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Enhancement of Solar Water Heater Performance Using Phase Change Materials

A Thesis
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By

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بسم الله الرحمن الرحيم

﴿ هُوَ الَّذِي جَعَلَ الشَّمْسَ ضِيَاءً وَالْقَمَرَ نُورًا وَقَدَّرَهُ مَنَازِلَ لِتَعْلَمُوا عَدَدَ السِّنِينَ وَالْحِسَابَ مَا خَلَقَ اللَّهُ ذَلِكَ إِلَّا بِالْحَقِّ يُفَصِّلُ الْآيَاتِ لِقَوْمٍ يَعْلَمُونَ ﴾ [يونس: 5]

صدق الله العظيم

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ABSTRACT

The solar water heater system (SWHS) is a well-known renewable energy technology that has gained a lot of global attention. The main drawback of such a system that it doesn't work on cloudy days or at night. This work introduces an approach to the integration of Phase Change Materials (PCMs) within Evacuated Tube Solar Collectors (ETSC) for SWHS for domestic applications. The benefit of this technique is to enhance the thermal performance by delaying heat release, thus providing hot water when the intensity of the solar radiation is insufficient or during high-demand hours. Two models of ETSC namely: a heat pipe (HP) and a U-shaped tube were experimentally tested with and without PCM. The SWHS was tested experimentally during normal operation and at mass flow rate of 0.5,1and1.5 l/min.The simulation model was developed using CFD ANSYS Fluent R21 to analyze the melting and solidification process of PCM inside U-tube ETSC. The experimental and numerical results showed that the time of the PCM melting process is directly proportional to the flow rate. The time of the solidification process is inversely proportional to the flow rate. The time delay for heat stored inside PCM integrated with HP -ETSC to HTF was approximately 2.16, 1.36 and 1.16 hours, for HTF flow rate of 0.5, 1and1.5 L/min respectively. The experimental abservations show that the enhancement efficiency of HP–ETSC with integrating of PCM reach up to 28%, 22% and 16% as compared with simple HP-ETSC corresponds to flow rates of 0.5, 1 and 1.5 l/min respectively. The maximum increase in useful energy of HP–ETSC was up to13%, 10% and 2% compared to simple configuration at flow rate of 0.5, 1 and 1.5 l/min respectively. Further the time period for heat release to HTF when using PCM with U-ETSC was approximately 77 ,60 and 31 min for HTF flow rate of 0.5,1,and 1.5 L/min respectively. However, enhancement in efficiency of U–ETSC with integrating of PCM up to 26%, 20% and 12% at flow rates of 0.5, 1 and 1.5 l/min respectively. as compared to simple configuration of U-ETSC. The maximum rise in useful energy of U -ETSC with PCM can be reached up to 15%, 14% 10% at flow rate of 0.5, 1 and 1.5 l/min respectively. compared with simple U-ETSC system. As can be seen that HP-ETSC thermal performance is better than U-ETSC by providing a higher difference in

HTF temperature between entry and exit and extended working time of SWHS during the night or cloudy days when integrated with PCM.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES		
Table No.	***Titles***	***Page no.***

Latin symbols

Symbol	Description	Unit
A_{mush}	Mushy zone constant	-
C_F	Inertial drag factor of the Metal Foam	-
$C_\mu, C_{1\varepsilon}, C_{2\varepsilon}$	Constants in (k-ϵ) Model	-
h	Sensible enthalpy	kJ/ kg
h_{ref}	Reference temperature enthalpy	kJ/ kg
k	Turbulent kinetic energy	kJ/ kg
k_{eff}	Effective thermal conductivity	W / m ^oC
k_{PCM}	Thermal conductivity of the PCM	W / m ^oC
L	Latent heat of the PCM	kJ/ kg
T	Local Temperature	^oC
T_O	Operating temperature of the PCM	^oC

