PALESTINE POLYTECHNIC UNIVERSITY

AL-QUDS UNIVERSITY

Master Program of Renewable Energy and Sustainability

The effect of using PCM in increasing the performance of solar hot water storage tank

By

Raef Mazen Al-Rajabi

Supervisor

Dr. Maher Al-Maghalseh

July, 2019

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The effect of using PCM in increasing the performance of solar hot water storage tank

BY: Raef Mazen Al-Rajabi

ABSTRACT

Storing heat energy using latent heat storage system is considered as one of the of the methods that are used to raise the performance and efficiency of solar hot water storage system (SHWST).Phase Change Materials (PCMs) may be added to solar hot water storage tank to act as latent heat storage media offering a high storage capacity compared to sensible heat storage.

This study investigates the effect of using phase change materials (PCMs) around a 60-liters solar hot water storage tank (SHWST). The study conducted on three different volumes that varies by the difference of the thickness of phase change materials (PCMs) surrounding the tank. Throughout this study, the use of paraffin wax (PW) as a phase change material (PCM) was investigated.

This study shows the importance of using phase change materials (PCMs) in solar hot water storage systems (SHWST) by comparing these modified systems with the traditional solar hot water storage systems. Due to thermal efficiency of these materials and its ability of storing and releasing heat energy, the performance and efficiency of the solar hot water storage tank (SHWST) were improved.

The results obtained from this study shows that using paraffin wax (PW) with a thickness of 4cm around the SHWST achieved better performance and higher efficiency compared to the traditional SHWST. The results of this study shows that the efficiency of this design is higher than the traditional solar hot water storage tank by 21.78% taking in consideration that it contains an isolation layer of polyethylene of the same thickness and function under the same conditions. Furthermore, the amount of heat loss was reduced by 65.3% and the thermal efficiency was raised by 3.96% and the energy efficiency by 6.35% as well.

تأثير استخدام مواد تغير الطور في رفع أداء خزان تخزين الماء الساخن الشمسي

اعداد: رائف مازن الرجبي

الملخص:

يعد تخزين الطاقة الحرارية بالطريقة الكامنة احدى الطرق المتبعة لرفع اداء وكفاءة أنظمة تخزين المياه الساخنة الشمسية. يتم اضافة مواد تغيير الطور (PCM) في خزان تخزين الماء الساخن بالطاقة الشمسية ليكون بمثابة وسائط تخزين حرارية كامنة التي توفر سعة تخزين عالية مقارنةً بالتخزين الحراري المعقول.

تم في هذا العمل دراسة تأثير اضافة مواد تغير الطور (PCM) حول خزان تخزين الماء الساخن بالطاقة الشمسية سعة ٦٠ لتر بثلاثة احجام مختلفة باختلاف سمك مادة تغير الطور(PCM) المحيطة بها حيث تم اختيار شمع البرافيين (PW) كإحدى انواع مواد تغير الطور (PCM).

اظهرت الدراسة أهمية استخدام مواد تغير الطور في انظمة التخزين الحرارية مقارنة مع انظمة التخزين التقليدية نظرا للفاعلية الحرارية لهذه المواد وقيامها بتخزين وتحرير الطاقة الحرارية مما أسهم في رفع الاداء والفعالية لخزانات تخزين الماء الساخن بالطقة الشمسية.

توصلت الدراسة الى أن اضافة شمع البرافيين (PW) حول خزان تخزين المياه الساخن بالطاقة الشمسية بسمك (٤سم) حقق افضل اداء وكفاءة بنسبة ٢١,٧٨% مقارنة مع خزان تخزين الماء الساخن بالطاقة الشمسية التقليدي الذي يحتوي على طبقة من العازل الحراري بولي أثيلين لها نفس السمك وعند نفس ظروف العمل. حيث انخفضت كمية الفقد الحراري للخزان بنسبة ٦٥,٣% وارتفعت الكفاءة الحرارية بنسبة ٣,٩٦% وبنسبة ٦,٣٥% ارتفعت كفاءة الطاقة المستفادة من الخزان.

DECLARATION

I declare that the Master Thesis entitled" **The effect of using PCM in increasing the performance of solar hot water storage tank**" is my own original work, and herby certify that unless stated, all work contained within this thesis is my own independent research and has not been submitted for the award of any other degree at any institution, except where due acknowledgement is made in the text.

Student Name: **Raef Mazen Al-Rajabi**

Signature: __________________________ Date:__________________

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Signature: ______________________________   Date:____________________

DEDICATION

To my Family ………………… For their support

To my Teachers …….......... For help me until the end

To my friends ………………. Who give me Positive sentiment

To oppressed people throughout the world and their struggle for social justice and egalitarianism

To our great Palestine

To my supervisor Dr Maher Al-Maghalseh

To all who made this work is possible

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LIST OF ABBREVIATIONS

SHWST	Solar hot water storage tank
PW	Paraffin wax
PCM	Phase change material
LHTES	Latent Heat Thermal Energy Storage
TES	Thermal Energy Storage
LHSS	Latent heat storage system
DPHX	Double Plate Heat Exchanger
CompHX	compact heat exchanger
RT35	Type of Commercial paraffin
H	Hour
In	Inside
ITS	Ice thermal storage
MPPT	Maximum Power Point Tracking
NIS	New Israeli shekel
No	Number
NOCT	Normal Operating Conditions Test
Out	Outside
O&M	Operation & Maintenance Cost
PBP	Payback Period
PV	Photovoltaic
RM	Malaysian Ringgit
SPV	Solar photovoltaic
STC	Standard Test Condition
TFM	Transfer Function Method
TR	Refrigeration Ton
TRANSYS	Transient System Simulation program
TRNBuild	TRANSYS Building input data visual interface
TST	Thermal Storage Tank
WHO	World Health Organization
Wp	Watt Peak
Ch	Charging
Disch	Discharging

Temp.	Temperature
Fig.	Figure
CFD	Computing fluid dynamic
Q	Heat
μ	Efficiency
$\int_{tf}^{t}$	Total
F	Final

LIST OF SYMBOLS

Variables	Units	Description
Cp	kJ/kg.K	Specific heat
M	Kg	Mass
ΔT	K or ^oC	Temperature difference
$Q_{sensible}$	kJ/s	Sensible heat
Q_{latent}	kJ/s	Latent heat
Δh_f	kJ/kg	Heat of fusion per unit mass
C_{ps}	kJ/kg.k	Specific heat of PCM in solid state
T_m	K	Melting point temperature
T_i	K	Water temperature inlet tank
T_f	K	Water temperature final
C_{pl}	kJ/kg.k	Specific heat of PCM in liquid state
Q_{prod}	kW	Product gain
q_s	kJ/h	Conduction heat flux
Q_{total}	W	Thermal cooling load for chamber
T	^oC	Temperature
T_r	$	Tariff price
U	$W/m^{2o}C$	Overall heat transfer coefficient
V	m^3	Volume
$\dot{v}$	m^3/sec	Volumetric flow rate
ρ	kg/m^3	density
ΔT	^oC	Temperature difference

CHAPTER 1

INTRODUCTION

1.1 Background

As fossil fuels continue to overload the atmosphere with carbon dioxide and other gas emissions, the world now is in need of a better alternative. Since fuel prices are continuously increasing, this alternative must not only be environmentally-friendly but more cost -effective too. In general, solar energy is one of the most widely used renewable energy sources in the world. In the case of Palestine, solar energy is the most used source of energy due to the high amount of sun hours during the year [1].

There are two main applications of solar energy which are the solar photo voltaic system and the thermal energy system. The first converts sunlight into electricity and the second converts sun radiation into heat.

Solar thermal energy has several applications in daily life, such as cooling and heating buildings, cooking, and producing hot water for domestic, industrial and agricultural purposes. However, solar energy is intermittent, unpredictable, variable and available only during the day. This presents a serious problem. One of the solutions for this problem is what several researchers have been attempting to find which is a method by which the surplus energy can be stored for later use. In the case of solar energy, several researches have been conducted in an attempt to find a method for storing the surplus of heat energy during the sunshine hours and use it during the night and that method is called the thermal energy storage.

Thermal energy storage is of a particular interest and significance in solar thermal applications. Thermal energy can be stored as sensible heat, latent heat or chemical energy.

The main method that is used for thermal storage system is latent heat which stores energy through phase change such as cold storage water/ ice and heat storage by melting paraffin wax. It is worth mentioning that sensible thermal energy storage system, which stores energy by changing the temperature of the storage medium is also widely used.

The latent thermal energy storage system seems to be more preferable than the sensible thermal storage system due to its high storage density with temperature change in addition to its unit size which is smaller than the sensible thermal storage system.

The thermal storage system ,which uses phase change material as a medium, is an innovative way that increases the efficiency of thermal storage system in a domestic thermal system.

1.2 Statement of the Problem

During the last decade ,the local thermal storage systems have been highly improved in terms of elevating the performance and efficiency of the isolating materials and the components of these systems. However, the studies, researches and attempts to improve these systems focused only on improving the sensible heat storage systems. This study aims at improving SHWST by adding latent heat storage systems. This is done by replacing the isolating material with PCM in order to raise the performance and efficiency of these systems and comparing them to the sensible heat storage systems.

1.3 Study Objectives

To achieve the aim of this study, the following objectives have been formulated:

- Experimentally investigate the effect of PCM on energy storage and the performance of SHWST.
- Design an innovative, low-cost SHWST using PCM that is available in local market.
- Develop a data analysis to process the obtained experimental data in a SHWST using PCM and comparing it with the data of traditional SHWST.

1.4 Methodology and Thesis Scope

The experimental tests of both traditional SHWST and using PCM will be conducted in parallel in two tests. In the first test, water will be heated using an electric heater inside the tank, raising the temperature of water and monitor it during period time (for test) where the energy from hot water is transferred to PW and placed around the SHWST. A set of thermocouples and sensitive heat flux sensors installed at different distances around the SHWST were used to obtain data on the heat transfer processes. This was done to gain better understanding of processes of heat and mass transfer in the SHWST during the phase change process. In this test , the amount of the heat loss coefficient(UAs) and the thermal efficiency are calculated. In the second test, hot water is introduced at a three deference temperatures into the hot water tank and a (draw –off) test is conducted for both design and heat loss is calculated in order to obtain realistic results for the energy efficiency of the water tank designs.

To achieve the aim of this study the following objectives need to be completed:

- Research previous investigations on PCM heat storage and SHWST system.
- Design SHWST using PCM.
- Prepare for an experiment test for SHWST using PCM.
- Improve the performance of the SHWST using PCM.
- Collect data and compare results for the improved design.
- Write up findings and any conclusions made in final report.

Equipment/Facilities to be used

- A traditional solar hot water storage tank that is available in the local market.
- Paraffin wax as one of the types of phase change materials that are available in the local market.
- Thermocouples and sensitive heat flux sensors.
- Data logger equipment.

1.5 Thesis Structure

Chapter two: In this chapter, thermal storage systems are discussed in terms of definition, importance, main methods, and the advantage and disadvantage of each method. This chapter also discusses the phase change materials in terms of their properties and classification: organic and inorganic PCMs. At the end of the chapter, thermal storage system using phase change material and the presentation of previous studies and researches are addressed.

Chapter three: This chapter discusses the specifications of the hot water storage tank used in the experimental test, materials , and tools used to complete the experiment as well as the practical steps to build the design in the three cases and contains the equations and arithmetic methods used in the analysis of the results and data.

Chapter four : This chapter discusses the data and the results obtained from the use of PW in SHWST in the three difference volumes (thickness 4-cm, 3-cm and 2-cm) around the tank in two differences test (rising water temperature to 45^{o}C without water flow (thermal storage tank test) and the draw-off test).This also shows the difference between traditional

SHWST and SHWST with PW. It discusses the benefits of using SHWST-Containing PW as well.

Chapter five : Contains thesis conclusion, recommendation and future work.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

As it was mentioned and briefly discussed before, solar thermal energy stands as one of the major applications of solar energy that converts sunlight into heat. Solar thermal systems consist of two main parts: solar collectors, and thermal Storage System. Thermal energy Storage (TES) in general, and phase change materials in particular, have been a major topic in the search for the last 20 years [2]. In this chapter, most of the relevant research and previous studies will be addressed.

2.2 Thermal energy storage

Thermal energy storage can be seen as a key factor for increasing the performance of the industrial process. TES is a technique that is used for storing excess heat energy and using it later when needed. Thermal energy storage technologies , along with their economic and environmental benefits, have been widely studied in the past two decades as one of the methods used in renewable energy systems. The use of thermal storage technologies has been associated with applications of solar energy systems as well as lost energy recovery systems. Thermal energy storage techniques have been used in solar applications. Solar energy is one of the renewable sources of energy that is always different from day to night and / or because of climatic fluctuations in different seasons of the year. Because of this difference, thermal energy cannot be controlled, so thermal energy storage techniques are used to control the lack of energy supply in solar applications under different conditions [2,3].

Thermal energy storage technique is mainly used in solar applications for storing heat energy during off-peak periods (charging in energy availability over energy) for later use during the night or peak times (discharging) shown Figure (2.1).

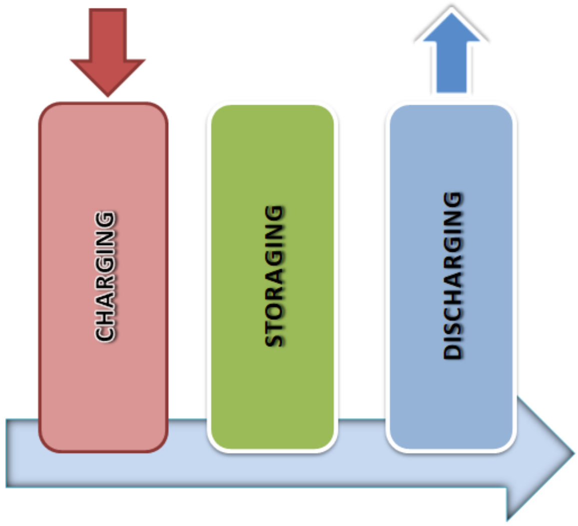

Fig (2.1) Flow diagram of a thermal storage process

Different methods of classification of thermal storage systems vary according to the standard used. Generally, when the standard that is used in classification differs, the classification differs accordingly. If the standard is the temperature, thermal storage systems are divided into two parts: heat storage systems, cold storage systems. If the standard is the storage period, it is divided into two parts: long-term storage, short-term storage.

The most important classification of thermal storage systems, which has been the basis of all studies and scientific research over the past two decades, is the design of the thermal storage system shown in figure (2.2) which can be explained follows:

1- Sensible heat storage
2- Latent heat storage
3- Thermochemical heat storage

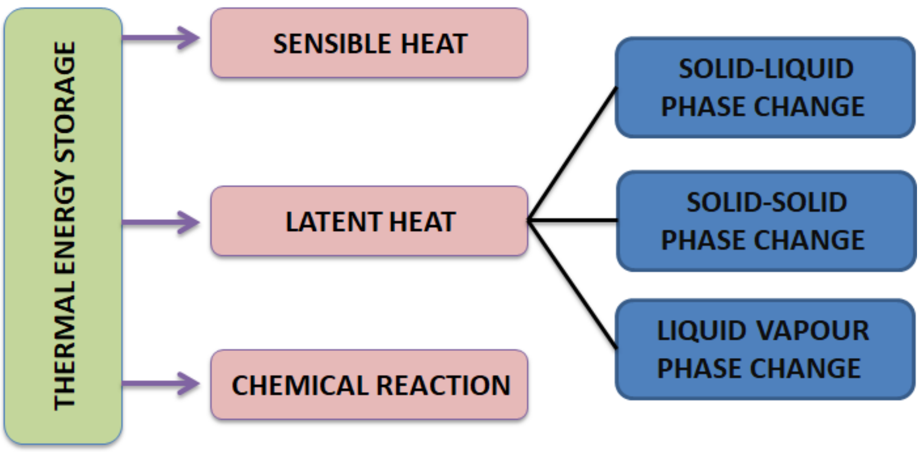

Fig.(2.2) Classification of thermal storage methods

These methods differ in the heat storage density in which they are stored, in contrast to the behavior of the temperature of the medium during heat storage and the application of storage technology [4].

2.2.1 Sensible Heat Storage

In sensible heat storage systems, the thermal energy collected and stored by changing the temperature of storage medium provided that the physical state and molecular structure of storage medium are not changed as shown in figure (2.3).

Sensible heat storage depends on :

1- Mass of storage medium (kg)
2- Specific Heat Capacity of the medium (kJ/kg. K)
3- Change of temperature during the storage process ΔT (K)

The sensible heat equation is:

$$Q_{sensible} = m_{medium} \times Cp_{medium} \times \Delta T$$

Sensible energy can be stored in solids and liquids, such as stone and water. Water is the most widely used as a medium for sensible heat storage as hot water is being largely used in domestic heating and residential heating applications [5].

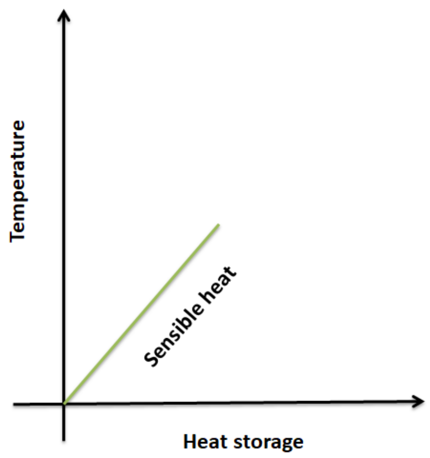

Fig.(2.3) Sensible heat diagram

Sensible heat storage has set of advantage and disadvantage as shown in the Table (2.1)

Table(2.1) Sensible heat storage advantage and disadvantage[6]

	Advantage	**Disadvantage**
Sensible heat storage	Most of the time , the working fluid and storage medium are the same in case of domestic heating.	Sensible heat storage system is a low storage density systems compared to other thermal storage method.
	Storage medium is cheap, easy to use and chemically stable .	Sensible heat storage system needs more volume than the other thermal storage methods .
	Change in volume storage medium during thermal storage process is little	The thermodynamic of the system is less than other method of thermal storage system because it depends on the difference in the temperature which increase the gap temperature between working fluid and storage medium.

2.2.2 Latent Heat Storage

In the latent heat storage system, energy is stored during the change phase of the storage medium. The phase of converting energy could be between solid and liquid phase as in melting and solidification or between liquid and vapor as in evaporation and condensation at a constant temperature as shown in figure (2.4). In latent heat storage system the energy stored in two phases:

1- Raising the temperature of the storage medium where part of the energy is stored in a form of sensible heat to reach the melting or evaporation temperature of the storage medium.

2- Storing of energy during the transformation of a medium from solid state to liquid or from liquid to vapor.

