

Performance comparison of packed bed latent heat storage systems for medium temperature applications

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Abstract

A packed bed latent heat storage system consisting of aluminium encapsulated eutectic solder (Sn63Pb37) capsules is experimentally evaluated during charging and discharging cycles. Sunflower Oil is used as the heat transfer fluid in the experiments. The effect of the flowrate on the charging performance is evaluated using three charging flowrates namely; 4 ml/s (low), 6 ml/s (medium) and 8 ml/s (high). The storage system is also evaluated with three different set heater charging temperatures (260 °C (low), 280 °C (medium) and 300 °C (high)). Discharging experiments are performed with the three different flowrates to evaluate the effect of the flowrate on the discharging characteristics. Charging and discharging results are presented in terms of the axial storage tank profiles, the energy rates and the exergy rates. The overall performance of the storage system is evaluated in terms of the energy and exergy storage efficiencies. The charging energy and exergy rates are seen to increase with the charging flowrate at the expense of a greater charging duration since higher flowrates tend to cool down the heater. The best charging flowrate of 6 ml/s is suggested which ensures a reasonable duration of charging, reasonable thermal stratification and reasonably high energy and exergy charging rates. The effect of the set heater temperature on the charging energy and exergy rates is insignificant as compared to the effect of the flowrate. The best set charging temperature of 280 °C is also suggested by the experimental tests. Increasing the flowrate results in faster heat transfer with higher peak energy and exergy rates during discharging. However, the stored energy and exergy is utilized for a shorter duration as compared to the lowest flowrate. Energy and exergy storage efficiencies decrease with an increase in the flowrate and the highest flowrate shows the lowest values due to the longer charging duration and the shorter discharging duration. The set heater charging temperature shows only a marginal effect on the energy and exergy storage efficiencies. A comparison of the energy and exergy rates of the solder during charging and discharging with adipic acid shows slightly better performance during charging cycles for adipic acid. For discharging cycles, the solder shows a better performance.

After evaluating the performance of the eutectic solder packed bed system, its thermal performance is compared to two other packed bed latent heat medium temperature thermal

energy (TES) storage systems during charging and discharging cycles at low flowrate (4 ml/s), medium flowrate (6 ml/s) and high flowrate (8 ml/s). The two phase change materials (PCMs) used in the storage systems are adipic acid and erythritol. The performances of these TES systems are evaluated in terms of the temperature profiles, total energy, total exergy, useful energy and useful exergy, during charging and discharging. Erythritol did not undergo phase transition during discharging at all the flowrates due to supercooling. The erythritol TES system shows the greatest efficiencies with regards to all the performance parameters considered with an overall energy efficiency of about 39.1 %. The efficiencies of all the TES systems generally decrease with an increase in the HTF flowrate. Though the eutectic solder TES stored and discharged greater quantities of energy at all the flowrates, its performance was hampered by the low degree of thermal stratification in its tank thus leading to long charging and discharging times. At the highest flowrate, the adipic acid TES possessed higher efficiencies than the eutectic solder TES in terms of useful energy and useful exergy. Erythritol charges up for the shortest duration, followed by adipic acid and lastly by the eutectic solder as a result of the combined effect of a lower thermal mass induced by a lower melting temperature and increased convective heat transfer. Erythritol shows a superior performance in terms of the charging energy and exergy rates since it shows higher values due to its lower melting point which induces more convective heat transfer and a greater degree of thermal stratification.

Keywords; Adipic acid; Erythritol; Eutectic solder; Packed bed latent heat storage system; Thermal performance

Declaration

I, Tlotlo Marvel Lefenya declare that this dissertation titled, "Performance comparison of packed bed latent heat storage systems for medium temperature applications", and the work presented in it are my own.

I confirm that:

- This work was carried out while I was a candidate for the Master of Science in Physics degree at North-West University.
- I have clearly stated that no part of this thesis has been previously submitted for a degree or any other qualification at this University or at any other institution.
- I have given sources of quotations from the work of others in this dissertation.
- I have acknowledged all main sources used in this dissertation.
- I have made clear any contributions from any other person apart from myself in this work.

Signed:

Date:

Dedication

I dedicate this dissertation to the Almighty God my creator, the source of my inspiration knowledge and understanding.

Acknowledgements

- Firstly, I would like to thank God for travelling with me through this academic journey of my research study.
- I am grateful to my supervisors, Prof. Ashmore Mawire and Dr. Adedamola Shobo who gave me the necessary guidance and motivation to do my studies. Their professional guidance during this research is highly appreciated.
- I would like to thank Dr. Getachew Mekonnen and Dr. Oyiwroth Abedigamba for giving me the moral support and motivation throughout my research journey.
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List of abbreviations

CFD	Computational fluid dynamics
CPCM	Composite phase change material
CSP	Concentrating solar power
CTES	Combined thermal energy storage
DMGT	Dish micro-gas turbine
DSC	Differential scanning calorimetry
DSG	Direct steam generation
FPCU	Flat plate cooking unit
HDPE	High density polyethylene
HTF	Heat transfer fluid
LHS	Latent heat storage
LHTES	Latent heat thermal energy storage
LMA	Low melting temperature alloy
LPTSP	Linear parabolic trough solar power plant
MEPCMs	Micro-encapsulated phase change materials
MH	Metal hydride
NTU	Number of heat transfer units
OECD	Organisation for Economic Co-operation and Development
PCM	Phase change material
PEEK	Polyetheretherketone
PEKK	Polyetherketoketone
PTFE	Polytetrafluoroethylene
TES	Thermal energy storage
TTES	Thermochemical thermal energy storage
SHS	Sensible heat storage
SHTES	Sensible heat thermal energy storage

List of symbols

c_{av}	Average specific heat capacity	$\text{Jkg}^{-1}\text{K}^{-1}$
c_S	Specific heat capacity of Sunflower Oil	$\text{Jkg}^{-1}\text{K}^{-1}$
$\dot{E}_{ch}$	Charging energy rate	W
E_{ST}	Total energy stored	J
$\dot{E}_{xch}$	Charging exergy rate	W
E_{XCHT}	Total charging exergy	J
$\dot{E}_{dis}$	Discharging energy rate	W
E_{DIST}	Total energy discharged	J
$\dot{E}_{xdis}$	Discharging exergy rate	W
E_{XDIST}	Total exergy discharged	J
t	Time	s
t_{ini}	Initial time	s
t_f	Final time	s
T_{amb}	Ambient temperature	K
T_{chin}	Charging inlet temperature	K
T_{chout}	Charging outlet temperature	K
T_{disin}	Discharging inlet temperature	K
T_{disout}	Discharging outlet temperature	K
$\dot{V}_{ch}$	Charging flowrate	m^3s^{-1}
$\dot{V}_{dis}$	Discharging flowrate	m^3s^{-1}
ρ_{av}	Average density	kgm^{-3}
ρ_S	Density of Sunflower Oil	kgm^{-3}
η_e	Overall energy efficiency	-
η_{ex}	Overall exergy efficiency	-

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Dissertation in article format based on publications

This dissertation contains articles that have been previously published by the student (TM Lefenya) as the author/co-author. The dissertation is presented in article format. It consists of the following three research papers;

1. Mawire A, **Lefenya TM**, Ekwomadu CS, Shobo AB. Performance of a medium temperature eutectic solder packed bed latent heat storage system for domestic applications. *Journal of Energy Storage* 2020; 28: 101294. In this particular paper, the student was involved in the majority of the experimental tests, and she did most of the analyses of the results. She also contributed to writing up a section of the literature review. This paper appears as Chapter 3 in the dissertation.
2. Mawire A, **Lefenya TM**, Ekwomadu CS, Lentswe KA, Shobo AB. Performance comparison of medium temperature domestic packed bed latent heat storage systems. *Renewable Energy* 2020; 146: 1897-1906. In this the paper, the student performed all the experimental tests, performed some of the analyses in the paper and helped with the literature review section. This paper appears as Chapter 4 in the dissertation.
3. **Lefenya TM**, Mawire A, Ekwomadu C, Shobo A. Charging characteristics of packed bed latent heat storage systems for medium temperature solar applications. In *Proceedings of the SASEC 2019, the 6th South African Solar Energy Conference*, East London, South Africa, 25-27 November 2019. The student wrote the paper, did all the experimental tests and performed most of the analyses. This paper appears as Chapter 5 in the dissertation.

Statement of consent 1

I, Ashmore Mawire as an author/co-author, endorse my consent for the use of published articles as part of Tlotlo Lefenya's dissertation as she contributed to the published work in a major way. The articles are listed below as follows;

1. **Mawire A**, Lefenya TM, Ekwomadu CS, Shobo AB. Performance of a medium temperature eutectic solder packed bed latent heat storage system for domestic applications. *Journal of Energy Storage* 2020; 28: 101294.
2. **Mawire A**, Lefenya TM, Ekwomadu CS, Lentswe KA, Shobo AB. Performance comparison of medium temperature domestic packed bed latent heat storage systems. *Renewable Energy* 2020; 146: 1897-1906.
3. Lefenya TM, **Mawire A**, Ekwomadu C, Shobo A. Charging characteristics of packed bed latent heat storage systems for medium temperature solar applications. In *Proceedings of SASEC 2019, the 6th South African Solar Energy Conference*, East London, South Africa, 25-27 November 2019.


Signed:.....

Date: 15 June 2020

Statement of consent 2

I, Chidiebere Ekwomadu as a co-author, endorse my consent for the use of published articles as part of Tlotlo Lefenya's dissertation as she contributed to the published work in a major way. The articles are listed below as follows;

1. Mawire A, Lefenya TM, **Ekwomadu CS**, Shobo AB. Performance of a medium temperature eutectic solder packed bed latent heat storage system for domestic applications. Journal of Energy Storage 2020; 28: 101294.
2. Mawire A, Lefenya TM, **Ekwomadu CS**, Lentswe KA, Shobo AB. Performance comparison of medium temperature domestic packed bed latent heat storage systems. Renewable Energy 2020; 146: 1897-1906.
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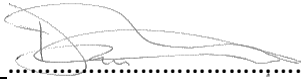
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The articles are listed below as follows;

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2. Mawire A, Lefenya TM, Ekwomadu CS, Lentswe KA, **Shobo AB**. Performance comparison of medium temperature domestic packed bed latent heat storage systems. *Renewable Energy* 2020; 146: 1897-1906.
3. Lefenya TM, Mawire A, Ekwomadu C, **Shobo A**. Charging characteristics of packed bed latent heat storage systems for medium temperature solar applications. In *Proceedings of SASEC 2019, the 6th South African Solar Energy Conference*, East London, South Africa, 25-27 November 2019.

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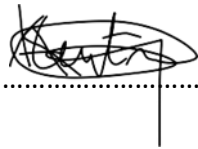
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1. Mawire A, Lefenya TM, Ekwomadu CS, **Lentswe KA**, Shobo AB. Performance comparison of medium temperature domestic packed bed latent heat storage systems. Renewable Energy 2020; 146: 1897-1906.

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Date: 15 June 2020

Chapter 1: Introduction

1.1 Background of the study

It has been clearly indicated in International Energy Outlook 2017 (IEO2017) report that world energy consumption is expected to increase by 28 % between 2015 and 2040, with more than half of the increase attributed to non-OECD (Organisation for Economic Co-operation and Development) countries in Asia (including China and India) where strong economic growth is the source of increasing demand for energy [1]. The industrial, residential and transportation sectors hold the biggest share of this consumption and as a result of this, reduction strategies to reduce the wastage of energy in the form of heat released to the surroundings need to be implemented [2]. To date, the measures put into practice to stabilize the global temperature rise is below target, and is likely to be insufficient. If this target is to be achieved, there must be an increased effort to decarbonize global energy consumption, which still relies heavily on fossil fuel energy sources [3].

The development and utilization of renewable energy has drawn great attention across the world in recent decades. Solar energy is one of the most promising renewable energies, as it is inexhaustible and environmentally friendly, however, solar irradiation varies daily and seasonally. In recent years, research activities have been devoted to improving the operation of solar energy by means of thermal storage to compensate for the lack of radiation during the night or low solar radiation periods such as cloudy periods [4]. Solar radiation is progressively becoming respected for its impact on human life, and the impact of its applications are valuable for economic development [5]. It is a continuous supply of renewable energy that has a vast capacity for a widespread range of uses since it is plentiful and within reach. It is increasingly earning attention as a complement to the limited non-renewable supplies of energy.

Energy sources are categorized into renewable and non-renewable sources. Non-renewable energy sources collectively known as fossil fuels are combustible carbon-based sources for example; coal, crude oil, natural gas or heavy oil which are environmentally unfriendly. The

renewable sources are represented in Figure 1, and all of them require some sort of storage for intermittent periods when they are not available.

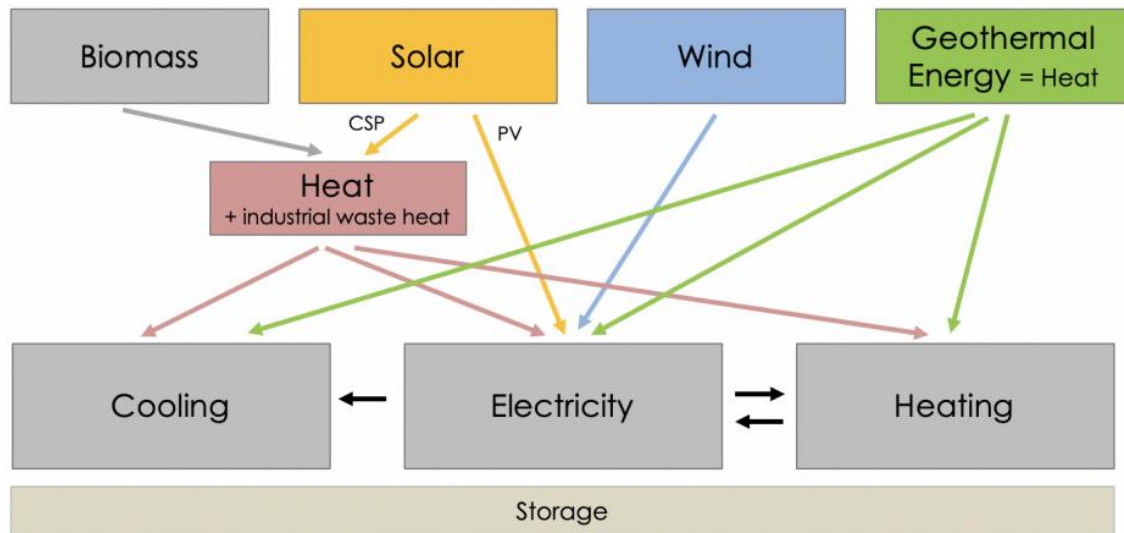


Figure 1.1: A chart showing the different renewable energy sources and their applications [6].

Solar energy has many applications and uses including lighting, air conditioning of buildings generating electricity, and supplying hot water. Solar energy systems are durable and require minimal maintenance once they are installed. Domestically, solar energy can be used for solar cooking, solar water heating, and food drying techniques. Solar energy technology applications are categorized into three temperature ranges which are; low temperature (less than 100 °C), medium temperature (greater than 100 °C and less than 400 °C) and high temperature (greater than 400 °C) applications. As already mentioned, the solar energy resource is intermittent, and for effective implementation of applications where heating is involved, thermal energy storage (TES) systems need to be developed. In thermal energy systems, where a temporal difference exists between the supply of energy and its utilization, TES is necessary to ensure the continuity of many thermal processes [8].

1.1.1 Thermal Energy Storage

TES refers to the technology that allows for the transfer and storage of heat energy [9]. Depending on the specific technology, it allows excess thermal energy to be stored and used

for hours, days and months. TES usage examples include; balancing of energy demand between day-time and night-time, storing summer heat for winter heating and winter cold storage for summer air conditioning [10]. TES can be achieved through three distinct ways; latent, sensible or thermochemical heat storage. Latent heat storage relies on the material's phase change enthalpy to store heat within a narrow temperature range, providing a greater energy storage density as compared to sensible heat storage. Sensible heat storage relies on the material's specific heat capacity to storage energy. Thermochemical heat storage has a much higher energetic storage capacity compared to sensible and latent heat storage, but since it relies on chemical reactions, its actual performance requires very strict and controlled charging and discharging conditions.

1.1.1.1 Latent Heat Thermal Energy Storage (LHTES) system

Latent heat storages use phase change materials (PCM) ideally to store and release heat at an almost constant, unique temperature. Phase change materials (PCMs) are latent heat energy storage materials that can absorb, store and release heat energy by changing their phases. PCMs exhibit the advantage of high storage density in a small temperature range [7]. As a result of this advantage, LHTES systems using PCMs have been widely used in solar energy thermal applications, however, there also disadvantages associated with PCMs. These disadvantages include improper nucleation during solidification, supercooling, poor thermal conductivity of some PCMs and phase segregation.

Not only do the PCM thermophysical properties strongly change during phase transition, the heat transfer also critically depends on melting and solidification temperatures. It is assumed that the PCM structure depends on two phases (solid and liquid phases), and the phase change transitions take place over a small temperature range in which both phases co-exist [11]. A solid to liquid LHTES system stores energy when charged up to the phase change temperature (melting temperature), and it releases the heat while cooling during discharging as the PCM solidifies. The equation for the heat stored during charging is given by;

$$Q = \int_{T_i}^{T_m} mC_l dT + fm\Delta h_f + \int_{T_m}^{T_f} mC_s dT \quad (1.1)$$

, where Q is the quantity of heat storage, C_l and C_s are specific heat capacities of liquid and the solid phases of the PCM used, Δh_f is the latent heat of fusion, T_m is the melting temperature, T_i initial temperature of the storage system and T_f is the final temperature.

1.1.1.2 Sensible heat thermal energy storage (SHTES) system

SHTES involves storing heat by raising the temperature of storage material that is in a solid, liquid, gaseous, or supercritical state without changing its state [12]. Sensible heat storage stores thermal energy in a heat storage medium whose temperature change is the result of the addition or removal of heat. The capacity of sensible heat storage is determined by its specific heat capacity and the mass of the heat storage medium as well as the allowed temperature change of operation. It is given by;

$$Q_s = \int_{T_i}^{T_f} m C_p dT \quad (1.2)$$

, where Q is the amount of heat stored, T_i is the initial temperature, T_f is the final temperature, m is the mass of heat storage medium and C_p is the specific heat capacity. Thermal storage density is an important parameter when choosing a storage medium for sensible heat storage systems. It is desirable to have a heat storage medium with a high value of the thermal mass (mC_p) in order to reduce the volume of the heat storage system. The heat capacity of a sensible storage system can also be expanded by increasing its operation temperature difference. The storage materials absorb heat by conventional heat transfer mechanisms of radiation, conduction, and convection [13]. As the materials cool at night or on cloudy days, the stored heat is released by the same modes. For example, gravel, pebbles, and bricks and ground or soil have been widely used as storage media in large-scale demonstration projects around the world. SHTES has a major advantage of being cheap using locally available materials but its energy storage density is very low when compared to LHTES.

1.1.1.3 Thermochemical thermal energy storage (TTES) system

Thermal energy can be stored as chemical energy in a process called thermochemical thermal energy storage (TTES). The thermal energy is used to drive a reversible endothermic chemical reaction, storing the energy as chemical potential. During periods of high solar insolation, an energy consuming reaction stores the thermal energy in chemical bonds (when energy is needed), and the reverse reaction recombines the chemical reactants and releases energy. Thermochemical storage achieves higher energy storage densities compared to latent or

sensible heat storage methods. In addition to sensible heat, energy is stored as chemical potential. The endothermic reactions that can be employed for solar TTES operate at significantly higher temperatures compared to the other two storage methods [13]. The disadvantages of a TTES system are the high cost of the installation and storage materials and the technical complexity in its operation.

1.1.1.4 Combined thermal energy storage (CTES) system

A combined thermal energy storage system is a combination of both sensible and latent heat materials to form one single storage system. The advantages of this system is that it can store more energy using a smaller volume as compared to a SHTES system in the same temperature range during charging. When comparing costs of developing LHTES to the combined system, it can be a cheaper option to develop, and it combines the advantages of both SHTES and LHTES [14]. However, the appropriate PCM for LHTES needs to be evaluated first before its usage in a CTES system.

1.2 Problem statement

Solar thermal energy storage can be used to store energy for usage during low solar radiation periods such as at night and in cloudy periods. The two main economically viable contenders for domestic solar thermal applications are SHTES and LHTES. SHTES involves storing of thermal energy due to the increase in the temperature of a material due its heat capacity. The heat stored in SHTES can be utilised by reversing the heating cycle during discharging of this type of storage system. LHTES involves storing of thermal energy in PCMs usually during solid to liquid phase transitions which release high latent heats of fusion in heating cycles. The reverse liquid to solid cooling cycles makes this latent heat to be utilised in thermal applications. LHTES involves absorption or release of heat during a phase transition of phase change material, from the solid to the liquid phase or from the liquid to the gas. Examples include fatty acids, inorganic salts, and sugars. LHTES has a larger thermal energy storage density as compared to SHTES hence it has gained popularity in recent years [15-17]. The other advantage of LHTES is its nearly isothermal response for temperature controlled applications. Recent research has focused on packed bed LHTES which are simpler in design especially for domestic applications and have high heat transfer rates [18]. Fewer studies have appeared in recent literature on oil based packed bed LHTES systems which addresses the

deficiency of water as a heat transfer fluid (HTF) since it needs to be pressurized for temperatures above its boiling point [19-20]. Sunflower Oil which is cheap, readily available, food grade and with comparable thermal properties to existing commercial heat transfer oils has been used recently for domestic heat storage applications [21-23]. The research intends to investigate and compare three locally available PCMs using Sunflower Oil as the heat transfer fluid (HFT). The three locally available PCMs are eutectic solder, adipic acid and erythritol. This study will focus on how locally available PCMs can improve the performance of medium temperature solar thermal applications such as solar cooking by investigating their charging and discharging characteristics. The study has never been done before using the mentioned materials, and it will add invaluable information on medium temperature domestic packed bed LHTES systems.

1.3 Aim and objectives

The aim of the research is to compare different packed bed latent heat storage systems for medium temperature applications experimentally. The specific objectives are to:

- Test different packed bed TES systems made of three different PCMs experimentally.
- Compare the performances of the three packed bed TES systems.
- Determine the optimal operating conditions for the packed bed systems so as to select the best thermal performance conditions.

1.4 Outline of the dissertation

Chapter 1 presents the introduction of dissertation which is categorised into the background of the study, problem statement and aim and objectives. Chapter 2 presents a comprehensive review of related literature on packed bed LHTES systems. Chapter 3 presents results of a published journal article (Journal of Energy Storage 2020, 28: 101294) which evaluates the performance of a eutectic solder packed bed LHTES system. Chapter 4 presents the results of another published journal article (Renewable Energy 2020; 146: 1897-1906). In this Chapter, the performances of three packed bed LHTES systems are evaluated and compared. Chapter 5 presents a paper from the 6th Southern African Solar Energy Conference 2019 (SASEC 2019) held in East London, South Africa from 25-27 November 2019. In this chapter, the energy and exergy performance of three packed bed LHTES systems during charging is compared.

Chapter 6 summarizes the conclusions drawn up from the papers presented, and presents recommendations for possible future work.

1.4 Summary of the chapter

The chapter presented a background of the research which focused on the demand of energy growing rapidly, and using thermal energy storage as one of the pathways for the mismatch between energy supply and demand. Three types of TES systems were discussed, namely; latent heat thermal energy storage (LHTES), sensible heat thermal energy storage (SHTES) and thermochemical thermal energy storage (TTES). The problem statement highlighting the motivations of the study, as well as the aim and the objectives were also presented. Lastly, the outline of the dissertation was presented.

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Chapter 2: Literature review

This chapter provides a literature review of packed bed latent heat storage systems since the aim of the study is to investigate and compare the performance three different latent heat packed bed storage systems for medium temperature applications.

2.1 Low temperature packed bed latent heat thermal energy storage systems

Low temperature packed bed latent heat thermal energy storage (LHTES) systems use phase change materials that have melting points between 0 °C to 100 °C, and the applications are within the same range. These thermal energy storage systems have been good contenders economically as they use cheap and readily available phase change materials (PCMs).

The performance evaluation of a paraffin wax latent heat storage system in the solidification phase was done in [1]. Water was used as the heat transfer fluid in the investigation with two inlet temperatures of 30 °C and 40 °C, respectively. Two evaluated parameters were the thermal gradient data and entropy generation rate. Results indicated that the reduction in the capsule diameter and the inlet temperature resulted in higher irreversibility in the system, but it was found that irreversibility did not have a considerable impact on the reduction of the performance of the system. The reduction in diameter of the capsule improved the efficiency of the system when compared to the reduction of the inlet temperature. Salunkhe and Krishnah [2] performed investigations on latent heat storage materials for solar water heating applications. Their investigations were targeted at thermophysical properties for heat storage applications between 25 °C and 100 °C. The parameters included thermal stability, corrosion, phase segregation, and sub cooling. It was found that PCMs such as lauric acid, palnic acid and paraffin wax were the best PCMs for solar water heating systems, whereas calcium chloride hexahydrate and P116 paraffin wax were not suitable candidates for latent heat thermal energy storage.

An analysis of a packed bed latent heat storage system using PCM capsules was done in [3]. The packed bed was made of capsules filled with paraffin wax, and water was used as the heat transfer fluid. The effects of the inlet temperature and the mass flowrate were examined. The results indicated that the time it took for solidification was too long as compared to the melting time, and this is due to very low heat transfer. The charging and

discharging rates were much higher for capsules with the smaller radius as compared to capsules with the larger radius. It was also found that greater Stefan numbers reduced the time required for completing charging. Lee et al., [4] studied the effect of capsule conduction and convection on the thermal storage performance of a thermal storage tank using n-octadecane acid in spherical capsules. Numerical models were used to examine the spherical capsules. The first model was used to apply boundary conditions on the outer surface of the PCM. The second model maintained a constant temperature on the surface of the capsule to investigate capsule conduction. The third model investigated convection outside the capsule. The modelling results showed that the model that included conduction and convection outside the capsule showed a lower discharging performance than the other models.

