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and Scientific Research
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Mechanical Engineering Department

Performance Enhancement of Triplex Tube Thermal Storage Unit Using Paraffin Wax-Metal Foam

A Thesis
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By

Jihad Majeed Hassan

Supervised by

Prof.Dr. Jasim Abdulateef (PH. D)

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بسم الله الرحمن الرحيم

كَمَا أَرْسَلْنَا فِيكُمْ رَسُولًا مِّنكُمْ يَتْلُو عَلَيْكُمْ آيَاتِنَا وَيُزَكِّيكُمْ
وَيُعَلِّمُكُمُ الْكِتَابَ وَالْحِكْمَةَ وَيُعَلِّمُكُم مَّا لَمْ تَكُونُوا تَعْلَمُونَ
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صدق الله العظيم

سورة البقرة (الآية 152)

DEDICATED TO MY FAMILY

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I owe thanks first and foremost to Allah for his mercy and love. He saved me and enabled me to run toward the goal of my life.

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ABSTRACT

Latent Heat Thermal Energy Storage (LHTES) based on Phase Change Material (PCM) provides an encouraging solution for the efficient utilization of discontinuous energy from the renewable such as wind, solar, and so on. Prospective applications of the PCMs in the fields of thermal management and thermal energy storage are well recognized. Nevertheless, the main problem of these materials is their poor thermal conductivity which necessitates the incorporation of thermal response enhancement techniques. Porous metal foam as an effective conductivity enhancement approach along with Triplex Tube Heat Exchanger (TTHX) thermal storage structure filled with PCM was used to enhance the PCM charging rate. An experimental investigation is carried out to establish a comparative performance assessment on two TTHX configurations: TTHX without foam (simple TTHX) and TTHX with copper foam (foamed TTHX) using water as a Heat Transfer Fluid (HTF). The numerical simulation was done using ANSYS Fluent. The heat transfer fluid (HTF) was water flowing through the heat exchanger tube at 69 ^{o}C, 72 ^{o}C, and 75 ^{o}C. The thermal behavior of two TTHX configurations Were investigated in terms of temporal variation of PCM temperature, PCM liquid fraction and energy stored for different opration condition of HTF inlet tempreture and mass flow rate . Experimental observations showed the foamed TTHX had a superior melting rate over the simple TTHX. For both TTHX configurations, the increasing of HTF temperature, the needed time for the process of charging decreases. effect of the temperature of HTF is significant for foamed TTHX, where the whole time of melting reduces for foamed TTHX and simple TTHX is (43%) and (34%) when the temperature of HTF is increased from (69ºC) to (75ºC). Furthermore, the overall enhancement can be performed with addition foam to LHTES of up to 44%, 36% and 33%

corresponding HTF flow rate 69℃,72℃ and 75℃ as compared with simple pure LHTES.further, The variation of flow rate has a little impact on thermal response for foamed THHX as compared with simple TTHX with consideration of flow rate variation. The highest accumulative energy stored enhancement reached up to (52%) was obtained by incorporating copper foam with TTHX at highest HTF temperature during melting process.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Latin symbols

Symbol	Description	Unit
a	Permeability of the Metal Foam	m^2
$Amush$	Mushy Zone Constant	-
CF	Inertial Drag Factor of the Metal Foam	-
$C_\mu, C_{1\varepsilon}, C_{2\varepsilon}$	Constants in (k-ϵ) Model	-
d_f	The Ligament Diameter of the Metal Foam	mm
d_p	The Pore Diameter of the Metal Foam	mm
h	The Sensible Enthalpy	kJ/kg
h_{ref}	Reference Temperature Enthalpy	kJ/kg
k	Turbulent Kinetic Energy	kJ/kg
k_{eff}	The Effective Thermal Conductivity	W/m°C
$k_{m.f}$	Thermal Conductivity of the Metal Foam	W/m°C
k_{PCM}	Thermal Conductivity of the PCM	W/m°C
L	The Latent Heat of the PCM	kJ/kg
T	Local Temperature	°C
T_O	The Operating Temperature of the PCM	°C