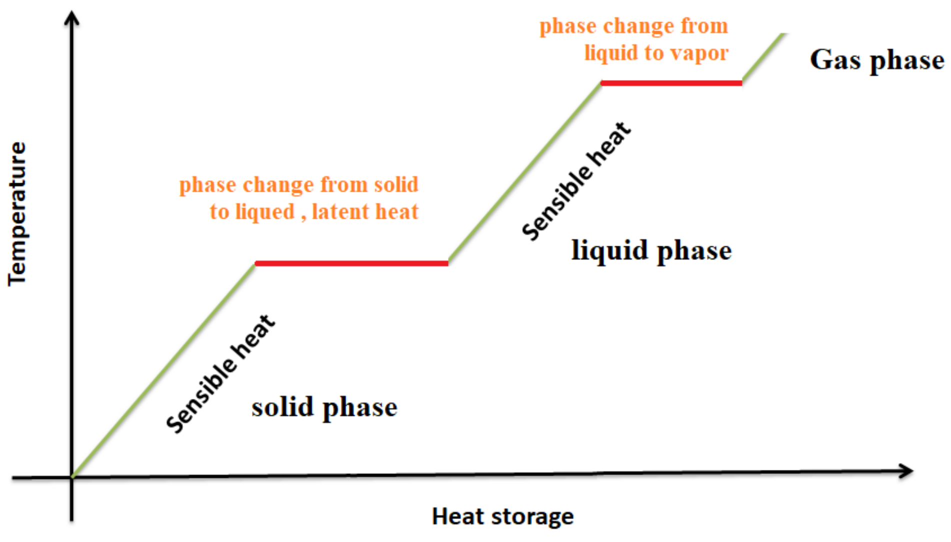

Fig. (2.4) Latent heat storage diagram

The latent energy storage equation is

$$Q_{latent} = m_{medium} \times \Delta h_f$$

where:

m_{medium} mass of heat storage medium (kg)

Δh_f heat of fusion per unit mass (kJ/kg)

In case of the existence of preheating and super heating for the phase change medium, the total energy stored equation is

$$Q_{PCM} = m[(C_{ps}(T_m - T_i) + \Delta h_f + C_{pl}(T_f - T_m)]$$

where:

m Mass of heat storage (kg)

C_{ps} Specific heat of PW in solid state (kJ/kg. k)

T_m Melting point temperature of PCM (k)

T_i Water temperature inlet tank (k)

Δh_f Latent heat of fusion of PCM (kJ/kg)

C_{pl} Specific heat of PW in liquid state (kJ/kg. k)

Table (2.2) contains the main advantages and disadvantages for latent heat storage process

Table (2.2) Latent heat storage advantage and disadvantage [6]

	Advantage	Disadvantage
Latent heat storage system	Latent heat storage systems are characterized by having high thermal storage density, due to the higher values of latent heat of fusion or evaporation when compared to the specific heat capacity of the medium.	Most phase change materials (PCMs) are characterized by a very low thermal conductivity which slows the heat transfer process during charging and discharging.
	Latent heat storage systems are characterized by a higher efficiency in storing energy, this is because any phase transformation occurs at mostly constant temperature, and this decreases the temperature gap between the working fluid and the thermal storage fluid.	Some PCMs are quite expensive, others are chemically unstable and degrades over time
		Low specific heat capacities which limits the benefit only at the melting temperature range.

2.2.3 Thermochemical heat storage

In thermochemical heat storage systems, the energy storage and recovery process is based on a reversible chemical reaction as shown in Figure (2.5). This reaction serves as an endothermic reaction during heat storage and as an exothermic reaction during energy recovery. A reversible chemical reaction can be illustrated as follows:

$$A + heat \leftrightarrows B + C$$

where (A) is the thermochemical material, this material absorbs energy and then being decomposed chemically into two materials (B) and(C) where each is stored separately.

During the energy recovery, materials (B) and (C) are recalled from their reservoirs and combined together releasing an amount of heat and forming back material (A) [7].

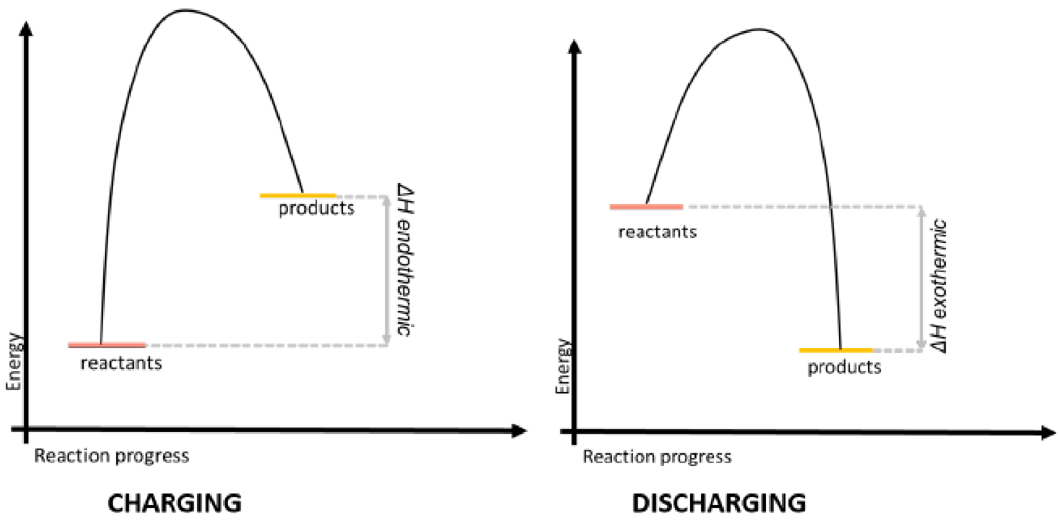

Fig. (2.5) Thermochemical heat storage diagram [5]

There are main advantage and disadvantage of thermochemical heat storage system as shown in Table (2.3)

Table (2.3) Advantages and disadvantages of thermochemical heat storage system [7]

	Advantage	Disadvantage
Thermochemical heat storage system	Thermochemical heat storage system has the highest energy storage density compared to other systems.	The design and application of this system is complex and does not apply to demotic applications Chemical reactions are costly and have an impact on the corrosion of materials and all chemicals must be safe and environmentally friendly. These systems mainly depend on the chemical reactions and some of these reactions may require high pressure which will lead to a pressurized system.

Thermal storage systems depend on capacity, power, efficiency and storage period. Table (2.4) shows a comparison of the three-storage process [8].

Table (2.4) Typical Parameters of Thermal Energy Storage Systems [2]

	Sensible thermal energy storage	Latent thermal energy storage	Thermo-chemical thermal storage system
Capacity (kWh/t)	10-50	50-150	120-250
Power (MW)	0.001-10	0.001-1	0.01-1
Efficiency (%)	50-90	75-90	75-100
Storage period	Days/months	Hours/months	Hours/months
Flexibility (regulation , partial ,charge ,discharge …etc)	High	Medium	Low

When comparing thermal storage systems, the thermal storage capacity for sensible heat storage is less than thermal storage. The thermo- chemical reaction is the best storage in thermal storage capacity, but the disadvantages and complexity of this system and the high cost lead us to choosing the storage of the latent heat for several reasons. These reasons can be listed as follows: the capacity, storage period and scope of the thesis (Domestic hot water application (Case study)). It seems to be better than other storage systems.

2.3 Phase Change Material (PCM)

Phase Change material (PCM) stands as the most important material that is used in the latent heat storage system. PCMs are materials that can change their physical state at a specific temperature within limits of a chosen thermal application [4].

The latent heat storage systems are divided into different types according to the properties of the material used and its applications. LHSS are classified into: Gas- Liquid, Solid-Gas, Solid-Liquid and Solid-Solid [6], shown Figure (2.6).

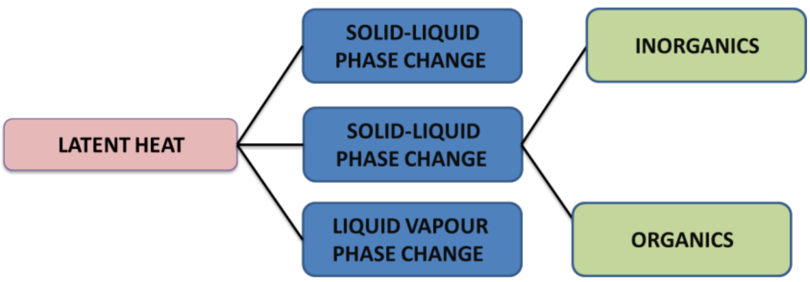

Fig. (2.6) Classification of latent heat storage system

- **Gas-liquid and Solid-gas Systems**: When the thermal storage process changes in volume , the system needs additional power to contain the gas and keep it within the system. This process requires a complex design and can lower the overall energy efficiency of the system.

- **Solid –Solid systems:** Phase transformation occurs in both solid phases where the material only changes its crystalline configuration from a certain lattice configuration to another such as Trimethylolethane (Pentaglycine). The change in enthalpy due to the phase transformations in solid-solid PCMs is in a lower range than that for solid-liquid phase change materials with phase transformation at the same temperature. Therefore, solid - liquid PCMs are a typically a better solution for latent thermal storage techniques.

Solid – Liquid PCM 's absorbs energy from surrounding areas when the phase of their change from solid-liquid state, while remaining at constant temperature. The heat of the material raising the energy of the constituent molecules, and as a result weakens the atomic bonds of the material. At the melting temperature, disintegrate the bonds of particles and state of material change from solid to liquid. The reversal of this process is solid faction, During this process the material transmits the energy to the surrounding area. The molecules lose energy and arrange themselves and turn into a solid phase [4]. Many types of Solid-liquid PCMs are used for thermal storage applications such as water, salt hydrates and paraffin. In figure (2.7) Solid – liquid PCMs are divided into two main groups: organic and inorganic [6].

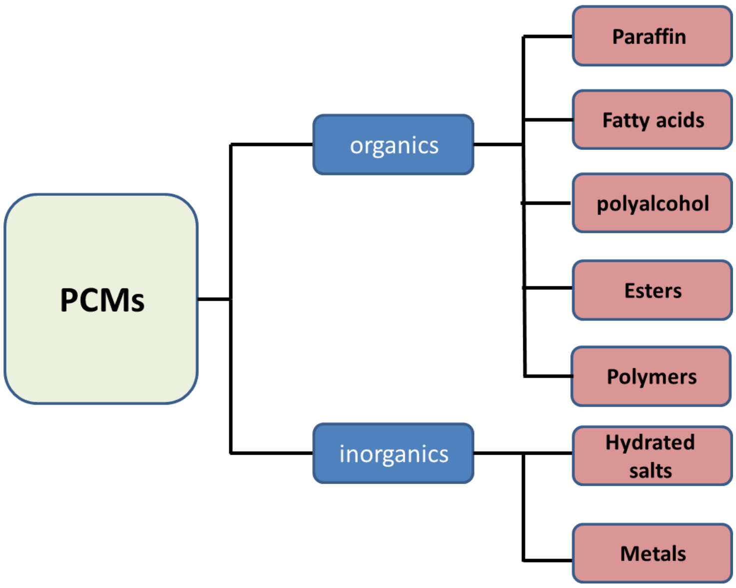

Fig. (2.7) Classification of PCMs

2.3.1 Organic Solid-liquid PCMs

Organic solid-liquid PCMs provide identical melting and are classified to paraffin and non-paraffin. Paraffin wax is the most traditional and common material for organic PCM due to the variability of melting temperature range (0-120^{o}C) which depends on the length of the carbon chain [3,9]. Paraffin has several advantages such as, having higher latent heat of fusion and higher melting temperature. It is also safe ,reliable, very cheap and non-anticorrosive in addition to its chemical stability, lack of insulation, sub-cooling, good nucleating and constant thermos-physical properties. However, these materials do have some disadvantages such as: low thermal conductivity, high temperature transition range, not compatible with plastic containers, high volume change during solid liquid transition and are often flammable [9].

Non-paraffin substances are fatty acids, esters, glycols and alcohol and represent the largest class of organic PCM. These materials are flammable and should not be exposed to excessive high temperature, flame or oxidizing agents. Fatty acids have high heat of fusion values similar to those of paraffin and also offer a good stability cycle and no sub-refrigeration. The disadvantages are corroded, toxic, high temperature instability and cost (2-2.5 times of paraffin). Alcoholic sugars and melting temperatures in the range between 90°C to 200°C, the current high-specific melting heat entropy per unit volume but also sub-cooling [10].

2.3.2 Inorganic Solid-liquid PCMs

The inorganic material used for PCM is divided into salt hydrates, salt and Metallics. When comparing inorganic and organic solid-liquid PCMs m the inorganic have several advantages such as higher thermal conductivity (0.6 W/m. K), high volumetric storage density (180-300 MJ/m^3), and being nonflammable and has low volume change. However, inorganic PCMs have also some other disadvantage such as sub cooling, phase segregation and corrosion of containment material[3].

In this study the paraffin wax was used as PCM due to its availability in the local markets, high thermal storage density and the range of melting point suitable for use in the thermal storage system (60-62^{o}C) as shown in table (2.5).

Table (2.5) Properties of paraffin wax (60-62 ^{o}C)

Melting temperature ^{o}C	Latent heat of fusion kJ/kg	Density kg/m^3 solid	Density kg/m^3 Liquid	Specific heat kJ/kg.K Solid	Specific heat kJ/kg.K liquid	Thermal conductivity W/m.K
60-62^{o}C	188.96 [11]	914 [12]	769 [14]	1.959 [14]	2.116 [14]	0.305 [14]

2.4 Thermal storage system using phase change material

As it has been discussed before, the ability of storing energy became a very important feature that a solar renewable energy generation system should have in order to make use of the excessive and surplus energy in peak hours and satisfy the load during hours where sun radiation is lower or absent. Energy storage has become an essential part of renewable energy technology systems in general and solar energy systems in specific. Thermal energy Storage (TES) is a technology that makes it possible to store thermal energy by heating or cooling the storage medium so that later stored energy can be used for cooling, heating and power generation systems [13]. TES systems are used in particular in buildings and in industrial processes. The use of TES increases the overall efficiency and improves thermal systems, and can lead to improve economy, reductions in investment and operating costs, less pollution of the environment, less carbon dioxide (CO_2) emissions [14].

As mentioned earlier, PCMs is used to store thermal energy in the form of latent and sensible heat. It also helps to provide efficiency when using or conserving solar energy or thermal waste. However, when compared to sensible heat storage, the latent heat storage provides higher density in energy storage while also being characterized by a shorter gap in temperature difference between the stored and released heat.

Zalba et al.[3] discussed the effect of heat storage in relation to solid - liquid phase change material , how heat transfer and applications used for 150 material as PCM , including 45 material commercially available. In related research by Sharma, A. [15], thermal energy storage technology with PCMs that are available were browsed and reviewed with different applications. and its usefulness in raising the efficiency of storage systems with emphasis on evaluating the thermal properties of various PCMs.

Alone the same line, Farid.M.M el al.[5] looked into latent thermal storage systems which are one of the most efficient ways to store thermal energy and made efforts to develop new categories of phase change materials for application in heat storage. He also examined three aspects which are: PCM materials, encapsulation, and applications. The paraffin wax has several advantages, including cheap cost and moderate density of thermal energy storage. The problems associated with the application of PCMs were discussed.

Several extensive researches have been carried out to in an attempt to increase the overall efficiency of latent heat storage system using phase change material. Regin, A. F.[18] looked for new and innovative techniques for thermal storage systems in order to achieve the goal of high storage density with higher efficiency possible . It was found that the use of PCM capsules packed as a packed bag is one of the important methods to achieve this goal. In a related research, Regin, A. F.[19] theoretically examined a solution for the behavior analysis of the thermal energy storage system inherent in the bed where the packed bed of spherical capsules was filled with paraffin wax. The results showed that for appropriate modeling of system performance, the temperature range of phase change must be strictly defined and should be taken into account.

Medrano el al.[20] experimentally investigated the heat transfer process during melting (charge) and solidification (discharge) of five small heat exchangers working as latent heat thermal storage systems. Commercial paraffin RT35 was used while filling PCM in one side of the heat exchanger and water circulates through the other side as heat transfer fluid. Results showed that the double-pipe heat exchanger with the PCM included in the graphite matrix (DPHX-PCM) has the highest values, in the range of 700-800 W / m^2 K, which is one of the higher volume than the second Best. On the other hand, the CompHX-PCM has the highest average thermal power (above 1 kW) due to the high proportion of heat transfer area compared to the external size.

Ways to enhance heat transfer in latent heat systems are important to increase thermal storage efficiency. Al-Maghalseh and Mahkamov [21,22] examined dozens of studies related to heat energy storage techniques using phase change materials (PCMs).This examination focused on the techniques applied to enhance the performance of thermal storage systems and the methods used to analyze heat transfer problems in PCMs. Ways of intensifying heat transfer and determining the optimal design for various heat transfer applications using PCM were investigated. In another research, Castell, A., [23] looked in the most common and promising design methodologies for PCM storage systems and highlighted their utility and limitations. These methodologies were categorized into six types: (1) experimental links and characterization parameters, (2) dimensional and relationship analysis, (3) Effectiveness-NTU, (4) temperature difference record (LMTD), (5) Transmission functions (CTF) and (6) numerical models. The links and functionality of the two-NTU ,which are the most common and direct ways, as well as the ways that provide more possibilities for general solutions were also examined .

Fan, and Khodadadi [24] Looked into several ways to enhance the thermal conductivity in PCMs. High conductivity has been used and fixed constant structure inserts made of various metals (e.g., nickel, aluminum, copper) not to mention the various kinds of types of carbon fiber materials. Additionally, they looked at storage thermal energy units, heat switches, and work status. Their findings indicated that minimizing conductive pathways which connected cold and hot ends using high conductivity inserts/structures showed promise for enhancing conductivity. In related research, Abokersh, M. el al.[25] examined the various technologies used to integrate PCM into solar water heating systems and methods used to enhance PCM heat transfer properties through the use of extended surfaces and high-conductivity additives.

Kenisarin, M.[26] looked in the assessment of the thermal properties of various PCMs, methods of heat transfer enhancement and design configurations of heat storage facilities to be used as a part of solar passive and active space heating systems, greenhouses and solar cooking.

Jesumathy, et al.[27] applied experimental study to investigate the melting and solidification processes of paraffin wax as a phase change material (PCM) in horizontal double pipe latent heat storage unit. This includes the studying of temperature variations along the axial distances in PCM, determination of heat transfer coefficient as well as the heat flow rate. The results showed an increase in Heat flow rate during the melting and solidification process by 25% and 11%, respectively, in the case of increase or decrease by 2 ^{o}C of the inlet HTF temperature. As showed that by increasing the inlet water temperature from 70 ^{o}C to 74 ^{o}C, the total melting time can be decreased by 31%.

Sari, and Kaygusuz [28], examined by experimentally studying thermal performance and phase change stability of stearic acid as a latent heat energy storage material . The experimental results showed that the melting stability of the PCM is better in the radial direction than in the axial direction. It was also observed that when the heat exchanger tube is in the horizontal position, the PCM has more effective and steady phase change characteristics than in the vertical position. The heat storage capacity of the container (PCM tube) is not as good and the average heat storage efficiency is 50.3%. This indicates that 49.7% of the heat is lost .

Alone the same line, Mazman, et al.[29] conducted several experimental studies by adding phase change materials at the upper side of the solar domestic hot water (SDHW) tank to increase thermal storage density and compensate heat loss in it. Results showed that the combination of paraffin and stearic acid gave the best results to improve the thermal performance of SDHW tank (74% efficiency).

Al-Hinti, et al.[30] applied by experimentally testing adding paraffin wax to traditional solar water heating systems. Using natural circulation patterns in a closed-loop system, the researchers measured storage capabilities by connecting the tank and flat plate collectors. The test findings showed that brief spurts of forced circulation had little to no impact on overall system performance, also investigated simulated daily-use patterns through applying both storage behavior and recovery impacts for the PCMs using open-loop systems.

Souliotis et al.[31] looked to develop three novel integrated collector storage solar water heaters (ICSSWHs), hoping to create low-cost devices that can operate using solar power and feature efficient thermal performance. Their findings indicated that the designs can be used year-round, which is an important step forward in the modifications of existing ICS-type solar water heaters.