The stratification analysis of a packed bed thermal energy storage system was done in [5]. The TES system was for a cooling application. The PCM used was PK6 manufactured by Rubitherm GMBH. The parameters that were used to characterize the storage tank were the stratification number, Richardson's number, Mix number, and the first and second law efficiencies. The storage tank with the PCM was compared to the one without PCM. The stratification number and the Richardson's number described thermal stratification correctly during charging for both tanks. The results obtained showed that the introduction of PCM to the storage system did not enhance stratification during charging. Karthikeyan et al., [6] performed parametric studies on a packed bed storage unit filled with PCM encapsulated spherical capsules for low temperature applications. The PCM that was used was paraffin, and an enthalpy based model was used to predict the thermal gradient inside the PCM. The results obtained indicated that the size of PCM ball, the fluid inlet temperature and the flowrate had an impact on the heat transfer rate of the bed. The poor thermal conductivity of the PCM had only a small effect on heat transfer.

A numerical heat analysis of a packed bed latent heat storage system was done by Xia et al., [7]. The numerical packed bed model investigated the flow field through voids of the PCM spheres, and the PCM used was RT20 paraffin. The thermo-fluid phenomena were validated with experiments for both the storage and effectiveness of heat energy. The influence of the arrangement of PCM encapsulation was also studied. The results indicated that random packing was more favorable for heat storage and heat retrieval as compared to specialised packing. The melting and solidification thermal characteristics of a low temperature PCM

packed bed during charging and discharging were studied in [8]. Air was used as the heat transfer fluid, and a commercial paraffin wax (RT-42) poured into celluloid balls was the PCM. Various bed thicknesses, air mass flowrates and inlet temperatures were tested. The results showed that the temperature of the PCM increased at a faster rate for melting, and decreased at a slower rate for the solidification processes. It was noted that the increase of the mass flowrate resulted in a higher heat transfer coefficient, while the total melting and solidification times were decreased. Experimental data compared well with simulated data. The data were used to correlate and estimate the air temperature and PCM bed thickness.

An experimental investigation of a packed bed LHTES using paraffin wax as a PCM for a concentrated solar collector was done by Senthil et al., [9]. Charging and discharging experiments through the packed bed were performed. The results indicated that the rate of charging of the TES system was affected by the quality of heat extracted from the solar collector. Energy and exergy analyses of a solar dryer integrated with sodium sulphate dehydrate and sodium chloride as thermal storage media were done in [10]. Red chilli was used as food for the drying process. The storage potential of sodium sulphate dehydrate and sodium chloride was studied. Energy consumption and exergy stability were also evaluated. Results indicated that the moisture content of red chilli reduced from 72.72 % to 7.6 %. The overall drying exergy efficiency varied from 10.61 % to 18.79 %, and the energy efficiency during non-sunshine hours ranged from 81.19 % to 66.82 %. The beneficial usage of a packed bed of latent heat energy storage for heating of a hydroponic greenhouse was presented by [11]. This work evaluated the effects of a solar air heater combined with a greenhouse by observing the changes in its inner climatic temperatures before and after heat storage. The results indicated that solar heating with TES improved the greenhouse microclimate temperatures. The temperature never dropped to less than 32 °C and 15 °C, respectively, during day and night times. He et al., [12] performed experiments on a thermocline storage tank with and without encapsulated paraffin wax. A conventional water TES tank and a latent heat storage tank using paraffin wax encapsulated capsules were experimentally investigated. The results showed that the performance of the PCM water tank was not as good as that of the water tank because the outlet temperature remained closer to the PCM temperature for a longer duration.

The effectiveness of the NTU (Number of Heat Transfer Units) packed bed PCM thermal energy storage model was evaluated by Amin et al., [13]. The thermal energy storage system was filled with ice encapsulated in spheres. A 2-D dimensionless model was used to predict the heat transfer of the PCMs instead of a 1-D dimensionless model. The thermal resistance between the heat transfer fluid and the PCM was investigated using isothermal and parallel heat transfer methods. Parallel heat transfer showed that phase change happened simultaneously and more efficiently as compared to isothermal heat transfer. An experimental investigation on a PCM based thermal energy storage system for a solar air heating application was done in [14]. The purpose of the study was to evaluate the performance of the solar air dryer in varying weather conditions. An HS-58 organic salt was used as the PCM. A solar collector was incorporated with a thermal energy storage unit to the solar dryer. Experiments were done to evaluate the charging characteristics of the PCM. Results obtained indicated that lower mass flowrates resulted in the storage system being more effectively charged for a longer period. Effects of the aspect ratio and dispersed PCM balls on the charging performance of a latent heat storage unit were presented in [15]. A cylindrical storage tank had spherical capsules filled with HS-89 as the PCM in a packed bed storage configuration. This solar storage system was for a solar water heater. The temperature profiles, charging efficiency stratification numbers, and the Richardson's number were investigated in this study. The results indicated that an increase in the stratification levels in the tank increased the instantaneous heat transfer. The packaging of the PCM balls in the storage tank also influenced stratification irrespective of the aspect ratio.

2.2 Medium temperature packed bed latent heat thermal energy storage systems

Raul et al., [16] performed modelling and experimental studies on latent thermal energy storage systems with encapsulated PCMs for solar thermal applications. In their work, a mathematical model of encapsulated PCM inside a storage tank was developed using two energy equations with an enthalpy based technique. The model was used to analyse the temperature of the PCMs and the heat transfer fluid (HTF). A lab scale latent heat thermal energy storage system (LHTES) made of A164, an organic PCM, was also designed to investigate the effects of the charging temperature and the flowrate. The heat transfer fluid used was Hytherm 600. The inlet charging and discharging temperature were 180 °C and

120 °C, respectively. The modelling results showed that the energy stored and extracted was much faster for the smaller diameter PCM capsules compared to the larger diameter capsules. The storage results showed that the maximum efficiency was around 75.69 %. Bhagat et al., [17] performed a numerical analysis of a LHTES system using encapsulated phase change material for a solar power plant. The packed bed LHTES was integrated with an organic Rankine cycle solar thermal power plant for the production of electricity. A commercial grade PCM (A164) with a melting temperature point of 171 °C was used. The heat transfer fluid used was Hytherm 600, flowing through the storage system at an inlet temperature of 200 °C. The results indicated that increasing the mass flowrate and inlet temperature significantly improved the ability of storing and realising heat in the storage system, however, the dimensions and porosity had no effect on the overall effectiveness of the system.

The performance evaluation of a nano-enhanced PCM storage system during discharging in a waste heat recovery system was done by Soni et al., [18]. In the study, recovery of waste heat for temperatures of 100 °C to 150 °C was numerically investigated. The model parameters studied involved phase change, heat transport and convection during discharging in a spherical capsule. The PCM was doped with high thermal conductivity nanoparticles to account for the low energy discharging rate. The PCM was erythritol, and a 5 % volume fraction of the nanoparticles namely; copper, aluminium and silicon was added to the PCM. A detailed study analysis on the performance of Cu over erythritol was done for the thermophysical properties, thermal field velocities and solidification fraction fields in the discharging process. The results showed that the Cu/erythritol composition showed increased thermal conductivity. It was also observed that addition of nanoparticles reduced the storage capacity. A study on a medium temperature chemical heat storage using mixed hydrates was done by Kato et al., [19]. The study demonstrated that the storage material mixed with metal hydroxides were capable of storing heat at temperatures of approximately 200 °C-300 °C. The results indicated that the mixture of hydroxides was potentially able to store medium temperature heat such as heat emitted for internal combustion solar energy systems.

Low to medium temperature TES applications were presented by Cunha et al., [20]. In their study, a comprehensive review of phase change materials for temperatures between 0-250 °C was presented. The method used for analysing the material was a practical indirect heat exchanger for latent heat storage systems. The conclusions made were that the latent

PCMs have a great potential to store large amounts of energy compared to sensible heat storage materials. Salt hydrates were the most interesting materials for temperatures below 100 °C. Eutectic mixtures of organic salts appeared to be the most promising PCMs for medium temperature applications. An experimental comparison of the thermal performance of acetanilide, meso-erythritol and In-Sn alloy in similar spherical capsules was done by Shobo and Mawire [21]. Charging and discharging experiments were done for the three PCMs inside spherical capsules for medium temperature applications. The HTF used was Sunflower Oil, and it was observed that at all charging rates meso-erythritol possessed the largest thermal energy storage capacity followed by the In-Sn alloy. The In-Sn alloy showed the best performance than the other PCMs because of little subcooling, and high thermal storage charging and discharging rates.

A dynamic thermal performance of four encapsulated PCM spheres for domestic medium temperatures application was presented by Mawire et al., [22]. Charging and discharging experiments were performed with four different phase change materials namely; high density polyethylene (HDPE), eutectic solder, erythritol and adipic acid encapsulated in spherical capsules made of aluminium. The PCMs chosen were candidates for applications for temperatures between 100 °C-250 °C. The thermal cycles were done with flowrates of 4 ml/s, 6 ml/s and 8 ml/s for charging and discharging experiments. The results indicated that the eutectic solder exhibited the most pronounced phase change transitions, and HDPE exhibited the least pronounced phase change transitions in both charging and discharging experiments. The estimation of the thermal endurance of multicomponent sugar alcohols as a phase change materials was done in [23]. Three sugar alcohols, namely; mannitol, dulcitol and inositol and their eutectic mixtures were selected as the PCMs. The thermophysical properties of the PCMs were characterized using differential scanning calorimetry (DSC) analysis. The second method involved constant temperature experiments based on the degradation of the latent heat of the PCMs. The results indicated that mannitol, dulcitol and inositol had high latent heats of fusion, which was a good indication for medium temperature storage applications. It was also observed that the degradation periods increased with the decrease in the melting temperatures of each sugar alcohol. Sugar alcohol mixtures were found to be promising PCM candidates in the temperature range of 100 °C-273 °C.

A study of the phase change of erythritol with nanocopper particles in spherical containers during heat transport was done by Zhang et al., [24]. The work proposed encapsulation of spherical balls arranged in a packed bed in a thermal energy storage tank. An amount of 0.4 % of nanocopper was added to 99.6 % of erythritol in the storage tank. The TES tank was separated by a groove in each layer of the packed bed. Thermal oil circulated through the grooves as the heat transfer fluid, and the experiment was started at 118 °C. A model was developed to validate the experimental results. The modelling results were in good agreement with the experimental results. The results indicated that the temperature of the oil bath had a great influence on the heat transferred to the PCM balls. Galactitol as a PCM for latent heat storage for solar cookers was investigated by John et al., [25]. The study was aimed at finding out the effect of the upper cycle temperature on the thermal behaviour of galactitol. Three bulk samples with three different upper cycling temperatures were studied. Differential scanning calorimetry (DSC) was used to measure the heat capacity of the bulk samples. The results indicated that the upper cycles had a great influence on the melting and freezing, cycling temperature, degree of subcooling and phase change enthalpy. Galactitol was found to be unstable with a short life span for practical applications for medium temperature TES.

The preparation and thermal properties of an exfoliated graphite, erythritol and mannitol eutectic composite as a form stable PCM for thermal energy storage was studied by Zengahu et al., [26]. The results obtained using DSC indicated that the eutectic composite melted stably at 114 °C. The thermochemical characteristics of polytetrafluoroethylene (PTFE), polyetheretherketone (PEEK) and polyetherketoneketone (PEKK) as encapsulation materials for medium temperature solar applications were investigated by Gupta et al., [27]. The commercially available phase change material (A16A) was used as the PCM, and it was poured into capsules made of the three materials. A capsule was made from each of the materials under study, and the mechanical properties were studied at 10 thermal cycles near their degradation temperature to understand their characteristics at high temperatures. The tests involved thermogravimetric analysis, tensile and compression testing and temperature profiles. Test results showed that PEEK was the best material that could be used up to 275 °C, which was suitable for medium temperature applications.

The integration of thermal energy storage in a metal hydride hydrogen storage tank was done by Mellouli et al., [28]. A metal hydride (MH) tank having a phase change material as a latent storage material was studied. The PCM chosen was sodium nitrate after considering PCMs with the melting temperature of 307 °C. Hydrogen was the heat transfer fluid used, and heat mass transfer analysis was done to understand the influence of the bed geometry on the relationship between the absorption of hydrogen and heat storage. The effect of aluminium foam as an enhancement of hydrogen was also studied. It was observed that the selection of a PCM was very important when related to a MH tank. It was also found that choosing another geometry like placing cylindrical tubes filled with PCM was better than encapsulating the spherical shells. Adding an aluminium foam reduced the hydrogen tank's storage capacity. The design, development and performance of a latent heat storage unit for a solar cooker was done by Sharma et al., [29]. In their work, a storage unit filled with acetamide PCM balls was studied. The stored energy was used to cook food in the evening. A comparison of the solar cooker with the PCM storage and a standard solar cooker was done. Rice was cooked in both the solar cooker with the storage, and in the solar cooker without the storage at different times. The results showed that evening cooking was possible with a solar cooker having the PCM and not possible for the cooker without PCM storage.

An assessment of the thermal performance of PCMs in a latent heat storage system for different applications was done by Abu-Hamdeh and Alnefaie [30]. Small acetamide PCM capsules were used as the storage material in a storage tank constructed from aluminium. The capsules were placed in a receiver of a reactor to receive sunlight, and when the PCM melted, the capsules were taken out of the receiver and put in an insulated heat container inside a cooking vessel. The temperature of the PCM at loading was 110 °C. Three different air flowrates through the cooker were used to determine the impact of air flowrate. It was observed that the temperature of PCM capsules decreased rapidly as the temperature of the cooking pan increased. The rate of charging also increased with an increase in the air flowrate. The performance assessment of a solar cooking system integrated with a thermal energy storage system was presented Kumaresan et al., [31]. The solar cooker was combined with a TES system. The PCM used was D-mannitol, and the heat transfer fluid was Therminol 55. The heat required for the experiment was set at 160 °C, and a heat balance for the cooking unit was evaluated. During the discharging process, HTF was circulated through the cooking unit.

The results indicated that they were heat losses in the flow circuit during discharging, but the stored heat was sufficient to cook different foods.

An experimental and numerical investigation of a solar flat plate cooking unit (FPCU) coupled to a storage system was done by Kumaresan et al., [32]. A flat plate cooking unit was developed for use in the indirect mode of cooking. The HTF used was therminol 55, and the PCM was D-mannitol. The heat requirements for the experiments were set at 160 °C. A computation fluid dynamics (CFD) analysis was done to analyse the heat transfer behaviour during the cooking period. The results indicated that the heat transfer rate of the FPCU was 0.6 kW. The overall system efficiency was found to be 9 %. A good agreement of the CFD results and experimental results was achieved. The thermal performance evaluation of a latent heat storage unit for late evening cooking in a solar cooker having three reflectors was done by Buddi et al., [33]. The PCM storage unit was designed to store heat during sunshine hours and use it for late evening cooking. The PCM used was a commercialized grade of acetanilide. The thermal effects of three reflectors and a single reflector on the absorbing plate temperature with and without any load was investigated. It was concluded that the cooker with three reflectors was much better than the single reflector cooker, and it was recommended for evening cooking at medium temperatures.

A review of latent heat energy storage systems for medium temperature solar process heat applications was done by Crespo et al., [34]. The focus for the study was on thermal energy storage for industrial applications at medium high temperatures of 120 °C to 400 °C, as they are few reported in recent literature. In the review, food, brewery and chemical industries were selected as they have a higher potential of incorporation with the TES systems. Latent heat storage materials for medium temperatures in packed beds were also studied. Organic eutectic composites were suggested as the group of PCMs with good potential of storing latent heat energy at medium temperatures. Naik et al., [35] presented a review of medium temperature systems and applications of concentrated solar thermal technology from an Indian perspective. In their work, they reviewed the potential markets for the use of medium temperature systems from 80 °C to 250 °C, including latent heat storage for these systems.

2.3 High temperature packed bed latent heat thermal energy storage systems

A linear parabolic trough solar power plant (LPTSPP) assisted with a latent thermal energy storage system was simulated dynamically in [36]. The system was used with a Rankine cycle for the production of electricity. A latent heat packed bed TES system was incorporated with the LPTSPP to improve its performance and capacity factor. In the study, TRNSYS software was implemented to perform a dynamic analysis on the parabolic trough concentrated solar plant. High temperature PCMs such as H_2SO_4 , NaNO_3 , and KNO_3 were tested in the LHTES. Thermal oil was used as the heat transfer fluid. Parameters such as the charging inlet temperature, different thermal cycles and solar fraction were studied. Results indicated that operating the Rankine cycle using NaNO_3 as the LHTES material was the best option. The concentrating solar power (CSP) plant with LHTES was enhanced by 90.5 % when compared to the CSP plant without LHTES.

The thermal investigation of a PCM based high TES system in a packed bed storage configuration was presented in [37]. The aim of the study was to assess the behavior of a packed bed TES system consisting of molten salt capsules. The heat transfer fluid used was also molten salt. Effects of the capsule diameter and the fluid inlet velocity were investigated. Concentric-dispersion equations and the enthalpy method for phase change inside the capsule were used to model the system. The results indicated that decreasing the size of the PCM capsule, and fluid inlet velocity increased the charging efficiency. Numerical and experimental studies of heat transfer characteristics of a thermal energy storage system packed with molten salt PCM capsules were presented in [38]. In the study, the dynamic performance of the high temperature LHTES was analysed. The capsules were filled with sodium nitrate, and air was used as the heat transfer fluid. Two dimensional equations models were developed, and the simulated results compared well with the experimental results. Results indicated that the Stefan's number had a great impact on the storage capacity of the TES tank. It was also observed that the shell properties of the capsules influenced the thermal conductivity of the PCM.

The dynamic performance of a molten salt packed bed energy storage system using PCM capsules was analysed by Wu et al., [39]. The TES system was filled with a packed bed of capsules containing high temperature molten salt as the PCM. The molten salt was also used

as the heat transfer fluid. A transient two dimensional dispersion concentric model was developed accounting for phase change between the PCM and the heat transfer fluid. Results indicated that there existed quasi-isothermal and thermocline regions in the molten salt temperature distribution. It was observed that decreasing the molten salt inlet velocity, and the capsule diameter effectively increased the discharging efficiency of the system. The heat transfer analyses of encapsulated PCMs were done in [40]. In this work, high temperature phase change materials with melting points above 400 °C (zinc and eutectic salts) were poured in different capsules. The PCMs were used to store large amounts of solar energy of around 600 MWh. The parameters investigated included the diffusion time, and the time for heating and cooling. The results indicated that the heat transfer period reduced with the size of the capsules.

A numerical and experimental study on the performance of a new layered high temperature packed bed TES system with macroencapsulated capsules was done in [41]. The effects of using two different diameter capsules was investigated, and molten salt was selected as the PCM using air as the heat transfer fluid. The effects of the charging rate, inlet temperature and mass flowrate were studied. The results concluded that the phase change of the lower layer having capsules with a smaller radius melted faster compared to the upper layer of the TES tank having capsules with the larger radius. It was also observed that increasing the HTF flowrate increased the performance of the system. An investigation on the performance of a high temperature packed bed LHTES system using Al-Si alloy was done by Ma et al., [42]. The PCM used was an Al-Si alloy which is a high temperature phase change material. Air was used as the heat transfer fluid, and a three dimensional numerical model of the packed bed LHTES was used to investigate the performance of the system based on an enthalpy based method. The parameters studied included the mean power, energy transfer and the discharging time. The results showed that the PCM TES was better compared to a rock TES. An investigation of the thermal performance of a high temperature packed bed TES system containing a carbonate salt based composite PCM (CPCM) was done by Li et al., [43] using air as the heat transfer fluid. A three dimensional model was developed to study the performance of the system. Radiation heat transfer, mass loading and heat transfer fluid effects were studied. The results indicated that the system containing the CPCM showed better performance compared to the system containing ferric oxide as a single PCM.

An experimental and numeral study on the performance of a new high temperature packed bed TES using macroencapsulated molten salt was done by Li et al., [44] using air as the heat transfer fluid. A mathematical model was developed to simulate the performance of the packed bed system. Thermal performance parameters such as temperature evolutions of the heat transfer fluid were investigated as well as the average charging and discharging times. Results indicated that heat transfer resistance of the capsule and the heat transfer fluid were the main influential factors in heat exchange. An increment of the inlet temperature and the mass flowrate increased the charging and discharging efficiencies. Liu et al., [45] reviewed storage materials, and the performance enhancement techniques for high temperature PCMs. In this paper, CSP plants that incorporated phase change materials with melting temperatures above 300 °C were studied. Various enhancement techniques for thermal performance at high temperatures were also presented.

2.4 Summary of the chapter

This chapter reviewed packed bed latent heat thermal energy storage that can be classified into three different temperature ranges namely; low, medium and high temperatures. The differences were based on applications and melting points of the PCMs used. It is evident that most low temperature packed bed LHTES systems are for applications such as space and air heating. Medium temperature packed bed LHTES systems are for use in applications such as cooking and industrial medium temperature heat generation, and high temperature packed bed LHTES systems are used mostly in concentrated solar power plants. Most of the literature focuses on low, medium and high temperature applications using air as the heat transfer fluid with organic and inorganic PCMs. Limited work has been done on medium temperature applications using heat transfer oils and metallic PCMs thus justifying the work presented in this dissertation.

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Chapter 3: Paper 1-Performance of a medium temperature eutectic solder packed bed latent heat storage system for domestic applications

The chapter presents results of a published journal article, Journal of Energy Storage 2020, 28: 101294.

In this particular chapter, a packed bed latent heat storage system consisting of aluminium encapsulated eutectic solder capsules is experimentally evaluated during charging and discharging cycles. The effect of the flowrate on the charging performance is evaluated using three charging flowrates namely; 4 ml/s (low), 6 ml/s (medium) and 8 ml/s (high). The storage system is also evaluated with three different set heater charging temperatures (260 °C (low), 280 °C (medium) and 300 °C (high)). Discharging experiments are performed with the three different flowrates to evaluate the effect of the flowrate on the discharging characteristics. Charging and discharging results are presented in terms of the axial storage tank profiles, the energy rates and the exergy rates. The overall performance of the storage system is evaluated in terms of the energy and exergy storage efficiencies. The charging energy and exergy rates are seen to increase with the charging flowrate at the expense of a greater charging duration since higher flowrates tend to cool down the heater. The best charging flowrate of 6 ml/s is suggested which ensures a reasonable duration of charging, reasonable thermal stratification and reasonably high energy and exergy charging rates. The effect of the set heater temperature on the charging energy and exergy rates is insignificant as compared to the effect of the flowrate. The best set charging temperature of 280 °C is also suggested by the experimental tests. Increasing the flowrate results in faster heat transfer with higher peak energy and exergy rates during discharging. However, the stored energy and exergy is utilized for a shorter duration as compared to the lowest flowrate. Energy and exergy storage efficiencies decrease with an increase in the flowrate and the highest flowrate shows the lowest values due to the longer charging duration and the shorter discharging duration. The set heater charging temperature shows only a marginal effect on the energy and exergy storage efficiencies. A comparison of the energy and exergy rates of the solder during charging and discharging with adipic acid shows slightly better performance during charging cycles for adipic acid. For discharging cycles, the solder shows a better performance.

3.1 Introduction

In developing countries, firewood is commonly used to cook food in the rural areas with the emission of smoke which when inhaled results in lung-related diseases. Additionally, cutting of wood for heating and cooking also increases the rate of de-forestation which has a negative impact on the environment. Sustainable and renewable energy resources such as solar energy can be used to cater for domestic purposes such as cooking food in developing countries [1]. The main problem of solar energy is that it is intermittent and it needs to be stored for usage when it is not available, for example during cloudy periods or at night. Night-time cooking is particularly attractive for rural communities to reduce the usage of greenhouse gases-generating fossil fuels. Thermal energy storage (TES) can offer a short-time solution for cooking needs during the night. This is done by storing solar thermal energy during daytime and using this stored energy at night [2-5]. The two main viable options of TES for domestic cooking applications are sensible heat TES (SHTES) and latent heat TES (LHTES). SHTES is cheaper and readily available as compared to LHTES, but its main drawback is its lower energy storage density implying larger energy storage tanks for even a moderate amount of energy. LHTES ensures compact thermal energy storage with the delivery of the stored heat at a controlled temperature for a longer duration since both sensible and latent heat can be extracted from such storage system.

The drive nowadays is to investigate different types of phase change materials (PCMs) for medium to high temperature applications [6]. In a recent study [7], an experimental and numerical study on the performance of a new high temperature packed-bed TES using macro-encapsulated molten salt phase change material was done. The shell and tube TES configuration system was compared to a packed bed TES configuration, and the charging and discharging rates of the packed bed were found to be 1.8–3.2 times more than that of the former. The overall efficiency of the packed bed system was also found to be 1.9–2.4 times that of the shell and tube TES system. It is thus justified to carry out research on latent heat packed bed storage systems since they have greater efficiency, and their design is less complicated as compared to the other designs. Recent research on packed bed latent heat storage systems for medium to high temperatures is rather limited and studies reported mainly used air as the heat transfer fluid [8-16].

In recent years, metallic alloy PCMs have also been suggested for high temperature applications [17]. The research highlighted the fact that metals and metal alloys possessed a high storage density on a volumetric basis as well as a substantially higher thermal conductivity. The study also revealed that some pure metals and metal alloys presented interesting thermal properties to be used as PCMs in thermal storage systems, but there was a lack of understanding on the implications of the metallurgical aspects related to the melting and solidification of these materials under thermal cycling at high temperatures. Limited recent work has been done on high temperature metallic PCMs to enhance their understanding [18-33]. Andraka et al., [18] proposed and tested a metallic PCM TES system for a Stirling dish system. The PCM (CaSi and CuMgSi) was successfully synthesized and characterized. The CuMgSi PCM had a very high latent heat of melting, minimizing the volume and mass of PCM needed for a 6-hour operation. Its cost was also reasonable, leading to a cost-effective storage system.

The macro-encapsulation of a metallic PCM using cylindrical-type ceramic containers for high-temperature TES was presented by Fukahori et al., [19]. A new macro-encapsulation method for the metallic PCM, Al-25 wt%Si, using Al₂O₃ containers was developed. An Al film was used as the sealing material for the encapsulation, and the PCM was completely encapsulated by the container. The prepared PCM capsule showed excellent cyclic durability. In a study by Nomura et al., [20], micro-encapsulated PCMs (MEPCMs) were developed from Al-Si alloys, in which four kinds of Al-Si microspheres with different Al-Si compositions: Al-12%Si, Al-17%Si, Al-20% Si, and Al-30%Si (mass %) were encapsulated. Three different temperatures, 1100 °C, 1150 °C, and 1200 °C, were chosen to study the effect of temperature on the shell morphology, structure, and latent heat storage capacity. The results revealed an increase in the MEPCM thermal storage capacity with decreasing Si content which lowered the operating temperature. The cyclic durability of the MEPCM was also evaluated through repeated heating and cooling processes in air. The results obtained showed no significant change in both the MEPCM structure and the thermal storage capacity.