Greek Symbols

Symbol	Description	Unit
α	Thermal diffusivity	m^2/s
γ	Liquid fraction	-
μ	Dynamic viscosity	kg / m.s
μ_t	Turbulent eddy viscosity	M
ρ	Density	kg / m^3
$\rho 0$	Operating density of PCM	kg / m^3
σ_ϵ, σ_k	Constants in (k-ϵ) model	-
$\nabla.$	Divergence	-
ϵ	Turbulent dissipation rate	m^2/s^2

Subscripts

Symbol	Definition
c	Cross-sectional
eff	Effective value
ref	Reference value
f	Ligament
H	Hydraulic
i, j	Tenser
in	Inlet
m	Melting
p	Pore
s	Surface
t	Turbulent

0	Operating Value

Abbreviations

Abbreviations	Definition
ETSC	Evacuated tube solar collector
FPC	Flat plate collectors
GNP	Graphene nanoplatelets
HP- ETSC	Heat pipe evacuated tube solar collector
HTF	Heat transfer fluid
LHTES	Latent heat thermal energy storage
MWCNT	Multi-walled carbon-nanotubes
Ne-PCM	Nano-enhanced PCM
PCMs	Phase Change Materials
PV/T	Photovoltaic Thermal
PEG	polyethylene glycol
SHTES	Sensible heat thermal energy storage
SC	Solar collector
SWDH	Solar water domestic heater
SWHS	Solar water heater system
TES	Thermal energy storage
TEA	Triethanolamine
U-ETSC	U pipe evacuated tube solar collector
UDF	User define function

CHAPTER ONE
INTRODUCTION

1.1. Background

The energy crisis is one of the biggest problems encountered in the world in recent decades, caused by rapid population growth, the rising in living standards and industrialization. Conventional energy resources like natural gas, coal, and petroleum takes around 80 % of the global production of commercial energy, **[1]**. However, researchers were driven to use clean energy resources to overcome the traditional limiting energy resources that affect human health and have major environmental impacts due to excessive CO_2 emissions **[2]**.

An example of a renewable energy resource is solar energy, which is approximately abundant all year and easy to implement with the help of renewable technology. For solar energy applications, the(SWHS) is one of the efficient applications for residential and industrial purposes. Solar energy has an intermittent nature and is time-dependent. A residential home heating requirements change over time. However, most of the time, especially in solar water heating applications, the energy source, and the needs of a house (or building) are incompatible. Although solar radiation is at its highest around noon, the greatest need for heating occurs in the late evening or early morning, when solar radiation is not present **[3]**.

Thermal energy storage (TES) offers a supply of energy to balance this mismatch and supply all energy requirements. It functions as a connection between the energy source and the applications. Thermal energy storage is important for the solar heating system. The thermal energy storage system is one of the most significant and important storage technologies. There are two main kinds of thermal energy storage systems, latent heat thermal energy storage (LHTES) and sensible heat thermal energy storage (SHTES) **[4]**. To get a high-density storage system with significant thermal performance enhancement, PCM have been purposed to utilize in latent heat storage systems for SWHS applications, heat pumps and spacecraft thermal control applications **[5]**.

1.2. Solar Collectors

Solar energy can be harvested and/or concentrated in thermal form using a solar collector Solar Collectors. The collected thermal energy can be transferred by using a working fluid in some thermal applications such as heating spaces and domestic water heating. There are two main types of SCs: concentrated and nonconcentrated SCs can be divided into tracking and non-tracking SCs. The non-tracking SCs are kept stationary at a specific orientation depending on the longitude and latitude of the location. The tracking collectors are used to track the sun to maximize the harvested solar energy and can be subdivided into single-axis tracking and dual-axis tracking, **[6]**. The common types of solar collectors can be shown in Fig (1.1) and Table (1.1)

Table (1.1) Thermal applications and temperature ranges for common types of solar collectors **[7]**.

