Ministry of Higher Education

and Scientific Research

University of Diyala

College of Engineering

Department of Mechanical Engineering

Performance Enhancement of Latent Heat Storage Units During Charging Process

A Thesis
Submitted to the Council of the College of Engineering, University of Diyala in Partial Fulfillment of the Requirements for the Degree of Master of Science in Mechanical Engineering

By

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(B. Sc. Mechanical Engineering, 2014)

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January, 2022 ***IRAQ*** ***1443***

بسم الله الرحمن الرحيم

كَمَا أَرْسَلْنَا فِيكُمْ رَسُولًا مِّنكُمْ يَتْلُو عَلَيْكُمْ آيَاتِنَا وَيُزَكِّيكُمْ وَيُعَلِّمُكُمُ الْكِتَابَ وَالْحِكْمَةَ وَيُعَلِّمُكُم مَّا لَمْ تَكُونُوا تَعْلَمُونَ (151) فَاذْكُرُونِي أَذْكُرْكُمْ وَاشْكُرُوا لِي وَلَا تَكْفُرُونِ (152)

صدق الله العظيم

سورة البقرة (الأية 152)

To the Memory of my Late Father and Mother

Luna

Acknowledgments

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.

I wish to express my sincere thanks, appreciation and gratitude to my supervisor "***Prof. Dr. Jasim Abdulateef***" for suggesting this project, his kind patronage, excellent scientific advice, help and guidance throughout the period of this work and for many helpful discussions and suggestions.

Moreover, special words of thanks and gratitude are also extended to ***my sister*** and ***my husband***, for their patience, understanding, endless help, and acceptance of my preoccupation with this work.

Luna Sabah Kareem 2021

Abstract

Promotion of renewable energy sources like solar, wind for responding to increasing global energy demand requires efficient means to correct their intermittent nature. Latent Heat Thermal Storage (LHTS) based on Phase Change materials (PCMs) offers a promising solution for efficient utilization of intermittent energy from renewable sources. However, the primary limitation is the poor thermal conductivity of PCMs, which requires employing of thermal performance enhancement techniques. To overcome this deficit, an open-cell structure with a high porosity copper foam is employed to enhance the overall thermal conductivity of PCM, leading to improved heat transfer exchange, and hence, promoting the PCM charging rates. This enhancement technique has been utilized to improve the LHTS performance having a shell and tube structure filled with PCM, where a copper foam is compounded to the PCM. For this purpose, an experimental setup was fabricated to examine the heat transfer performance on two shell-and-tube LHTS configurations: pure PCM-LHTS (pure LHTS) and PCM-copper-foam composite (foamed LHTS). The experimental observation is supported by computational models that allow the investigation of heat transfer performance, and track the phase change interface during melting. The numerical simulation was done using ANSYS fluent (version 19) CFD. The thermal behavior of LHTS configurations was investigated in terms of temporal evolution of PCM temperature in different axial and radial directions, PCM average liquid fraction, and thermal storage orientation at various inlet HTF temperatures. The heat transfer fluid (HTF) was flowing through the heat exchanger tube at different inlet temperature of 70 ^{o}C, 75 ^{o}C, and 80 ^{o}C. Experimental observations showed that the foamed LHTS configuration has a better performance than that of pure LHTS, while the variation of HTF was found to have a major impact on the heat transfer rate with both configurations. As a result, the reduction in total charging time, which

from 360 min to 65 min is clearly observed because of the foam. The saving in total melting time of simple LHTS was about 82% with provision of copper foam. The saving in total melting time of foamed LHTS arrange vertically was about 34% for an HTF temperature increase from 70 ^{o}C to 80 ^{o}C. The saving in phase change time for horizontal foamed LHTS was about 19% higher than vertical LHTS at completed melting process. Therefore, the results suggest that horizontal LHTS is preferable for full load conditions rather than vertical LHTS. It is also observed that the highest rate of stored energy can be obtained at a higher HTF temperature for both LHTS orientations. The role of adding copper foam on the development of phase change cycle was confirmed by visual observation.