Simulations and testing of a latent heat TES unit with metallic phase change material were presented by Kotzé et al., [21]. An aluminum eutectic silicon alloy, (AlSi₁₂) was used as the PCM because of its moderate melting temperature, high thermal conductivity, and high heat of fusion. A prototype TES test rig was built and tested to understand better the behavior of the latent heat TES system. A mathematical model was developed to predict the behavior of

the system. The model was compared with the behavior of the test rig during discharging, and the model simulated the latent heat thermal energy storage reasonably well. Wang et al., [22] developed a novel kind of high temperature phase change storage heater that could shift electricity demand from peak periods to off peak periods to provide significant economic benefits. The results showed that with a high heat of fusion and thermal conductivity, AlSi_{12} was a suitable heat storage medium. The results also showed that the heat storage ratio of the heater was high, and it increased with increasing heating power during the phase change process. The heater could provide a stable heat discharging rate which met the demand for indoors thermal comfort to some extent. The heater was also economical for domestic space heating because of its low operating cost. Zhang et al., [23] investigated the encapsulation of a copper-based PCM for high temperature TES. Copper capsules coated with refractory metallic shells were proposed as a novel metal PCM, which could work at temperatures up to 1000 °C. The structure investigations revealed excellent oxidation resistance of the capsules and good stability between copper and the chromium–nickel layer, even after long-term charging and discharging cycles.

Cárdenas and León [24] suggested the use of metal alloys as PCMs was underestimated by researchers, although they have desirable properties such as high thermal conductivity, low corrosivity, smaller volume changes associated with phase change and no subcooling. These alloys are suitable for certain applications where weight is not a decisive factor and they are able to compete with salts. The thermal performance of a micro-encapsulated paraffin PCM with a low melting temperature alloy (LMA) was presented by Praveen and Suresh [25]. The results obtained after using the LMA showed more complete melting and more uniform temperature distribution of the PCM.

Nazir et al., [26] presented a review on phase change materials for energy storage applications. They concluded that most of the recent publications are directed at solving problems related to improving performance stability, reducing super-cooling and lowering cost for thermal storage applications in power plants. In terms of enhancing the PCMs properties, the authors concluded that encapsulation and nanomaterial additives were the two most prominent approaches aimed at increasing the surface area, protection from the environment, increasing the compatibility with storage materials and reducing corrosion.

The role of metallic foams in heat storage in the presence of nanofluid and microencapsulated PCM was investigated in [27]. The use of a ternary fluid containing Al_2O_3 nanoparticles and a

microencapsulated phase change material (MEPCM) was investigated. Different heat flux intensities were applied on the outside wall of a porous pipe with the fluid entering at different flow rates. The results revealed that the addition of a metallic foam improved the heat transfer between the wall of the pipe and the fluid. The thermophysical characterization of an Mg-51%Zn eutectic metal alloy for direct steam applications was presented in [28]. A comparison with pure, binary and ternary inorganic salts used as PCMs was presented highlighting the advantages and disadvantages of the different systems. This alloy was proposed not only as a candidate for latent heat thermal energy storage for direct steam generation (DSG) in concentrated solar plant applications but it was also useful for high pressure and high energy steam processes as well.

Risueno et al., [29] investigated zinc-rich eutectic alloys for high energy density latent heat storage applications. The synthesis process, structural and thermo-physical characterization of 84%Zn-18.7%Al-7.3%Mg, 88.7%Zn-11.3%Al and 92.2%Zn-7.8%Mg eutectic metallic alloys was performed in order to evaluate their potential as PCMs for LHTES applications. The results showed melting temperatures of 344 °C, 382 °C and 371 °C, and heats of fusion of around 132 J/g, 118 J/g and 106 J/g respectively for the alloys. The obtained energy densities for the investigated alloys were found to be almost two times higher than the ones for similar metallic PCMs reported in literature.

Bashir et al., [30] performed thermal analyses on Mg_2Si and Fe_2Si_5 as PCMs for Dish Micro-Gas Turbine (DMGT) systems. Mg_2Si had a thermal conductivity that was around 2.8 W/mK at 300 K, which decreased with temperature. Fe_2Si_5 also showed a lower thermal conductivity, which decreased with temperature. The chemical compatibility test with SiC showed that the PCM samples did not react with SiC at temperatures up to 1000 °C. Ma et al., [31] developed Fe-shell/Cu-core encapsulated metallic PCMs prepared by an aerodynamic levitation method. These types of PCMs were found to be suitable for high temperature applications. Experimental evaluations of metallic PCMs for thermal transient mitigation were presented in [32]. The work presented the performance of two metallic PCMs (a Bi/In/Sn PCM and a Bi/Pb/Sn/In PCM) acting as integrated thermal buffers for high power 19 ms pulses. The Bi/Pb/Sn/In PCM was able to reduce the temperature rise during the period of the pulse by 60 °C for 120 W, and by 81 °C for 160 W using a dielectric gel as a baseline. Calabrese et al., [33] conducted an experimental study on the corrosion sensitivity of metal alloys for usage in PCM thermal energy storages. The corrosion behaviour of three metal alloys (AISI 1050

carbon steel, AA 6061 aluminium and CW024A copper alloys) was investigated with magnesium nitrate hexahydrate molten salt at 120 °C. The results showed good corrosion stability for the aluminium alloy, since no evidence of corrosion phenomena were observed on its surface. However, carbon steel and copper alloys showed significant electrochemical activity, together with a large amount of corrosion products, after just a few hours of immersion in severe environmental conditions.

High temperature metallic PCMs are more appropriate for industrial processes, and they present safety issues for domestic scale applications like cooking of food hence medium temperature metallic PCMs (100 °C to 300 °C) using heat transfer fluids are more appropriate. There are very limited studies that have appeared in recent years on medium temperature PCMs using heat transfer fluids [34-40]. Two oil based TES systems were compared experimentally by Shobo and Mawire [34]. The first storage medium was Sunflower Oil which was used both as the heat transfer fluid (HTF) and the storage medium. A packed bed of encapsulated erythritol was used as the second storage medium with Sunflower Oil as the HTF. Results indicated that the thermal performance of the storage was enhanced by encapsulated erythritol. The charging times of the storage system using encapsulated erythritol were, however, longer due to the increased thermal capacity. Shobo and Mawire [35] suggested that each individual spherical capsule encapsulated with PCM be tested experimentally before being used in a storage system. Three phase materials encapsulated in aluminum spheres were dynamically tested experimentally in a Sunflower Oil based TES system. Thermal performance characteristics of acetanilide, meso-erythritol and an In-Sn alloy were obtained. The In-Sn alloy showed the best thermal performance. The stratification distribution in a Sunflower Oil storage tank and in a packed bed of spherically encapsulated meso-erythritol using Sunflower Oil as the heat transfer fluid was investigated experimentally in [36]. Results obtained showed that the drop from peak stratification number for the oil TES unit was more pronounced as compared to the packed bed TES system due to the larger thermal mass presented by the packed bed system. The packed bed system slightly showed higher values of the peak stratification numbers. A solar cooking unit integrated with TES using Therminol 55 as the HTF and a packed bed of D-Mannitol PCM balls as the storage medium was presented by Kumaresan et al., [37]. The cooking experiments achieved a maximum temperature of 152 °C in a duration of 15 mins using olive oil. This duration was

comparatively shorter than the time taken by a conventional liquefied petroleum gas (LPG) stove in the simmering mode.

A modelling and experimental study of a latent heat thermal energy storage with encapsulated PCMs for solar thermal applications was presented by Raul et al., [38]. Experiments on a spherical capsule investigated the melting and solidification behaviour of the PCM from the measured temperature field. A lab-scale storage system was designed and fabricated to evaluate the effects of the charging temperature, discharging temperature and flowrate on thermal performance of the LHTES system during charging and discharging operations. Detailed parametric studies on the capsule diameter and porosity showed that the energy stored and extracted were faster for the smaller capsule diameter and higher porosity. The maximum efficiency of the storage was found to be 75.69 % for charging and discharging inlet HTF temperatures of 180 and 120 °C, respectively at a flow rate of 8.2 litres/min. Mawire and Shobo [39] experimentally investigated In–48Sn as a phase change material candidate for thermal storage applications using Sunflower Oil as the heat transfer fluid. Results obtained from differential scanning calorimetry indicated that the alloy was useful in storing sensible heat beyond its melting temperature as it exhibited very little decomposition up to 400 °C. Though In–48Sn possessed a low latent heat of fusion, its high density allowed for a larger thermal storage mass. The only problem of this solder was that it was very expensive since it was lead free.

Table 3.1: Some metallic alloys suggested for use as PCMs from the literature reviewed.

METALLIC ALLOY	TEMPERATURE RANGE OF APPLICATION
Cu-Mg-Si [18]	High temperature (≥ 755 °C)
Al-25%Si [19]	High temperature (≥ 577 °C)
Al-12%Si [20, 21, 22]	High temperature (≥ 576 °C)
Bi-Sn-In-Zn [25]	Medium temperature ($\geq 121 - 131$ °C)
Mg-51%Zn [28]	High temperature (≥ 342 °C)
84%Zn-18.7%Al-7.3%Mg [29]	High temperature (≥ 344 °C)
88.7%Zn-11.3%Al [29]	High temperature (≥ 382 °C)
92.2%Zn-7.8%Mg [29]	High temperature (≥ 371 °C)
Mg ₂ Si [30]	High temperature (≥ 1100 °C)
Fe ₂ Si ₅ [30]	High temperature (≥ 1145 °C)
Fe-23%Cu [31]	High temperature (≥ 1090 °C)
Bi-Pb-Sn-In [32]	Low temperature (≥ 58 °C)
In-48%Sn [35, 39]	Medium temperature ($\geq 118.64 - 119.70$ °C)

As it can be observed from Table 3.1, limited studies have considered the use of medium melting temperature metallic alloys as PCMs. Additionally, only the recent studies on the In-48Sn solder, using a single capsule have been reported [35, 39] in relation to oil-based metallic PCM packed bed latent heat storage system for domestic medium temperature applications. The promising results obtained by our previous work [35, 39] with an expensive solder justify carrying out experiments with a cheaper solder for domestic medium temperature applications. A packed bed latent TES configuration has been reported to be more efficient compared to a shell and tube configuration as mentioned earlier [7]. The use of an oil heat transfer fluid instead of air is justified by the fact that a lower pumping power is required, and the design of the storage system is less complicated since fewer pressurized components are required. Sunflower Oil as the HTF has been used as an HTF since it is cheap, food grade,

readily available, non-toxic and possesses characteristics comparable to other commercial HTFs as previously investigated in [40-42].

Eutectic solder consisting of Tin and Lead (Sn-Pb, (Sn63/Pb37)) manufactured locally in South Africa has never been used for any domestic medium temperature latent heat storage application in a packed storage configuration thus it is necessary to investigate its thermal performance. It has been stated earlier that metallic alloys have advantages of higher storage volumetric densities, higher thermal conductivities and most exhibit little or no super-cooling. The aim of the paper is to evaluate experimentally the performance of an eutectic solder metallic PCM based packed bed LHTES system during charging and discharging cycles. The study has never been done before using the mentioned PCM and it will add invaluable information on medium temperature metallic domestic packed bed LHTES systems. The novelty aspect of the work is that metallic alloy solders need to be investigated as alternatives to organic and inorganic PCMs utilised in medium to high temperature thermal energy storage systems since pure organic and inorganic PCMs have problems of low thermal conductivity and large degrees of sub-cooling. Additives are usually added to organic and inorganic PCMs to improve their thermal conductivity and sub-cooling characteristics. Using a metallic solder alloy will eliminate the use of these extra additives. The storage system will be useful for domestic medium temperature applications like cooking of food as well as other medium temperature industrial process heating systems such as steam generation.

3.2 Experimental setup and procedure

3.2.1 Encapsulation of PCM spherical capsules and thermophysical properties

Aluminum was used as the encapsulating material for the eutectic solder. Aluminum was selected over other high thermal conductivity metals such as copper due to its cheaper cost, lighter weight and the ease of manufacturing of the spherical capsules [53]. 2 mm thick solder wire was inserted into 40 capsules from the top opening until an internal volume 80 % was covered. The capsules were manufactured as hollow spheres with an opening at the top to allow for inserting of the wire PCM. The volume of the PCM wire in the capsules was about 80 % of the total internal volume of the capsule to allow for thermal expansion. A screw driver was used to press down on the solder wire to ensure that the solder occupied the maximum

volume. Care was taken to ensure that all 40 capsules had approximately the same mass of solder inside them.

The total mass of each capsule was measured with an electronic balance before and after inserting the solder wire. Each aluminum capsule had an approximate diameter of 0.05 m and a wall thickness of 0.001 m. After inserting of the PCM, four capsules had K-thermocouples fixed onto them to measure the PCM temperatures. These thermocouples which extended into the centre of the spheres, were fastened on the top of the spheres. The thermocouples acted both as sealing mechanisms and also as temperature monitoring devices. The rest of the PCM capsules were sealed with screw caps. Figure 3.1 shows a PCM capsule with a screw cap and one with a thermocouple screw cap. Each of the PCM capsule was heated up to its melting point in an oil bath to ensure that there were no PCM leakages before it was put into the storage tank.

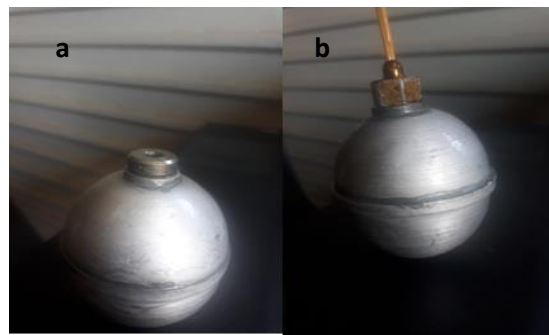


Figure 3.1: (a) Aluminum PCM capsule with screw cap. (b) Aluminium capsule with thermocouple screw cap

Thermophysical properties of the eutectic solder (Sn63/Pb37) obtained from open literature are shown in Table 3.2. The mass of the solder inside the capsules was around 164 g. The solder has a high thermal conductivity of around 50 W/mK, and its latent heat and melting temperatures are reported to be around 52.1 kJ/kg and 183 °C, respectively. It is important to note that these thermal properties were not determined in the laboratory due the expensive nature of the equipment involved in the measurements and quoted experimental values are given. Besides, previous work has been done on the thermal properties and the scope of this study is limited to the bulk performance of 40 capsules in a TES tank. No previous work has been reported on the bulk performance of this PCM in a packed bed TES configuration.

Table 3.2: Thermophysical properties of the eutectic solder.

Property	Value
Melting Temperature (°C)	183 [43, 45]
Specific Heat Capacity (kJ/kgK)	0.21 (30 °C) ([43]
Phase change enthalpy (kJ/kg)	52.1 [44]
Density(kg/m ³)	8400 [43, 45]
Thermal conductivity (W/mK)	50 [45]
Average mass of PCM in the capsule (g)	164

3.2.2 Experimental setup

The main components of the experimental setup are shown in the schematic diagram of Figure 3.2 [36]. The TES tank is an insulated stainless steel cylinder (a) with a diameter of 0.128 m and a height of 0.54 m fitted with K-type thermocouples placed at radial distances of 0.013 m, 0.038 m and 0.064 m to measure the HTF temperature at each axial level of the tank (Levels A-D). The average of the temperatures measured by the three thermocouples at each axial level was taken as the HTF temperature of that level due to radial temperature stratification at each level. Averaging the radial temperature at each axial level of the TES tank will help to reduce the error that would have been introduced by temperature measurement at one point. Forty spherical aluminium capsules filled with the eutectic solder were inserted randomly into the storage tank such that the capsules at the top of Level A were just

energy to the water in the pot. An HP 34970 data acquisition unit (j), connected to the thermocouples as well as the flow meter, converted the analogue signals to digital signals. A personal computer (i), connected to the data acquisition unit, was used to monitor the temperature profiles of the TES system as well as the HTF flowrate while recording the resulting data every 10 s.

During the charging cycles valves (1), (2), (4) and (7) were closed while valves (3), (5), (6) and (8) were opened. Charging of the storage system storage was terminated when the average bottom temperatures in the TES tank (T_D) was about 190 °C to ensure melting of the PCM at the bottom since this PCM had a melting temperature of around 183 °C. For the discharging experiments, valves (2), (4) and (7) were opened while valves (1), (3), (5), (6) and (8) were kept closed. Discharging was terminated when the inlet and outlet temperatures of the discharging unit (d) were equal indicating that no further thermal energy could be extracted from the TES tank.

Charging experiments were performed with flowrates of 4 ml/s (low), 6 ml/s (medium) and 8 ml/s (high) respectively at a set heater temperature of 280 °C in order to investigate the effect of the HTF flowrate on the TES charging performance. These seemingly low charging flowrates were used in order to easily attain the melting temperature of the eutectic solder as previously experimentally investigated in [54]. To investigate the effect of the charging temperature on the performance of the TES system, charging experiments were carried out with a fixed HTF flowrate of 6 ml/s, while the maximum heater temperature was set at 260, 280 and 300 °C respectively, for each run. The discharging experiments were carried out immediately after charging experiments with HTF flowrates of 4 ml/s (low), 6 ml/s (medium) and 8 ml/s (high), respectively, to investigate the effect of the HTF flowrate on the discharging performance. Charging and discharging experiments were performed with the HTF flowing from the top to the bottom of the TES tank since only one pump was used in order to limit the cost of the system. The high-temperature pump used was rather expensive as it costs about USD 2500. The pump was also unidirectional and as such, its flow direction could not be reversed for the discharging experiments.

3.3 Experimental thermal analysis

3.3.1 Thermal performance parameters

The energy charging rate depends on the inlet and outlet charging temperatures of the storage tank and it is expressed as;

$$\dot{E}_{ch} = \rho_{av} c_{av} \dot{V}_{ch} (T_{chin} - T_{chout}) \quad (3.1)$$

where ρ_{av} is the temperature dependent average density of the oil, c_{av} is the temperature dependent average density of the oil, $\dot{V}_{ch}$ is the volumetric charging flowrate, T_{chin} is the inlet charging temperature at the top of the storage tank and T_{chout} is the outlet charging temperature at the bottom of the storage tank. The total energy stored in stored tank can be estimated by integrating Eq. (3.1) from the start of charging to the end of charging for each small temperature measurement interval and this can be expressed as;

$$E_{ST} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{V}_{ch} (T_{chin} - T_{chout}) dt. \quad (3.2)$$

The charging exergy rate is expressed as; [46, 47]

$$\dot{E}_{xch} = \rho_{av} c_{av} \dot{V}_{ch} \left[(T_{chin} - T_{chout}) - T_{amb} \ln \left(\frac{T_{chin}}{T_{chout}} \right) \right] \quad (3.3)$$

, where T_{amb} is the ambient temperature. The total charging exergy is also evaluated by integrating Eq. (3.3) and it is expressed as;

$$E_{XCHT} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{V}_{ch} \left[(T_{chin} - T_{chout}) - T_{amb} \ln \left(\frac{T_{chin}}{T_{chout}} \right) \right] dt. \quad (3.4)$$

The discharging energy rate can be expressed as;

$$\dot{E}_{dis} = \rho_{av} c_{av} \dot{V}_{dis} (T_{disin} - T_{disout}) \quad (3.5)$$

,where $\dot{V}_{dis}$ is the discharging volumetric flowrate, T_{disin} is the discharging coil inlet temperature from the storage tank and T_{disout} is the discharging coil outlet temperature to

the storage tank. The total energy discharged from the stored tank can be estimated by integrating Eq. (3.5) from the start of discharging to the end of discharging for each small temperature measurement interval and this can be expressed as;

$$E_{\text{DIST}} = \int_{t_{\text{ini}}}^{t_f} \rho_{\text{av}} c_{\text{av}} \dot{V}_{\text{dis}} (T_{\text{disin}} - T_{\text{disout}}) dt . \quad (3.6)$$

The discharging exergy rate is expressed as;

$$\dot{E}_{\text{xdis}} = \rho_{\text{av}} c_{\text{av}} \dot{V}_{\text{dis}} \left[(T_{\text{disin}} - T_{\text{disout}}) - T_{\text{amb}} \ln \left(\frac{T_{\text{disin}}}{T_{\text{disout}}} \right) \right] \quad (3.7)$$

,and it can be integrated to give the total exergy discharged as;

$$E_{\text{XDIST}} = \int_{t_{\text{ini}}}^{t_f} \rho_{\text{av}} c_{\text{av}} \dot{V}_{\text{dis}} \left[(T_{\text{disin}} - T_{\text{disout}}) - T_{\text{amb}} \ln \left(\frac{T_{\text{disin}}}{T_{\text{disout}}} \right) \right] dt . \quad (3.8)$$

The energy storage efficiency can be expressed by the ratio of the total energy discharged to the total energy stored and this is expressed as; [46, 47]

$$\eta_e = \frac{E_{\text{DIST}}}{E_{\text{ST}}} . \quad (3.9)$$

The exergy storage efficiency can also be expressed as the ratio of the total exergy discharged to the total exergy charged and this is given as; [46, 47]

$$\eta_{\text{ex}} = \frac{E_{\text{XDIST}}}{E_{\text{XCHT}}} . \quad (3.10)$$

The variation of the density and the specific heat capacity of Sunflower Oil with temperature is given as; [40-42]

$$\rho_s = 930.62 - 0.65T \quad (3.11)$$

and

$$c_s = 2115.0 + 3.13T . \quad (3.12)$$

3.3.2 Experimental uncertainty

The uncertainty in the temperature measurements was estimated to be ± 2 °C from the accuracy of the thermocouples. For the flow-meter, the uncertainty in the flowrate was estimated to be $\pm 1\%$ of the measured value as determined from the accuracy of the flow-meter [48, 49]. The values of the uncertainties in the average density and the average specific heat capacity were $\delta\rho_{av} = \pm 0.069 \text{ g/cm}^3$ and $\delta c_{av} = \pm 0.021 \text{ J/gK}$ as determined from previous work [48, 49]. Experimental uncertainties in the calculated quantities (energy/exergy charging/discharging rates as well as energy/exergy storage efficiencies) were determined as reported in [48, 49]. As an example, for the energy charging rate the uncertainty is given as;

$$\delta \dot{E}_{ch} = \pm \sqrt{\left(\frac{\delta \dot{E}_{ch}}{\delta \rho_{av}}\right)^2 (\delta \rho_{av})^2 + \left(\frac{\delta \dot{E}_{ch}}{\delta c_{av}}\right)^2 (\delta c_{av})^2 + \left(\frac{\delta \dot{E}_{ch}}{\delta \dot{V}_{ch}}\right)^2 (\delta \dot{V}_{ch})^2 + \left(\frac{\delta \dot{E}_{ch}}{\delta T_{chin}}\right)^2 (\delta T_{chin})^2 + \left(\frac{\delta \dot{E}_{ch}}{\delta T_{chout}}\right)^2 (\delta T_{chout})^2} \quad (3.13)$$

The same procedure was repeated for the other calculated values. The range of the percentage uncertainties varied between 1-5 % of the calculated values and this was deemed to be acceptable in the experiments.

3.4 Results and discussion

3.4.1 Charging results

3.4.1.1 Effect of flowrate

Figure 3.3 shows the charging temperature profiles of the TES tank using low (4 ml/s), medium (6 ml/s) and high (8 ml/s) charging flowrates. It can be observed that the charging time increases with increase in the HTF flowrate. This is because the heating element in the heating unit gradually increases its temperature before attaining the set maximum temperature. At high HTF flow rates, before the heating element attained high temperatures, colder HTF arrive and flows through the unit fast and thus minimal heat was transferred to the HTF. Therefore, the HTF's loading temperature into the TES tank is reduced at high HTF flowrate than at lower HTF flowrates. This has also been reported by Lugolole et al., [32] who compared three different sensible heat storage materials using the same experimental set-up in this study. Mawire et al., [54] also reported the same effect recently when using the system for

comparing the performance four different PCM capsules in the storage tank.

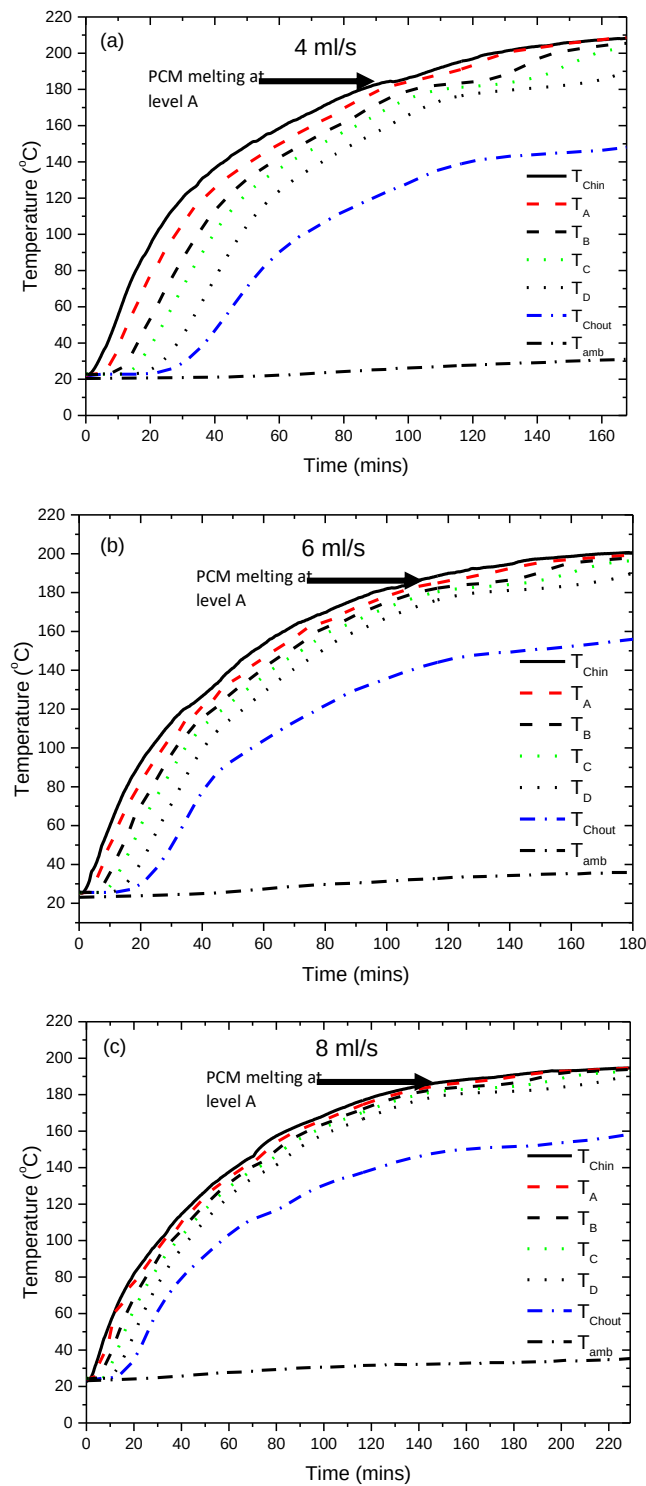


Figure 3.3: Charging temperature profiles at (a) low, (b) medium and (c) high flowrates for the eutectic solder TES system.