Collector Types	Temperature range	Application
Flat Plate Collectors (FPC)	30-80 C°	Water and air heating
Evacuated Tube Collectors (ETSC)	60-200C°	Domestic and industrial applications
Concentrated Solar Power (CSP)	400-800 C°	Thermal power plant for Electrical generation

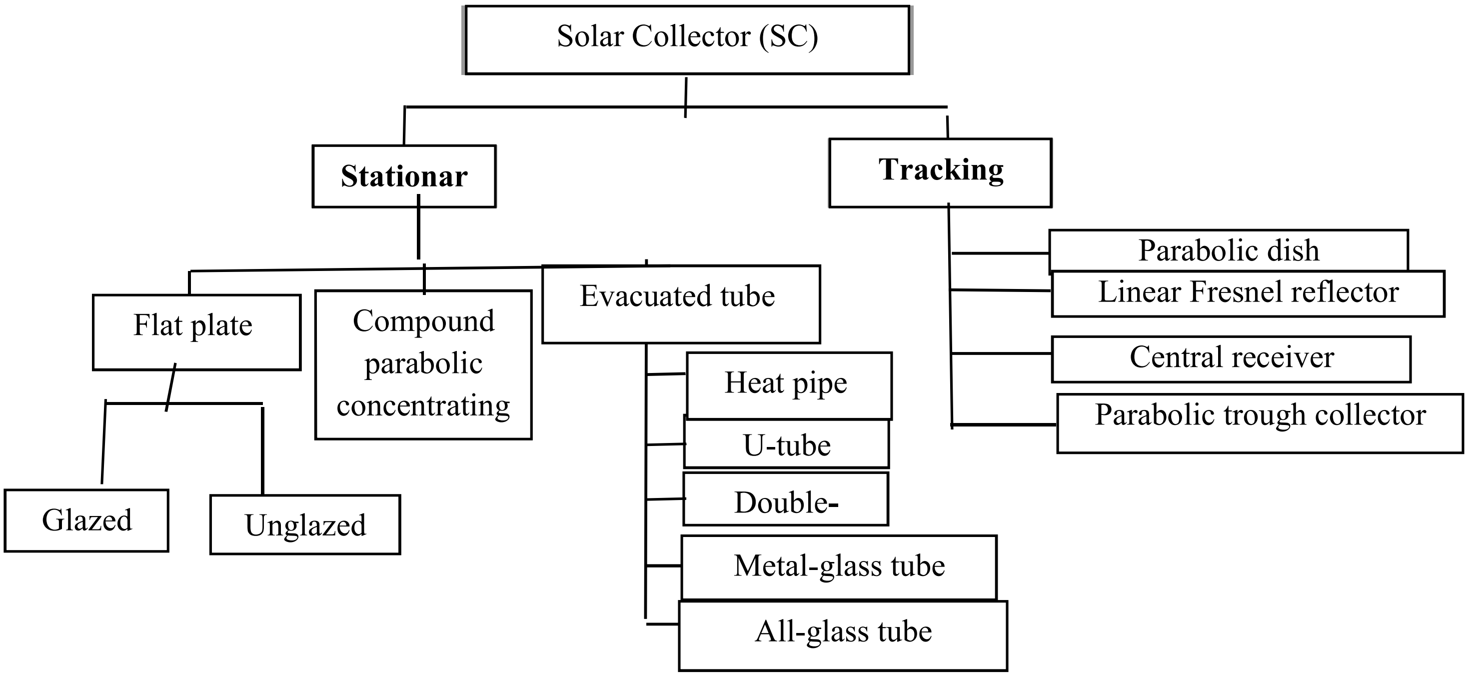


Fig. (1.1): Common solar collector types **[8]**.