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Latin symbols

Symbol	Description	Unit
a	Permeability of the Metal Foam	m^2
A_{mush}	Mushy Zone Constant	-
C_F	Inertial Drag Factor of the Metal Foam	-
d_f	The Ligament Diameter of the Metal Foam	m
d_p	The Pore Diameter of the Metal Foam	m
h	The Sensible Enthalpy	kJ/ kg
K	Turbulent Kinetic Energy	kJ/ kg
k	Thermal Conductivity	W / m ^oC
L	The Latent Heat of the PCM	kJ/ kg
T	Local Temperature	^oC
T_O	The Operating Temperature of the PCM	^oC
T_i	Inlet temperature	^oC
U_Q	Measurement Heat Transfer Rate	%
U_m	Measurement Error of Mass Flow Rate	kg/sec
U_T	Measurement Error of Water Temperature	^oC

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
ρ	Density	kg / m^3
ρo	The Operating Density of PCM	kg / m^3
∇	Divergence	-
€	Small Number (less than 0.001) to Prevent	-
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
in	Inlet
m	Melting
$m.f$	Metal Foam
p	Pore
PCM	PCM
out	Outlet
s	Surface
t	Turbulent
o	Operating Value

Abbreviations

Abbreviations	Definition
HTF	Heat Transfer Fluid
PCMs	Phase Change Materials
PPI	Pore Per Inch
TES	Thermal Energy Storage
LHTS	Latent Heat Thermal Storage
SHTS	Sensible Heat Thermal Storage
TTHX	Triple Tube Heat Exchanger
OD	Outer Diameter
ID	Inner Diameter

CHAPTER ONE
INTRODUCTION

Chapter One
Introduction

1.1 Background

The rapid development of human societies and economies has led to a significant increase in energy consumption in recent decades. The world's primary issue at the moment is reducing its reliance on the energy produced by fossil fuels burning, despite the several environmental repercussions, such as greenhouse gas emissions, which cause global warming, climate change…etc. As a result, the focus has moved lately toward friendly renewable energy sources such as solar, wind and hydro. Solar energy is the best source of energy on a worldwide scale since it is simple and direct to use, renewable, has safe and environmentally beneficial, and abundantly free. Solar energy deployment, on the other hand, is hampered by the fact that it is only accessible during hours of the daytime. Thus, methods for effectively storing solar energy during the day and using it at night have been suggested. Thermal energy storage is a critical technique for ensuring the long-term viability of solar energy.

Thermal Energy Storage (TES) is a very successful way of balancing the mismatch between energy consumption and production. Also, TES can be incorporated into resources of renewable energy to be permanent. It is possible to avoid the imbalance between energy supply and energy demand by energy storage technology using TES. For these purposes, TES is used to store excess of renewable energy through high production hours and then use it during low production hours.

Most phase change materials (PCMs) that are used as storage medium in TES systems, suffer from low thermal conductivity. This often leads to incomplete melting and solidification processes and also a significant temperature difference within PCM, resulting in material failure and system overheating. Practically, there are various engineering applications of PCMs in these systems, such as building heating, water heating, solar systems, electronic cooling, drying technology, refrigeration and cold storage, air conditioning, and waste heat recovery [1].

1.2 Thermal Energy Storage System

TES system is a technology that stores thermal energy by heating or cooling a storage material so that the stored energy can be used subsequently for heating and cooling applications and power generation. TES system uses a storage material to store heat during the charging process (melting), and then the heat will be released during the discharging process (solidification).

TES system can be classified according to different storage mechanisms, into three main categories: sensible heat energy storage, latent heat energy storage, and thermochemical storage, Fig. 1.1 shows these categories [2].

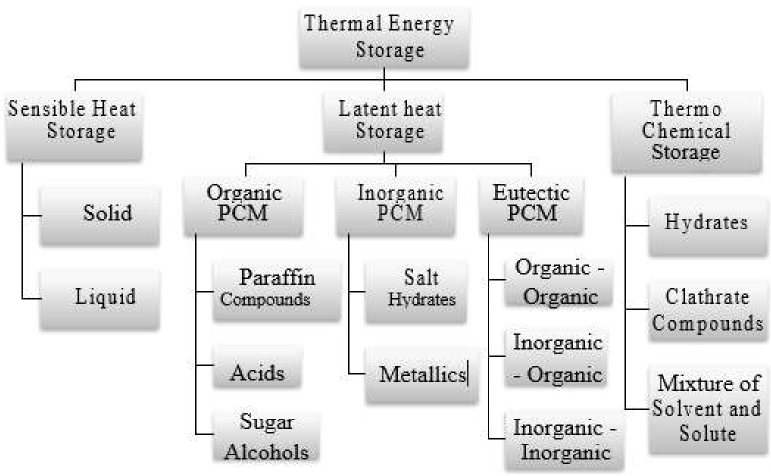

Fig.1.1 Classification of thermal energy storage [2]