The lower inlet charging temperatures for charging with 6 ml/s and 8 ml/s resulted in the bottom limiting experimental temperatures (190 °C) to be approached at later times when compared to charging with 4 ml/s. Even though the highest flowrate shows the longest

charging duration, the heat transfer rate is increased in the storage tank as the axial thermal profiles show a lesser degree of thermal stratification during the charging period with the highest charging flowrate (8 ml/s). The phase change process is seen to progress from the top to the bottom of the storage since the storage tank is charged from the top to the bottom. The phase change process occurs earlier for the lowest flowrate (4 ml/s) at around 100 mins, whereas for the other flowrates it starts at around 120 mins (6 ml/s) and 140 mins (8 ml/s), respectively. The reason for the later occurrence of the phase change process is the lower inlet charging temperatures for the higher flowrates (6 ml/s and 8 ml/s) which causes higher storage tank temperatures capable of melting the PCMs to be approached at later time intervals.

It is also important to note with the increase in the heat transfer rate induced by increasing the flowrate, the outlet charging temperature also increases to its highest value at the end of the charging with the highest charging flowrate (8 ml/s). This is as a direct result of charging for a longer duration induced by the lower inlet charging temperature. It seems the lowest charging flowrate (4 ml/s) results in the best thermal performance in terms of the charging duration. The degree of thermal stratification is also better at the end of charging. This result has also been confirmed by the experiments done by Lugolole et al., [42]. This however, does not directly infer better thermal performance in terms of the charging energy and exergy rates. More pronounced phase change transitions are also seen with lowest charging flowrate since it maintains a larger thermal gradient between the top and the bottom of the storage tank.

To quantitatively and qualitatively assess the storage performance in a more realistic way, charging energy and exergy rate profiles are presented in Figure 3.4. The charging energy rate plots (a) show initial rapid rises to peak values with the highest charging flowrate showing the fastest rise due to the fastest heat transfer rate. The peaks occur at around 20 mins, 25 mins and 30 mins for 8 ml/s, 6 ml/s and 4 ml/s, respectively. These peaks are caused by the initial rise in the inlet temperatures when the bottom of the storage tank is cold during the initial stages of charging, thus inducing larger initial thermal gradients along the height of the storage tank. As charging progresses, the energy rates drop from the peak values as the bottom becomes hotter and the thermal gradients reduce. The highest peak value of around 820 W is seen with 6 ml/s for the experimental tests suggesting that it is the best charging flowrate since a further increase to 8 ml/s results in a lower peak value for the experimental conditions. The higher

peak value for the 6 ml/s case is a result of the slightly higher initial storage temperatures induced by the slightly higher initial ambient temperature conditions.

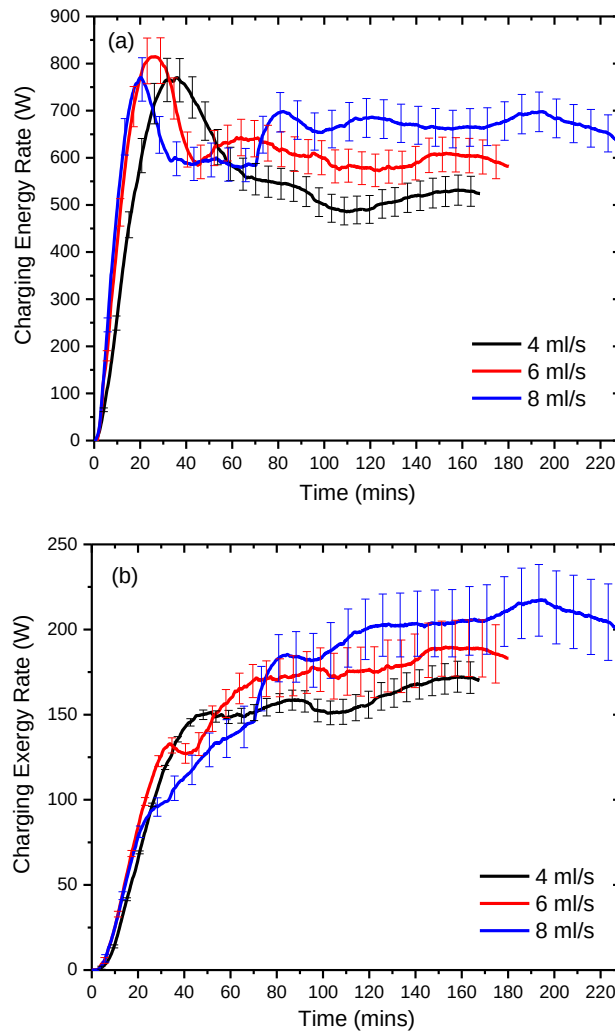


Figure 3.4 : Charging (a) energy rate and (b) exergy rate profiles at different charging flowrates for the eutectic solder TES system (with error bars).

The experiments were carried out when the initial storage tank temperatures were around 23 ± 2 °C, thus a slightly practical variation in the initial conditions was allowed according to the experimental uncertainty of the measurement thermocouples. It is also important to note that the ambient temperature for 6 ml/s was slightly higher for the duration of the experiment implying slightly less heat losses. In practice, the ambient temperature depends on the weather conditions and exact conditions for the start of the experiments are impossible. However, care was taken to ensure the variation of the ambient temperature was comparable. Although the 6 ml/s charging case shows a slightly higher peak energy rate value of 820 W, it is comparable and not considerably higher than the peak values of the other two

charging flowrates which are around 770 W.

Secondary peak values are seen when charging with the higher flowrates at around 60 mins for 6 ml/s, and 80 mins for 8 ml/s. This is possibly due to the change in the thermal gradient of the outlet temperature for the 6 ml/s case between 40 and 60 mins which shows a lower thermal gradient when compared to the initial gradient (Figure 3.3(b)). During the same period, the inlet temperature shows a higher thermal gradient when compared to the outlet temperature such that there is an increased temperature difference between the top and bottom of the storage tank causing a rise to a secondary peak value for the energy rate. A similar scenario is observed with the outlet temperature variation for the charging flowrate of 8 ml/s between 60 and 80 mins (Figure 3.3(c)). The slight drop of the outlet temperature thermal gradient for the higher charging flowrates which induces secondary peaks is possibly due to the increased radial and axial thermal conductivity of the fluid such that slightly more heat is transferred to walls of the storage tank causing heat losses. It is important to note that the thermal gradient of the outlet temperature also gradually reduces with an increase in the flowrate, although the outlet charging temperature achieves a higher value for the highest charging temperature due to a longer charging duration. Higher charging energy rates are seen with the highest flowrate for most of the charging duration from around 80 mins. This happens even with a lower primary peak value suggesting that it is more beneficial to charge with higher flowrates to increase the energy charging rates. On the other hand, the lower flowrate enables thermal stratification and charging for a shorter duration, thus the flowrate should be selected as comprise between obtaining higher charging rates and a shorter charging duration. Exergy charging rates are lower than the energy charging rates since heat losses are accounted for, and the highest flowrate shows higher values after 70 mins suggesting it is the best charging flowrate to obtain better exergy charging rates. The effect of the secondary peak energy rate values is also evident after 40 mins for 6 ml/s and after 70 mins for 8 ml/s. Again, a compromise should be made at selecting a charging flowrate that addresses the issues of a shorter charging duration and obtaining reasonably high exergy charging rates.

3.4.1.2 Effect of set charging temperature

The effect of the set charging temperature of the heater on the storage tank temperatures, and on the charging energy and exergy rates are presented in this section. Figure 3.5 shows

thermal profiles of the storage tank when charging with a flowrate of 6 ml/s at set heater charging temperatures of 260 °C, 280 °C and 300 °C, respectively. The temperature profiles seem to show a similar variation since the same flowrate was used and the effect of the charging temperature is almost insignificant when compared to the effect of the flowrate (Figure 3.4). The aspect to note is that increasing the set charging temperature from 260 °C to 280 °C reduces the charging time by around 20 mins from around 200 mins to 180 mins. The storage tank temperatures at the end of charging at the top of the storage tank are also slightly higher. As the charging temperature is increased from 280 °C to 300 °C, the charging time increases to around 200 mins which is comparable to charging with the 260 °C set temperature. The charging time is expected to reduce further for an increase from 280 °C to 300 °C as temperature difference between the bottom and top of storage tank increases due to a larger thermal gradient as reported by Mawire et al., [54], however, it reduces. This is because of the slightly lower ambient temperature conditions for the 300 °C test which in turn induces slightly lower initial charging temperature conditions and slightly higher heat losses causing an overall increase in the charging time. The storage tank temperatures are also lower for the 300 °C case due to these ambient temperature conditions. It is also important to state that in real world applications, the ambient temperature cannot be controlled and this effect cannot be eliminated for practical storage tanks. The results seem to suggest the best charging temperature of 280 °C according to the experimental conditions. The degree of thermal stratification with the set temperature of 280 °C is also slightly better as compared to the other set temperatures.

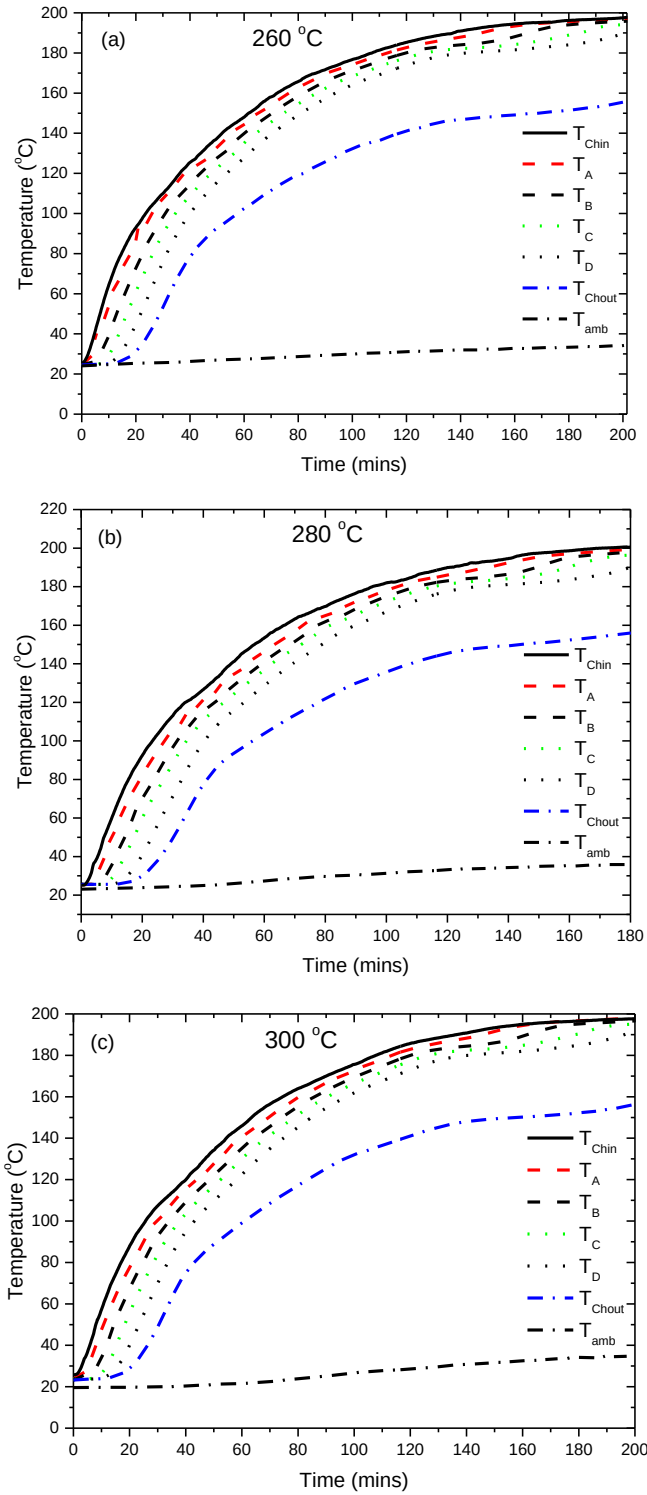


Figure 3.5: Charging temperature profiles at (a) low (260 °C) (b) medium (280 °C) and (c) high (300 °C) set charging heater temperatures using a flowrate of 6 ml/s.

To quantitatively and qualitatively assess the effect of the set temperature, charging energy and exergy rate profiles are presented in Figure 3.6.

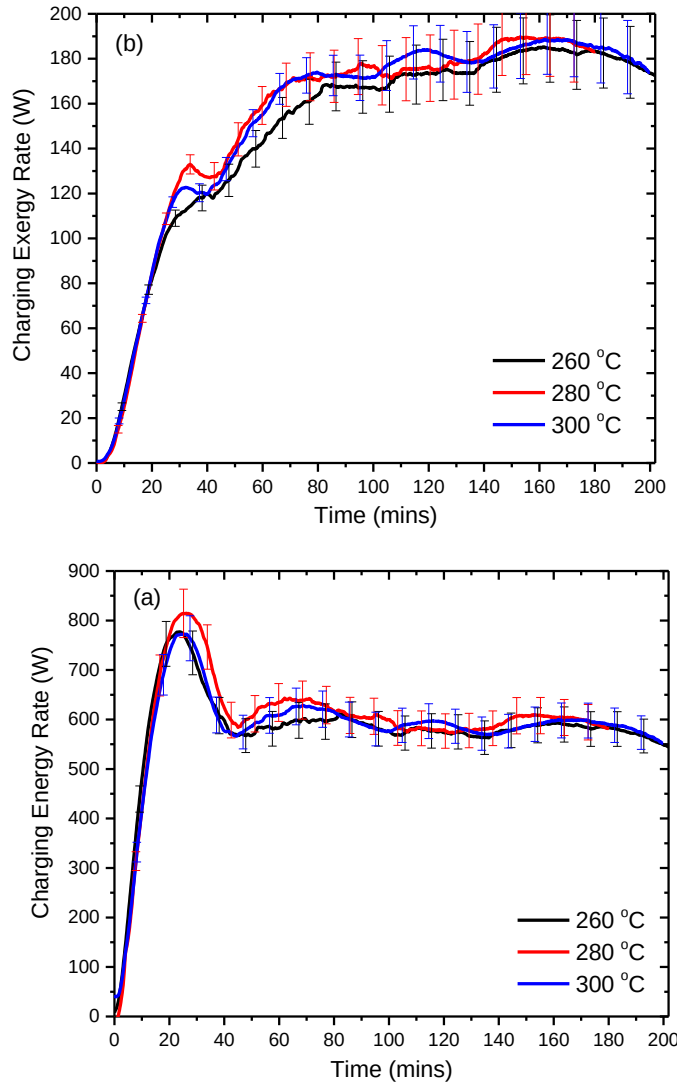


Figure 3.6: Charging (a) energy rate and (b) exergy rate profiles at different set heater charging temperatures for the eutectic solder TES system (with error bars).

The charging energy rate profiles show comparable values for the duration of charging especially for the 260 °C and 300 °C cases due similar heat transfer characteristics induced by the charging flowrate of 6 ml/s. The set temperature of 280 °C shows slightly higher values of the charging energy rate during the charging period and it attains the highest peak value of around 820 W. This is because of the slightly higher temperatures, and the slightly higher degree of thermal stratification. Charging exergy rate profiles are also comparable during the charging cycles with similar rises in the first 20 mins of charging. The set temperature of 280 °C shows slightly higher values for most of the charging period due to the greater degree of thermal stratification and higher thermal storage temperatures induced by the slightly higher initial storage temperatures and the slightly higher ambient temperature conditions. The charging flowrate seems to have more impact on the charging energy and exergy rates as

compared to the temperature. The overall charging results suggest that a charging flowrate and set charging temperature should be selected to achieve reasonable energy and exergy charging rates, at a reasonable charging duration and at a reasonable degree thermal stratification. The charging conditions for this particular system which achieve the mentioned criteria for the experimental tests done are a charging flowrate of 6 ml/s and a set charging temperature of 280 °C.

It is also important to point that the prevailing ambient conditions also have an effect on the initial storage tank temperatures and the resulting associated heat losses which can reduce or increase the duration of charging. Table 3.3 presents a summary of the experimental tests showing average charging energy and exergy rates with their associated calculated uncertainties. It is clear that the average energy and exergy rates increase with an increase in the flowrate. On the other hand, the average energy and exergy rates are almost constant and are not affected by an increase in the set heater charging temperature.

Table 3.3: Average charging energy and exergy rates for the different experimental conditions.

<i>Flowrate (ml/s)</i>	<i>Average charging energy rate (W)</i>	<i>Average charging exergy rate (W)</i>	<i>Set heater charging temperature (°C)</i>	<i>Average charging energy rate (W)</i>	<i>Average charging exergy rate (W)</i>
4.00 ± 0.04	533 ± 19	136 ± 5	260 ± 2	560 ± 8	148 ± 7
6.00 ± 0.06	596 ± 15	151 ± 4	280 ± 2	596 ± 11	151 ± 4
8.00 ± 0.08	638 ± 29	167 ± 8	290 ± 2	582 ± 20	153 ± 6

3.4.2 Discharging results

Discharging results with different discharging flowrates are presented in this section. The temperature profiles of the storage tank using different discharging flowrates are shown in Figure 3.7. The discharging duration is seen to decrease with an increase in the discharging flowrate since thermal energy is extracted at a faster rate with the higher flowrate causing the discharging unit temperatures to be equal in a shorter time. There is an initial rise in the storage tank temperatures for the low (4 ml/s) and medium (6 ml/s) discharging flowrates within the first 10 mins of discharging. This is attributed to the hot oil that is resident in the heating coil that is pushed downwards to the bottom due to discharging from the top to the

bottom. The hot oil from the top mixes with the cooler oil at the bottom causing a more pronounced temperature rise at the bottom of the storage tank (TD). For the highest flowrate, the heat transfer is greater and this seems to eliminate the initial rise.

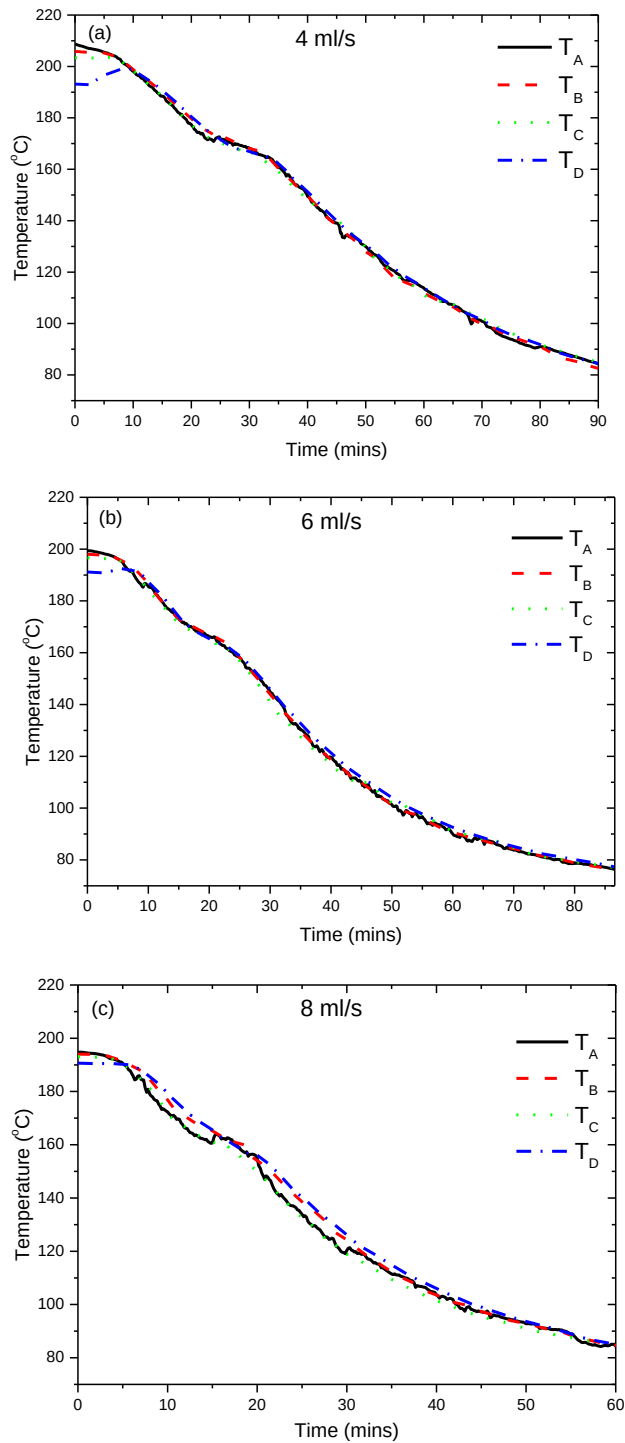


Figure 3.7: Discharging temperature profiles at (a) low, (b) medium and (c) high flowrates for the eutectic solder TES system.

The phase change transitions are evident for all the discharging flowrates and a longer phase change transition period is seen with lowest flowrate between 20 to 35 mins. The duration of phase change becomes smaller with an increase of the discharging flowrate. It is important also to note the highest flowrate results in the top storage tank (TA) to be lower than the other storage tank temperatures after 10 mins of discharging to around 30 mins which can be attributed to more thermal mixing between adjacent layers with the increase in the flowrate. The increase in turbulence is evident with the fluctuating profiles for the highest flowrate and this causes temperature profile reversals with the top of the storage tank showing lower values in some instances. Discharging from the top to the bottom contributes to this effect and the experiments had a limitation of one expensive pump which could not be reversed to discharge from the bottom to the top. It was also not economically viable to use two of these expensive pumps for charging and discharging experiments.

The discharging unit thermal profiles using different flowrates are shown in Figure 3.8. All flow rates show that discharging was terminated when the inlet and outlet temperatures were equal. The inlet temperatures rise to peak values during the initial stages of discharging when thermal energy is extracted from the storage tank. The peak value increases with an increase in the flowrate due to the increased rate of heat extraction. The duration of discharging decreases with an increase in the flowrate as thermal energy extracted is used more quickly to heat up water in the discharging unit. The outlet discharging temperatures show initial drops at the commencement of discharging possibly due to the lower water bath temperature. It thus takes a short time before the outlet temperatures start to rise. The discharging outlet temperatures progressively rise and the rate of rise decreases as the inlet temperatures are approached.

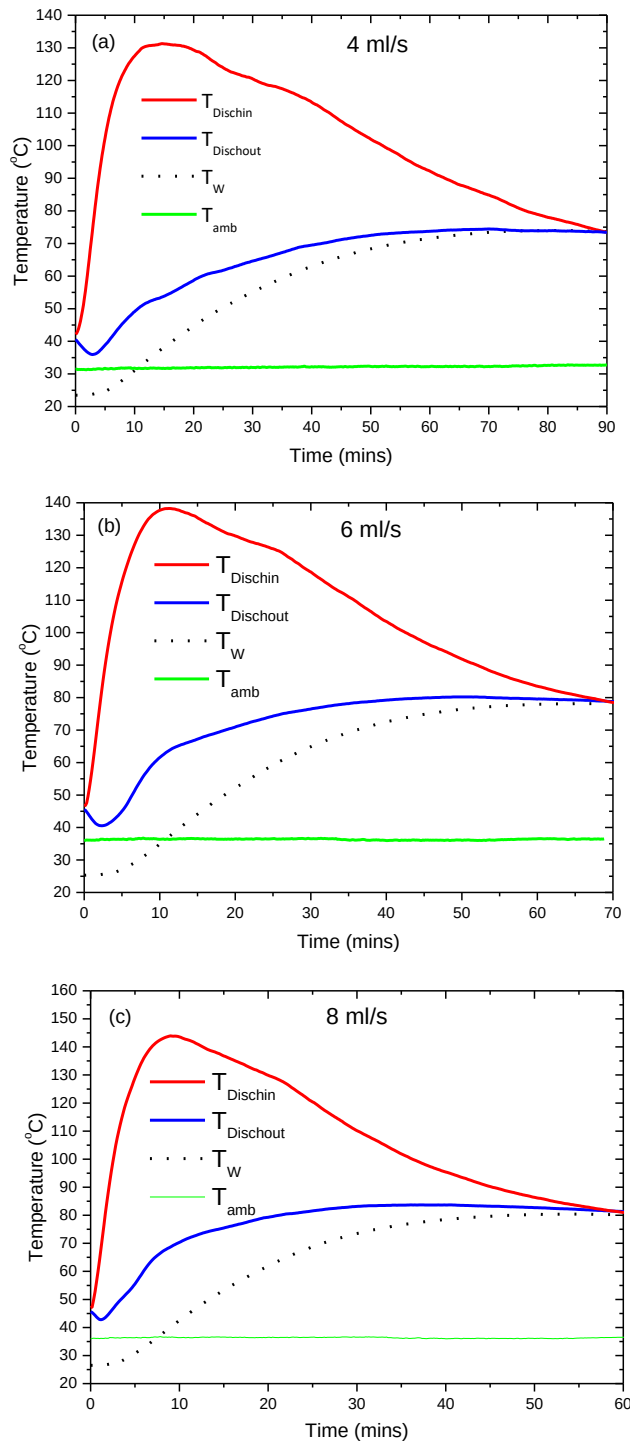


Figure 3.8: Discharging unit thermal profiles at (a) low, (b) medium and (c) high flowrates.