1.3 Common configurations of ETSC

The (ETSC) provides higher fluid outlet temperature with lesser heat loss than flat plate collectors due to the combined effect of vacuum insulation of the absorber and a highly selective surface coating **[9,10]**. According to many researchers, **[7, 11** and **12],** ETSCs have much higher thermal performances than FPCs. ETSCs can collect both diffuse and direct radiations. ETSCs have convenient installation and easy transportability, besides excellent thermal efficiencies. ETS is various in their construction and design. The shapes and materials of the absorber are the main differences in evacuated tubes. There are two main kinds of ETSC: all-glass tubes with a cylindrical absorber fin and glass-metal tubes with a copper fin absorber. However, these two groups of ETSC are further divided into many configurations such as U-shape pipe arrangement, heat pipe or direct liquid contact, **[13].** as shown in Figu (1.2**).**

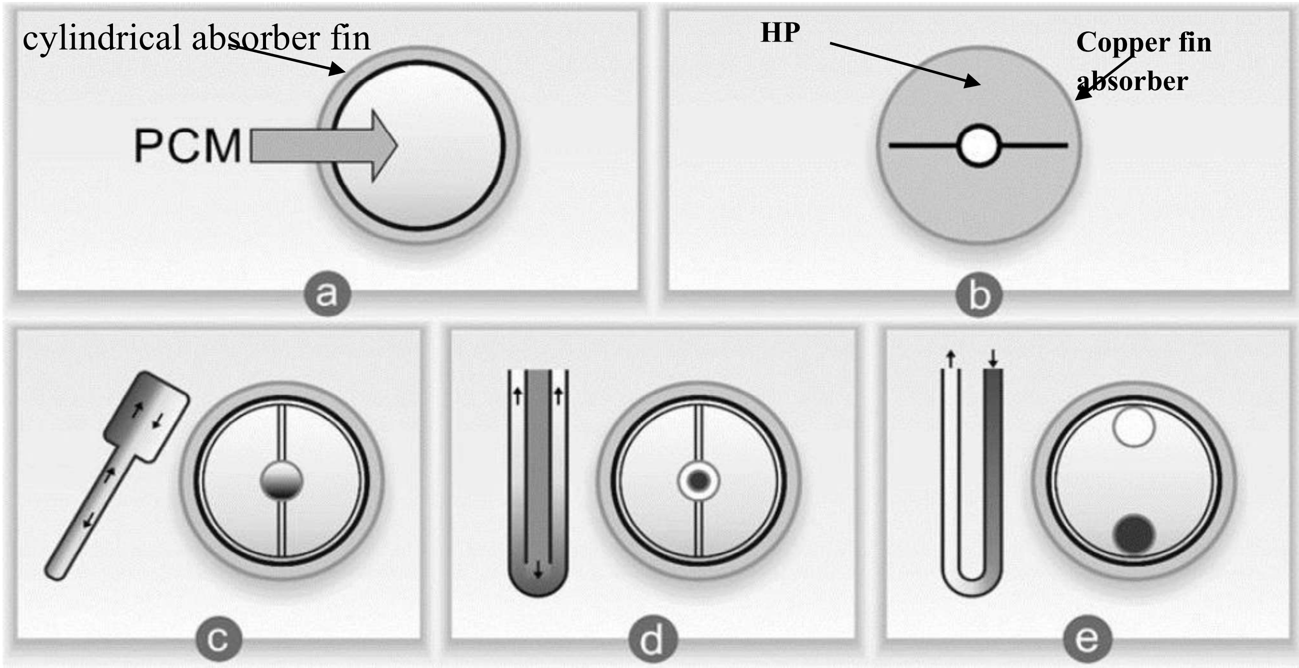
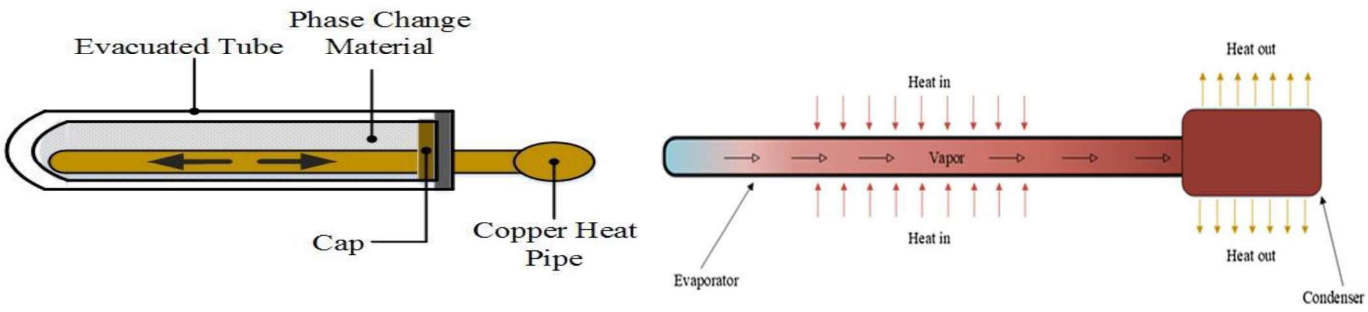