Liu, Wang, and Ma[32] examined the impact of rising temperature on storage systems in order to gain a deeper understanding of storage materials and thermal performance. The researchers compared PCMs melting temperature above 300°C and obtained a wide data base that will help improve the efficiency of latent heat storage systems. In other research, Rathod and Banerjee[33] looked into thermal stability of PCM in thermal energy storage systems. The researchers measured the stability of PCM by modifying the physical properties. The results of this research contributed to the formation of a database to determine the best PCM for various purposes when using the underlying heat storage systems.

Nkwetta, et al.[34] Looked in use of PCM to improve the thermal storage performance of residential hot water storage tank (HWT). The results that the combined use of PCM and sensible heat has led to improved thermal energy storage in (HWT).

Alone the same line, Nkwetta, et al.[35] Conducted a numerical study on the performance of the hot water tank (HWT) with phase change materials (PCM) using TRNSYS. The results showed improvements in thermal energy storage when using PCM and sensible heat with sodium acetate trihydrate +10% graphite compared to industrial grade granulated paraffin wax and RT58-Rubitherm through storage capacity and reduce charging time.

According to Chaabane, Manzan and Bournot [36], conducted A numerical study to store solar water heaters (ICSSWH). The results showed that the integration of phase change material (PCM) directly into ICSSWH showed an improvement in thermal storage efficiency. The LHSU is better than the reasonable unit during the day when using meristic acid as PCM. With regard to the night operation of this solar system, LHSU was found to be more effective for both PCM as it allows less heat loss and better heat preservation.

Bouadila et al.[37] conducted by experimental study of the storage system using paraffin as material change phase (PCM). So that it takes the shape of two rectangular cavities integrated behind the flat solar collector, taking into account the different weather conditions. The results showed that the PCM mode contributes to increasing the performance of the solar collector during night.

Other research by Trigui and Karkri[38] conducted experimental research on the thermos-physical properties of composite materials (epoxy / metal pipes) filled with developed paraffin to improve the various PCM properties to increase the efficiency of latent heat storage systems and the use PCM composite as integrated components in passive solar wall. The performance of the proposed system has been affected by the thermal efficiency of the phase change materials and the achievement of significant energy savings. The thermo-physical properties of compound compounds (epoxy / metal pipes) filled with paraffin also demonstrated their ability to combine high heat storage capacity and improved heat transfer at the same time.

CHAPTER 3
HOT WATER STORAGE TANK DESIGN

3.1 Introduction

This chapter discusses the specifications of hot water storage tank, main work steps and different designs, distribution of the sensors as required, link to data logger, and the most important obstacles faced during the designing process and the testing procedures.

3.2 Design of hot water storage tank and experiment setup

The water storage tank is made of steel : all dimensions are in centimeter (cm). The outer diameter is (14.33) cm, and the inside diameter is (12.83) cm, with a (58) cm length and insulation (4) cm between the tank and cover .See Figure (3.1).

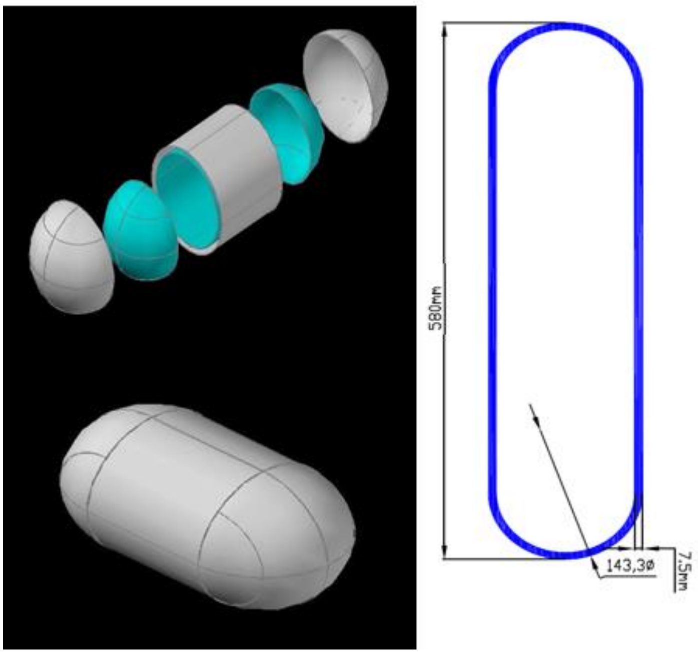

Figure (3.1) Hot water storage tank dimensions

The hot water tank system contains two pipes to inlet and outlet water. The dimensions of this pipe can be described as follows: the outer diameter is 2.54 cm, the inner diameter 1.905 cm and the length of the hot pipe is 49 cm.

The hot water storage tank contains an entrance diameter of 3.81 cm to install electric water heater (2500 watts capacity, length 30 cm). The electricity heater was used instead of the solar collector for two main reasons :The first is that solar radiation seems to be variable in various test conditions and this variability makes it hard to control the inside-temperature. The other reason is that the electric heater can better control the inside temperature in hot water storage tank, see figure (3.2).

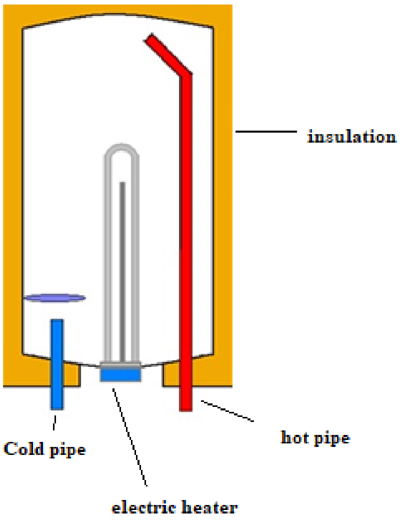

Figure (3.2) Hot water storage tank parts

In this study the insulation material will be replaced between the water tank and the cover with the phase change material used (paraffin wax) at three different volumes and conduct practical experiments to measure the performance of the tank after the addition of these materials.

3.3 Material, Equipment and devices

An experimental study has been conducted to study the effect of using phase change (paraffin wax) as an alternative to insulating material in order to increase the performance of solar water heating systems, so a range of devices and equipment have been used to conduct different experiments and tests.

3.3.1 Paraffin wax 60/62

As discussed in chapter two , Paraffin Wax is available in large quantities in the local market for its multiple uses and lowest cost. The paraffin wax was used 60/62 due to its melting point temperature at (60-62^{o}C) compared to the following Hot water storage systems[39]. **See appendix A.**

3.3.2 PT100 sensors

In this study the insulating material was replaced with paraffin wax. In order to inspect and monitor the effect of paraffin wax on the hot storage tank, sensors should be used and distributed on different points of the hot storage tank to monitor the temperature readings at each point and then compare them with the temperature inside the hot storage tank.

PT100-type sensors shown in figure (3.3) have been used due to their ability to withstand high temperatures and the accuracy of their readings [40]. **see appendix B**

Figure (3.3) PT100 Sensor

3.3.3 Data Logger device

Storing, observing and analyzing data is an important step toward drawing the conclusion of any study. To achieve the goal of this study, data collected and stored by data logger device were thoroughly analyzed. The general idea of this study is to examine the effect of replacing the insulating material with PW and the process of inspection and control through sensors installed inside the material and inside the tank. In order to ensure that sensor readings are monitored and recorded and compared to each other, it is necessary to use a device that is capable of storing readings for a long time and with good efficiency.

The device used to collect and store readings in this experiment is Field-logger device. See figure (3.4). The advantages of this device is the high storage capacity of sensor readings that consist of 8 entrances to the sensors of type PT100 [41]. **See appendix C**

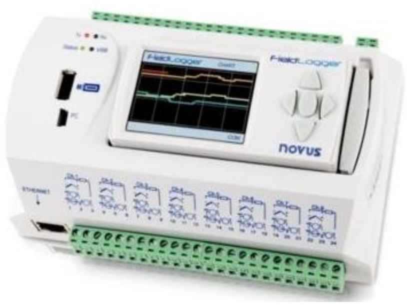

Fig. (3.4) Field logger data collection

3.4 Hot Water Storage Tank Using Paraffin Wax Design

Through previous specifications and designs, practical steps have been initiated to design HWST using PW, which consists of the following stages:

3.4.1 First stage (Materials and tools to design HWST using PW)

The first stage in the design of the HWST is the most complicated stage where you need to provide the appropriate materials and devices and access to dozens of specifications for those devices. The steps for this phase include the use of the following : 30 kg of paraffin wax, data logger of the type of Field logger, eight sensors type PT100, welding equipment, tools, cutting and drilling equipment, flame source and logistic support equipment.

3.4.2 Second stage (Building exterior design of HWST)

1- water tank test was performed by pumping water and examining the leak see figure (3.5)

Figure (3.5) HWST Leaking Test

2- The Design and construction of the lower and upper base for three cases.

A- First case (Base circumference (39.3 cm) with 4 cm mounting pole on HWST wall).

B- Second case (Base circumference (37.3 cm) with 3 cm mounting pole on HWST wall).

C- Third case (Base circumference (33.3 cm) with 2 cm mounting pole on HWST wall).

3- Prepare lower base, inside and outside water ways and vent hole see figure (3.6).

Figure (3.6) Preparation Lower Base for HWST using PW Design

4- Preparing HWST wall for three cases. See figure (3.7)

Figure (3.7) Preparation HWST Using PW Walls

5- Fixing PT100 sensors around and inside HWST. see figure (3.8)

Figure (3.8) Fixed PT100 Sensors in HWST Design Using PW

3.4.3 Third stage (Dissolving PW ,Insert it into HWST , Linkage PT100 sensors to Data logger)

1- Dissolved PW using flame source above melting point (60-62^{o}C). see figure (3.9)

Figure (3.9) Dissolved PW Using Flame Source Above Melting Point (60-62 ^{O}C)

2- Insert dissolved PW around HWST see figure (3.10)

Figure (3.10) PW at Liquid State Insert Around Hot Water Tank

The cost of PW is 10 NIS per kg. The following amounts have been added for the three cases:

A- The first case was the addition of 26.3 kg of wax at a cost of 263 NIS.
B- The second case 20.8 kg of wax was added at a cost of 208 NIS.
C- The third case 18.7 kg was added at a cost of 187 NIS.

3- Connecting PT 100 sensors to Data logger see figure (3.11)

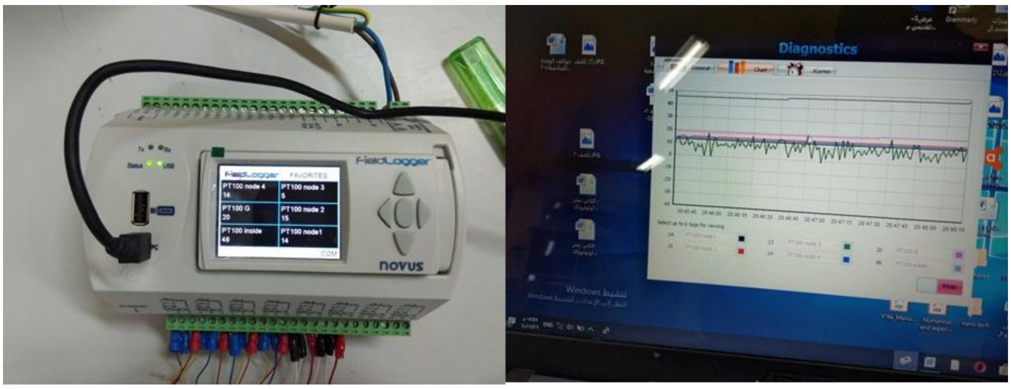

Figure (3.11) PT100 Sensors Connect to Data logger

3.5 Experimental setup and procedure for draw-off test

The procedures for the draw off test include introducing hot water at a temperature of 45^{o}C into the SHWST which is measured by a PT-100 sensor at a specific water flow rate controlled by a valve .That determines the rate of flow of the water inside and then measure the temperature of the water outside the HWST by using a PT-100 sensor at a specific water flow rate.

The experimental schema for the draw off test is shown in Fig.(3.12).

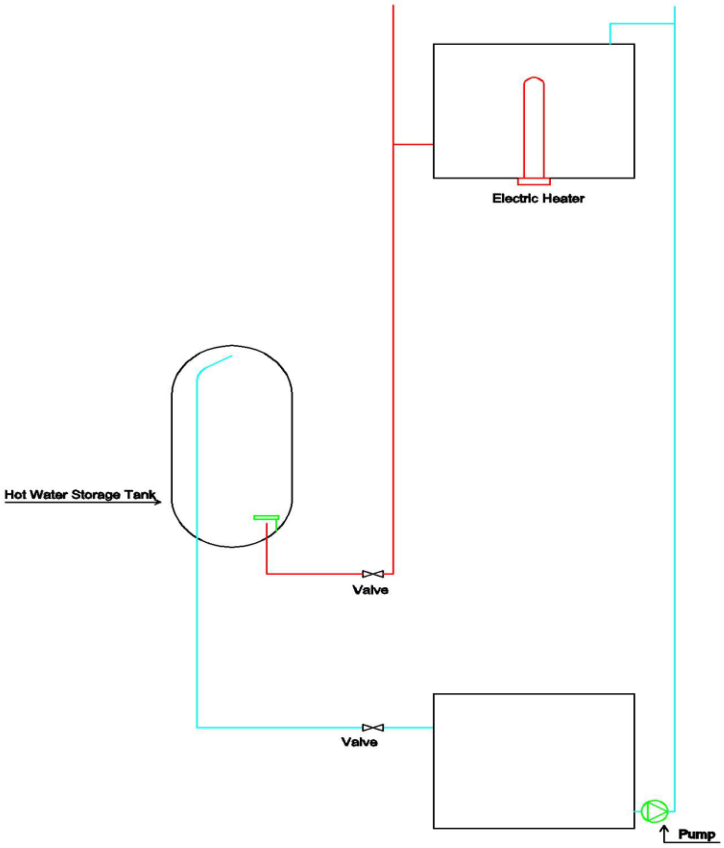

Figure (3.12) Experimental schema for the draw off test

In figure (3.13) shows the steps for the HWST draw-off test design.

Figure (3.13) Design steps for HWST draw-off test

3.6 Conditions and calculation of a hot water storage system

In this study, the thermal storage capacity of the hot water storage system will be tested in two different cases. The first case: raise the water temperature inside the tank to 45^{o}C and monitor the water temperature inside the tank for 48 hours without water flow. Case two : Insert water into the tank with a temperature of 45^{o}C and conduct a draw-off test for the SHWST.

3.6.1 Amount of hot water capacity needed in one day

Hot water storage system use need a variety of storage depending on how many persons are using the system. So, per person, and to maintain hot water temperature at 45^{o}C.

Some estimated calculations for three per-person standard usages are listed below:

1- High usage: 60-120 L / daily.

2- Medium usage: 30-60 L / daily.

3- Low usage: 15-30 L / daily.

In this study, the average daily consumption of hot water by three people was 60 L/daily.

3.6.2 Amount of electric power and electric cost

In this study, electric energy was relied upon to heat water for several reasons discussed earlier. The electric power is calculated

$$E_{el} = power \times Time \qquad (3.1)$$

$Where$:

E_{el}: $electricity\ power\ (kWh)$.

$Power$: $power\ of\ electric\ water\ heater\ (2500\ watt)$.

$Time$: $The\ time\ needed\ to\ raise\ the\ temperature\ of\ the\ water\ to\ the\ desired\ degree\ (h)$.

To calculate the cost of using electric power to heat water through the following[42]

$$cost\ (NIS) = 0.578 \frac{NIS}{KWh_{[42]}} \times E_{el} \qquad (3.2)$$

3.6.3 Amount of Storage heat loss coefficient (UAs)

Heat loss is recognized as an extremely important factor in the thermal efficiency of SHWST. In such cases, it is useful to have an overall measure of the effectiveness of SHWST.

The storage tank energy balance is calculated [43]:

$$M_s \times C_p \times T_s = UA_s \times (T_a - T_s) \quad (3.3)$$

$Where$:

Ms: $Mass\ water\ inside\ the\ HWST\ (kg)$.

C_p: $Specific\ heat\ capacity\ of\ the\ water$ (4.18 $kJ/kg.K$).

T_s: $liquid\ temperature\ in\ the\ tank\ (K)$.

UA_s: $Storage\ heat\ loss\ coefficient\ (W/\ ^oC)$

T_a: $Ambient\ air\ temperature\ (K)$.

By assuming a fully mixed storage losing heat to ambient temperature of T_a it is possible to integrate the storage tank energy balance equation (3.3) over the test duration; i.e. t in seconds to compute the storage heat loss coefficient as

$$UA_s = -\frac{1}{t} \times M_s \times C_p \times In\left\{1 - \frac{T_{sf} - T_{si}}{T_a - T_{si}}\right\} \quad (3.4)$$

Where:

T_{sf}: $Final\ liquid\ temperature\ of\ the\ water\ (K)$.

T_{si}: $Initial\ liquid\ temperature\ of\ the\ water\ (K)$.

The thermal efficiency (μ_{th}) expressed as

$$\mu_{th} = \frac{Q_{out}}{Q_{in}} \quad (3.5)$$

Where:

$Qout = Ms \times Cp \times Tf$

$Qin = Ms \times Cp \times Ti$

3.6.4 Total heat storage in water (Q_{total}) (with water flow) and energy efficiency

The charging energy rate depends on the inlet and outlet charging temperatures of the storage tank and is expressed as [44]:

$$\dot{Q_{ch}} = \rho_{av}\, C_{p(av)} \dot{v}_{ch}(T_{chin} - T_{chout}) \quad (3.6)$$

Where:

ρ_{av} temperature dependent average density of the water (kg/m^3)at the start and end of charging

$C_{p(av)}$ temperature dependent average specific heat capacity of the water (kJ/kg.K) at the start and end of charging

$\dot{v}$ is the volumetric charging flow rate $(m^3$/sec)

T_{chin} inlet charging temperature of the storage tank (K)

T_{chout} outlet charging temperature of the storage tank (K)

The total energy stored in tank can be estimated by integrating Eq. (3.6) from the start of charging to the end of charging for each small temperature measurement interval and this can be expressed as

$$Q_{ch} = \int_{t_{ini}}^{t_f} \rho_{av}\, C_{p(av)} \dot{v}_{ch}(T_{chin} - T_{chout})dt \quad (3.7)$$

The discharging energy rate (energy loss) can be expressed as

$$\dot{Q_{disch}} = \rho_{av}\, C_{p(av)} \dot{v}_{ch}(T_{dischin} - T_{dischout}) \quad (3.8)$$

(3.20)

Where:

ρ_{av} temperature dependent average density of the water (kg/m^3) at the start and end of discharging

$C_{p(av)}$ temperature dependent average specific heat capacity of the water (kJ/kg.K) at the start and end of discharging

$\dot{v}$ is the volumetric discharging flow rate $(m^3$/sec)

T_{chin} inlet discharging temperature of the storage tank (K)

T_{chout} outlet discharging temperature of the storage tank (K)

The total energy discharged (energy loss) from the tank can be estimated by integrating Eq. (3.8) from the start of discharging to the end of discharging can be expressed as

$$Q_{disch} = \int_{t_{ini}}^{t_f} \rho_{av}\, C_{p(av)} \dot{v}_{ch}(T_{dischin} - T_{dischout})dt \quad (3.9)$$

For equation (3.7),(3.9) the total energy effective expressed as

$$Q_{effective} = Q_{ch} - Q_{disch} \tag{3.10}$$

For the equation (3.7),(3.10) ,the energy efficiency (μ) expressed as

$$\mu = \frac{Q_{effective}}{Q_{ch}} \tag{3.11}$$

Chapter 4

RESULTS AND DISCUSSION

4.4 Introduction

In order to achieve the objectives of the experimental study for SHWST using PW, there are three different possible designs according to volume of paraffin wax around the tank (thickness 4cm, 3cm and 2cm).