The inlet temperatures drop from peak values whereas the outlet temperatures and the water bath temperatures rise for the whole duration of discharging. The water bath temperature at the end of discharging shows a small increase as the flowrate increases at the end of discharging due to the increase in the discharged energy from the storage tank. For

example, the water temperature increases from around 73 °C with a flowrate of 4 ml/s to around 80 °C with a flowrate of 8 ml/s.

The discharging energy and exergy rates are presented in Figure 3.9 to quantitatively and qualitatively evaluate the discharging characteristics.

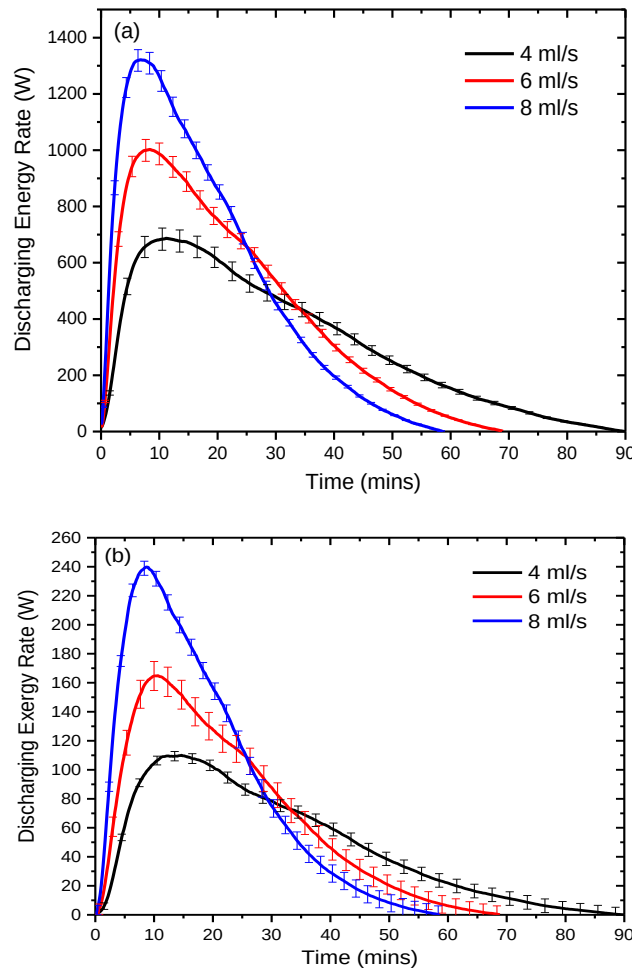


Figure 3.9: Discharging (a) energy rate and (b) exergy rate at different charging flowrates for the eutectic solder TES system (with error bars).

The discharging peak energy rate is seen to increase with an increase in the discharging flowrate at the expense of a shorter discharging time and a greater drop from the peak value. Although the lowest flowrate shows the lowest initial energy rate values at the commencement of discharging, the stored energy is used more effectively for a longer duration as compared to the higher discharging flowrates. The discharged energy is used for around 90 mins with a flowrate of 4 ml/s which is 30 mins longer as compared to the highest flowrate which extracts all the stored energy in 60 mins. The exergy rate profiles show the same trend as the energy rate profiles but the values are lower since heat losses are

accounted for. Again as with the charging flowrates, the 6 ml/s case shows a good compromise between obtaining a longer discharging period and higher energy and exergy heat extraction rates.

3.4.3 Energy and exergy storage efficiencies

To assess the overall performance of the storage tank for both charging and discharging cycles, energy and exergy storage efficiencies can be used. Figure 3.10 shows the effect of the flowrate on the energy and exergy storage efficiencies.

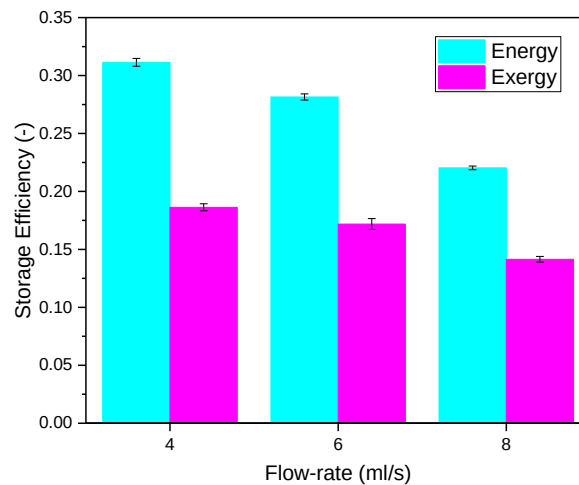


Figure 3.10: The effect of the HTF flowrate on the energy and the exergy storage efficiencies (with error bars).

The energy storage efficiency is seen to drop from a value of 0.31 to 0.21 for an increase in the flowrate from 4 ml/s to 8 ml/s. The lowest flowrate shows the best energy storage efficiency possibly due the shorter charging duration and the more pronounced thermal stratification with the lowest charging flowrate, and the longer discharging duration with the lowest flowrate. However, as already mentioned the charging and discharging performance should be a compromise between reducing the charging time, increasing the charging and discharging heat transfer rates and increasing the discharging time, therefore an appropriate flowrate is 6 ml/s which shows an energy storage efficiency of 0.28 that is comparable to the best efficiency of 0.31. A further increase in the flowrate from 6 ml/s to 8 ml/s causes a more pronounced drop from 0.28 to 0.22, thus higher flowrates are not beneficial to the storage

and release of thermal energy. Exergy storage efficiencies are lower than energy storage efficiencies, and the exergy storage efficiency also reduces initially from 0.19 to 0.14 for an increase in the flowrate from 4 ml/s to 6 ml/s.

The effect of set heater temperature on the energy and exergy storage efficiencies is shown in Figure 3.11. The results also seem to reveal for these experimental conditions that a charging temperature of 280 °C is the most appropriate since maximum energy and exergy storage efficiencies of 0.28 and 0.17, respectively are obtained. An increase in the set charging temperature from 280 °C to 300 °C causes a slight reduction in the energy and exergy storage efficiencies possibly due to the lower initial storage tank temperature and lower ambient temperatures during charging. The effect of the set charging temperatures on the storage efficiencies is marginal as compared to the effect of the flowrate.

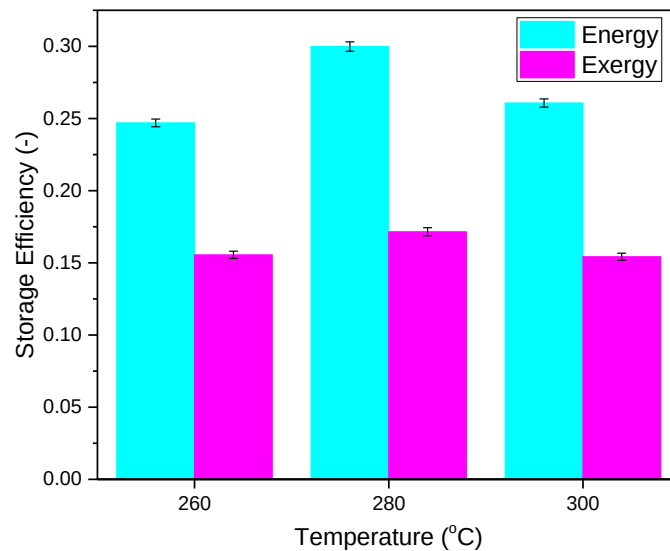


Figure 3.11: The effect of the set heater temperature on the energy and the exergy storage efficiencies (with error bars).

3.4.4 Comparison of performance with adipic acid

In order to evaluate the suitability of the eutectic solder as a medium temperature PCM, the charging as well as the discharging energy and exergy rates of the eutectic solder TES in this study, are compared to those of a similar TES set-up but using adipic acid as the PCM in similar aluminium capsules. Adipic acid PCM has been suggested as a suitable PCM candidate for medium temperature applications [50-52]. Figure 3.12 shows the charging energy and exergy rates comparison for low and high flowrates.

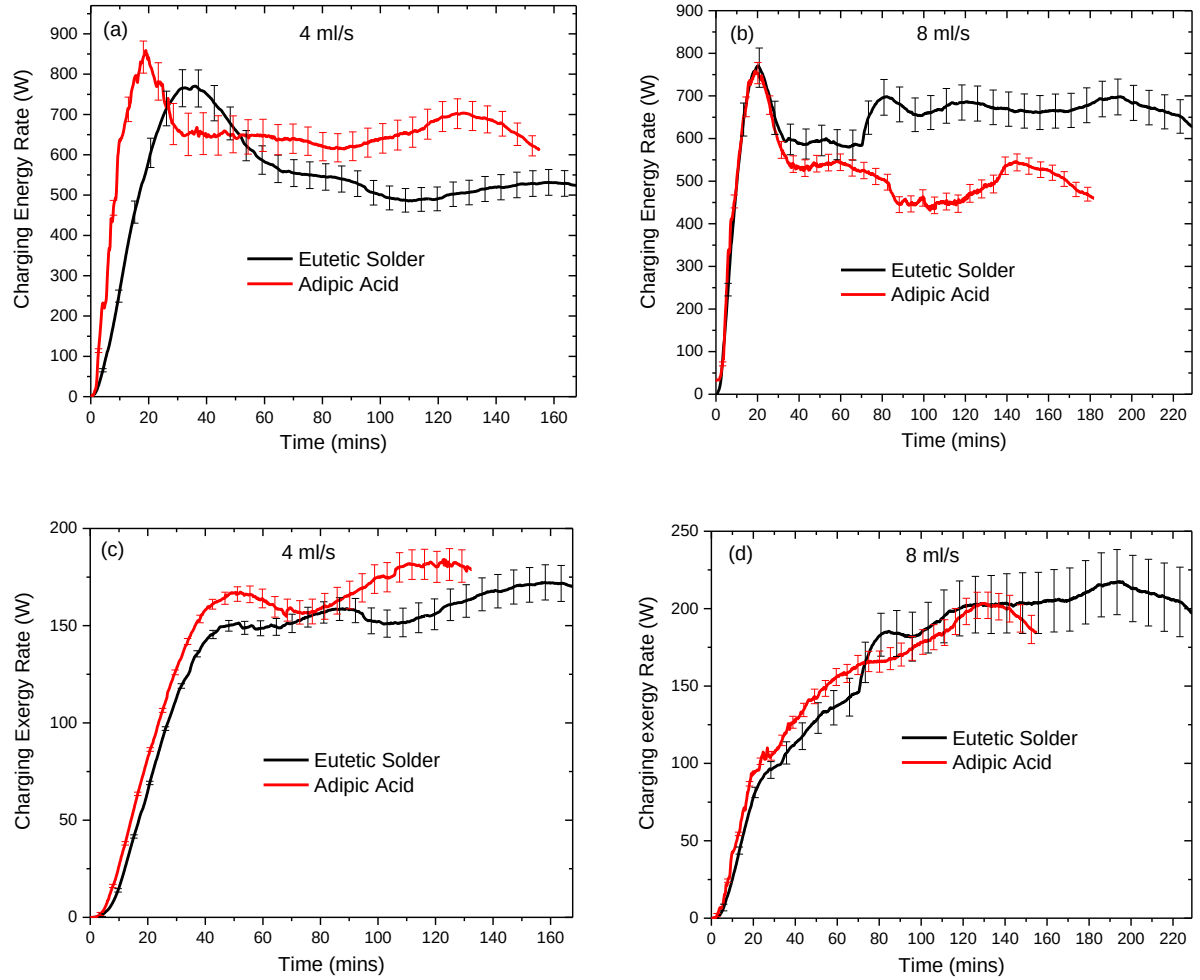


Figure 3.12: Charging energy rates at (a) low flowrate (b) and high flowrate and charging exergy rates at low flowrate (c) and high flowrate for adipic acid and the eutectic solder.

For the lowest charging flowrate, adipic acid shows higher values of the charging energy rates except for a short duration around 20 mins to 50 mins of charging where the solder shows better values. It is also important to note that the charging duration for adipic acid is shorter due to the lower limiting temperature of 170 °C at the bottom level (Level D) since higher temperatures were not possible due to the flash point of adipic acid which is around 190 °C . The rate of rise of the energy rate with the lower flowrate is also faster for adipic acid. However, for the higher flowrate, the rate of rise of the energy rate is comparable and the solder shows a comparable performance to adipic acid from 70 mins until the end of charging. Exergy rate values are more comparable for the two PCMs for the two flowrates considered

although adipic acid shows slightly higher values during the initial and final stages of charging for the lower flowrate. For the higher flowrate, the eutectic solder actually shows higher charging exergy rates during the later stages of charging after 130 mins.

To compare the discharging characteristics, discharging energy and exergy rates for the two PCMs are shown in Figure 3.13 (a) - (d) for low and high flowrates. The eutectic solder shows greater energy and exergy rate values from the start of discharging to around 60 mins with the lowest flowrate. For the highest discharging flowrate, the solder shows greater energy and exergy values from the start of discharging to around 33 mins. Adipic acid then shows slightly high values from 33 mins to the end of discharging. In general, the performance of adipic acid with a lower melting point (of around 152 °C) is slightly better but comparable to that of the solder during charging. The solder, however, shows a superior performance to adipic acid during discharging cycles.

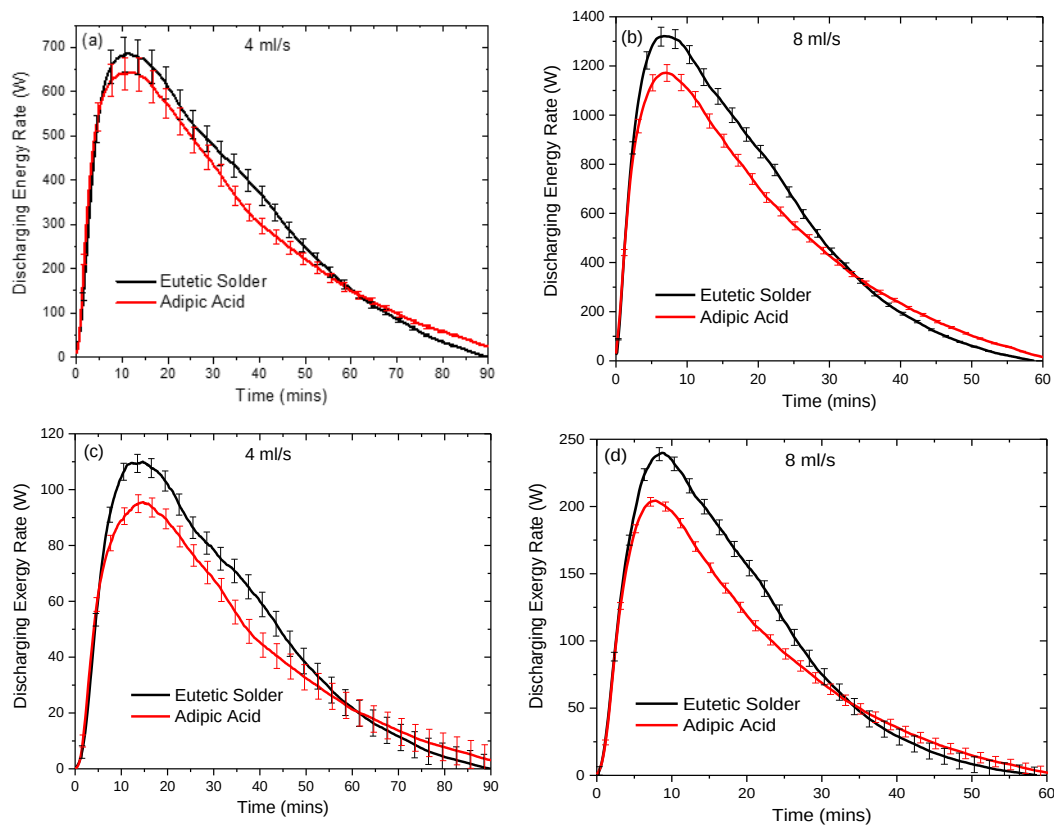


Figure 3.13: Discharging energy rates at (a) low flowrate (b) and high flowrate and charging exergy rates at low flowrate (c) and high flowrate for adipic acid and the eutectic solder.

3.5 Conclusion

A packed bed latent heat storage system consisting of aluminium encapsulated eutectic solder (Sn63Pb37) capsules has been experimentally evaluated during charging and discharging cycles. Sunflower Oil was used as the heat transfer fluid in the experiments. To evaluate the effect of the flowrate on the charging performance, three charging flowrates were used: 4 ml/s (low), 6 ml/s (medium) and 8 ml/s (high). The performance storage system was also evaluated with three different set heater charging temperatures: 260 °C (low), 280 °C (medium) and 300 °C (high). Discharging experiments were also performed with the three different flowrates to evaluate the effect of the flowrate on the discharging characteristics. Charging and discharging results are presented in terms of the axial storage tank profiles, the energy rates and the exergy rates.

The overall performance of the storage system was evaluated in terms of the energy and exergy storage efficiencies. The charging energy and exergy rates were seen to increase with the charging flowrate at the expense of a greater charging duration. The best charging flowrate under the experimental conditions was 6 ml/s, since it ensured a reasonable duration of charging, reasonable thermal stratification and reasonably high energy and exergy charging rates. The effect of set heater temperature on the charging energy and exergy rates was insignificant as compared to the effect of the flowrate and the best charging temperature of 280 °C was suggested by the results under the experimental test conditions.

For the discharging cycles, an increase in the flowrate resulted in faster heat transfer with higher peak energy and exergy rates. The stored energy and exergy was, however, utilized for a shorter duration as compared to the lowest flowrate. Discharging results also suggested the best discharging flowrate as 6 ml/s for reasonable energy and exergy rates, and for a reasonably longer duration of discharging. Energy storage efficiencies decreased with an increase in the flowrate and the highest flowrate showed the lowest values due to the longer charging duration and the shorter discharging duration. The exergy storage efficiencies initially decreased with an increase in the flowrate. The set heater charging temperature showed only a marginal effect on the energy and exergy storage efficiencies, and the best set heater temperature of 280 °C was suggested by the results under the experimental test conditions. A comparison of the energy and exergy rates of the solder during charging and discharging with adipic acid showed slightly better performance during charging cycles for

adipic acid. For discharging cycles, the solder showed a better performance. The solder can be a viable PCM for domestic medium temperature applications like cooking of food since reasonably good results were obtained. The storage system can also be useful for medium temperature industrial process heating systems such as a steam generation. To make the storage system cheaper, it may be combined with cheaper, solid sensible heat storage material with a high thermal energy storage density. Further studies need to be carried out in the near future to assess the performance of such combined thermal energy storage system using the solder.

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Chapter 4: Paper-2 Performance comparison of medium temperature domestic packed bed latent heat storage systems

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In this chapter, the thermal performance of three packed bed latent heat medium temperature thermal energy (TES) storage systems is evaluated during charging and discharging cycles at low flowrate (4 ml/s), medium flowrate (6 ml/s) and high flowrate (8 ml/s). The three phase change materials (PCMs) used in the storage systems are adipic acid, erythritol and eutectic solder (Sn63Pb37). Each TES tank comprises of a packed bed of 40 similar aluminium spherical capsules with the three different PCMs inside each tank. The thermal performance of these systems is evaluated in terms of the temperature profiles, total energy, total exergy, useful energy and useful exergy, during charging and discharging. Erythritol did not undergo phase transition during discharging at all the flowrates due to super-cooling. The erythritol TES system shows the greatest efficiencies with regards to all the performance parameters considered with an overall energy efficiency of about 39.1 %. The efficiencies of all the TES systems generally decreased with an increase in the heat transfer fluid (HTF) flowrate. Although the eutectic solder TES stored and discharged greater quantities of energy at all the flowrates, its performance was reduced by the lower degree of thermal stratification in the tank and longer charging and discharging times.

4.1 Introduction

In developing countries, domestic heating applications such as water heating, space heating and cooking can be catered for by harnessing the solar energy resource. Small domestic thermal energy storage (TES) systems can store solar thermal energy during non-peak periods when supply is abundant, and this stored thermal energy can be used during periods of minimal or no solar radiation, for example at night, where there is usually a peak demand for energy. The two most viable options for TES for domestic applications are sensible heat storage (SHS) and latent heat storage (LHS). SHS is the most widely adopted since it is cheaper than LHS but it possesses a lower energy storage density as compared to LHS. For compact energy storage, the LHS option seems more viable, particularly with its other advantage of

the quasi-isothermal behaviour during storage and release of thermal energy for temperature controlled applications [1].

With the highlighted advantages of LHS systems, limited experimental investigations of LHS systems for domestic medium-temperature applications (100 °C to 250 °C) have been reported in literature [2-6]. Moreover, a lot of complexities exist in making a choice of the suitable phase change material (PCM) to use in such LHS systems [7]. The phase change temperature (liquid-solid) of a PCM principally determines the type of application that the LHS system may be used for [8]. However, some drawbacks which hinder the use of some PCMs include: corrosiveness [9], toxicity/potential health hazards [10], chemical and physical instability [8] as well as low thermal conductivity [11]. Unlike the other factors, overcoming the drawback of the low thermal conductivity of a PCM is easily achieved by adding highly thermally conductive substances or an appropriate choice of containment and arrangement in a TES tank or both [12-13]. The packed bed TES configuration is simpler in design as compared to other LHS heat transfer enhancement configurations such as the shell-in-tube. The packed bed configuration was also reported by Tehrani et al., [14], to give better performance than the shell-and-tube configuration when used in a two-tank TES designed for a concentrated solar power plant and constrained strictly to its ideal operational limits.

Apart from not exhibiting the highlighted drawbacks, it is also desirable that a PCM for a particular TES application possesses a high latent heat of fusion, a high density, and a high specific heat capacity. However, for a particular TES application, there is no single PCM that possesses exactly all the outlined characteristics [15]. Both organic PCMs and inorganic PCMs (except metallics) have been reported to generally have higher latent heat of fusion than metallic PCMs. However, due to the high density of metallic PCMs, they possess high latent heat of fusion per unit volume [16]. The instability of most inorganic PCMs, caused by phase segregation and supercooling as well as the corrosive nature of most, discourages their consideration for use in TES systems [17].

Shobo and Mawire [18] experimentally compared the thermal performances of two organic PCMs (erythritol and acetanilide) with that of a metallic PCM (In-Sn) in similar spherical capsules, for medium temperature TES applications. Erythritol exhibited large degrees of supercooling which reduced the quantity of useful energy discharged. Acetanilide, on the other hand, possessed the least thermal energy storage capacity of the three PCMs due to its low density. The metallic alloy showed very good thermal responses (high thermal

conductivity), high thermal energy storage capacity (high density), very little supercooling and the delivery of large quantities of useful thermal energy. The authors also pointed out that an initial study of the charging and discharging characteristics of a single PCM capsule intended for use in a packed bed TES tank, will give some idea of a packed bed of similar PCM. Mawire et al., [19] compared the charging and discharging characteristics of three organic PCMs namely; erythritol, adipic acid and High-density polyethylene (HDPE) with those of a eutectic solder, Sn63/Pb37, all inside similar spherical aluminum capsules. The results indicated that erythritol possessed the highest charging rates due to its large thermal energy storage capacity, though its exhibition of supercooling reduced its performance during discharging. The metallic alloy showed good potential as a PCM, with stable charging and discharging characteristics as well as large charging/discharging rates. Although the eutectic solder possessed the least values of specific heat capacity and phase change enthalpy, it possessed the highest density of the four PCMs. The performance of adipic acid was third, and the phase change transition of adipic acid occurred within the medium temperature range although it exhibited some degree of super-cooling. HDPE showed the poorest performance of all the four PCMs.

Against the background study initially carried out, this study aims to compare the thermal performances of similar packed bed TES systems, one containing adipic acid, another containing erythritol, and the last one containing an eutectic solder, Sn63/Pb37. The choice of the PCMs initially was due to the fact that their phase change transition temperature falls within the medium temperature range, i.e. 100 °C - 250 °C. While the use of erythritol as a PCM has been reported by a number of studies [19-23], the use of adipic acid [24] and the eutectic solder (Sn63/Pb37) as PCMs is still limited in literature. The thermal performances of the TES systems are compared with reference to their potential use for food cooking applications.

4.2 Experimental setup and procedure

4.2.1 Encapsulation of PCM spherical capsules and thermophysical properties

Each of the PCMs (erythritol, adipic acid and Sn63/Pb37) was filled into forty spherical aluminum capsules, with diameters of 0.05 m and wall thicknesses of 0.001 m, while leaving expansion space for the PCM in each capsule. 80 % of the total volume of each sphere was

filled to allow for thermal expansion. A clearer description of the mode of encapsulating the PCMs can be found in [19-20].

Thermophysical properties of erythritol, adipic acid and the eutectic obtained from open literature are shown in Table 4.1. The mass of PCM inside the erythritol capsules was almost similar to the mass inside the adipic acid capsules. The eutectic solder had the largest mass of PCM inside the capsules due its higher density. Adipic acid shows the largest phase change enthalpy while the eutectic solder has the least. The thermal conductivity of the solder is highest, while the thermal conductivities of the two organic PCMs are comparable. The average phase change enthalpy capacity for each type of TES tank was estimated from the values from Table 4.1 from the product of the average mass of the PCM in each TES tank and the phase change enthalpy of each PCM. Adipic acid showed the greatest latent heat storage/release capacity while erythritol showed the least. It is important to note that these thermal properties were not measured directly in this study but values obtained from literature were relied on. Besides, the scope of this study is limited to the bulk performance of 40 PCM capsules in a TES tank. Very limited experimental studies have reported the bulk performance of the PCMs considered, in a packed bed storage configuration.

Table 4.1: Thermophysical properties of the three PCMs.