Fig. (1.2) Classification of evacuated tubes collectors **[14]**: **a.** Sydney type (cylindrical absorber) **b.** copper fin absorber **c.** heat pipe **d.** double-pipe (direct flow) **e.** U-tube.

1.3.1 Heat pipe evacuated tube solar collector

In the heat pipe evacuated tube solar collector (HP- ETSC), heat pipe is inserted inside evacuated tube. As seen in Figure (1.3a), the heat pipe, which was employed to increase heat transfer, was strongly held against the tubes that had been selectively coated by a set of spring clips. The heat pipe principle utilized in HP- ETSC can be illustrated in Figure (1.3b). The heat pipe is a device which works on principle of two-phases and contains heat transfer fluid with a low boiling temperature. Low boiling fluid vaporizes and rises to the condenser section (cooling zone) of the heat pipe when heat is delivered to the evaporator section of the heat pipe. As a result, heat pipes' condenser sections heated the fluid moving through the manifold **[15]**.



(a) (b)

Fig. (1.3) Heat pipe evacuated tube solar collector filled with PCM [**15**]

1.3.2 U-shape evacuated tube solar collector

Direct flow ETSC widely known as U-pipe ETSC (U-ETSC) is different from to previous ones in that heat pipe is inserted inside the middle of evacuated tube. One copper pipe serves as the flow pipe in this configuration, and the other copper pipe serves as the return pipe. The evacuated tube bottom pipe has a U-bend where both pipes are brazed together. In this setup, a U-shape tube is put into the evacuated tube as seen in Figure (1.4). To improve heat transfer between the the working fluid and inner surface of the evacuated tube, a metal fins are placed at the U-tube. Compared to installing a U-pipe collector, installing a heat pipe ETSC is simpler due to the "dry" connection between the absorber plate and manifold. Moreover, there is no need for disassembly. If an evacuated tube cracks or breaks, or if the vacuum is lost, it merely replaces the tube rather than emptying the entire arrangement. Closed-loop solar designs benefit from HP-ability ETSC's to expand the number of evacuated tubes **[8]**.

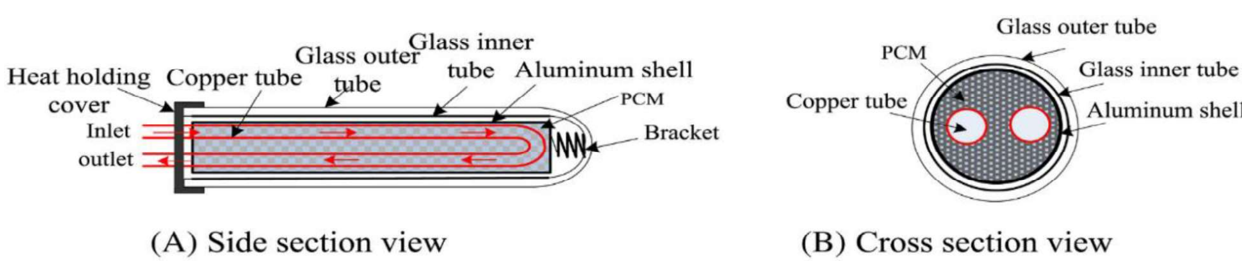


Fig (1.4) PCM integrated with water-in-glass U-tube evacuated solar collector **[16].**