Two different experiments of these designs will be conducted in parallel with the traditional tank. In the first experiment, water temperature inside the SHWST will be raised to 45^{o}C without water flow and the performance of SHWST will be monitored during 48 hours (thermal storage tank test). In the second experiment, draw-off test where hot water is introduced at difference temperatures (35,45 and 60^{o}C) into the tank with a flow rate of (7.14 liters/min), measuring the temperature of the water outlet of the SHWST and calculating its SHWST efficiency.

4.5 First Experiment, the temperature of SHWST is raised to (45^{o}C) in a closed system without water flow (thermal storage tank test)

This experiment is based on testing the SHWST in specific working conditions and monitoring the actual performance of the wax in raising the performance of the SHWST and measuring the amount of heat losses.

This experiment simulates the SHWST's ability to maintain the temperature of the water inside it in different working conditions during the night and cloudy days.

4.5.1 First case (Raise the temperature of SHWST using PW to (45^{o}C) (thickness 4-cm) in a closed system without water flow)

This case is based on raising the temperature of the SHWST with PW and the traditional HWST to 45^{o}C by using electrical heater and then observing and studying the temperature of the water inside the tank and the amount of SHWST capacity to maintain thermal storage within the water in both designs by using Field data logger.

4.5.1.1 Behavior and transformations of PW in SHWST

The behavior of PW is an important factor in increasing the performance of thermal storage capacity of the SHWST because of its ability to store the excess water heat by shifting the condition of the material from the solid state to the liquid state (melting) and supplying this stored heat to the water inside the tank and thus transforming the condition of the material from liquid to solid state (solidification).

SHWST designs maintain the temperature of the water inside the tank. The water temperature at the upper side of the tank differs from bottom side. The transfer of hot water from the top to the bottom affects the behavior of wax surrounding the tank.

Six sensors were installed at different distances around the tank. Three sensors were installed at the upper side at the distance of (0.5cm,1cm and 2cm) to study the amount of energy stored inside the wax wall and the other three sensors were installed at the same distance at the bottom side.

Figure (4.1) illustrates the PW behavior at the upper side through three sensors in different distance mounted on the SHWST wall during (48 h).

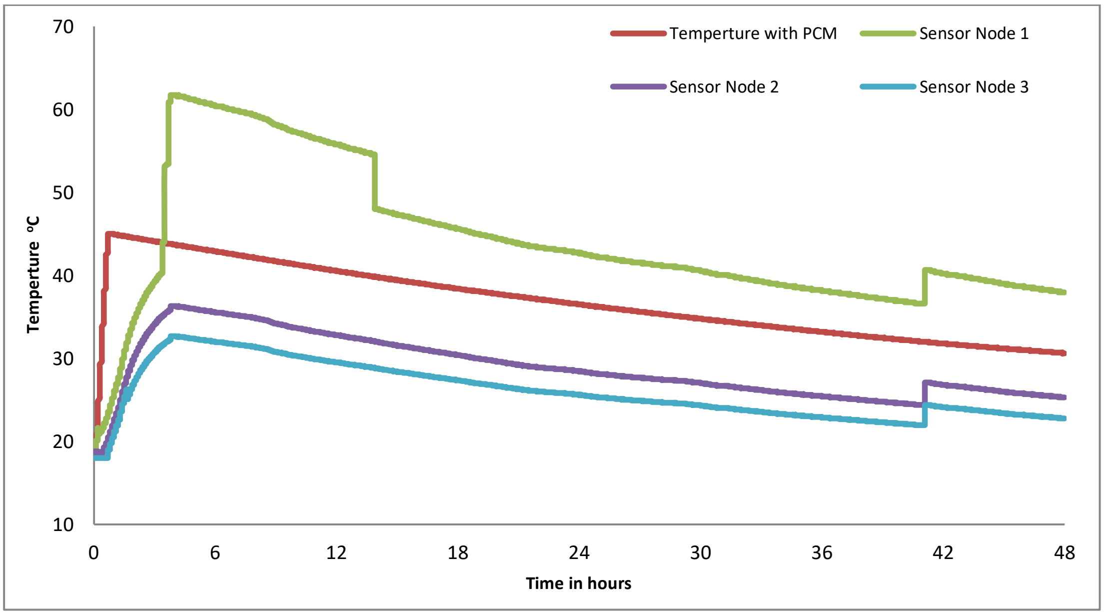

Fig.(4.1) Behavior of PW in SHWST upper side (thickness 4-cm) rise water temperature to 45^{o}C during (48 h)

As shown in Figure (4.1), the PW heats up continuously when the water temperature is raised inside. The wax continues to gain the heat of excess water after separating the heat source until reaching the highest degree possible in order to allow it to store the maximum amount of thermal energy .On the other hand the highest temperature that the sensor node 1 reached (62^{o}C) after the beginning of the experiment by 4.2 hours (meting point).Sensor node 2 reached (36.3^{o}C) within 4 hours and sensor node 3 reached (33^{o}C) during 4.2 hours. 30% of the PW surrounding the tank has reached meting state and it is storing excess heat within it.

Figure (4.2) shows the behavior of PW in the lower side of the SHWST and its relation to the amount of heat stored inside it.

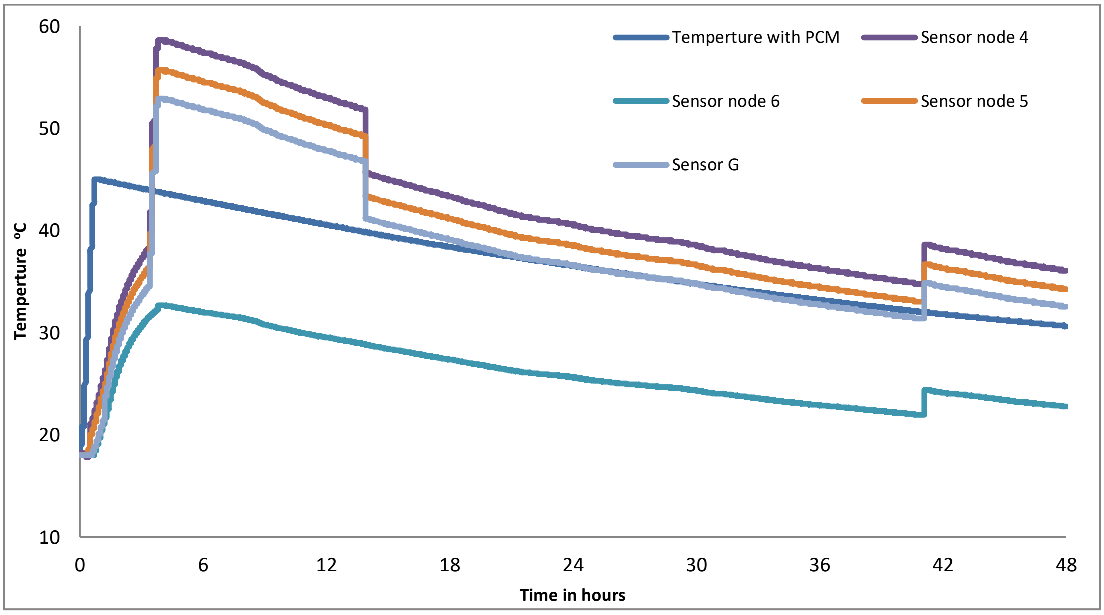

Fig.(4.2) Behavior of PW in SHWST Lower Side (thickness 4-cm), rise water temperature to 45^{o}C during (48 h)

As shown in figure (4.2) ,it can be noted that the amount of acceleration of the overall PW temperature is lower than in the upper side. The highest degree reached by sensor node 4 within 4 hours was 58.2^{o}C.Sensor node 5 reached 55.8^{o}C within 3.9 hours. Sensor node 6 reached 32.4^{o}C within 4.1hours and sensor G reached (52.9^{o}C) within (4.2 h) .This shows that the heat stored in PW at the bottom base is less than upper side and that it loses heat more quickly due to the low temperature of the water in this side of the SHWST.

4.5.1.2 Time Period of thermal storage capacity

This case shows clear difference in the design's ability to maintain the water temperature inside the tank.

In the SHWST containing PW, the temperature is raised to 45^{o}C by an electric heater during 0.8 hour where the bulk of this heat is used to heat the water and the other part is stored inside the PW compared to the traditional HWST which requires 0.7 h to raise water temperature to the same degree.

Figure (4.3) shows the difference in water temperature inside the SHWST in both designs during a time period of (48 h).

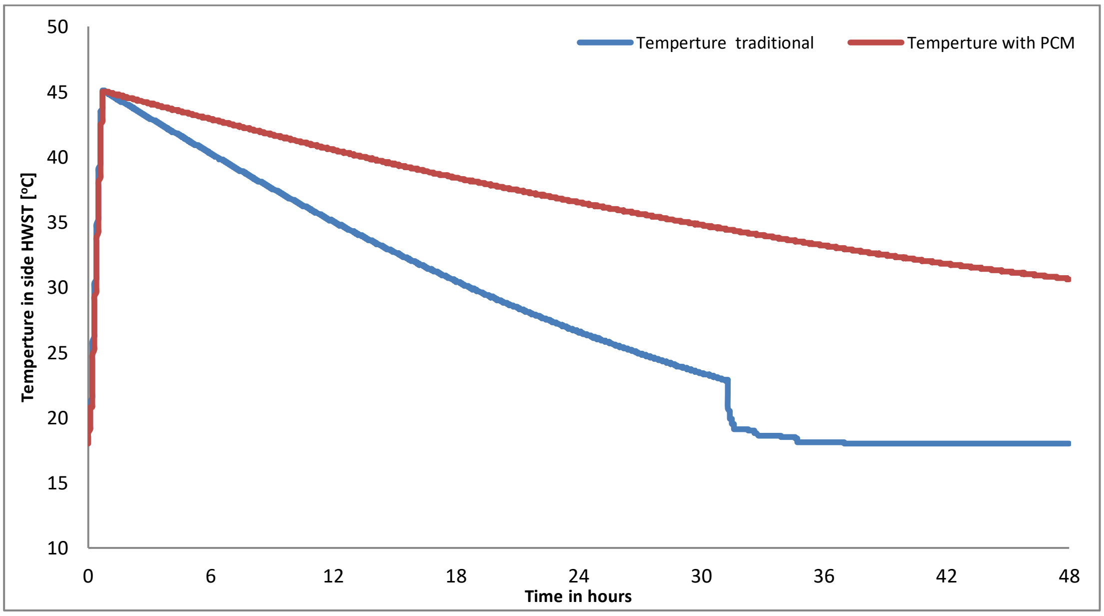

Fig (4.3) Water Temperature inside tank for HWST using PW (thickness 4-cm) and traditional SHWST, rise water temperature to 45°C during (48h)

The conclusion we can arrive at by studying figure (4.3) is that there is a clear difference in the ability to maintain water temperature inside the tank for both designs within 48 hours. In a SHWST using PW design, the water temperature reached 31°C after 48 hours compared to the traditional SHWST which required 31.4 hours to reach the temperature (17.9°C). Therefore, it needs to operate an electrical source 1.35 times to reach the same period as SHWST with PW.

4.5.1.3 Amount of storage tank heat loss coefficient (UA_s) and thermal efficiency

The amount of heat stored in water is a major factor that affects the performance of SHWST designs which largely depends on the temperature difference within the tank.

Figure (4.4) Shows the amount of heat input by an electronic heater and total heat storage in water for traditional SHWST during 48 hours.

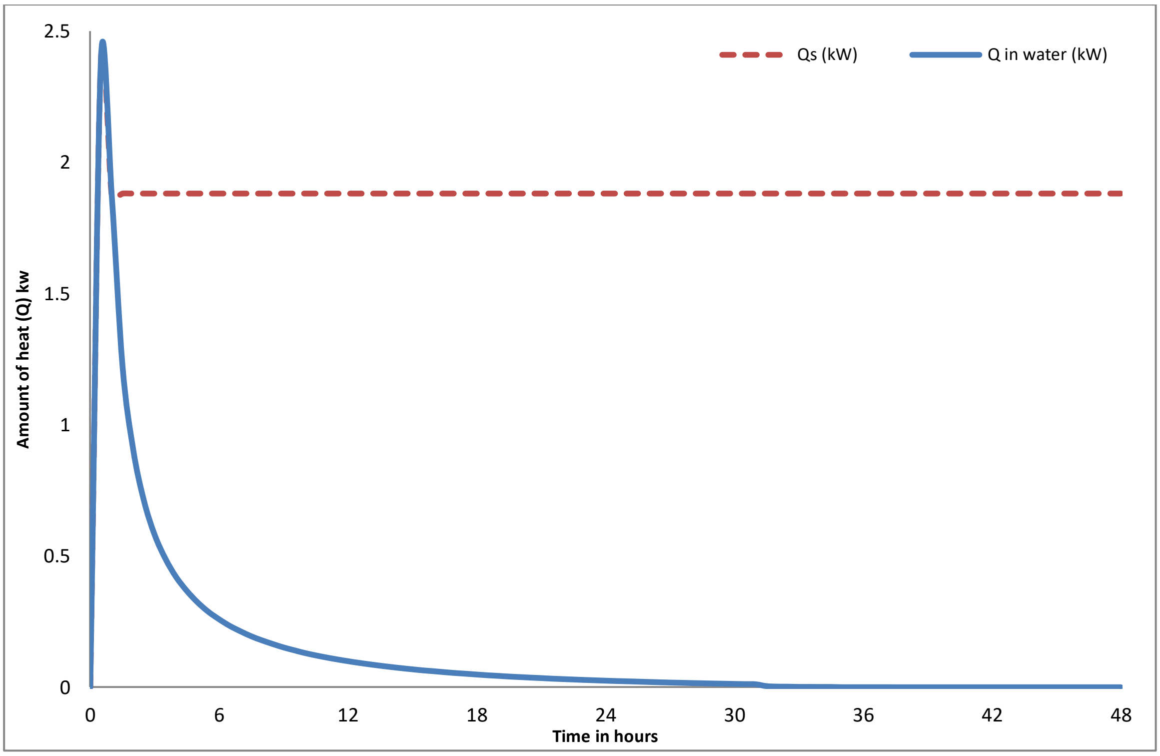

Fig.(4.4) Amount of heat input by electronic heater and total heat storage in water for traditional SHWST during 48 hours

The figure (4.4) shows the amount of heat stored in the water in the traditional SHWST, where it shows that the material around the tank works to reduce the amount of heat loss by isolating the tank to take advantage of hot water in various conditions when the energy source is not required to raise water temperature.

The storage tank heat loss coefficient (UA_S) was computed at 3.312 W^oC^{-1}, a value considered relatively good for such thermal storage where thermal efficiency reached 91.51%.

Figure (4.5) shows the amount of heat input by electronic heater and total heat storage in water for SHWST using PW (thickness 4-cm) during 48 hours.

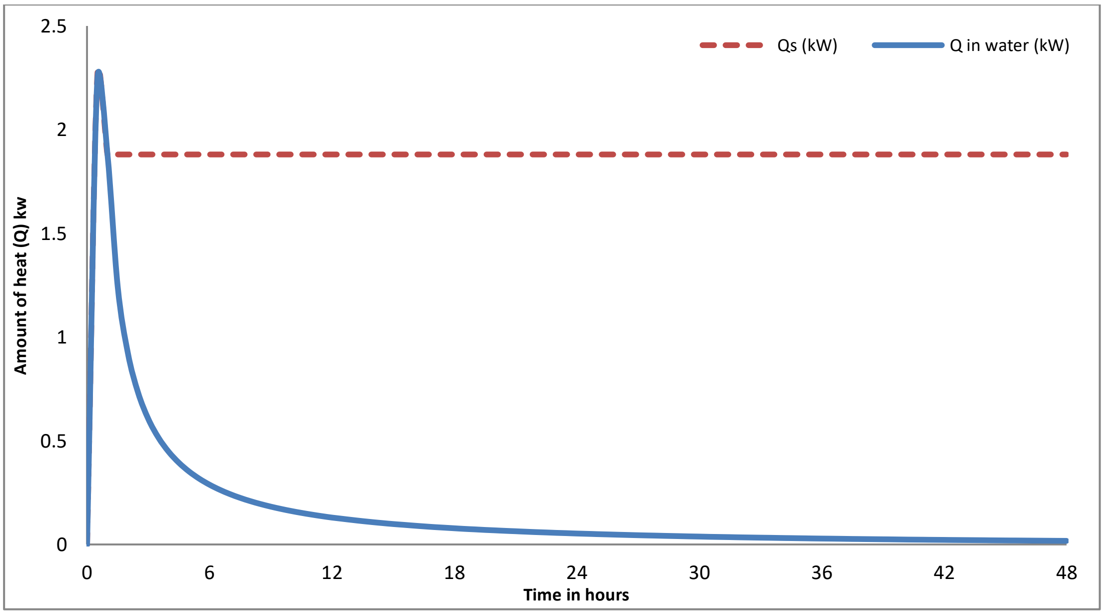

Fig.(4.5) Amount of heat input by electronic heater and total heat storage in water for SHWST using PW (thickness 4-cm) during 48 hours

The figure (4.5) shows the amount of heat stored in the water for SHWST using PW (thickness 4-cm). The figure shows the high capacity to maintain the amount of heat stored inside the tank. The reason for that is PW, part of it was the transformed from solid state to liquid (melting) and the excess heat was stored inside it to benefit from it when the water temperature inside the tank drops. The tank's ability to maintain the water temperature (thermal efficiency) was improved by 10.41% compared with the traditional HWST and storage tank heat loss coefficient (UA_S) is equal 1.152 W^oC^{-1}.