Property	Erythritol	Adipic Acid	Eutectic Solder (Sn63Pb37)
Melting Temperature (°C)	118 - 122 [20]	150-152 [24]	183 [27, 29]
Specific Heat Capacity (kJ/kgK)	1.38 (20 °C), 2.76 (140°C) [20]	1.59 (20 °C), 2.26 (150 °C) [25]	0.21 (30 °C) [27]
Phase change enthalpy (kJ/kg)	139.7 [20]	213–260 [24]	52.1 [28]
Density (kg/m ³)	1210 [20]	1360 (20 °C), 1093 (163 °C) [25]	8400 [28]
Thermal conductivity (W/mK)	0.130 (120 °C) [20]	0.142-0.162 [25]	50 [29]
Average mass of PCM in a capsule (g)	44	40	164
Average phase change enthalpy capacity per TES tank (kJ)	244.6	380.0	341.8

4.2.2 Experimental setup

The description, the composition and the mode of operation of the experimental setup can also be found in [19-20]. For each PCM type, all the experiments were carried out with forty similar PCM capsules in the TES tank. Thus, all the TES tanks had the same storage volume (~ 7.1 l) and the same void fraction (~ 0.49). Charging and subsequent discharging of the TES tanks were each done at HTF flowrates of 4 ml/s, 6 ml/s and 8 ml/s. Sunflower oil was used as the HTF and the direction of its flow is from the top of each TES tank to the bottom, during both charging and discharging cycles. The charging experiments were discontinued when the PCM at the bottom section (D) in each TES was observed to have completely melted. The discharging experiments on the other hand, were discontinued when the temperatures at the inlet (T_{disin}) and the exit (T_{disout}) of the discharging units became equal, indicating no more heat transfer in the unit.

4.3 Experimental thermal analysis

The energy charging rate (or power) depends on the HTF's inlet and outlet temperatures into and out of the TES tank respectively and it is expressed as:

$$\dot{E}_{ch} = \rho_{av} c_{av} \dot{V}_{ch} (T_{chin} - T_{chout}) \quad (4.1)$$

,where ρ_{av} is the temperature dependent average density of the oil, c_{av} is the temperature dependent average density of the oil, $\dot{V}_{ch}$ is the volumetric charging flowrate, T_{chin} is the HTF's inlet temperature at the top of the TES tank and T_{chout} is the HTF's outlet charging temperature at the bottom of the TES tank. The total energy stored in stored tank can be estimated by integrating Eq. (4.1) from the start of charging to the end of charging for this can be expressed as:

$$E_{ch} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{V}_{ch} (T_{chin} - T_{chout}) dt. \quad (4.2)$$

The charging exergy rate is expressed as [30 - 31]:

$$\dot{E}_{XCH} = \rho_{av} c_{av} \dot{V}_{ch} \left[(T_{chin} - T_{chout}) - T_{amb} \ln \left(\frac{T_{chin}}{T_{chout}} \right) \right] \quad (4.3)$$

, where T_{amb} is the ambient temperature. The total charging exergy is also evaluated by integrating Eq. (4.3) and it is expressed as:

$$E_{XCH} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{V}_{ch} \left[(T_{chin} - T_{chout}) - T_{amb} \ln \left(\frac{T_{chin}}{T_{chout}} \right) \right] dt. \quad (4.4)$$

The discharging energy rate can be expressed as:

$$\dot{E}_{dis} = \rho_{av} c_{av} \dot{V}_{dis} (T_{disin} - T_{disout}) \quad (4.5)$$

, where $\dot{V}_{dis}$ is the discharging volumetric flowrate, T_{disin} is the temperature of the HTF as it enters into the discharging unit and T_{disout} is the temperature of the HTF as it exits from the discharging unit. The total energy discharged from each TES tank can be estimated by integrating Eq. (4.5) from the start of discharging to the end and this can be expressed as:

$$E_{dis} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{V}_{dis} (T_{disin} - T_{disout}) dt. \quad (4.6)$$

The discharging exergy rate is expressed as:

$$\dot{E}_{XDIS} = \rho_{av} c_{av} \dot{V}_{dis} \left[(T_{disin} - T_{disout}) - T_{amb} \ln \left(\frac{T_{disin}}{T_{disout}} \right) \right] \quad (4.7)$$

, and it can be integrated to give the total exergy discharged as:

$$E_{XDIS} = \int_{t_{ini}}^{t_f} \rho_{av} c_{av} \dot{V}_{dis} \left[(T_{disin} - T_{disout}) - T_{amb} \ln \left(\frac{T_{disin}}{T_{disout}} \right) \right] dt. \quad (4.8)$$

The variation of the density and the specific heat capacity of the HTF with temperature is given as [32-33]:

$$\rho_s = 930.62 - 0.65T \quad (4.11)$$

, and

$$c_s = 2115.0 + 3.13T. \quad (4.12)$$

Experimental uncertainties in the calculated values were determined as reported in [21, 34]. The range of the percentage uncertainties varied between 1 - 6 % of the calculated values and this was deemed to be acceptable in the experiments.

4.4 Results and discussion

4.4.1 Charging results

The charging temperature profiles along the height of the three TES tanks, using a low HTF charging flowrate (4 ml/s), are shown in Figure 4.1.

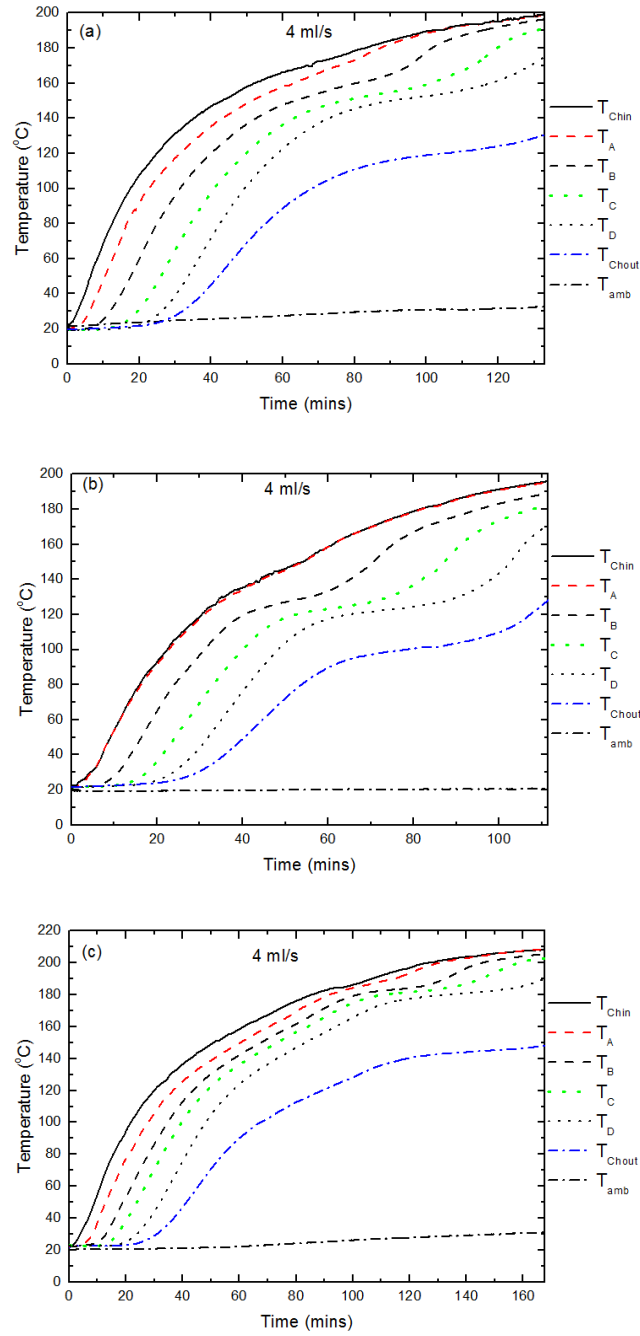


Figure 4.1: Charging temperature profiles at a low flowrate (4 ml/s) for (a) the adipic acid packed bed TES, (b) the erythritol packed bed TES system and (c) the eutectic solder packed bed TES system.

The melting of the PCMs is seen to progress from the top of the storage tank to the bottom since the HTF flows from the top to the bottom of the TES tanks. The erythritol TES shows the fastest phase transition due to the PCM's lower melting temperature of about 120 °C with the top level (Level A) showing phase change after about 30 mins, whereas for the adipic acid TES, the phase change transition at the top only becomes evident after 60 mins while for the eutectic solder TES, the phase change transitions at the top only occurs after 90 mins.

Erythritol is seen to have the shortest charging time possibly due to its low average phase change enthalpy capacity. The erythritol TES tank thus approaches the bottom limiting temperature earlier due a faster charging rate. Adipic acid charges for a shorter interval of just above 130 mins as compared to the eutectic solder which charges in around 170 mins. The is due to thermal mass effect in the liquid state for adipic acid with increased convective heat transfer in the adipic acid packed bed as compared to the solder.

Another plausible explanation for the shorter charging duration is the lower phase change temperature of adipic acid which enhances convective heat transfer in the liquid state for adipic acid earlier. It is important to also note that the solder presents a much higher thermal mass than the other PCMs and also its high phase transition temperature accounts for its longer charging time. The larger thermal conductivity of the solder appears only to have influence at the start (first 20 mins) of the experiment with the observed higher temperature rise in the solder TES tank as compared to the others. The erythritol TES system shows the best thermally stratified distribution between adjacent PCM layers in the TES tank implying more efficient charging with the larger axial thermal gradients possibly due the lower melting point of this PCM.

Figure 4.2 shows the charging temperature profiles in the three TES tanks using a medium charging flowrate (6 ml/s). The charging time is observed to have increased with the flowrate. A similar effect of an increase of the charging time with the charging flowrate has been reported by Lugolole et al., [39] who compared three different sensible heat storage materials in the same storage system. The reason of the longer charging time with the highest flowrate is due to the lower inlet temperature attained with the higher flowrate of 6 ml/s. The lower inlet temperature to the storage tank with 6 ml/s is a direct result of more pronounced cooling of the electrical heater with this flowrate. This is because the same heating power was used for the two flowrates as measure of ensuring controlled experiments. With an increase of flowrate, the heater was slightly cooled more at the same heating power output resulting in a lower inlet temperature to the storage tank from the outlet of the charging heater. The lower inlet charging temperatures for charging with 6 ml/s resulted in the bottom limiting experimental temperatures (170 °C) to be approached at later times when compared to charging with 4 ml/s.

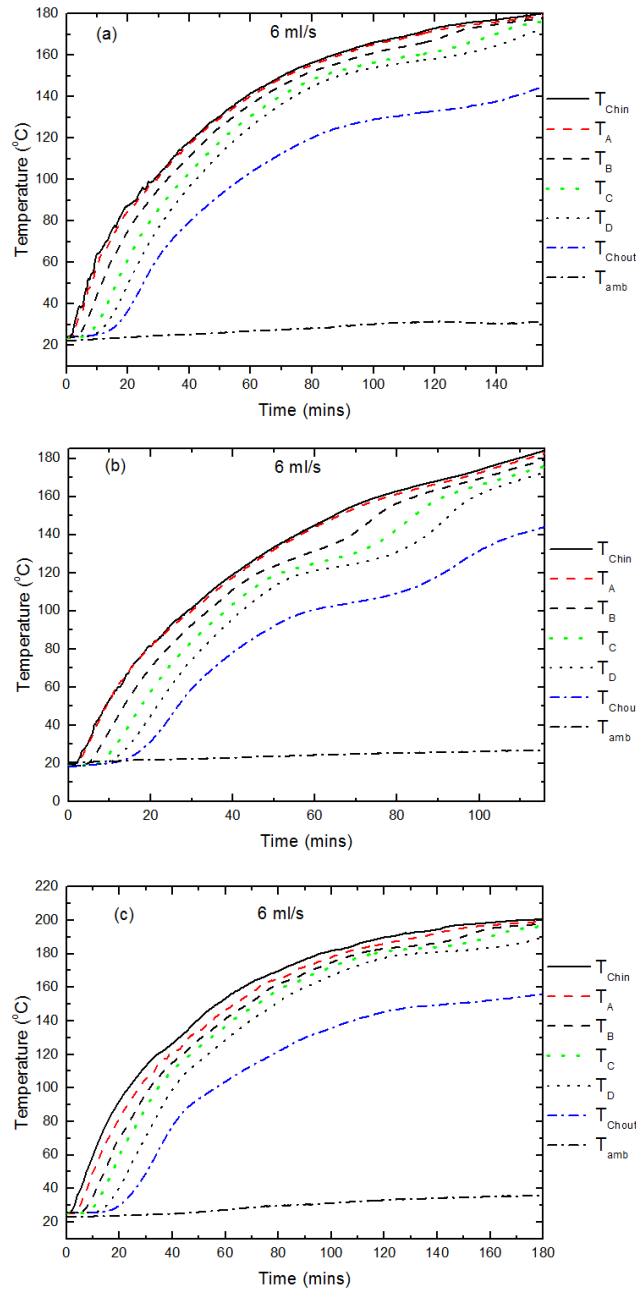


Figure 4.2: Charging temperature profiles at a medium flowrate (6 ml/s) for (a) the adipic acid packed bed TES, (b) the erythritol packed bed TES system and (c) the eutectic solder packed bed TES system.

Similar trends in the charging times, as with the lower flowrate case, can be observed. Similar reasons earlier given will suffice for the observed trend in the TES systems charging times. The erythritol TES tank shows the best thermally stratified distribution in the tank which can be used to qualitatively infer more efficient charging. The phase change transitions of the PCMs in all the TES tanks occurred at later times as compared with the lower charging flowrate due to the lower charging rates due to the higher heater cooling with the flowrate of 6 ml/s. The degree of the thermal stratification in all the TES tanks can be observed to be

less as compared to the low flowrate due to greater mixing of adjacent layers of HTF in the tanks. The eutectic solder TES tank can be observed to have attained higher temperatures than the other tanks. With higher rate of heat transfer to the eutectic solder bed, the rate of heat losses to the environment increased and thus, a longer time for the bottom section of the tank to reach the experimental cut off temperature.

The charging temperature profiles with a high charging flowrate (8 ml/s) are shown in Figure 4.3. The charging times are even longer as compared to the other flowrates and the same trends can be observed with this flowrate when compared to the other flowrates due more enhanced cooling of the electrical heater which results in lower inlet charging temperatures for the storage tank. With these high flowrates, the degree of thermal stratification in all the tanks was reduced due to greater mixing of adjacent HTF layers caused by larger HTF momentum. Meanwhile, the erythritol TES still exhibits the best thermally stratified distribution.

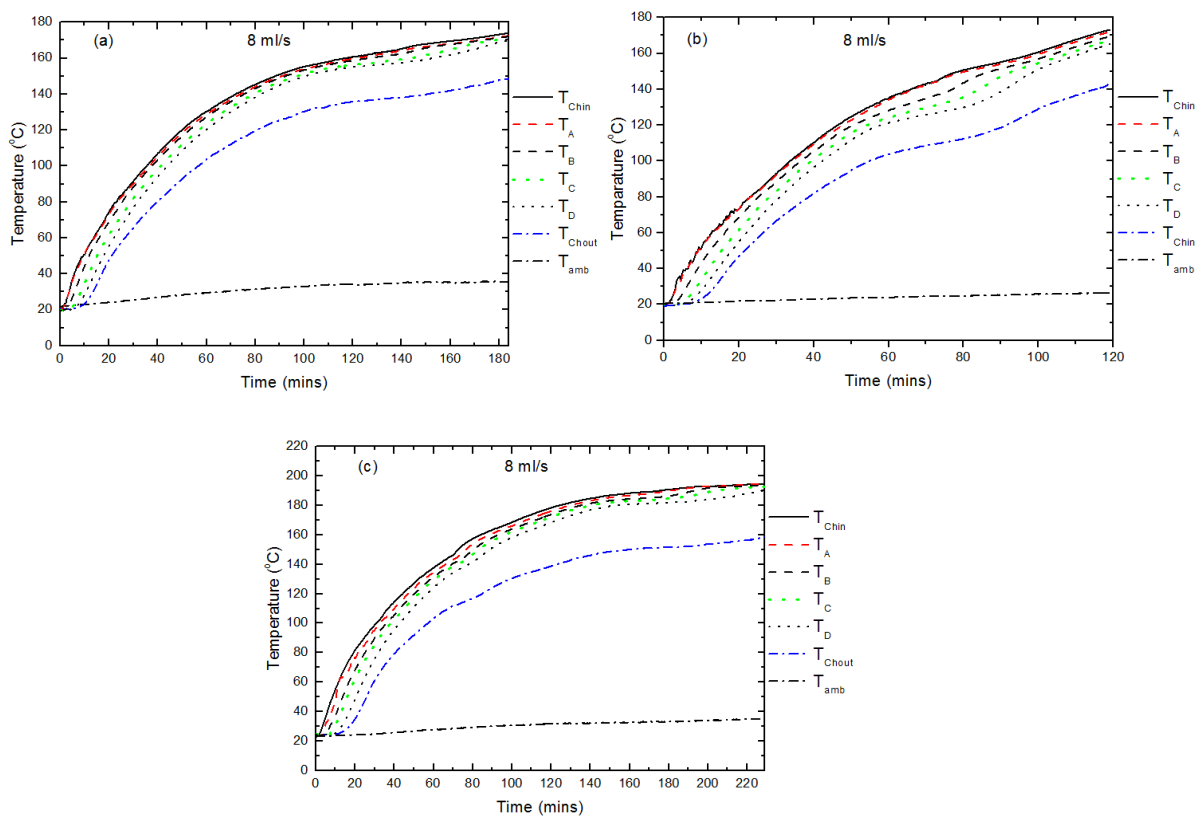


Figure 4.3: Charging temperature profiles at a high flowrate (8 ml/s) for (a) the adipic acid packed bed TES, (b) the erythritol packed bed TES system and (c) the eutectic solder packed bed TES system.

4.4.2 Charging energy and exergy analyses

For a quantitative means of comparison of the performances of the TES systems during charging, Table 4. gives the summary of the energy and the exergy analyses of the TES.

Table 4.2: A summary of the energy and the exergy analyses of the three TES systems during charging.

HTF FLOWRATE	PARAMETER	PACKED BED TES TYPE		
		ADIPIC ACID	ERYTHRITOL	EUTETIC SOLDER
Low (4 ml/s)	$E_{ch} (kJ)$	498.4	396.8	536.9
	$\dot{E}_{ch} (W)$	62.5	59.3	53.4
	$E_{XCHT} (kJ)$	112.6	93.0	136.9
	$\dot{E}_{Xch} (W)$	14.1	13.9	13.6
	$E_{C100} (kJ)$	463.5	356.8	498.0
	$E_{XC100} (kJ)$	110.0	89.3	133.5
Medium (6 ml/s)	$E_{ch} (kJ)$	595.8	501.7	645.9
	$\dot{E}_{ch} (W)$	63.9	72.2	59.8
	$E_{XCHT} (kJ)$	138.9	112.9	163.6
	$\dot{E}_{Xch} (W)$	14.9	16.2	15.1
	$E_{C100} (kJ)$	495.5	402.2	546.3
	$E_{XC100} (kJ)$	129.0	103.5	158.0
High (8 ml/s)	$E_{ch} (kJ)$	724.2	547.5	878.2
	$\dot{E}_{ch} (W)$	65.5	76.7	63.9
	$E_{XCHT} (kJ)$	166.0	122.1	228.0
	$\dot{E}_{Xch} (W)$	15.0	17.1	16.7
	$E_{C100} (kJ)$	600.1	426.4	780.2
	$E_{XC100} (kJ)$	153.6	109.6	220.5

Greater quantities of thermal energy/exergy can be observed to have been stored in the eutectic solder TES tank than the other TES systems at all the flowrates, though its charging rate (energy and exergy) is the least. This is as a result of its large thermal mass and the high phase change temperature, thus the solder TES tank takes a longer time to charge up, lowering the average charging rate. The adipic acid TES system comes in second in terms of quantities of thermal energy and exergy stored possibly due to its large thermal mass when compared to those of the erythritol TES system. Additionally, this is also due its high phase change transition temperature and enthalpy. However, at the medium and high charging flowrate, the average charging rate of the erythritol TES system increased due to higher

convective heat transfer rate from the HTF to the bed, compared to that of the adipic TES system since erythritol is in the liquid state for a longer duration. Thus, the adipic acid TES shows lower energy and exergy charging rates than the erythritol though it stored greater quantities of both energy and exergy than the erythritol TES system. Since we are interested in the thermal energy to be used for domestic heating applications at temperatures between 100 °C and 250 °C, it becomes necessary to focus on the quantities of thermal energy stored in the TES systems at this temperature range. The sum of the quantities of both thermal energy and exergy stored in the TES systems, at temperatures of 100 °C and above, were computed as E_{100} and E_{x100} respectively in Table 4.2. Greater quantities of this useful thermal energy were delivered to the eutectic solder TES system at all the flowrates, followed by the adipic acid TES system and lastly by the erythritol TES system. It can be concluded that more useful thermal energy is delivered with a higher melting temperature PCM. For all the TES systems and at all the flowrates considered during charging, all the performance indicators show an increasing trend with an increase in the charging flowrate.

4.4.3 Discharging results

Discharging thermal profiles at a low flowrate (4 ml/s) for the three TES systems are shown in Figure 4.4. For all the three TES systems, there is an initial rise of temperatures in the TES tank, at all axial sections within the first 10 mins. This is attributed to the hot HTF still resident in the flow-pipe that is pushed into the TES tanks as discharging was from the top to the bottom. The hot oil from the top section of the TES tanks mixed with the cooler oil at the bottom causing a more pronounced temperature rise at the bottom of the TES tanks (T_D). All TES systems also show initial drop in the discharging unit's outlet temperatures within the first 5 mins due to the initial lower water temperature. In general, the temperature at the top section (T_A) fell to lower temperatures than the temperatures at the other lower axial sections of the tanks after the initial rise. This is due to the impact of the HTF entering to the top section of tank and penetrating into the lower section of the tank (B) before thermal energy is transferred to the bottom resulting in temperature profile reversals. For the eutectic solder, this temperature profile reversal is not very evident as there appears to be very negligible temperature stratification in the TES tank. The eutectic solder shows distinct solidification phase change transitions at all sections of the TES tank, from about 20 mins to about 35 mins from around 175 °C to 170 °C implying proper nucleation and discharge of the stored latent

heat. In contrast to this behaviour of the solder, erythritol showed no phase change transition due to its characteristic supercooling.

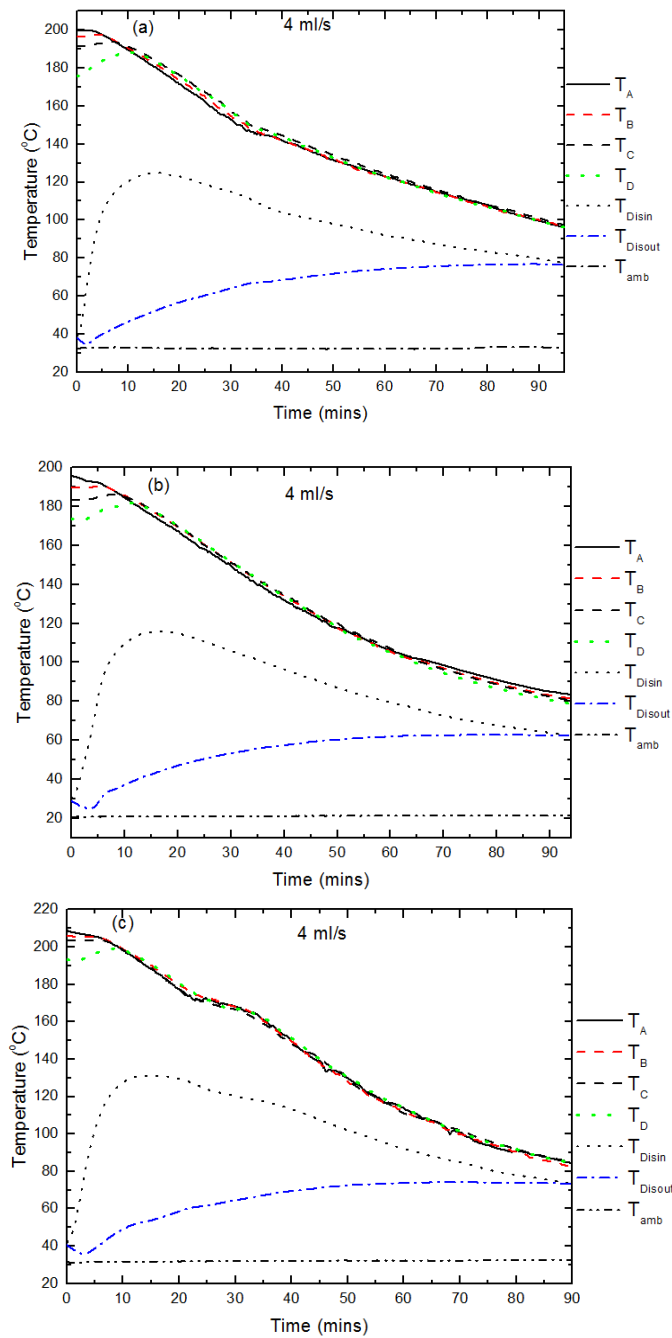


Figure 4.4: Discharging temperature profiles at a low flowrate (4 ml/s) for (a) the adipic acid packed bed TES, (b) the erythritol packed bed TES and (c) the eutectic solder packed bed TES system.

Adipic acid shows noticeable phase change transition for a short duration between 30 and 40 mins. For all three TES systems, the temperature at the inlet of discharging unit (T_{disin}) rose to peak value within the first 15 mins of discharging as thermal energy is extracted from the TES

tanks. The peak value of T_{disin} for the solder TES tank is slightly higher due to the larger thermal energy it stored during charging. Moreover, the phase transition accompanied by discharging of the phase change enthalpy occurred earliest and at a high temperature, in the solder TES tank compared to the other TES tanks. The discharging durations are comparable for all the three TES systems; however, the eutectic solder shows a slightly shorter duration. This is possibly due to the higher thermal conductivity of the eutectic solder which promoted a higher rate of heat transfer from the packed bed to the HTF.