Greek Symbols

Symbol	Description	Unit
α	Thermal Diffusivity	m^2/s
β	Liquid Fraction	-
γ	Thermal Expansion Coefficient	1/°C
ε	Metal Foam Porosity	-
μ	Dynamic Viscosity	kg/m.s
μ_t	The Turbulent Eddy Viscosity	M
ρ	Density	kg/m^3
$\rho 0$	The Operating Density of PCM	kg/m^3
σ_ϵ, σ_k	Constants in (k-ϵ) Model	-
$\nabla.$	Divergence	-
€	Small Number (less than 0.001) to Prevent divided to Zero .	-
ϵ	Turbulent Dissipation Rate	m^2/s^2
ω	Metal Foam Pore Density	PPI

Subscripts

Symbol	Definition
c	Cross-Sectional
eff	Effective Value
ref	Reference Value
f	Ligament
H	Hydraulic
i, j	Tenser
in	Inlet
m	Melting
m.f	Metal Foam
p	Pore
PCM	Phase change material
out	Outlet
s	Surface
t	Turbulent
0	Operating Value

Abbreviations

Abbreviations	Definition
HTF	Hot Fluid Flows
LHTES	Latent Heat Thermal Energy Storage
PCMs	Phase Change Materials
PPI	Pores Per Linear Inch
STES	Sensible Thermal Energy Storage
TES	Thermal Energy Storage
TTHX	Triplex Tube Heat Exchanger

Chapter One

Introduction

1.1 Introduction

The rise in prices and depletion of fossil fuel associated with increase in greenhouse gas emissions are indicated as the key driving forces behind efforts to successfully utilize several of renewable energy sources. Among the various types of renewable energy resources, solar energy being regarded the best promising energy source in different global parts. The characteristics of solar energy like easily, directly, utilized, freely available abundant, environmentally friendly and safe, making it an interested replacement to the fossil fuels. Furthermore, solar energy suffers from the shortcoming of becoming intermittent with day time, seasons and weather. To overcome the mismatch between energy supply and demand, solar energy systems required Thermal Energy Storage (TES) [1].

As a result, the TES unit becomes a crucial component in solar thermal utilization systems to ensure that a solar energy system continues to work reliably and efficiently. Because of their elevated thermal energy density per unit mass and volume, TES systems, especially latent Heat Thermal Energy Storage (LHTES), has recently attracted more attention [2].

LHTES based on Phase Change Materials (PCMs) are an important type of thermal energy storage, which are based on the capture and release of energy when a material undergoes a phase change from solid to liquid or liquid to gas or vice versa [3]. The thermal conductivity of the PCMs employed as a storage medium in TES system is low. This frequently

leads to incomplete solidification and melting processes and also a considerable temperature difference within PCM resulting in materials failure that causes system overheating. PCMs are utilized in different engineering applications like the thermal storages of equipment and building structures, involving heating and cooling systems, refrigerator and cold storage, domestic hot water, drying technology, electronic products, solar cookers and solar air collectors [4].

1.2 Thermal Energy Storages

Thermal energy can be stored in a liquid or solid medium as sensible heat. The total amount of energy stored and released depends on temperature of the storage medium. The thermal energy can be stored as latent heat as the material changes phases during the charging and discharging processes. During phase change, the temperature of these materials remains constant. This can also be stored as chemical energy or outcome from a reversible chemical reaction. According to [5], there are several advantages of employing TES systems, such as reducing the energy consumption, reducing costs, increasing flexibility of operation, enhancing indoor air quality, and decreasing initial and maintenance costs. These systems can also be classified in many categories depending on kinds of the storage medium namely Sensible Heat Thermal Energy Storage (SHTES) and latent thermal energy storage (LTES). Figure (1.1) summarizes the classifications of thermal energy storage types.