4.5.1.4 Electric cost to raise water temperature (45°C) within 48 hours

The cost of raising water temperature in SHWST is calculated using the electric heater by equation (3.1) and (3.2)

1- Electric cost for SHWST using PW

$$E_{el} = power \times time$$

$$E_{el} = 2.5 \text{ Kw} \times 0.82 \text{ h} = 2.05 \text{ Kwh} \qquad (4.1)$$

$$cost\ (NIS) = 0.578 \frac{NIS}{KWh} \times E_{el}$$

$for\ value\ in\ equation$ (4.1)

$$\text{Cost (NIS)} = 0.578 \times 2.05 = 1.19 \text{ NIS} \qquad (4.2)$$

To raise the temperature of the water inside the HWST using PW ,0.82 hours is needed to reach the temperature of 45^{o}C, during 48 h the temperature has reached to 31^{o}C .By using this data , the amount of annual cost for the use of electric power can be calculated.

$$Days = \frac{hours}{24\ hour} = \frac{48}{24} = 2\ days \tag{4.3}$$

$for\ value\ in\ equation$ (4.3)

$$The\ number\ of\ times\ the\ electric\ heater\ runs\ in\ month = \frac{30\ days}{2\ days}$$

$$= 15\ \ times \tag{4.4}$$

$for\ value\ in\ equation$ (4.2), (4.4)

$$cost\ of\ electric\ power\ in\ month = 1.19(NIS) \times 15\ times = 17.85\ NIS$$

$$cost\ of\ electric\ power\ in\ one\ year = 17.85\ NIS \times 12\ moth = 214.2\ NIS$$

2- Electric cost for traditional HWST

$$E_{el} = power\ \times time$$

$$E_{el} = 2.5\ Kw \times 0.91\ \ h = 2.275\ Kwh \tag{4.5}$$

$$cost\ (NIS) = 0.578 \frac{NIS}{KWh} \times\ E_{el}$$

$for\ value\ in\ equation$ (4.5)

$$Cost\ (NIS) = 0.578 \times 2.275 = 1.3\ NIS \tag{4.6}$$

To raise the temperature of the water inside the traditional HWST , 0.91 hours are required to reach the temperature of 45^{o}C .During 17 h, the temperature has reached to 31^{o}C .By using this information , the amount of annual cost for the use of electric power can be calculated.

$$Days = \frac{hours}{24\ hour} = \frac{17}{24} = 0.7083\ days \tag{4.7}$$

$for\ value\ in\ equation$ (4.7)

$$The\ number\ of\ times\ the\ electric\ heater\ runs\ in\ month = \frac{30\ days}{0.7083\ days}$$

$$= 42.35\ times \quad (4.8)$$

$for\ value\ in\ equation\ (4.6), (4.8)$

$$cost\ of\ electric\ power\ in\ month = 1.3\ (NIS) \times 42.35\ times = 55.06\ NIS$$

$$cost\ of\ electric\ power\ in\ one\ year = 55.06\ NIS \times 12\ moth = 660\ NIS \quad (4.9)$$

Note that the use of HWST using PW (thickness 4-cm) has reduced the cost of using electric power by 67.5% compare with traditional HWST annually.

4.5.2 Second Case (Raise the temperature of SHWST using PW to (45^{o}C) (thickness 3-cm) in a closed system without water flow)

In this case, SHWST wall is designed(thickness 3-cm) from the tank and paraffin wax is melted inside it. The amount of dissolved paraffin wax inside the SHWST wall is 20.8 kg and all parts surrounding the tank are full. The same procedures have been followed in the first scenario in terms of design and distribution of sensors around the wall of SHWST and were linked in parallel with the traditional SHWST.

This scenario is similar to the first scenario and follows the same steps .The main reason for this design is to study the heat storage capacity for SHWST when reducing amount of PW surrounded around the wall tank.

4.5.2.1 Behavior and transformations of PW in SHWST

Wax behavior is affected by the different amount of PW. In this scenario the amount of PW that transformed from solid state to liquid state increased when compared with the first scenario by about 25%

In figure (4.8) shows the temperature of PW at the upper side for SHWST with the water temperature inside the thank.

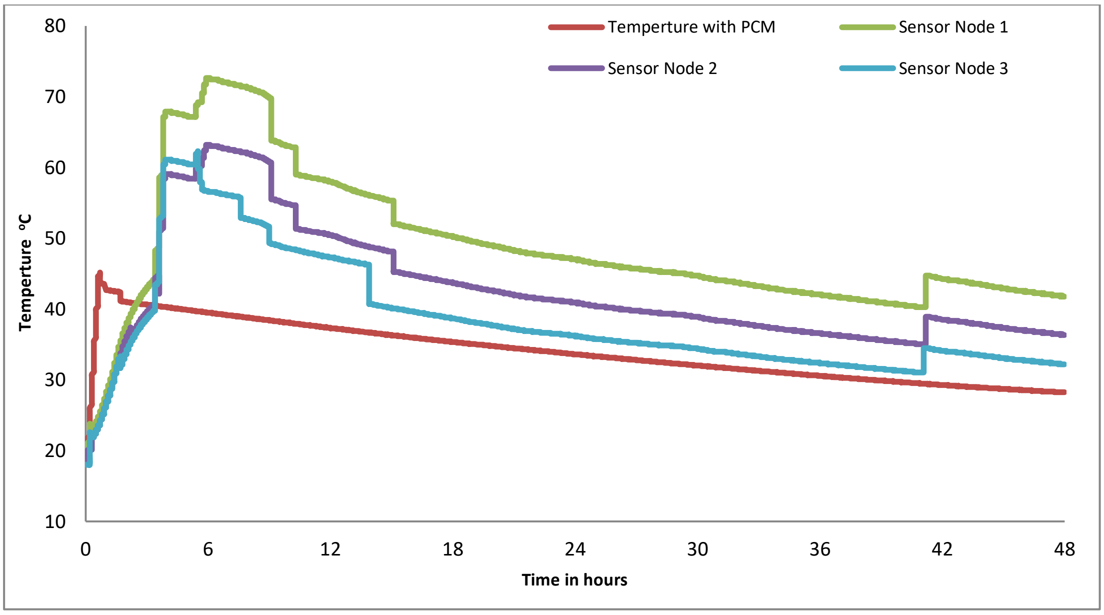

Fig.(4.6) Behavior of PW in SHWST upper side (thickness 3-cm) rise water temperature to 45°C during (48 h)

In figure (4.6) The temperature of the sensor node 1 reached 74.1 °C by 6 h and the node 2 reached 65.2 °C by 6.1 h, that mean large amount of PW transform from solid state to liquid state (melting) than the first case.

Figure (4.7) shows the temperature of PW in the lower side for SHWST with the water temperature inside the tank.

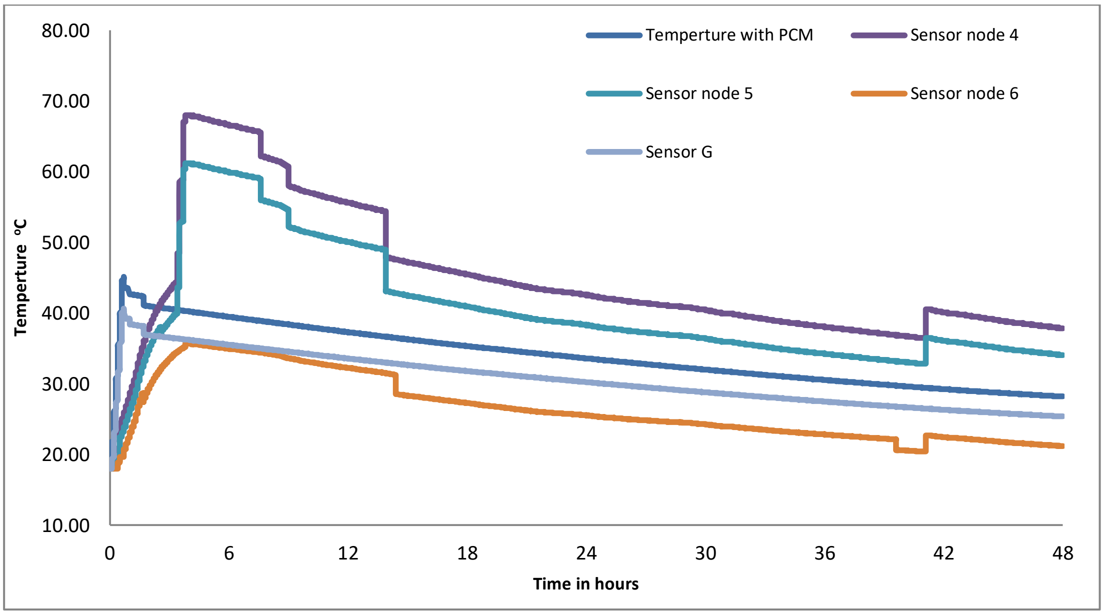

Fig.(4.7) Behavior of PW in SHWST lower side (thickness 3-cm) rise water temperature to 45°C during (48 h)

The observation in figure (4.7) highest temperature in sensor node 4 reached 69.7°C within 5.8 h , node 5 reached 61.7°C within 5.8 hours and lower base temperature reached 41.2°C in 2.15 h this shows the best results (PW) transform for solid state to liquid state (melting) compared to the first case.

4.5.2.2 Time period of thermal storage capacity

In this case, as shown in Figure (4.8), the temperature of the SHWST using PW was raised to 45°C within 0.7 h and the water temperature reached 29.5°C after 48 h.

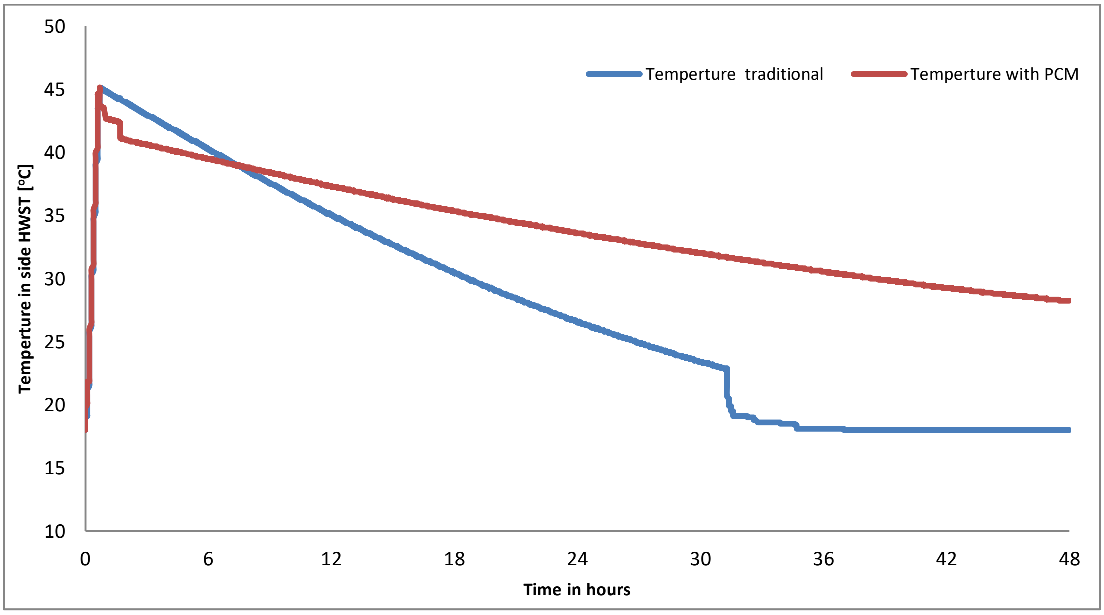

Fig (4.8) Water Temperature inside tank for SHWST using PW (thickness 3-cm) and traditional SHWST, rise water temperature to 45°C during (48h)

In figure (4.8) the SHWST using PW (thickness 3-cm) performance in less than the first case by 33.4% at the same condition.

4.5.2.3 Amount of storage tank heat loss coefficient (UAs) and thermal efficiency

It turns out that the amount of heat stored in the water in this design is lowered by 3.56% compared to the first case as shown in Figure (4.9) .This is due to reduce the amount of PW where the amount of heat stored in water is proportional to the amount of PW around the tank. The tank's ability to maintain water temperature was improved by 25.2% compared to the traditional HWST.

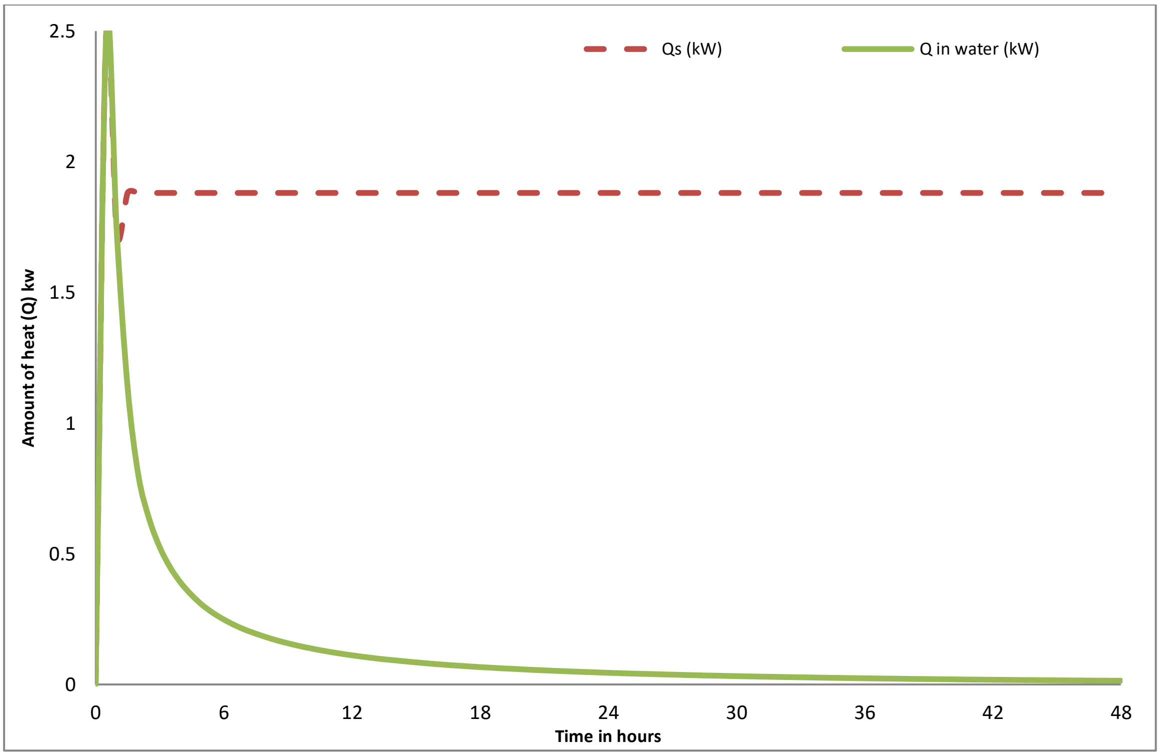

Fig.(4.9) Amount of heat input by electronic heater, heat losses and total heat storage in water for SHWST using PW (thickness 3-cm) during 48 hours

The figure (4.9) shows that the amount of heat loss coefficient (UA_S) in the tank is higher than the first case by 19.21% ($1.37 W^oC^{-1}$) and thermal efficiency is 94.8%, This is due to the large amount of PW transformed from solid to liquid state and therefore the outer layers of PW became highly exposed to the air surrounding the SHWST.

4.5.2.4 Electric cost to raise water temperature (45^oC) within 48 hours

The cost of raising water temperature in HWST is calculated using the electric heater by equation (3.1) and (3.2)

1- Electric cost for HWST using PW (thickness 3-cm)

$$E_{el} = power \times time$$

$$E_{el} = 2.5 \text{ Kw} \times 0.82 \text{ h} = 2.05 \text{ Kwh} \quad (4.10)$$

$$cost\ (NIS) = 0.578 \frac{NIS}{KWh} \times E_{el}$$

$for\ value\ in\ equation$ (4.10)

$$\text{Cost (NIS)} = 0.578 \times 2.05 = 1.19 \text{ NIS} \quad (4.11)$$

To raise the temperature of the water inside the HWST using PW (thickness 3-cm) 0.91 hours are required to reach the temperature of 45^{o}C. Water temperature is reached to 31^{o}C during 45 hours. By using this information , the amount of annual cost for the use of electric power can be calculated.

$$Days = \frac{hours}{24\ hour} = \frac{45}{24} = 1.875\ days \qquad (4.12)$$

$for\ value\ in\ equation\ (4.12)$

$$The\ number\ of\ times\ the\ electric\ heater\ runs\ in\ month = \frac{30\ days}{1.875\ days}$$

$$= 16\ times \qquad (4.13)$$

$for\ value\ in\ equation\ (4.11), (4.13)$

$$cost\ of\ electric\ power\ in\ month = 1.19\ (NIS) \times 16\ times = 19.04\ NIS$$

$$cost\ of\ electric\ power\ in\ one\ year = 19.04\ NIS \times 12\ month = 228.48\ NIS$$

By using the value in equation (4.9) ,the use of HWST using PW with (thickness of 3-cm) has reduced the cost of using electric power by 56.42% compared with traditional HWST annually.

4.5.3 Third Case (Raise the temperature of SHWST using PW to (45^{o}C) (thickness 2-cm) in a closed system without water flow)

In this case, the SHWST wall is designed (2-cm) away from the tank and paraffin wax is melted inside it. The amount of paraffin wax dissolved inside SHWST wall is 18.7 kg and all the parts surrounding the tank are full. The same procedures have been followed in previous cases in terms of designing and distributing sensors around the SHWST wall and linking them in parallel with the traditional SHWST.

4.5.3.1 Behavior and transformations of PW in SHWST

In this case, the behavior of PW differs from the previous design due to reduced wax around tank.

Figure (4.10) shows the temperature of PW at the upper side for SHWST and the water temperature inside the tank.

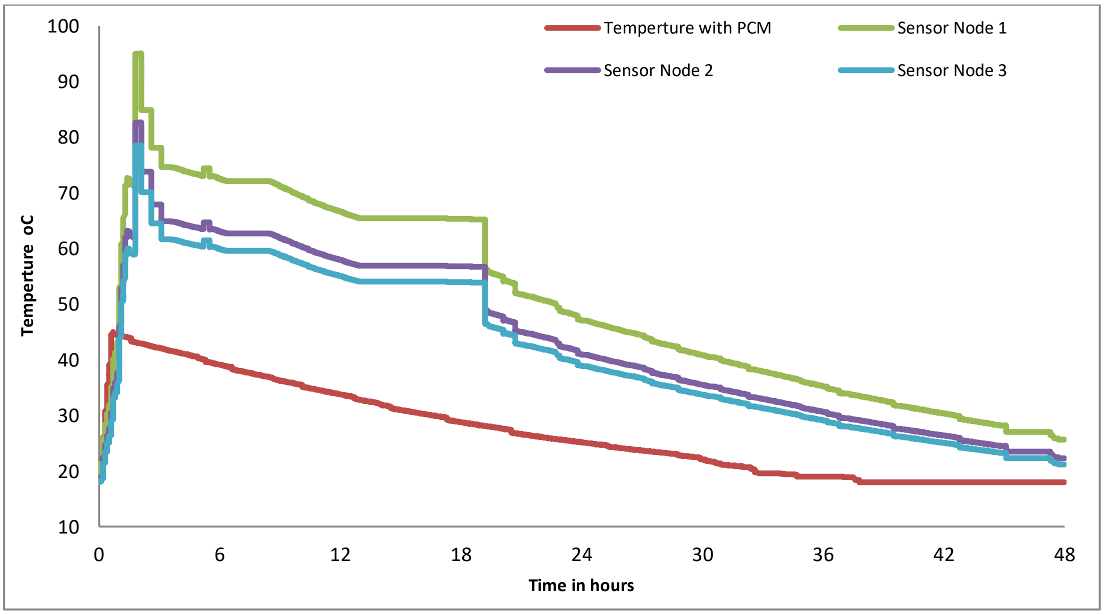

Fig.(4.10) Behavior of PW in SHWST upper side (thickness 2cm),rise water temperature to 45°C during (48 h)

Figure (4.10) shows the rapid transformation of the material from solid state to liquid state (melting) where sensor node 1 reached the melting point within 1.31 hours and sensor node 2 in 1.2 hours. The rapid loss of heat is also shown inside the wax due to the rapid transformation of the wax condition, especially in the outer layers that make contact with the surrounding air which leads to rapid loss of heat inside it.

Figure (4.11) shows the temperature of PW in the lower side for SHWST and the water temperature inside the tank.

