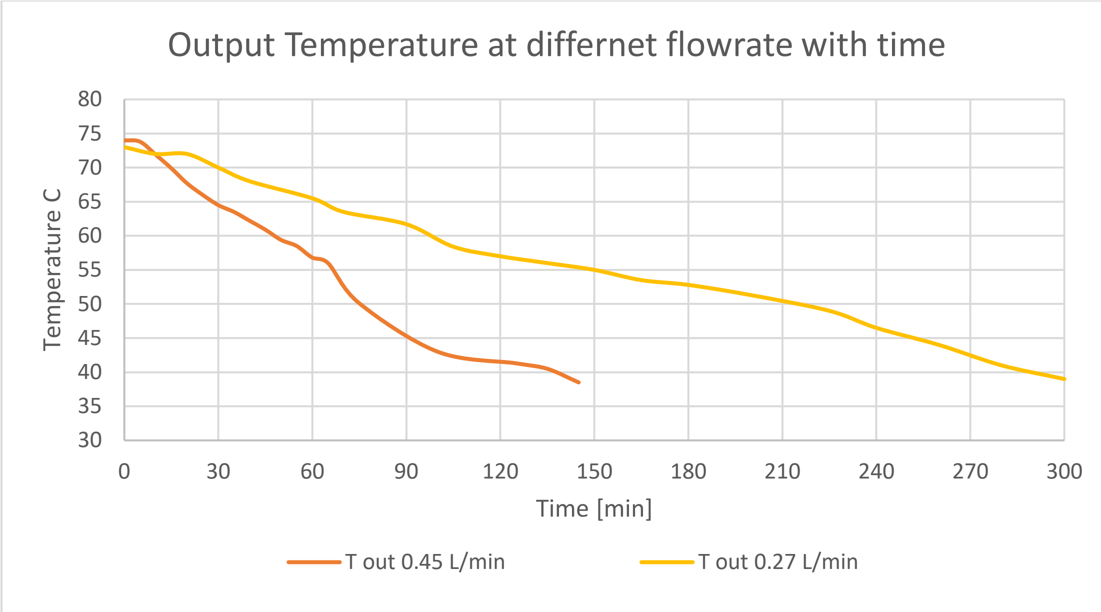

Figure 40: Effect of flowrate on PCM behavior and water outlet temperature.

Chapter Eight: **Conclusion and Recommendation:**

Solar water heating system plays an important role in sustainable energy management in Palestinian households as well as worldwide. Such an effort will not only be useful in improving the quality of life but also in environmental protection. This work focused on the past and current research of energy storage through PCMs for solar water heating systems, in addition, working to enhance and improve its performance.

Experimental study reveals enhancement of a model solar water heater using PCM. Paraffin with certain thermo physical properties has been chosen as PCM in a hollow cylinder shape with 26 pipe holes in the tank of solar water heater.

The storage tank is of jacketed shell type and the solar radiation is modeled in three radiation levels of 500, 700, 900 watt. Mass flow rates of water charging and discharging periods for each case is selected to within a range of 0.25 - 0.3 L/min for all modes.

By inspecting the time, water heater system can supply hot water for the two cases of the tanks with and without PCM, it is revealed that in all cases there was a dramatic improvement. As a result of using PCM, the time that the water heater system can supply hot water, extended up to (27% to 33%) for different cases.

Different parameters such as supplied power which simulates practical solar power, PCM temperature and behavior, output water temperature and time of supply, flow rate of input cold water and the temperature distribution along the storage tank were studied while performing different experimental tests for the water heater system through changing and discharging periods with and without PCM.

The main findings of the results analysis are:

By inspecting the PCM behavior in the three batchwise tests (500, 700 and 900 watt), it has melted completely after 320 ,120 and 190 min of heating respectively. On the other hand, the continuous tests (700 and 900 watt) showed that longer time to complete melting of PCM after 380 and 280 min of heating. It is because the input cold water in continuous tests.

Respecting to time of hot water supplied, there was a great improvement of the hot water suppling time in all tests in batchwise (500, 700 and 900 watt) by 33%, 27% and 30% respectively, moreover, in the continuous tests (700 and 900 watt) there were also good expanding of the time by 30% in both tests.

The recommendations for any future work:

- Study the system with different types of PCM with different melting temperature or by using dual type of PCM.
- Study new configuration that are not mentioned in this report.
- Study the suggested system by using flat plate collector or evacuated tubes instead of the electric heater.

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