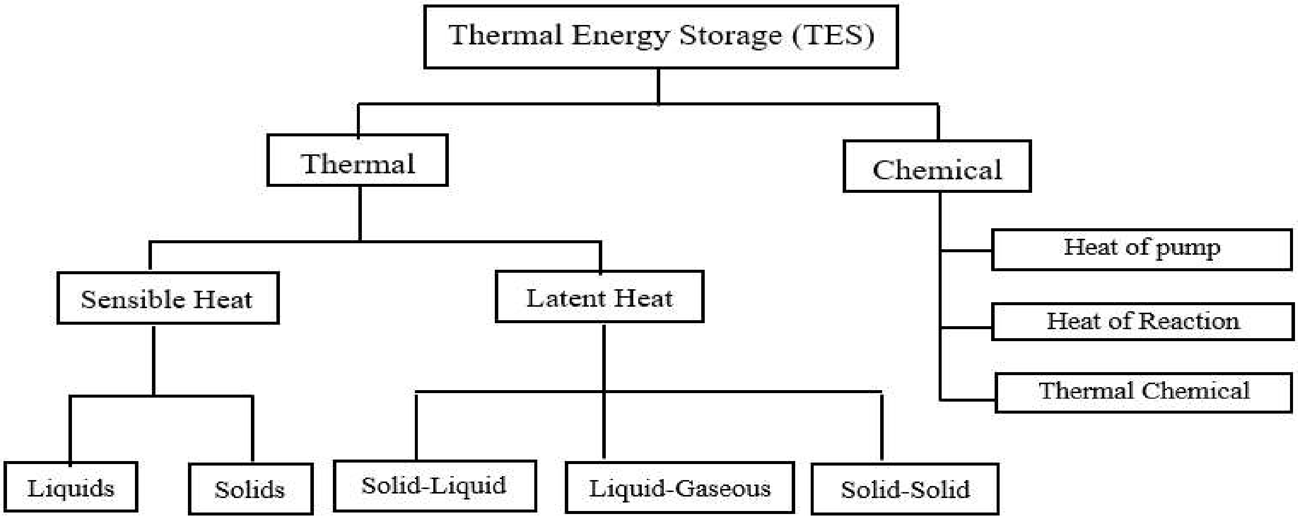


Figure (1.1): The classifications of thermal energy storage [6]

1.2.1 Sensible Heat Thermal Energy Storage

Sensible Heat Thermal Energy Storage (SHTES) is the simplest method based on two storage mediums, including: liquid and solid medium. These mediums can be employed by increasing its temperature without phase-change. for example, rock, Liquid mediums are also used as oil-based-liquids, including: water and molten salt. Water medium is considered as one of the most common storage mediums that employed to store the sensible heat energy. This is due to it is abundant and, cheap, has a high density and a high specific heat [6].

1.2.2 Latent Heat Thermal Energy Storage

Latent Heat Thermal Energy Storage (LHTES) can be defined as the amount of heat absorbed or deliberated from the storage medium when the material is changed from phase to another. With sensible heat, the thermal storage process starts. Through this process, the material temperature changed from ambient temperature (initial temperature) to phase-transition temperature after this. The thermal storage material absorbs the heat energy received, and then completely transformed to another phase after losing its temperature [6].