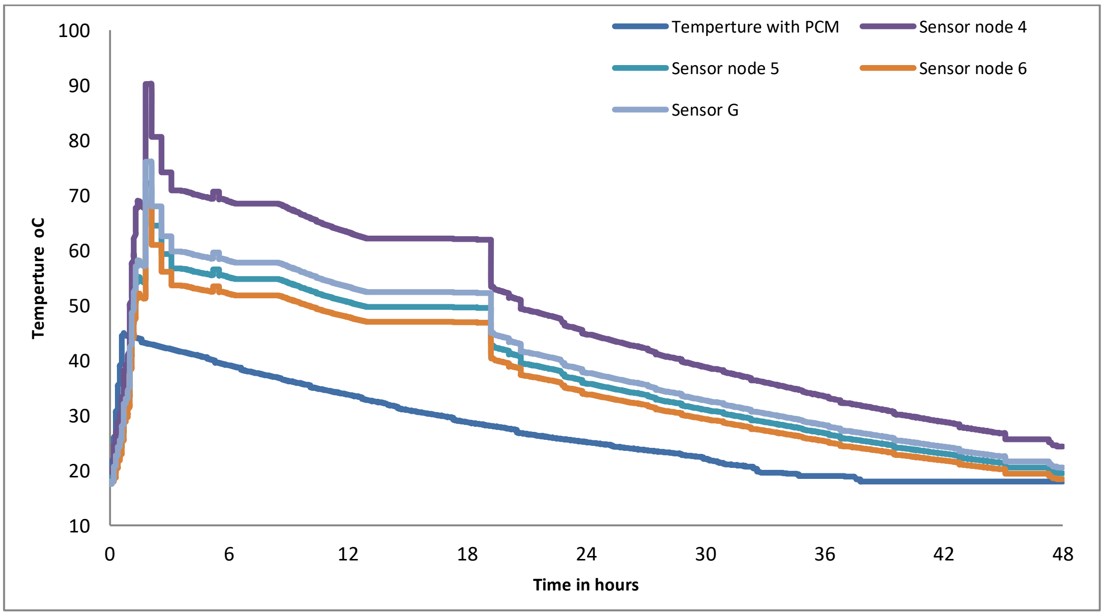

Fig.(4.11) Behavior of PW in SHWST lower side (thickness 2cm) ,rise water temperature to 45°C during(48 h)

Figure (4.11) shows a significant transformation in PW (melting) within the design and rapid loss of stored heat.

4.5.3.2 Time period of thermal storage capacity

In this case, as shown in Figure (4.12), the SHWST temperature was raised using PW to 45°C within 0.72 hours and reached temperature (18°C) during 32 h.

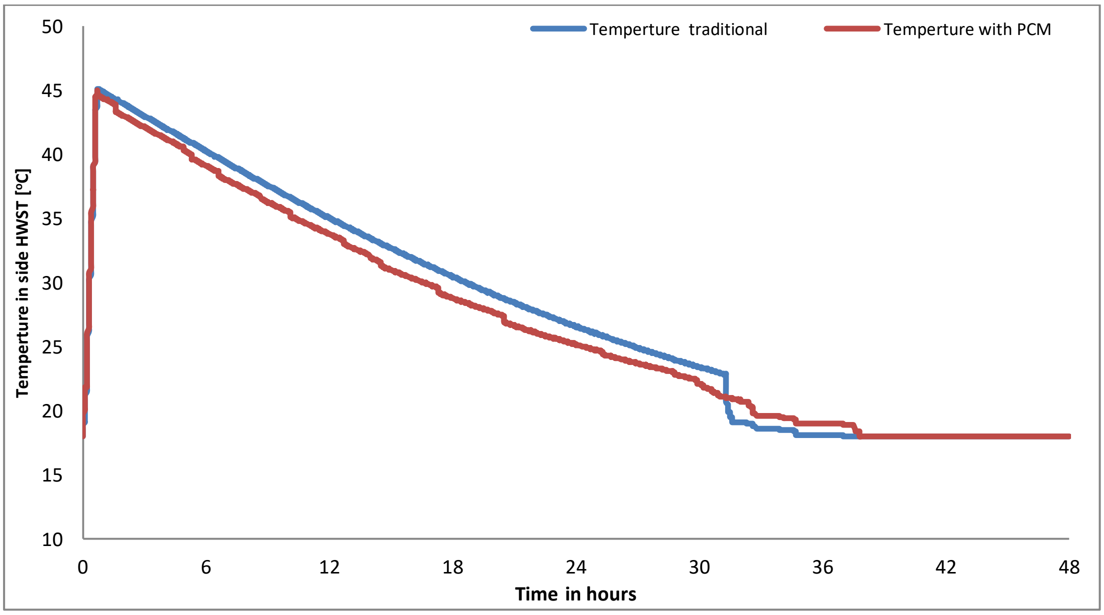

Fig (4.12) Water Temperature inside tank for SHWST using PW (thickness 2cm) and traditional SHWST, rise water temperature to 45°C during (48h)

Figure (4.12) shows the convergence of performance between the traditional SHWST and contains of PW.

4.5.3.3 Amount of storage tank heat loss coefficient (UA_s) and thermal efficiency

In this case, the difference in the amount of heat water stored in the tank is lower compared to the two previous cases. It was decreased by 31.2%, 20.45%. See Figure (4.13). This is due to the reduction of the amount of PW where the amount of heat stored in water is proportional to the amount of PW about the tank and the capacity of storage PW .The tank's ability to maintain water temperature (thermal efficiency) was increased by 1.05% compared to the traditional SHWST and the amount of storage tank heat loss coefficient (UA_S) is 3.217W°C^{-1}.

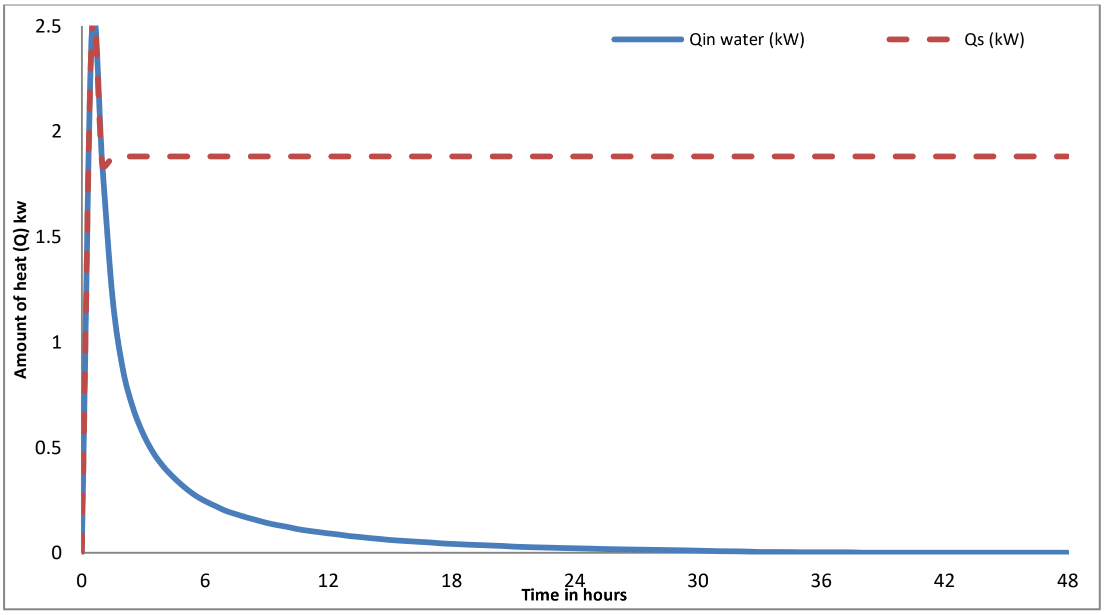

Fig.(4.13) Amount of heat input by electronic heater and total heat storage in water for SHWST using PW (thickness 2-cm) during 48 hours

The figure (4.13) shows the amount of heat lost from the tank, where it shows a significant increase in the amount of PW compared to the previous two cases due to the transformation of a large part of the wax layers connected to the outer cover of the tank from solid to liquid state (melting) and a significant loss of heat stored inside the wax.

4.5.3.4 Electric cost to raise water temperature (45°C) within 48 hours

The cost of raising water temperature in HWST is calculated using the electric heater by equation (3.1) and (3.2)

1- Electric cost for HWST using PW (thickness 2-cm)

$$E_{el} = power \times time$$

$$E_{el} = 2.5\ \text{Kw} \times 0.72\ \text{h} = 1.8\ \text{Kwh} \quad (4.14)$$

$$cost\ (NIS) = 0.578 \frac{NIS}{KWh} \times E_{el}$$

$for\ value\ in\ equation$ (4.14)

$$\text{Cost (NIS)} = 0.578 \times 1.8 = 1.04\ \text{NIS} \quad (4.15)$$

To raise the temperature of the water inside the HWST using PW (thickness 2-cm) 0.72 hours are required to reach the temperature of 45°C. Water temperature is maintained for

14.5 h to reach the temperature of 31°C .By using this information, the amount of annual cost for the use of electric power can be calculated.

$$Days = \frac{hours}{24\ hour} = \frac{14.5}{24} = 0.604\ days \qquad (4.16)$$

$for\ value\ in\ equation\ (4.16)$

$$The\ number\ of\ times\ the\ electric\ heater\ runs\ in\ month = \frac{30\ days}{0.604\ days}$$

$$= 49.67\ times \qquad (4.17)$$

$for\ value\ in\ equation\ (4.15), (4.17)$

$$cost\ of\ electric\ power\ in\ month = 1.04\ (NIS) \times 49.67\ times = 51.7\ NIS$$

$$cost\ of\ electric\ power\ in\ one\ year = 51.7\ NIS \times 12\ month = 619.2\ NIS$$

By using equation (4.9) the HWST using PW (thickness 2-cm) has reduced the cost of using electric power by 6.1% compare with traditional HWST annually.

4.6 Second Experiment, hot water storage tank draw-off tests and energy efficiency (μ)

In this test, the water temperature is raised to (35,45 and 60°C) and then it flows into the SHWST and the temperature of the water flowing out of the tank is measured. Conducting a draw off test for SHWST is important in order to evaluate the practical performance of the tank.

The draw-off test is done in order to determine the maximum amount of hot water that can be used before water temperature becomes lower than the pre-determined value for domestic use. The test begins after raising the water temperature outside the tank. The inlet valve is opened for the hot water to flow in .Then the water temperature is monitored using the thermocouples sensor. After that, the flow rate per second for the water flowing in the tank is calculated. The same procedures are done using the thermocouples sensor to monitor the temperature of water flowing out of the tank and then the flow rate per second is calculated.

The test lasts until we reach a volume of (60.120 and 180 liters) coming out of the three tanks taking into consideration that the capacity of tank used in this test is 60 liters.

Using the data obtained from the experiment , the total amount of charged heat in the water before flowing in the tank and the amount of discharged heat after water flows out of the tank were calculated.

The figure (4.14) shows the temperature of water flowing out of the traditional SHWST during the draw-off test with a flow rate average of 7.14 liter/min.

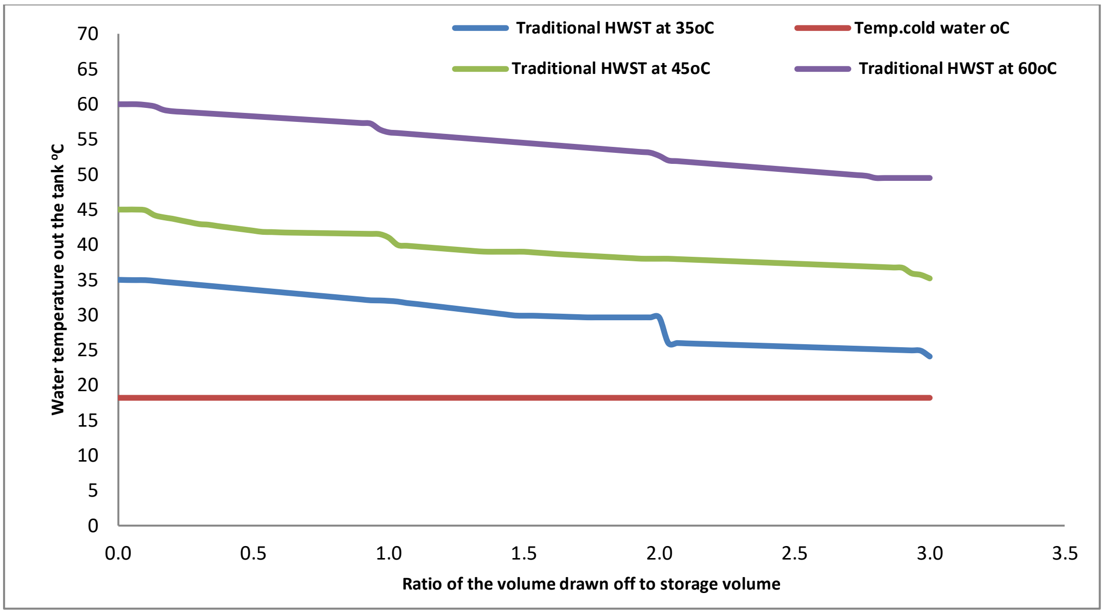

Fig.(4.14) Draw-off curves for the different water temperature flowing in the traditional SHWST (7.14l/min)

Figure (4.14) shows the actual performance of the traditional SHWST at the different temperatures of water flowing into the tank for the three used volumes. Using the equations (3.7-3.11),the energy efficiency of the tank is calculated as shown in tables (4.1 , 4.2 ,4.3)

Table 4.1: Amount of heat charge ,heat discharge and the energy efficiency of the traditional SHWST when water flows into the tank at 60°C ($\dot{m} = 7.14$ L/min)

The First Test Water flows into the tank at a temperature of 60°C						
	T_{in} (°C)	**T_{out} (°C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	60	56.4	642.56	23.9	618.67	96.2
Volume 2	56	52.65	599.67	23.3	576.38	96.1
Volume 3	52	49.5	504.32	21.28	483.09	95.78
Total	60	49.5	1711.02	68.49	1642.53	96

Table 4.1 shows the energy efficiency of the traditional SHWST when water flows into the tank at 60°C .It also shows that the actual energy efficiency of the tank reached 96%.

Table 4.2: Amount of heat charge ,heat discharge and the energy efficiency of the traditional SHWST when water flows into the tank at 45°C ($\dot{m} = 7.14\ L/min$)

The Second Test Water flows into the tank at a temperature of 45°C						
	T_{in} (°C)	**T_{out} (°C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	45	41.5	411.27	35.37	375.9	91.3
Volume 2	41	38	340.23	32	308.26	90.6
Volume 3	38	35.2	295.47	12.3	283.17	95.8
Total	45	35.2	1046.96	79.5	967.31	92.39

Table 4.2 shows the actual energy efficiency of the traditional SHWST when water flows into the tank at 45°C where it reached 92.39% .This result is lower than the result obtained in the first experiment which will affects the actual performance of the traditional SHWST.

Table 4.3: Amount of heat charge ,heat discharge and the energy efficiency of the traditional SHWST when water flows into the tank at 35°C ($\dot{m} = 7.14\ L/min$)

The Third Test Water flows into the tank at a temperature of 35°C						
	T_{in} (°C)	**T_{out} (°C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	35	32	250.7	20.67	230.03	91.75
Volume 2	32	29	218.17	25.9	192.3	88.15
Volume 3	29	26.2	373.96	38.2	335.8	89.8
Total	35	26.2	624.66	58.85	565.8	90.58

Table 4.3 shows that the actual energy efficiency of the traditional SHWST when water flows into the tank at 35^{o}C equals 95%.

By studying the previous obtained data for the three tests , it can be clearly noted that the tests showed good results in terms of the energy efficiency of the traditional SHWST. It has also shown that the energy efficiency seems to differ by the difference in the temperature of the water flowing into the tank. The average of the energy efficiency of the traditional SHWST reached 93%.

This thesis aims at improving the actual performance and the efficiency of the traditional SHWST by adding phase change materials (paraffin wax).

Using the same procedures and under the same conditions , the three draw-off tests were done for the three different tank designs and with three different amounts of paraffin wax around the tank (thickness of 4-cm,3-cm and 2-cm).

The figure (4.15) shows the temperature of water flowing out of the SHWST using PW (4-cm) during the draw-off test with a flow rate average of 7.14 liter/min.

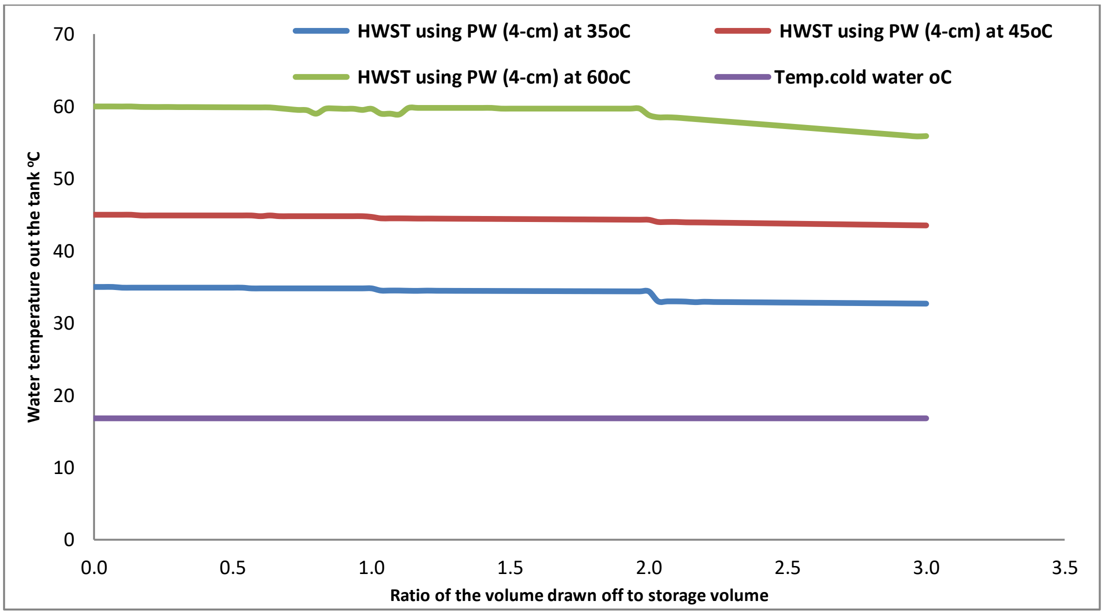

Fig.(4.15) Draw-off curves for the different water temperature flowing in the SHWST using PW(4-cm) (7.14l/min)

Figure (4.15) shows the actual performance of the tank surrounded by 4-cm of paraffin wax .Using this data and using the equations (3.7-3.11),the actual energy efficiency is calculated as shown in tables (4.4,4.5,4.6).

Table 4.4: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (4-cm) when water flows into the tank at 60°C ($\dot{m} = 7.14\ L/min$)

The First Test **Water flows into the tank at a temperature of 60°C**						
	T_{in} (°C)	**T_{out} (°C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	60	59.67	666.1	3.07	663.07	99.5
Volume 2	59	58.6	629.7	-9.4	639.1	100.1
Volume 3	58.5	55.9	622.27	9.42	602.85	97.2
Total	60	55.9	1918.15	13.1	1905.05	99.32

Table (4.4) shows the importance of using phase change materials in improving the performance and efficiency of SHWST where the energy efficiency was raised by 3.23% compared to the traditional SHWST.