Discharging thermal profiles of the TES tanks with the medium HTF flowrate (6 ml/s) are shown in Figure 4.5. The discharging times of all the TES systems are generally shorter as compared to the lower flowrate due to the higher heat transfer rates from the packed beds to the HTF. For the adipic acid and erythritol TES tanks, more of the thermal energy discharged to the HTF occurred near the top sections (A and B) of the beds. The HTF then flowed down these beds without much heat exchange with the lower sections of the tanks after the first 10 mins. This is evident with T_A and T_B being lower than T_C and T_D . However, due to the higher thermal conductivity of the solder there existed high heat exchange between the HTF and the eutectic solder packed bed. Thus, further heat exchange occurs between the HTF and the lower sections of the bed as the HTF flows down the tank. Hence, the temperatures at all sections in the solder TES tank were similar. Coupled with this fact, the eutectic solder TES tank possessed a higher thermal energy content which was responsible for its longer discharging time. The greatest thermal stratification can be observed in the adipic acid TES tank followed by the erythritol and lastly, the eutectic solder TES tank. The peak temperature attained by the inlet HTF into the discharging unit gives some indication of the quantity of thermal energy discharged by each of the TES systems.

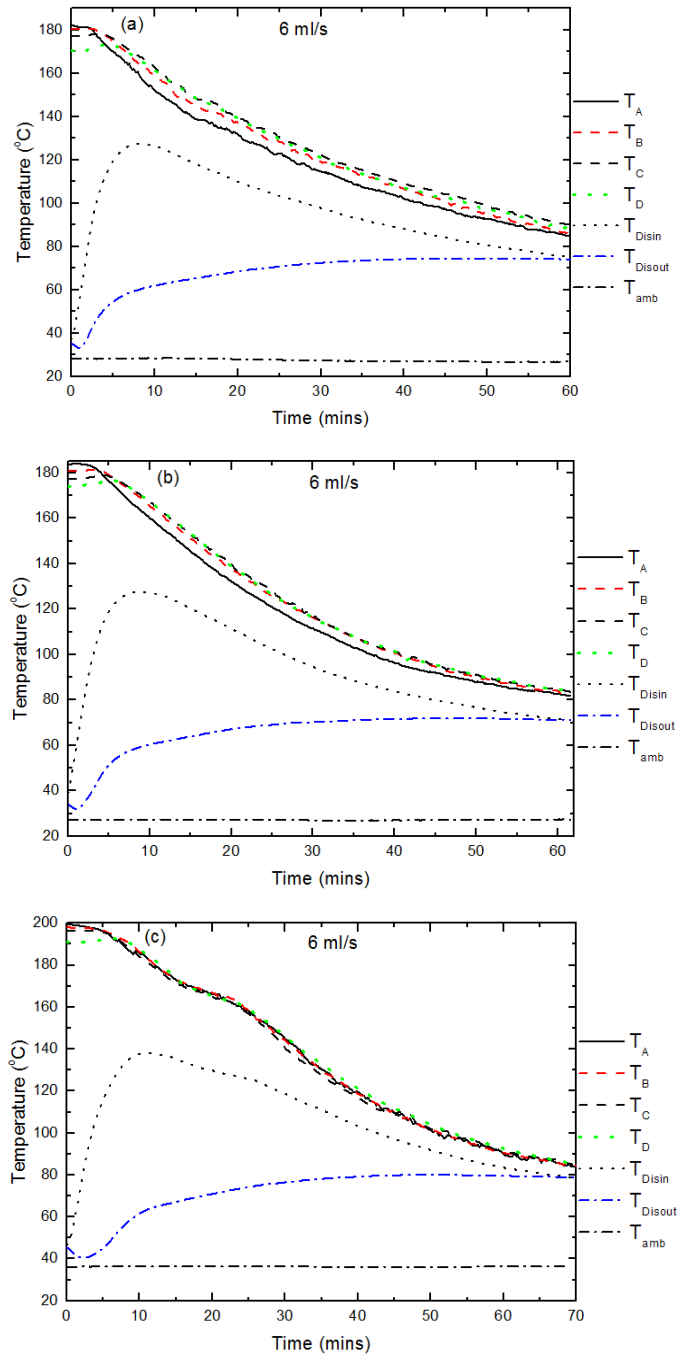


Figure 4.5: Discharging temperature profiles at a medium flowrate (6 ml/s) for (a) the adipic acid packed bed TES, (b) the erythritol packed bed TES and (c) the eutectic solder packed bed TES system.

Discharging thermal profiles of the TES tanks with the high flowrate (8 ml/s) are shown in Figure 4.6. The discharging times for the three TES tanks generally reduced from the medium HTF flowrate due to higher rates of thermal energy transfer from the packed beds to the HTF. A similar trend in the discharging times for the TES systems is seen with the highest flowrate as compared to the medium flowrate. However, greater thermal stratification can be observed in the adipic acid and the eutectic solder TES tanks compared to lower flowrates.

There is an obvious greater convective heat transfer from the packed bed to the HTF at the highest flowrate.

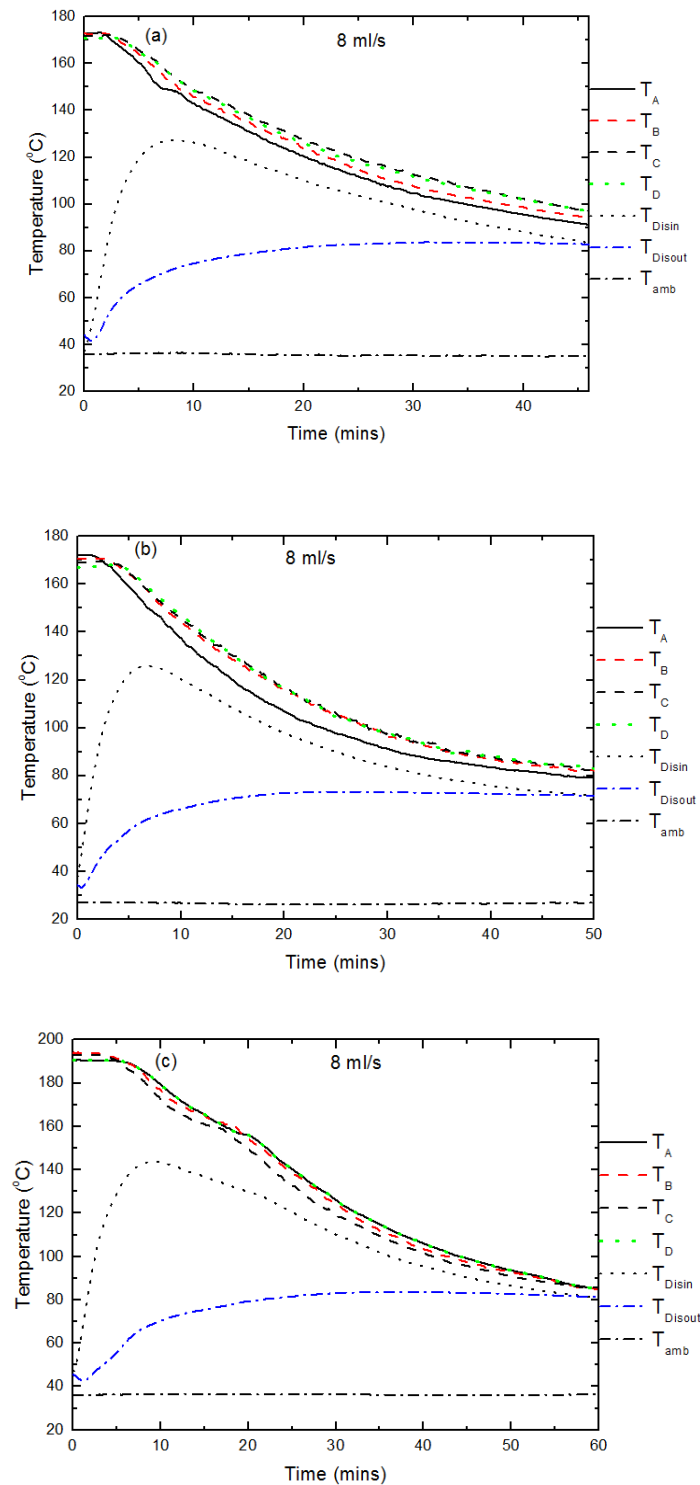


Figure 4.6: Discharging temperature profiles at a high flowrate (8 ml/s) for (a) the adipic acid packed bed TES, (b) the erythritol packed bed TES system and (c) the eutectic solder packed bed TES system.

4.4.4 Discharging energy and exergy analyses

In order to properly understand the discharging processes for the TES systems and quantify them, the total energy and exergy discharged, the discharging energy and exergy rates as well as the useful energy and exergy discharged by the TES systems are determined and given in Table 4.3.

Table 4.3: A summary of the energy and the exergy analyses of the three TES systems during discharging.

HTF FLOWRATE	PARAMETER	PACKED BED TES TYPE		
		ADIPIC ACID	ERYTHRITOL	EUTETIC SOLDER
Low (4 ml/s)	$E_{dist} (kJ)$	160.7	155.2	167.2
	$\dot{E}_{dist} (W)$	23.3	27.5	31.0
	$E_{XDIST} (kJ)$	23.0	23.6	25.5
	$\dot{E}_{XDIST} (W)$	3.3	4.2	4.7
	$E_{D100} (kJ)$	120.5	142.2	139.1
	$E_{XD100} (kJ)$	17.8	22.3	22.1
Medium (6 ml/s)	$E_{dist} (kJ)$	177.2	180.7	181.8
	$\dot{E}_{dist} (W)$	47.4	49.0	43.9
	$E_{XDIST} (kJ)$	28.6	29.0	28.1
	$\dot{E}_{XDIST} (W)$	7.7	7.9	6.8
	$E_{D100} (kJ)$	129.3	169.1	158.4
	$E_{XD100} (kJ)$	21.8	28.0	25.4
High (8 ml/s)	$E_{dist} (kJ)$	175.7	180.9	193.5
	$\dot{E}_{dist} (W)$	63.2	60.3	55.0
	$E_{XDIST} (kJ)$	27.6	29.5	32.3
	$\dot{E}_{XDIST} (W)$	9.9	9.8	7.6
	$E_{D100} (kJ)$	145.3	167.7	172.1
	$E_{XD100} (kJ)$	23.6	28.2	29.9

The eutectic solder TES system can be seen to have discharged the largest quantities of thermal energy and exergy, and it possesses the highest energy and exergy discharging rates at a flowrate of 4 ml/s. This was due to its large thermal energy content. However, the erythritol TES discharged the greatest quantities of useful energy and exergy (E_{D100} and E_{XD100} respectively) due to the high heat capacity of the liquid erythritol as well as the greater thermal stratification in its TES tank. At 6 ml/s and 8 ml/s, the eutectic solder TES system still discharged the largest quantities of thermal energy and exergy but due to the lower degrees of stratification in its TES tank, its discharging rates (energy and exergy) are lower than those of the erythritol and adipic acid TES tanks. However, at the HTF flowrate of 6 ml/s, the erythritol TES tank also discharged the greatest quantities of useful energy and exergy, followed by the solder TES tank and lastly, by the adipic acid TES tank. This was due to large heat capacity of liquid erythritol. It should be noted that erythritol did not undergo

phase change transition due to its exhibition of large degrees of supercooling. With the HTF flowrate of 8 ml/s, the eutectic solder TES system discharged the greatest quantities of thermal energy and exergy, as well as useful energy and exergy. Increased thermal stratification in the solder TES tank is suspected to have influenced the higher quality of both energy and exergy discharged from the solder TES tank at this flowrate. The adipic acid TES tank possessed the highest discharging energy and exergy rates due to its shorter discharging time as compared to the other storage systems. Despite the supercooling exhibited by erythritol, the erythritol TES performed very well in terms of useful energy discharged.

4.4.5 Energy and exergy storage efficiencies for the TES systems

The efficiencies of the TES tanks were evaluated respectively, based on the total thermal energy stored and the total thermal exergy discharged as well as the useful energy stored and the useful exergy discharged by the TES tanks as follows:

$$\varepsilon_{Energy\ overall} = \frac{\text{Total thermal energy discharged}}{\text{Total thermal energy stored}} \quad (4.13)$$

$$\varepsilon_{Exergy\ overall} = \frac{\text{Total thermal energy discharged}}{\text{Total thermal energy stored}} \quad (4.14)$$

$$\varepsilon_{Energy\ useful} = \frac{\text{Quantity of useful energy discharged}}{\text{Quantity of useful energy stored}} \quad (4.15)$$

$$\varepsilon_{Exergy\ useful} = \frac{\text{Quantity of useful exergy discharged}}{\text{Quantity of useful exergy stored}} \quad (4.16)$$

Table 4.4 gives a summary of the TES efficiencies determined by Eqs. (4.13) - (4.16). At the low flowrate, the erythritol TES system possessed the highest efficiencies in terms of all the indices used. At the medium flowrate, the erythritol TES system was the most efficient in terms of total energy, useful energy and useful exergy, while the eutectic solder TES system was the most efficient in terms of total exergy.

Table 4.4: Summary of the energy and the exergy storage efficiencies of the three TES systems during discharging.

HTF FLOWRATE	PARAMETER	PACKED BED TES TYPE		
		ADIPIC ACID	ERYTHRITOL	EUTETIC SOLDER
Low (4 ml/s)	$\epsilon_{Energy\ overall}$	32.2	39.1	31.1
	$\epsilon_{Exergy\ overall}$	20.4	46.4	18.6
	$\epsilon_{Energy\ useful}$	26.0	39.9	27.9
	$\epsilon_{Exergy\ useful}$	16.2	25.0	16.6
Medium (6 ml/s)	$\epsilon_{Energy\ overall}$	29.5	36.0	28.2
	$\epsilon_{Exergy\ overall}$	20.6	25.7	26.8
	$\epsilon_{Energy\ useful}$	26.1	42.0	29.0
	$\epsilon_{Exergy\ useful}$	16.8	27.1	16.1
High (8 ml/s)	$\epsilon_{Energy\ overall}$	24.3	33.0	22.0
	$\epsilon_{Exergy\ overall}$	16.6	24.2	23.6
	$\epsilon_{Energy\ useful}$	24.2	39.3	22.1
	$\epsilon_{Exergy\ useful}$	15.4	25.7	13.6

At the highest flowrate, the erythritol TES system presents the greatest efficiencies with respect to all the performance parameters. The adipic acid TES system came second in terms of total energy efficiency, useful energy efficiency and useful exergy efficiency while the eutectic solder TES system came second only in terms of total exergy efficiency.

The results obtained in this study are compared with those from some available previous literature, in Table 4.5. Though the size of the TES systems in this study are less than all the ones listed from the literature, the overall energy efficiencies obtained from this study look encouraging and comparable to the average energy storage efficiencies of the previous works. The reason for the lower efficiencies is that the storage tanks were not completely discharged to their initial storage temperatures since only useful energy stored is considered. In the future, a similar study utilizing the PCMs used in this study in a larger TES tank will be pursued for possible better TES efficiencies.

Table 4.5: Summary of previous studies on packed bed TES systems and the present study.

Configuration	PCM	Encapsulating Material	HTF	Melting Temperature (°C)	Flowrates (ml/s)	TES Tank Capacity (litres)	Number of EPCMs	Average energy storage efficiency (%)
Packed bed [35]	Al64	Stainless Steel	Hytherm 600	168.7	118, 137, 115	8.17	209	62.6
Packed bed [36]	D-Mannitol	Stainless Steel	Therminol 55	167.0-169.0	114	261.34	126	10.2
Packed bed [37]	Paraffin Wax	Stainless Steel	Water	67.0-69.0	139, 250	750.00	9170	20.0
Packed bed [38]	Li ₂ CO ₃ -K ₂ CO ₃ -Na ₂ CO ₃ (32–35–33 wt%)	304 Stainless Steel	Air	395.1	50, 61, 72	26.81	385	81.0
Packed bed 1- Present work	Erythritol	Aluminium	Sunflower oil	118.0-122.0	4, 6, 8	7.10	40	39.1
Packed bed 2- Present work	Adipic acid	Aluminium	Sunflower oil	150.0-152.0	4, 6, 8	7.10	40	32.2
Packed bed 3- Present work	Eutectic solder (Sn63Pb37)	Aluminium	Sunflower oil	183.0	4, 6, 8	7.10	40	31.1

4.6 Conclusion

The thermal performances of three different packed bed latent heat medium-temperature TES systems were evaluated during charging and discharging cycles, at three HTF flowrates through the beds. The respective TES systems were packed beds of adipic acid, erythritol and eutectic solder (Sn63Pb37). The PCMs were encapsulated in similar aluminium spherical capsules while Sunflower Oil was used as the HTF. The performance of these storage systems was evaluated in terms of the temperature profiles, total energy, total exergy, useful energy and useful exergy during both charging and discharging. The useful energy and exergy were defined as the total energy and exergy stored or discharged at temperatures above 100 °C for the temperature applications the systems were intended for. The overall efficiencies of the TES systems in terms of energy and exergy were also evaluated. The major conclusions of the study can be summarized as follows;

1. The eutectic solder TES system stored the greatest quantities of energy, exergy, useful energy and useful exergy at all the flowrates during charging. This may be attributed to the large thermal energy and phase change enthalpy storage capacities as well as the high phase transition temperature of the eutectic solder. However, the eutectic solder TES system showed lower charging performances in terms of all the performance indicators due to its longer charging time. At the lowest flowrate, the

adipic acid TES system showed the highest charging rates in terms of energy, exergy, useful energy and useful exergy. Erythritol on the other hand, had the greatest charging rates in terms of energy and exergy at the medium flowrate and the high flowrate. The erythritol TES tank also exhibited the greatest thermal stratification during charging. Charging times increased while thermal stratification reduced progressively for all the TES systems with increase in the HTF flowrate during charging.

2. During discharging, the eutectic solder TES system discharged the greatest quantity of thermal energy at all the flowrates as well as the greatest thermal exergy at the low flowrate and at the high flowrate, while erythritol discharged the greater thermal exergy at the medium flowrate. The high thermal energy content of the eutectic solder TES system, after charging, can be attributed to its performance in this respect. The largest thermal stratification during discharging was observed in the adipic acid TES tank at all three flowrates. The lowest thermal stratification was observed in the eutectic solder TES tank. Thermal stratification in all the TES tanks however, increased with an increase in flowrate. Although phase transition was not observed at all the axial sections of the erythritol TES tank and at the flowrates during discharging, the TES system still discharged the highest quantities of useful energy and exergy. This is attributable to the high specific heat capacity of erythritol in its liquid state.
3. Although erythritol exhibited supercooling at all the flowrates considered in this study, the erythritol TES system possessed the greatest overall efficiency of the three systems, in terms of total energy, total exergy, useful energy and useful exergy.
4. Generally, the overall efficiencies of all the TES systems reduced with increasing flowrate. The low efficiency of the eutectic solder TES system is thought to be due to the longer charging duration because of the higher melting temperature. This longer charging duration induces greater thermal losses to the environment from the tank due to the higher thermal conductivity of the solder as well as the poor thermal stratification in the TES tank.
5. The adipic acid TES system showed a promising edge over the eutectic solder TES at the high flowrate in terms of the overall useful energy and exergy efficiencies. The eutectic solder TES however, showed better potential in terms of the useful energy and exergy efficiencies, than the adipic acid TES system at the lowest flowrate.

In the future, a similar study utilizing the PCMs used in this study in a larger TES tank will be

pursued for possible better TES efficiencies. The authors also wish in the future, to investigate the performance of cascaded latent heat storage systems using two or more PCMs with different melting points in the same storage tank to find out if the storage efficiency will increase.

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Chapter 5: Paper 3-Charging characteristics of packed bed latent heat storage systems for medium temperature solar applications

This chapter presents a paper from the 6th Southern African Solar Energy Conference 2019 (SASEC 2019) held in East London, South Africa from 25-27 November 2019. The conference focussed both on Solar Photovoltaic and Solar Thermal Energy technology systems and applications.

The packed bed storage configuration is particularly attractive because of its greater heat transfer rates and its simpler design when compared to the shell and tube configuration. Three locally available phase change materials (PCMs); eutectic solder, erythritol and adipic acid are thus characterized experimentally for medium temperature solar thermal applications in a packed bed storage configuration. The PCMs are encapsulated in aluminium spherical capsules, and Sunflower Oil is used as the heat transfer fluid (HTF). The performance of these storage systems is evaluated in terms of the temperature profiles during charging and the charging energy and exergy rates. Erythritol charges up for the shortest duration, followed by adipic acid and lastly by the eutectic solder as a result of the combined effect of a lower thermal mass induced by a lower melting temperature and increased convective heat transfer. Erythritol shows a superior performance in terms of the charging energy and exergy rates since it shows higher values due to its lower melting point which induces more convective heat transfer and a greater degree of thermal stratification. The worst thermal performance in terms of the charging energy and exergy rates is seen with the solder, however, in some instances its performance is comparable to adipic acid.

5.1 Introduction

Latent heat thermal energy storage systems using phase change material are essential in thermal energy storage applications due to their high storage density with smaller temperature thermal gradients during storing and releasing energy. However, the low conductivity of most phase change materials, leads to decreased heat transfer rates which reduce the efficiency of latent heat thermal energy storage (LHTES) systems, thus metallic encapsulation assists with increasing thermal conductivity. Phase change materials (PCMs) arranged in a packed bed configuration are particularly attractive because of their greater heat transfer rates as compared to the shell and tube configuration [1]. Added to this, packed

storage configurations are simpler and cheaper to design. In a packed bed latent heat storage configuration, heat is transferred from a heat transfer fluid flowing through the voids between the PCM capsules and the tank. The PCMs absorb the heat and melts when the temperature of the fluid becomes equal to or greater than the melting points of the PCMs.

There has been limited research work that has been done on LHTES for solar domestic medium temperature applications like cooking of food [2-6]. Fewer studies have also appeared in recent literature [7-9] on oil based packed bed LHTES systems, which addresses the deficiency of water as a heat transfer fluid (HTF) since it needs to be pressurized for temperatures above its boiling point.

Recent work has suggested the use of erythritol as a suitable PCM for domestic solar thermal applications [10-13], due to its high latent heat and melting temperature close to the boiling point of water. Only very few recent applications of adipic acid as a PCM have also been reported [14-16], thus there is a potential to investigate the performance of this material further for thermal energy storage. No study has ever been done on it in a packed bed storage configuration. In a recent study [17], an expensive metallic solder was suggested as suitable PCM for domestic TES applications and there seems to be no follow-up studies on the use of metallic solders as PCMs. The eutectic solder consisting of Tin and Lead (Sn-Pb, (Sn63/Pb37)) manufactured locally in South Africa has never been used for any domestic PCM application. Promising results obtained with the In-Sn solder in [17], justify the experimental testing of solders as PCMs. Sunflower Oil has been used recently as a heat transfer fluid (HTF) in domestic TES applications since it is cheap, food grade, readily available, non-toxic and possesses characteristics comparable to other commercial HTFs as previously investigated in [18-19].

The aim of the paper is to compare experimentally three packed bed latent heat storage systems (erythritol, adipic acid and eutectic solder) during charging processes. There are very few studies that have been done using the mentioned materials, and it will add invaluable information on medium temperature domestic packed bed storage systems. The packed bed latent heat storage system is suitable for enhancing the usefulness of solar cookers.

5.2 Experimental setup and procedure

Figure 5.1 shows a photograph of the main components of experimental setup. The schematic diagram of the operation of the experimental setup is shown in Figure 5.2. Two of the above mentioned PCMs, erythritol powder and adipic acid powder were each poured into forty spherical aluminium capsules separately with diameters of 0.05 m and wall thicknesses of 0.001 m. The capsules were manufactured as hollow spheres with an opening at the top and a cap for closure to allow pouring of the PCM. The volume of the PCM in the capsules was about 80 % of the total internal volume of the capsule to allow for thermal expansion. After pouring the adipic acid and erythritol, four of the capsules of each material had K-type thermocouples fixed onto them to measure the PCM temperature changes. These thermocouples which extended into the centre of the spheres were fastened on the top of the spheres. The capsules were placed at the bottom, lower middle, middle and top levels of the tank to measure the PCM temperatures. There were other thermocouples placed in the tank to measure the different temperatures in the tank, and the inlet and outlet temperatures as shown in Figure 5.2.



Figure 5.1: A photograph of the main components of the experimental thermal energy storage system [20].

Eutectic solder wire strips were fitted into the capsule and a screw driver was used to press down the wire to make sure that the amount desired was achieved. Similarly, K-type thermocouples were inserted into four of the eutectic solder capsules to measure the PCM temperatures at the different levels of the storage tank.

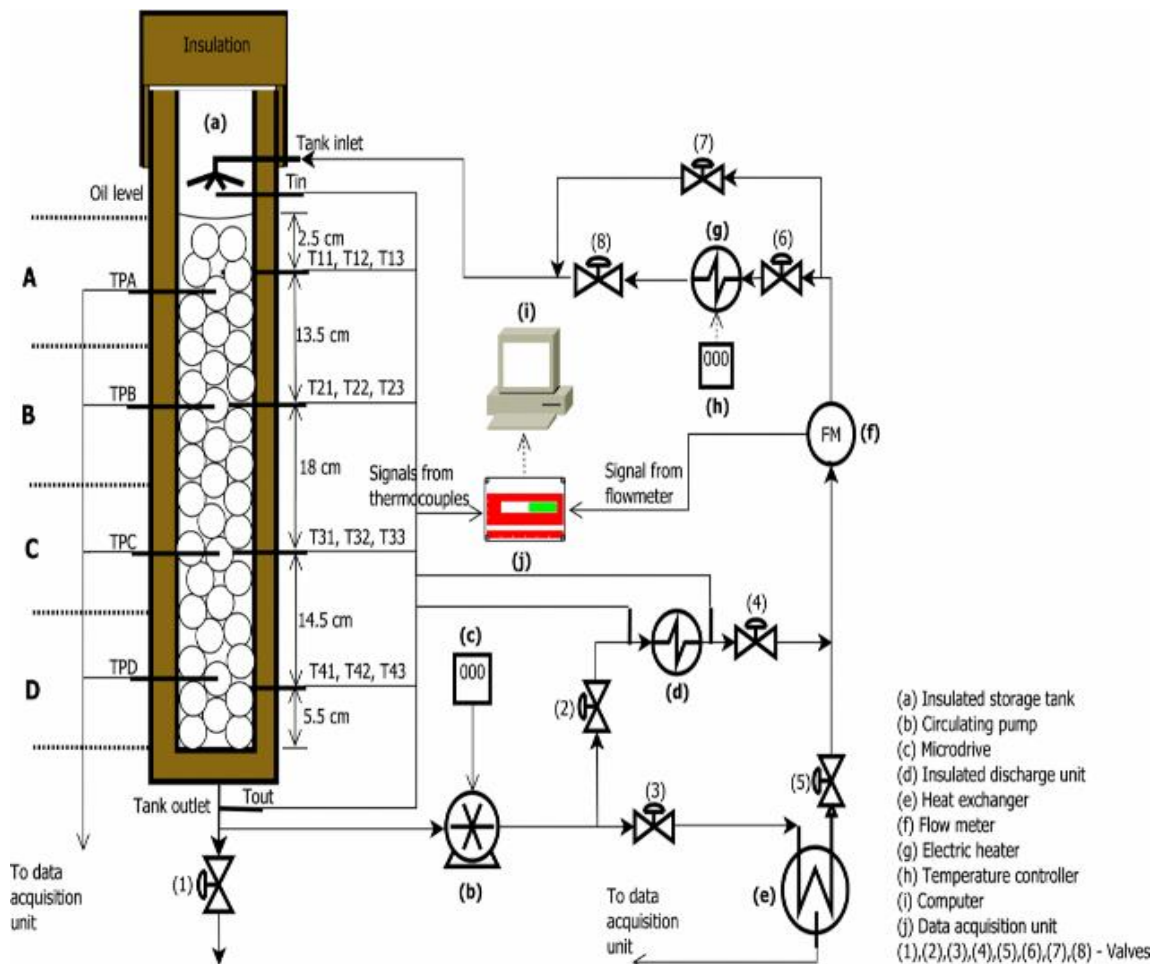


Figure 5.2: Schematic diagram of experimental setup.