1.3.3 Major Applications of ETSC

Due to their unique ability to collect energy from the sun all day at low angles because of their tubular design, ETSCs are growing in popularity every day. Domestic and industrial application of ETSC is required to heighten. Applications such as air conditioning, refrigeration, desalination of seawater, industrial heating and building heating require higher temperatures, and the thermal performance of an ETSC is better than an FPC for high-temperature operations **[17]**. The utilization of ETSC can be divided in two categories which are industrial and domestic applications **[8]**.

1. Domestic applications: An ETSC is a mature technology for domestic applications as it can operate over a wide range of temperatures from medium to high according to the requirement such as solar hot water, solar cooker, swimming pool, air conditioning and residential houses.
2. Industrial applications: For industrial use, a higher temperature is required compared to domestic applications. An ETSC is capable of generating temperatures up to 200 ^{o}C such as thermal steam plants, solar drying, steam generation for thermal power plants, desalination of sea water, textile, paper, drug , pharmaceutical, and leather industries.

1.4 Enhancement Techniques in ETSCs

There are numerous methods for the performance augmentation in ETSCs which include structural modifications, changing the coating to improve absorptivity or using alternative working fluids within the collector as described in the following sections.

1.4.1 ETSC with Fins

Fins or extended surfaces can provide an additional heat transfer surface in the thermal system and thus increase the heat transfer rate. The commonly used enhancing technique is the use of fins because of its simplicity, ease of fabrication, and reasonable cost **[18,19]**, Several studies investigated the employment of fins with ETSC system, the significant enhancement for ETSC system with using fins, see Fig. 1.2b.

1.4.2 ETSC with Nanofluids

Nanofluids are dilute liquid suspensions of nanoparticles with at least one of their principal dimensions smaller than 100nm. The striking features which make nanoparticles suitable and can dilate for suspension in fluids are small size and a large surface area, less particle momentum, and high mobility. Due to the very small sizes and large specific surface areas of the nanoparticles, nanofluids have many superior properties like minimal clogging inflow passages, long-term stability, and homogeneity, other than having an obvious high thermal conductivity; thermal conductivity of common solid additives and base fluids to achieve a stable nanofluid **[20].** Fig.1.5 shows the application of nanofluids in solar system. Several studies have been conducted on thermal performance enhancement of SWHS by adding nanofluids. Improving the thermal efficiency of the evacuated solar tube collector in solar water heating systems, requires the addition of materials to improve thermal conductivity with nanofluids that give maximum enhancement to improve ETSC efficiency due to excellent heat and heat transfer properties of GNP nanofluids.