1.2.1 Sensible Heat Thermal Storage

Sensible heat thermal storage (SHTS) is dependent on the amount of heat stored in the storage medium, which may be a solid or liquid that can be heated without charging its phase, as demonstrated in Fig. 1.2[3]. Metals, rock, and concrete are some of the solid medium utilized, while liquid mediums include oil-based liquids, including molten salts and water. The most often utilized storage medium is water, which may be used to store thermal energy in the form of perceptible heat due to its abundance, low cost, high specific heat, and density [4].

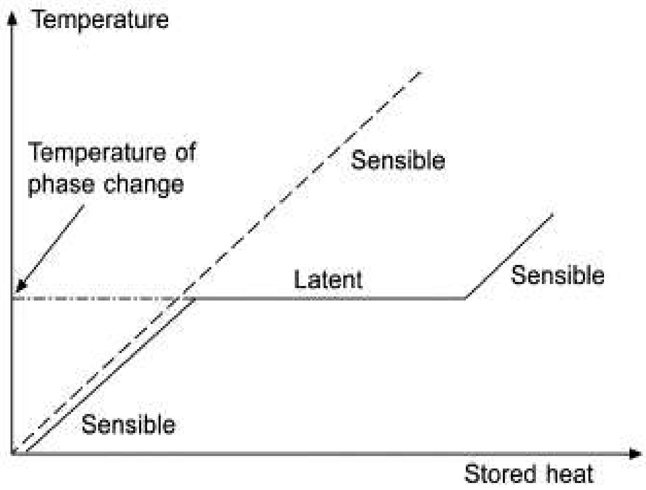

Fig. 1.2 Sensible and latent heat storage [3]

1.2.2 Latent Heat Thermal Storage

Latent heat thermal storage (LHTS) is defined as the amount of heat released/stored material from a thermal storage medium using the phase transition of its. As illustrated in Figure (1.2), the storage process begins with sensible heat, which causes the material's temperature to change to its phase change temperature, while heat energy transferred to the storage material. The substance retains its constant state until the phase has been completely transformed. Due to the large storage capacity per unit volume/mass at a practically constant temperature, latent heat storage is more advantageous than sensible energy storage [5].

1.3 Applications of LHTS

As compared to (SHTS), latent heat thermal energy storage has been shown to be a superior engineering choice due to its many benefits, such as high energy storage for a given volume, uniform energy storage/supply, and compactness

[6]. As a result, various configurations of LHTS units found widespread use in a variety of technical disciplines.

The selection of PCM suitable for any application, the PCM should have a melting temperature within the applications realistic range. Numerous applications for PCMs have been suggested. Table 1.1 summarizes some of the application areas for which PCMs were chosen for research, as given by [7]. As shown in Table 1.2, the majority of research on phase change issues has been conducted within the temperature range of 0–65 ºC, which is appropriate for residential cooling/heating.

Table 1.1 Applications of LHTS systems [6]

No.	fields
1	Solar based dynamic space power generation
2	Solar thermal applications
3	Industrial wasted heat recovery
4	Automobiles
5	Cooling of electronics
6	Textless
7	Passive heating of buildings
8	Air conditioning systems

Table 1.2 Application of target areas for some PCMs [7]

Temperature range(°C)	PCMs studied/melting temperature(°C)	Target applications area (rationale behind selection of (PCM)
0-65(°C)	Paraffins(-3-64), water/ice/0,stearicacid/41-43, n-octadecane/27.7	Storage for domestic heating/cooling. Passive storage in bio-climatic building/architecture. thermal storage of solar energy. Applications in off-peak electricity for cooling and heating protection of electrical devices.
80-120(°C)	Erythntol/117.7;RT100(99) ;MgCl_2.6H_2O(116.7)	Storage for the hot-side of LiBr/H_2O absorption cooling system with generator temperature requirement of less that 120(°C).
>150(°C)	NaNO_3/310,KNO_3/330 ,KOH/380,ZnCl_2/280	Storage for solar power plants based on parabolic trough collectors and direct steam generation.