The experimental system consists of a thermal energy storage (TES) unit (a), heated up by a heating unit (g) which consists of two electrical spiral coils (power rating: 220V, 900 W each) which heat up circulating oil in a copper spiral. A TZN4S temperature controller (h) (display accuracy: $\pm 0.3\%$) is used to set and control the required maximum temperature. A magnetic-drive pump (b) is used to circulate Sunflower Oil through the heating unit, while a VLT Micro drive (c) is used to control the frequency of the pump so as to set a desired flowrate. An HP 34970 data acquisition unit (j) was connected to the thermocouples and it was used to convert analogue signals to digital signals. A personal computer (i) was used to monitor the temperature profiles of the TES systems and the PCMs, and it recorded data every 10s.

Charging experiments were performed with flowrates of 4 ml/s (low), 6 ml/s (medium) and 8 ml/s (high) respectively at a set heater temperature of 260 °C to investigate the effect of the flowrate for the three packed bed systems.

Thermophysical properties of erythritol, adipic acid and the eutectic obtained from open literature are shown in Table 5.1. The mass of PCM inside the erythritol capsules was almost similar to the mass inside the adipic acid capsules. The eutectic solder had the largest mass of PCM inside the capsules due its higher density. Adipic acid shows the largest phase change enthalpy while the eutectic solder has the least. The thermal conductivity of the solder is highest while the thermal conductivities of the two organic PCMs are comparable.

Table 5.1: Thermophysical properties of the PCMs.

Property	Erythritol	Adipic Acid	Eutectic Solder (Sn63Pb37)
Melting Temperature (°C)	118-122 [17]	150-152 [22]	183 [24, 26]
Specific Heat Capacity (kJ/kgK)	1.38 (20 °C), 2.76 (140°C) [17]	1.59 (20 °C), 2.26 (150 °C) [23]	0.21 (30 °C) [24]
Phase change enthalpy (kJ/kg)	139.7 [17]	213–260 [22]	52.1 [25]
Density(kg/m ³)	1210 [17]	1360 (20 °C), 1093 (163 °C) [23]	8400 [26]
Thermal conductivity (W/mK)	0.130 (120 °C) [17]	0.142-0.162 [23]	50 [26]
Average mass of PCM in the capsule (g)	44	40	164

5.3 Experimental thermal analysis

The energy charging rate (or power) depends on the inlet and outlet charging temperatures of the storage tank and it is expressed as;

$$\dot{E}_{ch} = \rho_{av} c_{av} \dot{V}_{ch} (T_{chin} - T_{chout}) \quad (5.1)$$

, where ρ_{av} is the temperature dependent average density of the oil, c_{av} is the temperature dependent average density of the oil, $\dot{V}_{ch}$ is the volumetric charging flowrate, T_{chin} is the inlet charging temperature at the top of the storage tank and T_{chout} is the outlet charging temperature at the bottom of the storage tank. The charging exergy rate is expressed as;

$$\dot{E}_{xch} = \rho_{av} c_{av} \dot{V}_{ch} \left[(T_{chin} - T_{chout}) - T_{amb} \ln \left(\frac{T_{chin}}{T_{chout}} \right) \right] \quad (5.2)$$

, where T_{amb} is the ambient temperature.

5.4 Results and discussion

The charging temperature profiles along the height of the three TES tanks, using a low HTF charging flowrate (4 ml/s), are shown in Figure 5.3. The melting of the PCMs is seen to progress from the top of the storage tank to the bottom since the HTF flows from the top to the bottom of the TES tanks. The erythritol TES tank shows the fastest phase transition due to the PCM's lower melting temperature of about 120 °C with the top level (Level A) showing phase change after about 30 mins, whereas for the adipic acid TES, the phase change transition at the top only becomes evident after 60 mins, while for the eutectic solder TES, the phase change transitions at the top only occur after 90 mins. Erythritol is seen to have shortest charging time possibly due to its low average phase change enthalpy capacity. The erythritol TES tank thus approaches the bottom limiting temperature earlier due to a faster charging rate. Adipic acid charges for a shorter interval of just above 130 mins as compared to the eutectic solder which takes close to 170 mins. This is due to thermal mass effect in the liquid state for adipic acid with increased convective heat transfer in the adipic acid packed bed as compared to the solder. This shows that the faster the charging rate, the faster the phase change of material hence the higher the ability to store heat.

Similar charging temperature profiles for medium (6 ml/s) and high (8 ml/s) flowrates have been presented elsewhere in our recent study [21]. The results show that the charging time increases with the charging flowrate due to more pronounced cooling of the electrical heater

which reduced the inlet charging temperature such that the bottom limiting experimental temperatures (170 °C for erythritol and adipic acid, and 190 °C for eutectic solder) were approached at a later time. This same effect of the increase in the charging time with an increase in the flowrate was also reported by Lugolole et al., [20] who characterized three sensible heating storage systems using the same experimental setup.

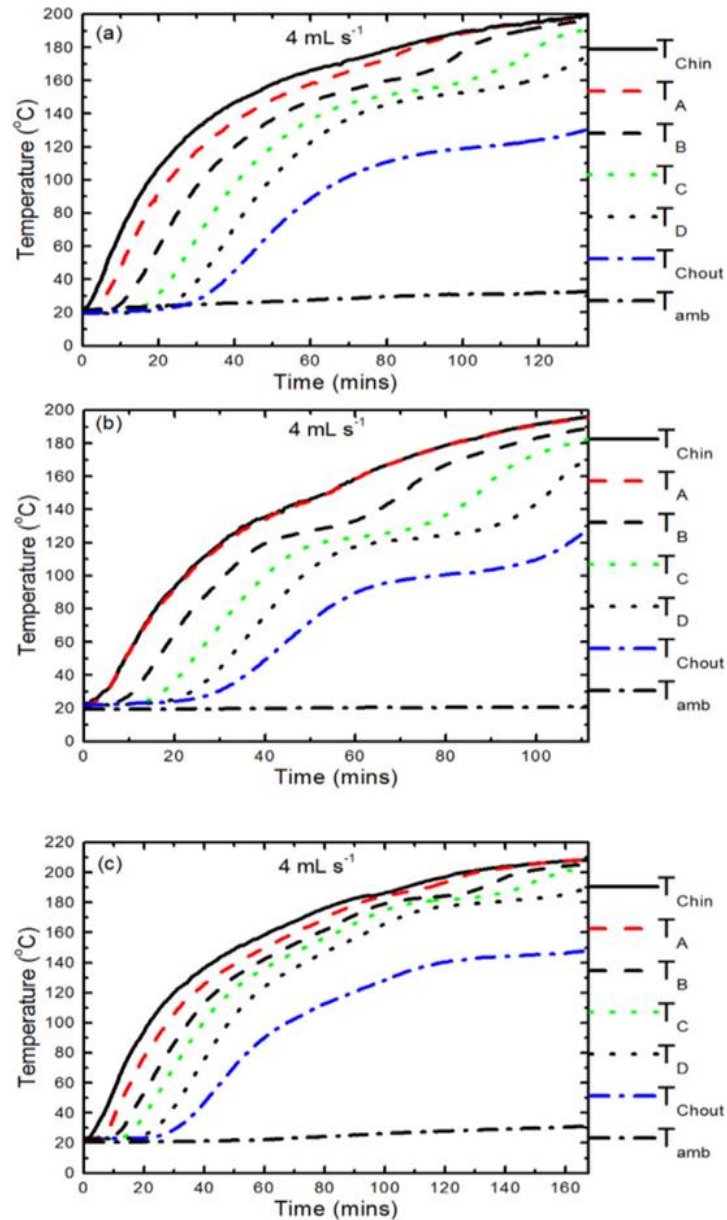


Figure 5.3: Charging temperature profiles at a low flowrate (4 ml/s) for (a) the adipic acid packed bed TES, (b) the erythritol packed bed TES system and (c) the eutectic solder packed bed TES [21].

To compare more qualitatively and quantitatively, the charging processes in the storage systems, charging energy rate profiles are presented in Figure 5.4. The charging energy rates are presented for low (4 ml/s), medium (6 ml/s) and high (8 ml/s) flowrates. For the lowest flowrate (plot (a)), the energy rate profiles are seen to initially rise to peak values at around 35 mins due to the initial rises in the inlet charging temperatures when the bottom of the storage tank temperatures are lower resulting in large thermal gradients between the top and the bottom of the storage tanks.

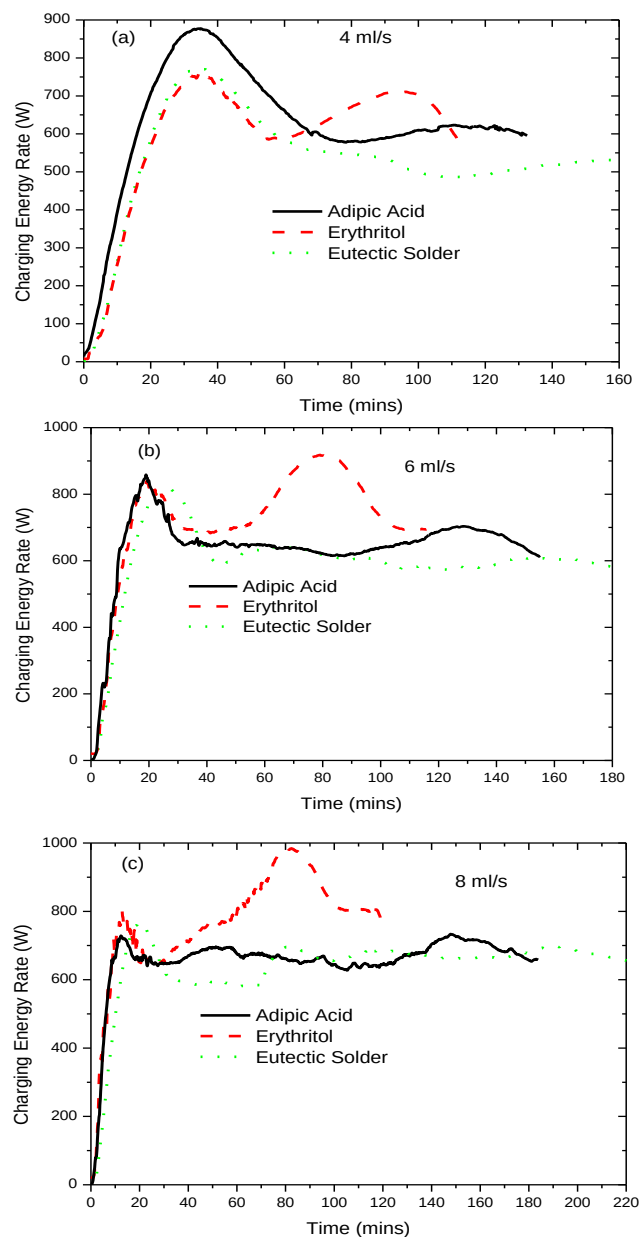


Figure 5.4: Charging energy rate profiles at (a) low, (b) medium and (c) high flow rates for the three storage systems.

As charging progresses after 35 mins, the energy rates drop as the charging outlet temperatures begin to rise causing drops in the thermal gradients. Erythritol is the first PCM to melt, and this induces a slow rise in the outlet charging temperature at around 60 mins causing the thermal gradient to increase thus consequently causing a secondary peak in the energy rate at around 90 mins. Further charging of the erythritol based TES system after 90 mins, induces a rise in the outlet charging temperature which reduces the thermal gradient thus there is a drop in the energy rate. For the other two storage systems, the rise is not pronounced possibly due to the higher melting points making heat transfer slower as the liquid PCMs are denser. A slight rise in the energy rate profile is seen with adipic acid after 70 mins, and this corresponds to the time when the rate of rise in the outlet charging temperature becomes slower. For the eutectic solder TES system, the rise is less pronounced as compared to the other two storage systems and it occurs much later after around 110 mins.

Adipic acid shows the highest peak value of the energy rate and this possibly due to the lower initial rise of the outlet charging temperature. This lower initial rise is possibly due to a combined effect of the slightly higher density of adipic acid as compared to erythritol and a lower thermal conductivity as compared to the solder. The peak energy rate values for erythritol and the solder are comparable, however, erythritol shows a much higher secondary peak as compared to the other two PCMs. For this low flowrate, adipic acid shows a better performance between 0 to 60 mins, whereas erythritol due to its secondary peak shows a better performance between 60 to around 110 mins.

Increasing the flowrate from lowest to the medium flowrate, generally increases the heat transfer such that the initial peak values are obtained earlier within 20 mins of charging. The peak values of the energy rates are comparable for three storage systems and they are all around 830 W. A slighter slower rise in the energy charging rate is seen with the solder possibly due the faster initial rise of the outlet charging temperature induced by its higher thermal conductivity which reduces the initial temperature gradient in the storage tank.

The secondary peak for erythritol is more pronounced when compared to the lower charging flowrate and the secondary peak value is higher (900 W) as compared to the primary peak value (820 W). The secondary peak value for adipic acid is more pronounced with the higher flowrate. This is a direct result of the increase in the heat transfer rate. The primary peak

values for the solder based system and erythritol seem to increase slightly with the increase in the charging flowrate. Erythritol outperforms the other two PCMs with higher energy rate values under medium flowrate charging. The performance of adipic acid and the eutectic solder is comparable especially between 50 mins and 90 mins, however, the secondary peak effect is more pronounced for adipic acid and it results in higher energy rate values between 100 and 140 mins.

For the highest charging flowrate, the primary peak values are attained earlier due to the increase in the heat transfer rate and the peak values are lower possibly due to the higher initial rates of rise in the outlet charging temperatures. Erythritol shows a larger secondary peak close to 1000 W as compared to the lower flowrates. The performance of erythritol in terms of the charging energy rate is better when compared to the other PCMs due to the high values obtained. Generally, the performance of the solder is comparable to that of adipic acid except between 20 to 60 mins of charging. The energy rate evaluations show that the best performance is shown with erythritol followed by adipic acid and lastly by the eutectic solder. Exergy rate values presented in Figure 5.5 quantify the available or the quality of the energy with reference to the surrounding environment. These tend to be more useful since irreversible changes such as heat losses are present in thermal systems. The exergy rate profiles for the lowest flowrate, show higher values for adipic acid up to around 60 mins which is also consistent with the energy rate profiles depicted in Figure 5.4(a). However, exergy rate profiles which consider heat losses are lower than the energy rate profiles and do not rise and fall too drastically as the energy rate profiles. In fact, the drops are much less pronounced and the exergy rate profiles seem to generally rise as charging progresses for all the flowrates considered in this study. The pronounced secondary peak rise for erythritol with the lowest flowrate can be used to account for the sharp rise in the exergy rate from around 60 mins to 100 mins. The exergy rate performance for the eutectic solder and erythritol is also comparable between 0 to 50 mins with the lowest flowrate as with case of the energy rate profiles (Figure 5.4(a)). The highest exergy rate values for the lowest flowrate are obtained with erythritol followed by adipic acid and lastly by the solder possibly as consequence of the larger thermal gradients in the erythritol based storage system.

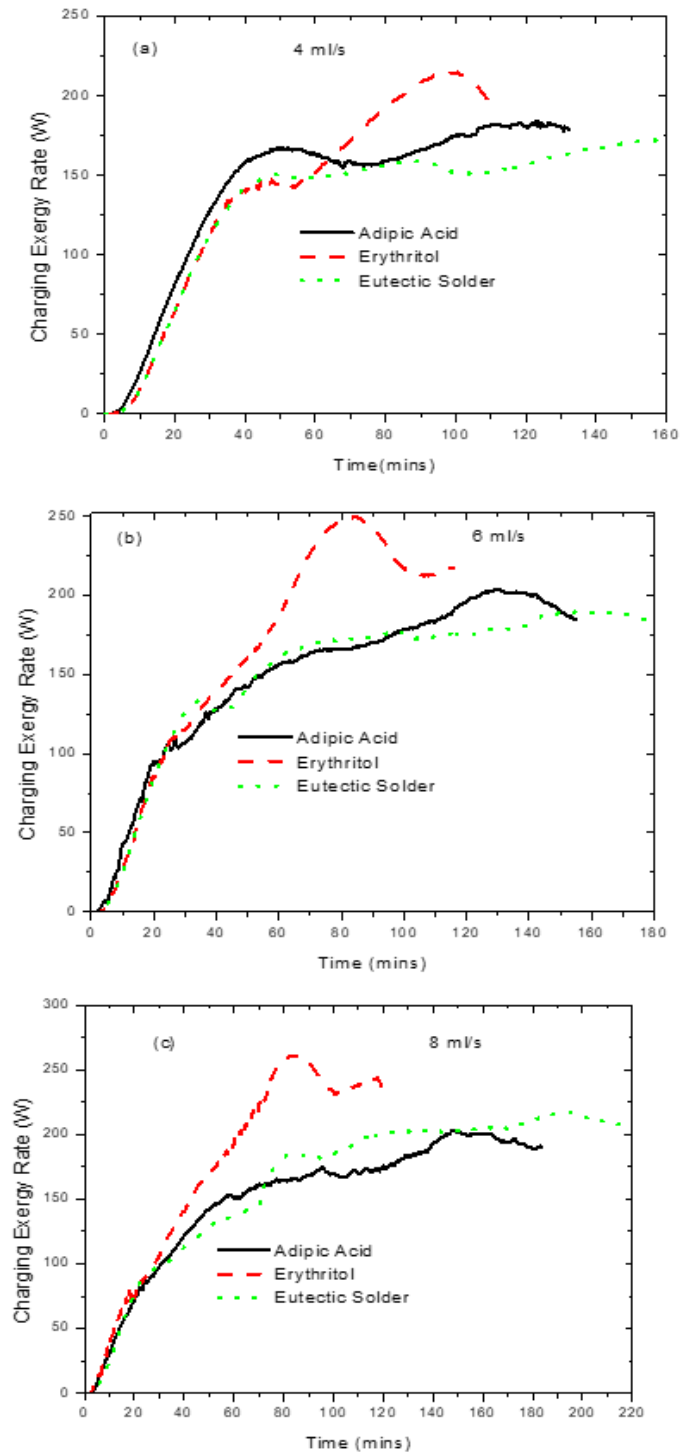


Figure 5.5: Charging exergy rate profiles at (a) low, (b) medium and (c) high flow rates for the three storage systems.

Increasing the flowrate from low to medium flowrate charging, seems to increase the quality of the energy stored as the peak exergy rate values become higher. For instance, the peak exergy rate value for is close to 250 W for erythritol as compared to around 225 W for the lower flowrate. The exergy rate performance for the medium is comparable during the first 30 mins for the three PCMs, however, erythritol shows higher values after 30 mins possibly due to the more pronounced secondary peak effect. The performance of adipic acid and the eutectic solder is comparable up to around 90 mins. After this, adipic acid shows higher values to the end of charging as result of the secondary peak values induced by the greater thermal gradient during this period.

A further increase in the flowrate from medium to high flowrate charging causes a faster rate of rise of the exergy rate profiles. As with the other cases, erythritol shows the highest values and the peak exergy rate value is greater than 250 W. Interestingly, the performance of the solder is generally comparable to that of adipic acid suggesting similar thermal gradients and ambient temperature conditions. However, the peak exergy rate value for the solder becomes greater than for adipic acid at the end of the charging process for the solder. Comparable exergy rate values are seen for adipic acid for medium and high flowrate charging, whereas for the solder the values are slightly higher.

5.5 Conclusion

The thermal performance of three packed bed latent heat medium temperature storage systems was evaluated during charging cycles. The three phase change materials (PCMs) used in the storage systems were adipic acid, erythritol and an eutectic solder (Sn63Pb37). The PCMs were encapsulated in aluminium spherical capsules and Sunflower Oil was used as the heat transfer fluid (HTF). The performance of these storage systems was evaluated in terms of the temperature profiles during charging and the charging energy and exergy rates. Erythritol charged up for the shortest duration followed by adipic acid and lastly by the eutectic solder as a result of the combined effect of a lower thermal mass induced by a lower melting temperature and increased convective heat transfer. Erythritol showed superior performance in terms of the charging energy and exergy rates since it showed higher values due to its lower melting point which induced more convective heat transfer and a greater degree of thermal stratification. The worst thermal performance in terms of the charging energy rates was seen with the solder, however, in some instances its performance was

comparable to adipic acid. The best overall performance was seen with erythritol followed by adipic acid which had a comparable performance to the eutectic solder.

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Chapter 6: Conclusions and recommendations of future work

6.1 Conclusions

The performance comparison of packed bed latent heat storage systems for medium temperature applications was presented in this dissertation. Three research papers were presented on medium temperature packed bed LHTES systems. The first paper evaluated a packed bed latent storage system of eutectic solder capsules for its suitability in medium temperature applications. The other two papers compared the performances of packed bed LHTES systems of eutectic solder, erythritol and adipic acid. The major conclusions of the study are as follows;

1. In a separate evaluation of the eutectic solder TES system, the charging energy and exergy rates were seen to increase with the charging flowrate at the expense of a greater charging duration. The best charging flowrate under the experimental conditions was 6 ml/s, since it ensured a reasonable duration of charging, reasonable thermal stratification and reasonably high energy and exergy charging rates. The effect of set heater temperature on the charging energy and exergy rates was insignificant as compared to the effect of the flowrate and the best charging temperature of 280 °C was suggested by the results under the experimental test conditions. For the discharging cycles, an increase in the flowrate resulted in faster heat transfer with higher peak energy and exergy rates. The stored energy and exergy was, however, utilized for a shorter duration as compared to the lowest flowrate. Discharging results also suggested the best discharging flowrate as 6 ml/s for reasonable energy and exergy rates, and for a reasonably longer duration of discharging. Energy storage efficiencies decreased with an increase in the flowrate and the highest flowrate showed the lowest values due to the longer charging duration and the shorter discharging duration.
2. In the experimental charging comparisons, the eutectic solder TES system stored the greatest quantities of energy, exergy, useful energy and useful exergy at all the flowrates during charging. This may be attributed to the large thermal energy and phase change enthalpy storage capacities as well as the high phase transition temperature of the eutectic solder. However, the eutectic solder TES system showed

lower charging performances in terms of all the performance indicators due to its longer charging time. At the lowest flowrate, the adipic acid TES system showed the highest charging rates in terms of energy, exergy, useful energy and useful exergy. Erythritol on the other hand, had the greatest charging rates in terms of energy and exergy at the medium flowrate and the high flowrate. The erythritol TES tank also exhibited the greatest thermal stratification during charging. Charging times increased while thermal stratification reduced progressively for all the TES systems with increase in the HTF flowrate during charging.

3. During the discharging cycle comparisons, the eutectic solder TES system discharged the greatest quantity of thermal energy at all the flowrates as well as the greatest thermal exergy at the low flowrate and at the high flowrate, while erythritol discharged the greater thermal exergy at the medium flowrate. The high thermal energy content of the eutectic solder TES system, after charging, can be attributed to its performance in this respect. The largest thermal stratification during discharging was observed in the adipic acid TES tank at all three flowrates. The lowest thermal stratification was observed in the eutectic solder TES tank. Thermal stratification in all the TES tanks however, increased with an increase in flowrate. Although phase transition was not observed at all the axial sections of the erythritol TES tank and at the flowrates during discharging, the TES system still discharged the highest quantities of useful energy and exergy. This is attributable to the high specific heat capacity of erythritol in its liquid state.
4. Although erythritol exhibited supercooling at all the flowrates considered in this study, the erythritol TES system possessed the greatest overall efficiency of the three systems, in terms of total energy, total exergy, useful energy and useful exergy. Generally, the overall efficiencies of all the TES systems reduced with increasing flowrate. The low efficiency of the eutectic solder TES system is thought to be due to the longer charging duration because of the higher melting temperature. This longer charging duration induces greater thermal losses to the environment from the tank due to the higher thermal conductivity of the solder as well as the poor thermal stratification in the TES tank. The adipic acid TES system showed a promising edge over the eutectic solder TES at the high flowrate in terms of the overall useful energy and exergy efficiencies. The eutectic solder TES however, showed better potential in

terms of the useful energy and exergy efficiencies, than the adipic acid TES system at the lowest flowrate.

6.2 Recommendations for possible future work

In the future, a similar study utilizing the PCMs used in this study in a larger TES tank will be pursued for possible better TES efficiencies. The performance of cascaded latent heat storage systems using two or more PCMs with different melting points in the same storage tank to find out if the storage efficiency will increase needs to be investigated. A numerical model for the parametric studies on performance characterisation and optimisation needs to be developed. The model will be validated with experimental results presented in this work. Future work will also look at using the packed bed LHTES systems with a solar cooker to find out if off-sunshine cooking is possible. Other locally available cheap PCMs for medium temperature applications need to be investigated both experimentally and numerically. The possibility of combining packed beds of sensible and latent storage materials needs to be investigated experimentally and numerically to reduce the cost of TES.