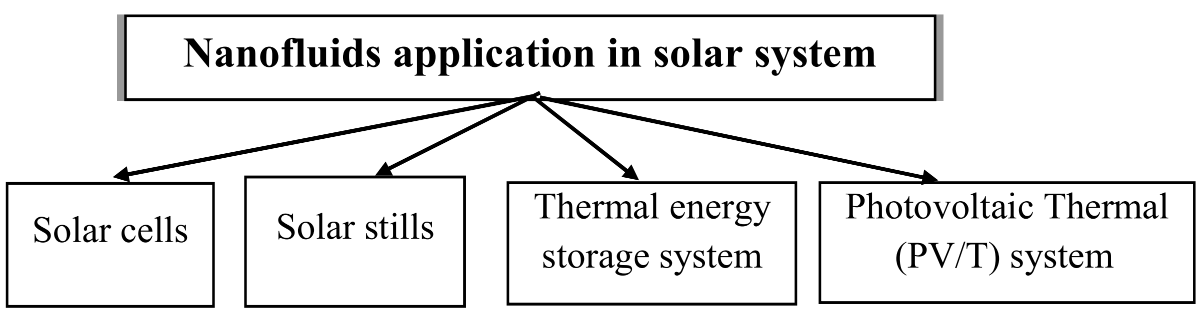


Fig. (1.5) Application of nanofluids in solar system

1.4.3 ETSC integrated with PCM

The conventional SWHS store the energy in the form of sensible heat based on increasing of water temperature. All though this methodology of heating is simple but it is insufficient because of the limitation of TES capacity. Thus, the employment of the TES based on PCM is essential to improve the thermal performance in such systems. The PCM is presented with SWHS through many techniques, including (i) The utilization of a traditional solar collector with a separate unit filled with PCM only. (ii) The utilization of a tank filled with PCM only or with PCM modules as (capsules) inside the water tank supplied by traditional solar collectors (iii) The utilization of solar collectors integrated with PCM. The energy stored within the PCM can be utilized at any time, even when solar radiations are insufficient **[21]**, see Fig. (1.2).and Fig. (1.4)

1.5 Problem Statement

The utilization of solar water heating systems for residential and industrial applications is increasing day by day due to the awareness regarding renewable energy technologies and their beneficial impact on the environment. However, the non-continuous operation due to the nature of solar radiation during the night represents a major drawback of using such systems. Further, the conventional solar water heater systems require important space, and considerable structural components and weight for energy storage. Weight and space needs are a barrier to a further development of solar water domestic heater (SWDH) in buildings with limited structural and space capacities. This makes using these systems more challenging and expensive. When solar water heating systems are added to older buildings, this issue gets considerably worse. Furthermore, a significant problem with solar energy applications is the lag between energy production and consumption. As a solution, ETSC systems can be coupled to TES using PCM as a thermal booster. PCM can be a good solution for these problems due to their low-cost, high storge density and isothermal operation and easy construction to the system. These reasons help the PCM to be worked in a wide range of thermal applications like solar water heating for domestic purposes.

1.6 Objectives of the Present Work

Solar water heater based on ETSC has been proposed to evaluate the thermal performance with and without adding PCM to the ETSC. The main object of the present study is to investigate numerically and experimentally the thermal performance enhancement of two types of ETSCs (U-pipe and heat pipe) with and without the integration of PCM during charging and discharging processes. Therefore, the objectives of this study can be stated as follows:

1- To develop three-dimensional numerical model used to simulate thermal performance behavior of ETSC system, phase transition characteristics of PCM during melting and solidification, and the time needed for these processes in the type U-ETSC type.

2- To enhance the efficiency of ETSC system by employing PCM during melting and solidification processes.

3- To investigate the impact of mass flow and inlet temperature of heat transfer fluid (HTF) on the thermal efficiency of ETSC system

4- To fabricate two ETSC configurations (U-pipe and heat pipe) used to evaluate experimentally the thermal performance of SWHS with and without PCM.

5- To validate the simulation results of SWHS and experimental measurements with and without PCM.

1.7 Outline of Thesis

Basically, this work consists of six chapters and references. All chapters describe the researchable activates that have been carried out on the SWHS with and without PCM. Each chapter can briefly be summarized as shown below:

Chapter One shows the background of the research work, the problem statement, the objectives, and finally the outline of thesis.

Chapter Two provides the literature view of PCM properties and the configurations, of ETSC. Heat transfer enhancement techniques to improve the thermal response of SWHS are also discussed.

Chapter Three presents the numerical modelling and solution procedures for U-pipe evacuated tube SWHS. Two physical configurations of U-ETSC model were simulated with and without PCM. Software Ansys Fluent 2020R1 has been used to simulate this configuration.

Chapter Four presents the experimental setup of both types (heat pipe and U-pipe) ETSC systems. The descriptions of the main components, instrumentations, and experimental procedures are presented in detail.

Chapter Five, the numerical and experimental results that were obtained from simulation work and experiments are presented. The phase-transition characteristics and isothermal contours of the melting and solidification have been presented for both types of ETSC with and without PCM.

Chapter Six reported overall conclusions and significant recommendations. The recommendations have included specific ideas for future studies to follow up by researchers in the near future.