Table 4.5: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (4-cm) when water flows into the tank at 45°C ($\dot{m} = 7.14\ L/min$)

The Second Test **Water flows into the tank at a temperature of 45°C**						
	T_{in} (°C)	**T_{out} (°C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	45	44.7	434.9	1.94	432.9	99.55
Volume 2	44.5	44.2	413.4	1.42	411.93	99.6
Volume 3	44	43.5	405.9	3.5	402.4	99.14
Total	45	43.5	1254.1	6.86	1247.2	99.45

Table 4.5 shows that the actual energy efficiency of the SHWST that was surrounded by 4cm of the paraffin wax reached 99.45% .This result is higher than the traditional SHWST by7.06%.

Table 4.6: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (4-cm) when water flows into the tank at 35^{o}C ($\dot{m} = 7.14\ L/min$)

The Third Test **Water flows into the tank at a temperature of 35^{o}C**						
	T_{in} (^{o}C)	**T_{out} (^{o}C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	35	34.7	265.2	1.61	263.6	99.39
Volume 2	34.5	33.4	263.1	1.52	261.58	99.42
Volume 3	33	32.7	258.21	2.37	255.84	99.1
Total	35	32.7	786.52	5.5	781.02	99.3

The results obtained from the third test ,shown in table 4.6, shows the actual energy efficiency of the SHWST using PW (thickness of 4-cm).When water flows in at 35^{o}C , the energy efficiency increase by 8.72% compared to the traditional SHWST under the same conditions.

The average of the energy efficiency of the SHWST, using an amount of paraffin wax of 4cm ,reached 99.36% which seems to be higher than the traditional SHWST by 6.36%.

The figure (4.16) shows the temperature of water flowing out of the SHWST using PW (3-cm) during the draw-off test with a flow rate average of 7.14 liter/min.

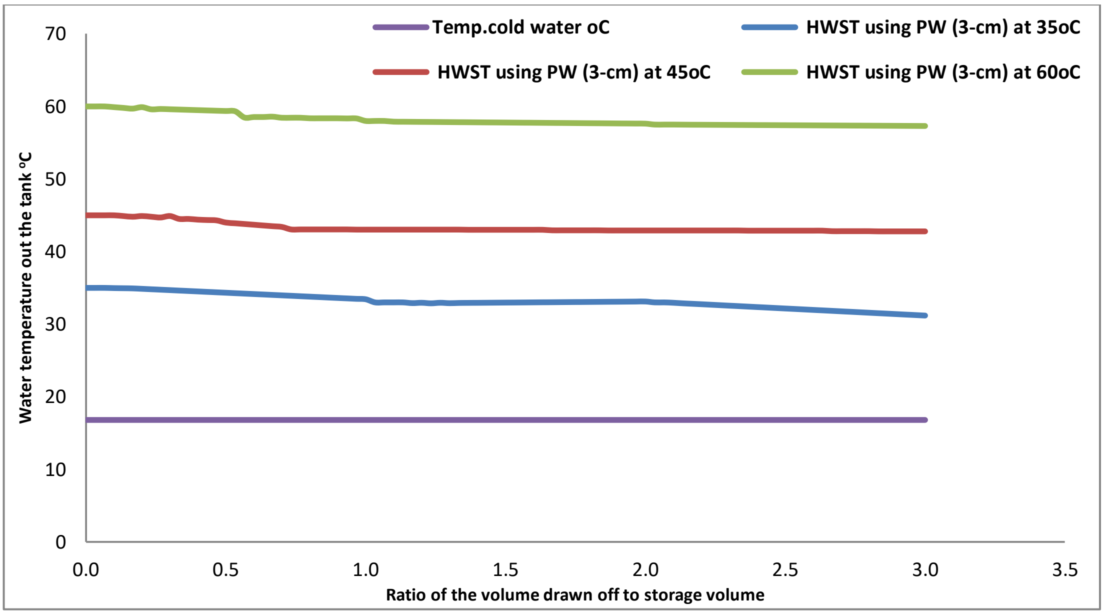

Fig.(4.16)Draw-off curves for the different water temperature flowing in the SHWST using PW(3-cm) (7.14l/min)

Figure (4.16) shows the actual performance of the SHWST surrounded by 3cm of paraffin wax at different temperatures of water flowing into the tank. It also shows that the actual efficiency of the SHWST ,using PW of 3cm, is higher than the traditional SHWST .However, this design's efficiency seems to be lower than the tank surrounded by 4cm of PW. The tables (4.7,4.8,4.9) shows an analysis of the energy efficiency of this design.

Table 4.7: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (3-cm) when water flows into the tank at 60°C ($\dot{m} = 7.14\ L/min$)

The First Test Water flows into the tank at a temperature of 60°C						
	T_{in} (°C)	T_{out} (°C)	Q_{ch} (kW)	Q_{disch} (kW)	$Q_{effective}$ (kW)	μ (%)
Volume 1	60	59.2	471.12	5.76	465.36	98.73
Volume 2	58	57.63	401.63	7.74	393.89	98
Volume 3	57.5	57.3	407.21	2.73	404.42	99.31
Total	60	57.3	1279.96	16.23	1263.72	98.73

The results shown in table (4.7) shows that the energy efficiency of the tank surrounded by 3cm of PW reached 98.73% which is higher than the traditional SHWST by 2.73% and lower than the tank surrounded by 4cm of PW by 1.6%.

Table 4.8: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (3-cm) when water flows into the tank at 45°C ($\dot{m} = 7.14\ L/min$)

The Second Test Water flows into the tank at a temperature of 45°C						
	T_{in} (°C)	T_{out} (°C)	Q_{ch} (kW)	Q_{disch} (kW)	$Q_{effective}$ (kW)	μ (%)
Volume 1	45	43.03	275.2	6.85	268.35	97.51
Volume 2	43	42.05	296.3	7.85	288.45	97.35
Volume 3	42	41.68	253.32	6.7	246.62	97.3
Total	45	41.68	824.82	21.4	803.42	97.41

As shown in table (4.8) ,the results obtained from the second test shows that the energy efficiency of the tank surrounded by 3cm of PW reached 97,41% which seems to be higher than the traditional SHWST by 5% and lower than the tank surround by 4cm of PW by 2%.

Table 4.9: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (3-cm) when water flows into the tank at 35°C ($\dot{m} = 7.14\ L/min$)

The Third Test Water flows into the tank at a temperature of 35°C						
	T_{in} (°C)	T_{out} (°C)	Q_{ch} (kW)	Q_{disch} (kW)	$Q_{effective}$ (kW)	μ (%)
Volume 1	35	34.23	270.31	16.95	253.36	93.72
Volume 2	34	33.61	254.26	13.48	240.78	94.7
Volume 3	33.5	31.19	261.2	14.88	246.32	94.3
Total	35	31.9	785.77	45.31	740.46	94.23

As shown in table (4.9) , the energy efficiency became lower by 5.72% compared to the SHWST that is surrounded by 4cm of PW ,and higher than the traditional SHWST using the same procedures and under same conditions .

As shown in table (4.7 ,4.8 ,4.9), the energy efficiency seems to be lower by 3.75% compared to the previous design .The reason for this is the amount of PW that was used compared to the previous design .However , the energy efficiency using this design seems to be higher than the traditional SHWST by 2.75%.

The figure (4.17)) shows the temperature of water flowing out of the SHWST using PW (2-cm) during the draw-off test with a flow rate average of 7.14 liter/min.

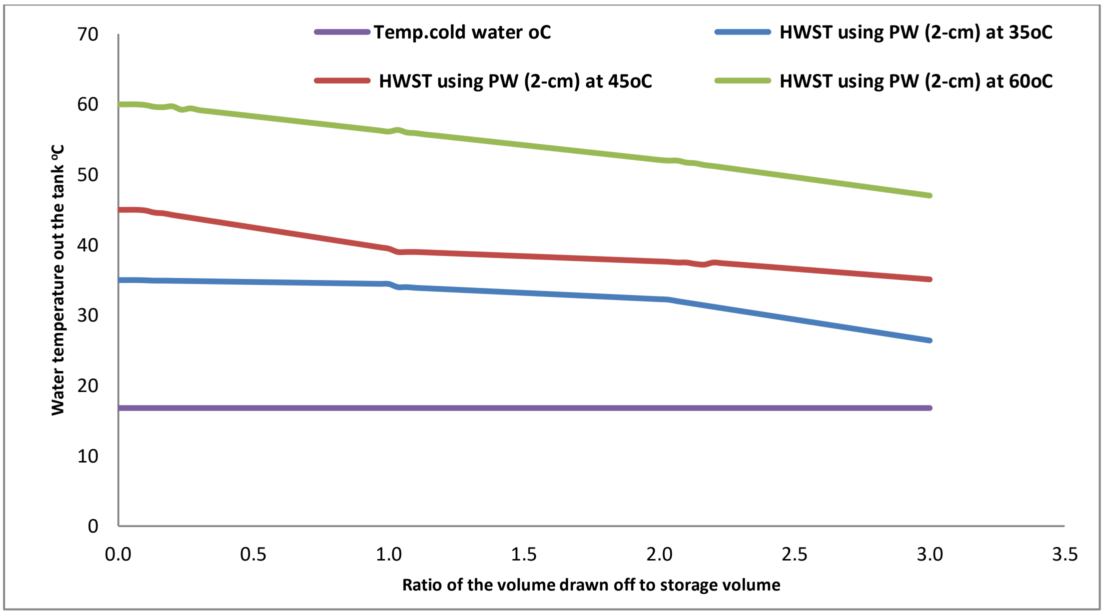

Fig.(4.17) Draw-off curves for the different water temperature flowing in the SHWST using PW(2-cm) (7.14l/min)

Figure 4.17 shows that the performance and efficiency of the SHWST seems to be lower compared by the two previous designs .The is due to two reasons : the first is small amount of PW that surrounded the tank compared to the previous designs. The second reason is the increase in the temperature of PW which will result in loss in the heat stored inside the PW.

The tables (4.10,4.11,4.12) shows an analysis of energy efficiency for SHWST using PW (thickness of 2cm) at different temperatures of water flowing in the tank.

Table 4.10: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (2-cm) when water flows into the tank at 60°C ($\dot{m} = 7.14\ L/min$)

The First Test Water flows into the tank at a temperature of 60°C						
	T_{in} (°C)	**T_{out} (°C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	60	56.4	666.14	26.93	639.21	95.96
Volume 2	56	52.33	604.46	29.89	574.57	95.05
Volume 3	52	47	507.77	36.46	471.31	92.82
Total	60	47	1253.10	56.82	1196.28	95.47

The results shows that the energy efficiency of the tank surrounded by 2cm of PW reached 95.47% which is lower than the traditional SHWST by 0.53% and lower than the previous designs by 3.5% and 2.7%.

Table 4.11: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (2-cm) when water flows into the tank at 45°C ($\dot{m} = 7.14\ L/min$)

The Second Test Water flows into the tank at a temperature of 45°C						
	T_{in} (°C)	**T_{out} (°C)**	**Q_{ch} (kW)**	**Q_{disch} (kW)**	**$Q_{effective}$ (kW)**	**μ (%)**
Volume 1	45	39.4	434.84	39.46	395.38	90.93
Volume 2	39	37.6	342.32	10.10	332.23	97.05
Volume 3	37.5	35.1	298.60	15.87	282.73	94.69
Total	45	35.1	766.13	48.86	717.26	93.61

The results in table 4.11 shows that the energy efficiency of the design reached 93.61% which is higher than traditional tank by 1.2% and higher than the previous two designs by 3.7% and 6.1%.

Table 4.12: Amount of heat charge ,heat discharge and the energy efficiency of the SHWST using PW (2-cm) when water flows into the tank at 35°C ($\dot{m} = 7.14\ L/min$)

The Third Test Water flows into the tank at a temperature of 35°C						
	T_{in} (°C)	T_{out} (°C)	Q_{ch} (kW)	Q_{disch} (kW)	$Q_{effective}$ (kW)	μ (%)
Volume 1	35	34.1	280.64	4.15	276.5	98.5
Volume 2	34	32.4	265.22	13.6	251.7	94.8
Volume 3	32	26.4	219.26	41.28	177.97	81.1
Total	35	26.4	765.13	58.1	707	92.41

The results presented in table 4.12 shows that the energy efficiency of the design reached 92.4% which is higher than the traditional by 1.8% and lower than the previous designs by 4.2% and 2%.

By studying the results and data that were obtained from the 3 tests , it can be noted that the energy efficiency of design (with 2cm of PW) seems to be lower than the two previous designs . The results shows that the energy efficiency was decreased by 6.71% compared to the first design and by 3.12% compared to the second design .With that being said, the energy efficiency increased by 1.25% compared to the traditional SHWST.

The results obtained from this study shows that adding phase change materials (PCMs),which are regarded as the most used material in latent heat storage system, to the SHWST resulted in raising the performance and the efficiency of the SHWST. Table 4.13 shows the actual performance of different designs of the SHWST using PCMs compared to the traditional SHWST that uses sensible heat.

Table 4.13: Energy efficiency ,thermal efficiency and heat lose coefficient (UAs) for the three different SHWSTs using PW (thickness 2,3 and 4cm) compared to the traditional SHWST

	Sensible heat storage(SHS)	Latent heat storage (LHS)					
	Traditional SHWST	SHWST using PW (thickness 2-cm)	Performance indicators Compare with traditional SHWST	SHWST using PW (thickness 3-cm)	Performance indicators Compare with traditional SHWST	SHWST using PW (thickness 4-cm)	Performance indicators Compare with traditional SHWST
Heat lose coefficient (UAs)	3.321 W^oC^{-1}	3.271 W^oC^{-1}	-1.5%	1.37 W^oC^{-1}	-58.74%	1.152 W^oC^{-1}	-65.3%
Thermal efficiency (%)	91.51%	92.01%	+0.5%	94.8%	+3.29%	95.47%	+3.96%
Energy efficiency at 35°C (%)	90.58%	92.41%	+1.83%	94.23%	+3.65%	99.3%	+8.72%
Energy efficiency at 45°C (%)	92.39%	93.61%	+1.22%	97.41%	+5.02%	99.45%	+7.06%
Energy efficiency at 60°C (%)	96%	95.47%	-0.53%	98.73%	+2.73%	99.32%	+3.32%

Chapter 5

CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

This thesis presents an experimental study on the use of paraffin wax as a type of phase change material in the hot water storage tank. This experiment was conducted by studying three different cases depending on the amount of wax that is used around the tank (thickness 4-cm, 3-cm and 2-cm) .In this thesis ,two experimental tests are discussed. The first was done by raising water temperature inside the tank to 45°C without water flow rate (thermal storage tank test) and the second is a draw-off test in which the flow rate is calcualated.The main conclusions that were derived from this thesis can be stated as follows:

- The use of latent storage systems improves the efficiency of thermal storage systems.
- In the first case ,when the PW's thickness around the tank is 4 cm, the thermal efficiency was improved by 4.23% compared to the traditional SHWST and the storage tank heat loss coefficient (UAs) equal 1.152W^oC^{-1}. Consequently, electricity consumption to raise the temperature of water inside the tank is reduced annually by 67.5% compared with traditional SHWST.
- In the second case ,when the PW's thickness around the tank is 3 cm, the thermal efficiency was improved by 3.29% compared to the traditional SHWST and the storage tank heat loss coefficient (UAs) equal 1.37W^oC^{-1}. Consequently, electricity consumption to raise the temperature of water inside the tank is reduced annually by 56.42% compared with traditional SHWST.
- In third case, when PW's thickness is around the tank 2 cm, negative results were obtained compared to the previous two cases. The thermal efficiency was improved by 1.5 % compared to the traditional SHWST and the storage tank heat loss coefficient (UAs) equal 3.217 W^oC^{-1}. Consequently, electricity consumption to raise the temperature of water inside the tank is reduced annually by 6.1% compared with traditional HWST.
- By comparing the energy efficiency ,which was derived from the draw-off test, it was noted that the energy efficiency was increased by 6.35% in first case ,3.8% in second case, and 0.8% in the third case compared to the traditional SHWST.

Finally, the development of heat storage systems helps in the utilization of excess energy. The use of phase change materials in these systems helps to increase their thermal storage capacity and thermal efficiency.

5.2 Recommendation and future work

This study showed the use of paraffin as a type of phase change material in thermal storage system resulted in increasing thermal efficiency for these systems . However, this application requires further studies to facilitate its use in future designs .

The recommendation for future work includes experimental, numerical and analytical studies in order to better understand the latent heat storage system by using phase change material and building better designs for these systems .

- In this study, an experiment on the use of PW was conducted as a surrounding hot water storage tank material .This design requires the building of a numerical model using CFD software for better comparing the results obtained from the practical experiment with the theoretical study results at the same working conditions .
- Conducting a comprehensive analytical on renewable energy sources in Palestine and the amount of annual solar radiation as well as studying the potential and suitability of using solar thermal storage systems in Palestine .
- Adding the design of hot water storage tank with paraffin wax on the solar thermal storage system and conducting theoretical and practical experimental studies .
- In this study , paraffin wax was used as a type of phase change material .The need for further studies on different types of these materials is required for using them in solar thermal storage system application .

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APPENDICES

Appendix A : paraffin wax (60-62 ^{o}C) Specification

Appendix B: PT100 Sensor Specification Data Sheet

Appendix C : Field-logger Data sheet

Appendix A : paraffin wax (60-62 °C) Specification [39]

HEBEI BLUE STONE COPPER INDUSTRY CO., LTD

Technology Electronic Square of West Business Buildings, Xinhua District,Shijiazhuang City, Hebei, China

TEL: 0086-311-80818565 FAX: 0086-311-67265126

Kunlun Brand Paraffin Wax

Specifications we supply:

Fully Refined Paraffin Wax Slab: 54#, 56#, 58#, 60#, 62#,64#, etc;
Semi Refined Paraffin Wax Granular: 54#, 56#, 58#, 60#, 62#,64#, etc.
Packing Method: (Slab) 50+/- 0.3kg Plastic Woven Bag,
(Granular) 25+/- 0.3 kg Plastic Woven Bag.