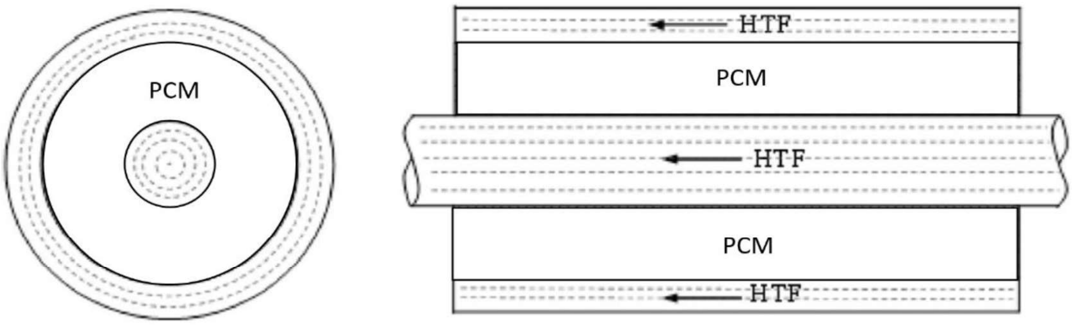
Thermal energy storage systems allow for the storage of large amounts of thermal energy, especially LHTES systems, which require a smaller volume and weight of material, compared with conventional SHTES systems. The LHTES system has also the ability to store fusion heat at a constant value or near constant temperature, which corresponds to the PCM temperature for phase-transition.

1.3 Utilizations of LHTES

As compared to SHTES, the method of latent heat thermal energy storage has proved to be a better engineering choice due to its different benefits, like a large storage of energy for a given volume, uniform energy storage/supply, compact ness etc. [4]. Therefore, different geometries of the systems of LHTES find their broad applications in various engineering fields such as the solar thermal applications, solar based dynamic space power generation, cooling of electronics, industrial waste heat recovery, passive heating building, Systems of air conditioning systems, and automobiles. The choice of a suitable PCM for any application needs the PCM to have the temperature of melting within the working range of application. Numerous uses are as have been proposed for the PCMs studied. It can be observed that the majority of researches on the problems of PCM have been conducted within the range of temperature (0–65^{o}C) appropriate for the domestic heating/cooling application [4].

1.4 Triplex Heat Exchangers

Triplex Tube Heat Exchanger (TTHX) is utilized in different products and equipment's such as found in the food, dairy, pharmaceutical beverage industries [7]. TTHX with PCMs in the middle tube can be employed as thermal energy storage to enhance the heat transfer area and improve the heat transfer process compared with other heat exchanger configurations as shown in Figure (1.2) [8]. As (HTF) flows from both sides, i.e., from the inner and outer tube, better heat transfer better heat transfer can be performed.



could be performed.

Figure (1.2): Triplex tube heat exchanger with PCM only [8]

Majority of the PCMs have limited applications due to their low thermal conductivity. and, this leads to extend the period needed for the of process melting and solidification. Therefore, it's essential to reduce the time needed for charging process by using enhancement heat transfer techniques.Metal foams are distinctive porous matrices with small openings called pores or voids. The use of metal foams offers remarkable solutions for heat transfer enhancement in various engineering applications due to their high thermal conductivity and large area-to-volume ratio, see Figure 1.3

[9]