1.4 Problem Statement
A significant disadvantage of using PCM thermal energy storage is the difficulty of charging and discharging the thermal energy storage. Due to the low thermal conductivity of the PCM, the melting and solidification processes take more time. Recent studied on PCM thermal storage have shown the need for heat transfer improvement methods that may significantly reduce the time necessary for charging and discharging operations. Over the past three decades, significant research has been conducted to increase heat transfer between the PCM and heat transfer fluid (HTF). These methods are achieved by increasing heat transfer area (via the use of finned tubes, multitube heat exchangers, and heat pipes) or by enhancing the thermal conductivity of the PCM (insertion of metal matrix into the PCM, utilization of bubble agitation in the PCMs, impregnation of porous material and application of PCM dispersed with high conductivity particles) [6].

As previously stated, conventional PCMs' thermal conductivity may be increased by using high conductivity materials. Researchers have approached the use of high conductivity materials to improve the thermal conductivity of traditional PCMs in a variety of methods, which may be described as follows [6]:

- PCM impregnation with porous materials has a high conductivity.
- Dispersion of particles with high conductivity inside the PCM.
- Incorporation of metallic structures into the PCM.
- The use of materials with high conductivity and low density.

Advanced materials such as low weight, exceptional acoustic and thermal properties, high energy absorption capacity, metal foams and so on, have garnered considerable attention in recent decades as a porous material with high conductivity that can be impregnated with PCM-LHTSs to enhance their performance. The metal foam-PCM composite has higher effective heat conductivity than pure PCM. When the thermal response of LHTS with foam is compared to that of pure PCM, the composite has higher effective thermal conductivity results in more dramatic effects [8].

1.5 Objectives of the Present Work

The main objective of this research is to improve the thermal performance of shell and tube LHTS by impregnating the PCM with a high conductivity porous material. Since copper has the highest heat conductivity among the metals, the copper foam-PCM composite was used in the LHTS during the charging process. The thermal performance of LHTS, on the other hand, is measured in terms of PCM temperature evolution, charging time, PCM liquid percentage, and energy stored at various input temperatures of HTF with constant mass flow rates. The current research objectives can be summarized as follows:

1. To evaluate the thermal performance of shell and tube LHTS utilizing pure PCM during the charging process numerically.
2. To improve shell and tubes thermal performance LHTS during the charging process using copper foam-PCM composite.
3. To investigate the effect of operation parameters/ (inlet temperature of HTF), and orientation of LHTS (vertical and horizontal) on the charging time, solid-liquid interface.
4. Fabrication shell and tube LHTS test section to experimentally investigate the thermal behavior, phase-transition characteristics of the PCM, and time required to achieve melting during the charging process.

1.6 Thesis Outline

Basically, this thesis consists of six chapters and list of references. All chapters describe the research activates that have been carried out on the PCM-LHTS. Each chapter can briefly be summarized as shown below:

The current chapter shows the background, problem statement, research objectives and thesis outline.

Chapter Two provides the literature review of PCM and metal foam properties and the configurations of LHTS. Heat transfer enhancement techniques to improve the thermal response of LHTS are discussed.

Chapter Three presents the numerical modelling and solution procedure for LHTS. Two physical configurations of shell and tube model were simulated including (1) PCM-LHTS without foam (pure LHTS), and (2) LHTS with copper foam-PCM composite (foamed LHTS). Software Ansys Fluent (version19) and software Gambit 2.4.6 have been used with the enthalpy porosity and the finite-volume methods.

Chapter Four presents the experimental setup of the LHTS system. The primary components descriptions, instrumentations, and experimental procedures are presented in details.

Chapter Five, the numerical results of simulation work are reported in this chapter. The phase-transition characteristics and isothermal contours of the melting have been presented for both pure LHTS tube and foamed LHTS. The experimental results are also discussed in this chapter.

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