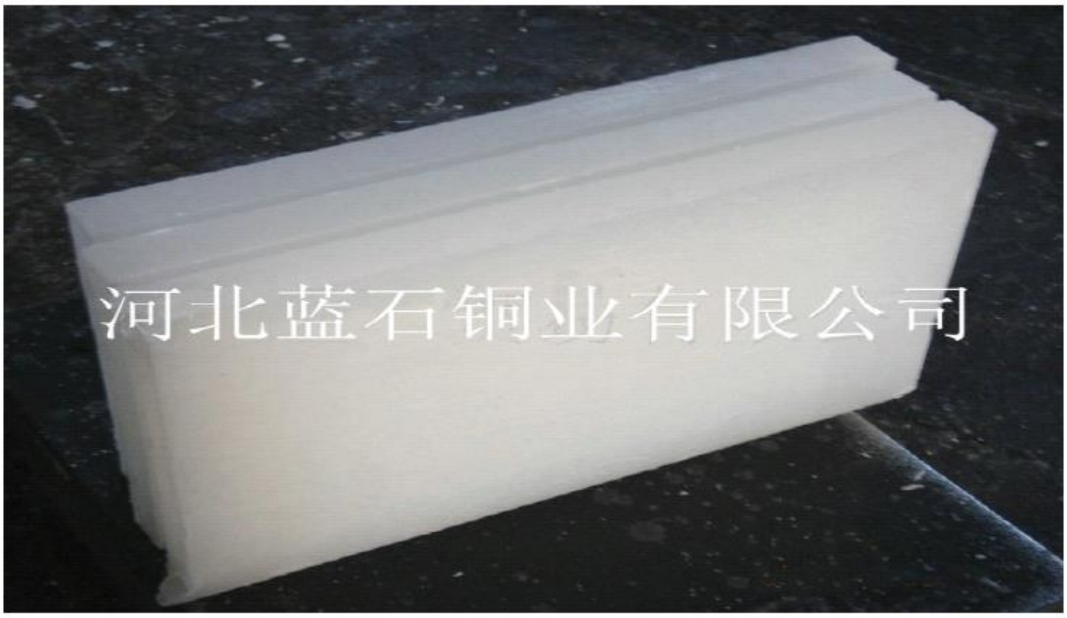
Paraffin Wax Quality Index Parameter

Specifications of the Fully Refined Paraffin Wax:

Items \ Products	54#	56#	58#	60#	62#	64#
Melting Point	54-56℃	56-58℃	58-60℃	60-62℃	62-64℃	64-66℃
Oil Content, %（m/m）	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5
Penetration（25℃,100g) 1/10mm	≤18	≤18	≤18	≤16	≤16	≤16
Color White) No.	≥+28	≥+28	≥+28	≥+25	≥+25	≥+25
Light Stability	≤4	≤4	≤4	≤5	≤5	≤5
Odour	0	0	0	0	0	0

Specifications of the Semi Refined Paraffin Wax:

Products / Items	54#	56#	58#	60#	62#	64#
Melting Point	54-56℃	56-58℃	58-60℃	60-62℃	62-64℃	64-66℃
Oil Content, %（m/m）	≤1.5	≤1.5	≤1.5	≤1.5	≤1.5	≤1.5
Penetration（25℃,100g) 1/10mm	≤23	≤23	≤23	≤23	≤23	≤23
Color（White) No.	≥+17	≥+17	≥+17	≥+17	≥+17	≥+17
Light Stability	≤6	≤7	≤7	≤7	≤7	≤7
Odour	0	0	0	0	0	0



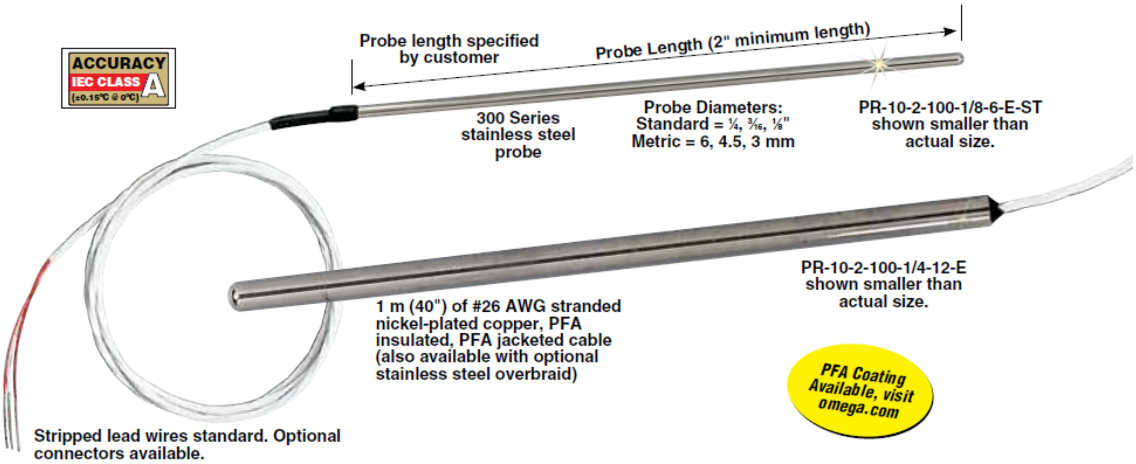
Appendix B : PT100 Sensor Specification Data Sheet [40]

General Purpose RTD Probes

With PFA Jacketed Cables for Laboratory Applications

OMEGA™

- Transitions Directly to Lead Wires (No Transition Fitting)
- Compact Design for Applications with Space Restrictions
- Available in Standard and Metric Sizes
- Temperature Range: -200 to 600°C (Cable and Last 2" of Probe to 260°C)
- High-Accuracy Wire Wound, 100 Ω Class "A" DIN Platinum Elements per IEC 751 (alpha = 0.00385 Ω/Ω/°C)
- 2-, 3-, 4-Wire Constructions Available



Standard Dimensions

To Order

Model Number	Lead Wire Style*	Sheath Length
PR-10-2-100-(*)-6-E	3 Wire	6"
PR-10-2-100-(*)-12-E	3 Wire	12"
PR-10-2-100-(*)-18-E	3 Wire	18"
PR-10-2-100-(*)-24-E	3 Wire	24"

** Specify "**-1/8**", "**-3/16**", or "**-1/4**" for probe diameter in inches. To order with shrink tube strain relief, specify "**-ST**" at end of model number. To order probes in intermediate lengths, change model number, using next longer probe price. Over 24", add additional cost per inch of probe length. Stainless steel overbraid or BX cable also available. For leads longer than 40", add lead length to end of model number for additional cost. For 4-wire configuration, change "**2**" in model number to "**3**" for additional cost (note: 4-wire not available in ⅛ or 3 mm sizes). **Note:** SB braid not available on ⅛" diameter probes.*

***Ordering Example: PR-10-2-100-1/8-12-E-OTP,** 100 Ω, class "A" RTD with a ⅛" diameter by 12" long probe, 40" of 3-wire cable and OTP connector.*

Metric Dimensions

Model Number	Lead Wire Style*	Sheath Length
PR-10-2-100-(*)-150-E	3 Wire	150 mm
PR-10-2-100-(*)-300-E	3 Wire	300 mm
PR-10-2-100-(*)-450-E	3 Wire	450 mm
PR-10-2-100-(*)-600-E	3 Wire	600 mm

** Specify "**-M30**" for 3 mm, "**-M45**" for 4.5 mm or "**-M60**" for 6 mm for probe diameter in millimeters. To order with shrink tube strain relief, specify "**-ST**" at end of model number. To order probes in intermediate lengths, change model number, using next longer probe. Over 600 mm, add additional cost per 25 mm of probe length. For leads longer than 1 m, add lead length to end of model number, for additional cost per meter to price. For 4-wire configuration, change "**2**" in model number to "**3**" for additional cost to price (note: 4-wire not available in ⅛ or 3 mm sizes). **Note:** SB braid not available on 3 mm diameter probes.*

***Ordering Example: PR-10-2-100-M45-150-E-OTP,** 100 Ω, class "A" RTD with a 4.5 mm diameter by 150 mm long probe, 1 m of 3-wire cable and OTP connector.*

Appendix C : Field-logger Data sheet [41]

NOVUS
We Measure, We Control, We Record

Introduction

FieldLogger

FieldLogger is a versatile, powerful and yet cost effective data logger. The **FieldLogger** handles analog and digital input signals. Powerful mathematical functions and high resolution and speed make it the ideal data logging solution. FieldLogger features high performance along with high connectivity and ease of configuration and operation.

FieldLogger's local inputs include 8 software configurable analog inputs for thermocouples, Pt100, Pt1000, voltage and current signals. Two relay outputs and 8 digital ports are included. Digital ports are individually configurable as inputs or outputs. Up to 64 channels of remote inputs are available. Power supply availability of 90 to 240 V or 24 V.

Up to 128 mathematical channels can be used to perform operations on the measured values. Up to 32 alarm events can be detected, allowing output activations, e-mails and SNMP traps for e-mail notification. Networking greatly expands available alarm and calculation capability.

The RS485 interface can operate as a Modbus RTU master or slave. As a master, it can read and log up to 64 remote channels. It's 10/100 Mbps Ethernet interface allows access through a browser (HTTP), remote data download (FTP cliente and server), e-mails (sending SMTP, SNMP) and Modbus TCP.

FieldLogger has one USB interface to be connected to a computer (for configuration, monitoring and data download) and another USB port for plug-in flash drive for data retrieval. The 512k logging basic memory is used to store data and it can be greatly expanded to over 16 GB with an SD card.

An exclusive color HMI (human-machine interface) can be attached locally or remotely installed for indication or configuration. Our FREE user friendly configuration and monitoring software can be accessed by Ethernet, USB or RS485 and also provides on-line monitoring, data logging, plus downloading and exporting to spread sheets.


Model with HMI


Model without HMI

Resources for

Measurements and Loggings

Input channels

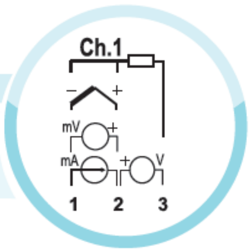
- Available types:
  - Analog
  - Digital
  - Remote (registers read from external Modbus slaves)
  - Virtual (outcomes from mathematical operations on other channels)

* All channels can be logged and/or used for alarms.

Digital I/O

- Digital I/O individually configured as inputs or outputs
- 2 relay outputs (NO, NC and common)
- Pulse count capability

Analog inputs



- 8 universal analog input channels:
  - Thermocouples (J, K, T, N, E, R, S and B), 0-5V, 0-10V, mV, mA, Pt100 and Pt1000
  - Reading rates of up to 1000/second
  - 24 bit A/D conversion resolution

Mathematical operations

- Capable of up to 128 virtual channels
- Each virtual channel is a mathematical or logical operation on the input channels
- The outcome of a virtual channel can be used as an input for another channel, allowing the implementation of complex formulae

Alarms

- Up to 32 configurable alarms
- Any channel can be used in a comparison with a setpoint
- Alarm actions may include:
  - Relay activations
  - Digital outputs activations
  - E-mails sending for multiple targets
  - SNMP traps sending
  - Loggings start and stop

Loggings

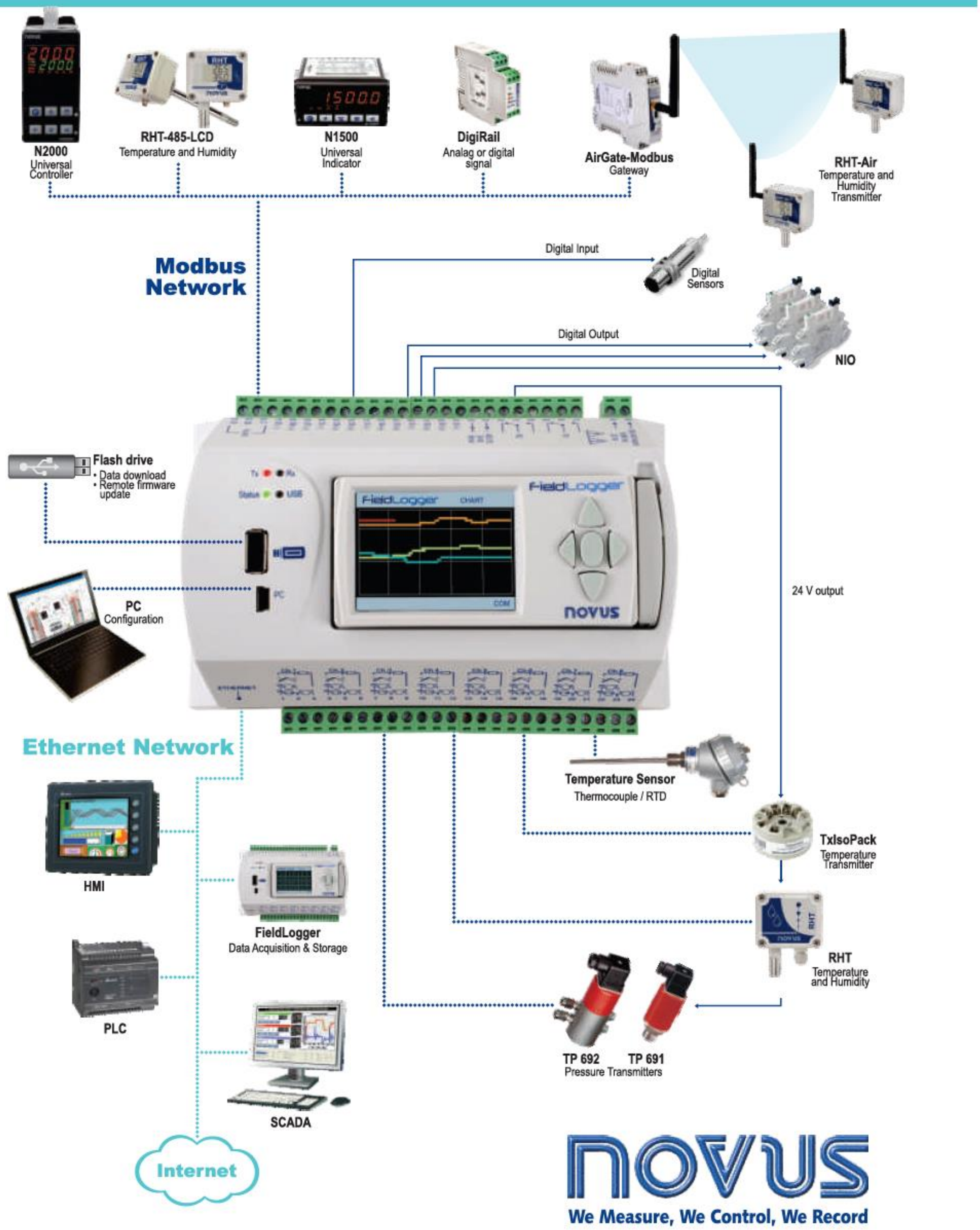
- Basic internal memory up to 512,000 loggings can be stored and up to 100 channels recorded
- When inserting a SD or SDHC card (optional), memory capability is expanded
- Data files are encrypted to meet FDA 21 CFR Part 11 and other Federal Agency requirements
- Logging rate can be as fast as 1000/second
- Data download can be done with the configuration software through a flash drive, USB device, RS485 or Ethernet interface
- Using the configurator, downloaded data can be viewed and exported for several formats: XLS, PDF, CSV, RTF, NOVUS SuperView and FieldChart

Remote Registers

- Operating as a Modbus master, allows reading and logging up to 64 remote channels (a remote channel is a register read from an external Modbus slave)

Resources for

Modbus Network / Ethernet Network



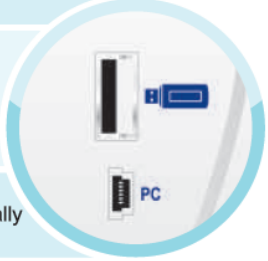
Multiple Interfaces

RS485 / USB / Ethernet

RS485 Interfaces

- Modbus RTU protocol
- The main interface can act as a master or slave (communicating with SCADA systems)
  - Communication with multiple Modbus RTU slave devices
  - Allows acquisition of up to 64 external channels (remote channels)
- The secondary interface is always slave and alows HMI connection

USB Interface



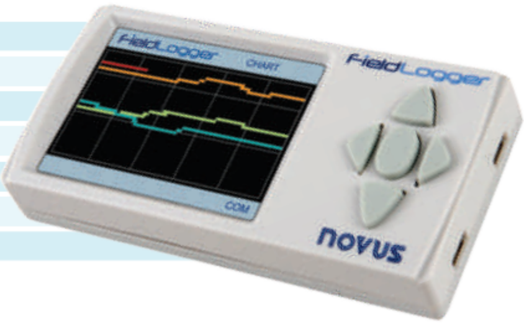
- Has two USB interfaces
- USB Device: connecting with a computer
  - Configuration and logged data download
  - Uses a standard Mini-B USB cable (included)
  - Computer USB port is seen as a virtual serial (COM) port
  - Communication using Modbus RTU protocol
- USB Host: flash drive
  - When a flash drive is plugged in download of the logged data is started automatically
  - The period of time for the data transfer to the flash drive is adjustable

Interface Ethernet

- Ethernet 10/100 Mbps
- Services and protocols available:
  - DHCP: Search network parameters automatically
  - HTTP: Server of customizable pages with equipment information, alarms and channels readings
  - FTP (Client and Server): Download of the logged data (CSV format in Client mode)
  - SNMP: Allows monitoring via network management software
  - SMTP (Client): Sends e-mail messages on alarm conditions
  - Modbus TCP: Communication with SCADA systems
  - Can serve pages in XML format,which allows data to be worked externally (example: creation of customized web pages)
  - NOVUS Cloud Gateway connection
- Can act as a gateway between a Modbus TCP and a Modbus RTU networks

Introduction

FieldLogger HMI

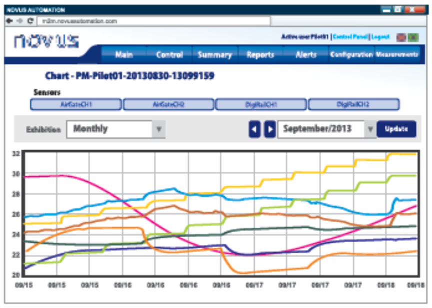


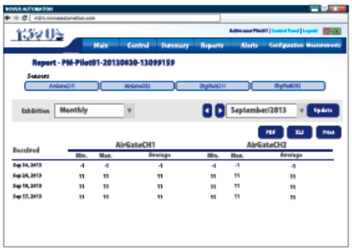
- Color QVGA screen 2.4”
- 96 x 48 mm format
- Shows the current channel values or a historical chart
- Indicates FieldLogger status and alarms information
- Allows parameter checking and configuration
- Local or remote installation with RS485 communication
- Optional: kit for HMI remote mounting

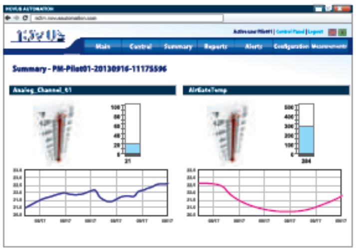
Software Tools

NOVUS Cloud Gateway

The FieldLogger is fully compatible with the **NOVUS Cloud Gateway** service. Binding the **FieldLogger** to the Cloud brings a new way to store, analyze and export historic data from remote or local processes. Acting as a simple Modbus packet router or as online data storage server, the **NOVUS Cloud Gateway** offers an intuitive web interface that allows users to view recent data, connection status, reports on logged data and also system exceptions of all remote telemetry points.

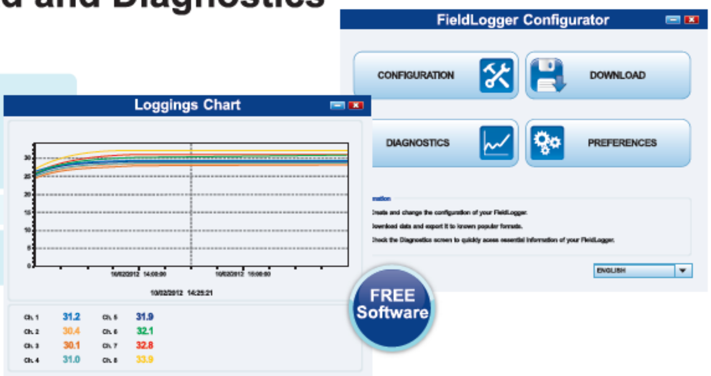






Configuration, Download and Diagnostics

- User friendly interface to:
  - Download, view and export data
  - Configuration and set-up
  - System diagnostics
- "Wizard" format (step-by-step guide)
- Can communicate through USB, RS485 or Ethernet



Check some other NOVUS products

- Process Controllers
- Electronic Thermostats
- Pressure Transmitters
- Conditioners & Isolators
- Temperature Transmitters
- Humidity Transmitters
- Data Loggers
- DAQ - Data Acquisition
- Softwares & RTUs
- Recording & Supervision
- Timers & Counters
- Calibrators & Handhelds

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