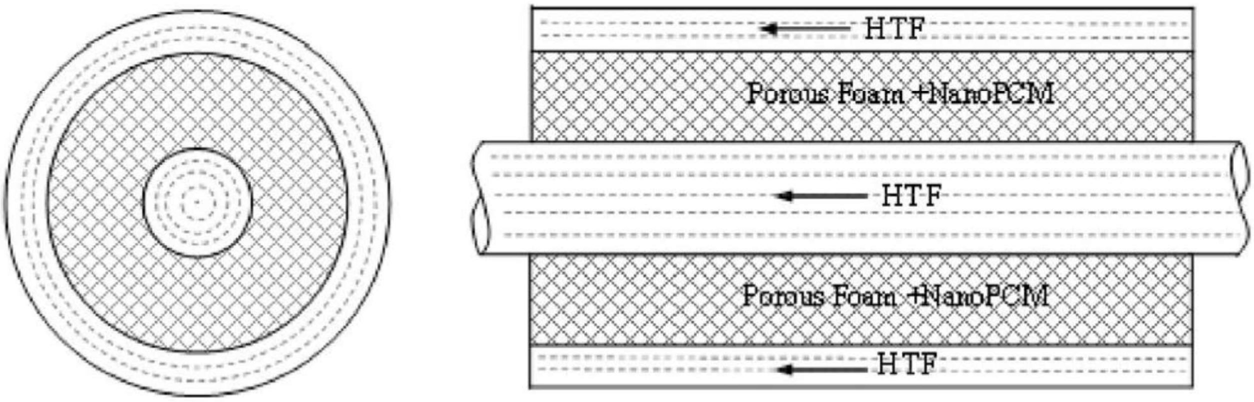


Figure (1.2): Triplex tube heat exchanger with PCM and metal foam

1.5 problem of study

A major issue with the application of PCMs in TES is the difficulty of heat transfer in charging as well as discharging the TES. Because of the low thermal conductivity of PCM, the time required to fully charging the thermal storage tanks longer duration. For efficient utilization of thermal energy storages, it is necessary to incorporate the transfer enhancement techniques to improve the thermal response of the (LHTES). The Presently development in PCM thermal energy storage have high tined the need for enhancement heat transfer techniques to reduce the time needed for phase change process.

As mentioned above, the traditional PCMs' thermal conductivity can be improved via utilizing elevated conductivity materials. The elevated conductivity materials application for enhancing the traditional PCMs' thermal conductivity has been treated within various techniques via investigators, which can be briefed as [4]:

- The elevated conductivity porous material's impregnation with the PCM
- The elevated conductivity particles' dispersal into the PCM
- The metal structures' placement into the PCM.
- The usage of elevated conductivity, low density materials.

Due to excellent properties, such as low weight, high energy absorption capacity, exceptional acoustic and thermal properties, etc., metal foams have received much attention in the last decades as a porous material having an elevated conductivity which can be impregnated with the PCM-LHTESs to enhance their performance. The influential thermal conductivity of the metal foam-PCM composite is higher than that of pure PCM. The higher influential thermal conductivity gives further dramatic outcomes if the LHTES thermal response is compared between the composite and the Pure PCM [10].

1.6 objective of the present study

The major objective of the present study is to enhance the thermal performance of TTHX - LHTES by employing of high conductivity porous material with the PCM. Copper possesses an high thermal conductivity among the metallic materials; thus, copper foam-PCM composite has been employed with in LHTES during charging process. The objectives of this study can be summarized as follows:

1. To investigate numerically the thermal performance of TTHX LHTES during the charging process using PCM only .
2. To enhance the TTHX LHTES performance during the charging process employing copper foam-PCM composite.
3. To investigate the effect of the operation parameters of the thermal energy storage system including the (inlet temperature and flow rate of HTF), on their charging time, solid liquid interface and energy storage rate .
4. To fabricate TTHX LHTES to investigate the thermal conduct of LHTES system as well as supporting the numerical result.

1.7 Thesis out line

Basically, this thesis consists of six chapters and references. Each chapter can briefly be summarized as shown below:

- ***Chapter One*** shows the background of the research work, the problem statement of the research work, the objective of the research work, and finally the outline of thesis.
- ***Chapter Two*** provides the literature view of PCM and metal foam properties and the configurations of LHTES. Heat transfer enhancement techniques to improve the thermal response of LHTES are discussed.
- ***Chapter Three*** introduces the numerical modelling and solution procedure for LHTES. physical configurations of the TTHX model have been simulated, including: The PCM-TTTX without foam (pure TTHX sample) and the PCM-TTHX with copper foam (foamed TTHX sample). Software Ansys Fluent 2020R1 has been used with the enthalpy porosity and the finite-volume methods.
- ***Chapter Four*** presents the experimental setup of the LHTES system. The descriptions of the main components, instrumentations, and experimental procedure are presented in details.
- ***Chapter Five*** clarifies the numerical results that were obtained from simulation work. The phase-transition characteristics and isothermal contours of the melting processed have been presented for both pure TTHX and foamed TTHX samples. The experimental results are also shown in this chapter.
- ***Chapter Six*** illustrates the overall conclusions and the significant recommendations. The recommendations have been included specific ideas for future studies to follow up by researchers in the near future.