

**EXPERIMENTAL AND NUMERICAL INVESTIGATION  
OF PHASE MATERIAL AS HEAT STORAGE FROM A  
CONCENTRATING SOLAR COLLECTOR**



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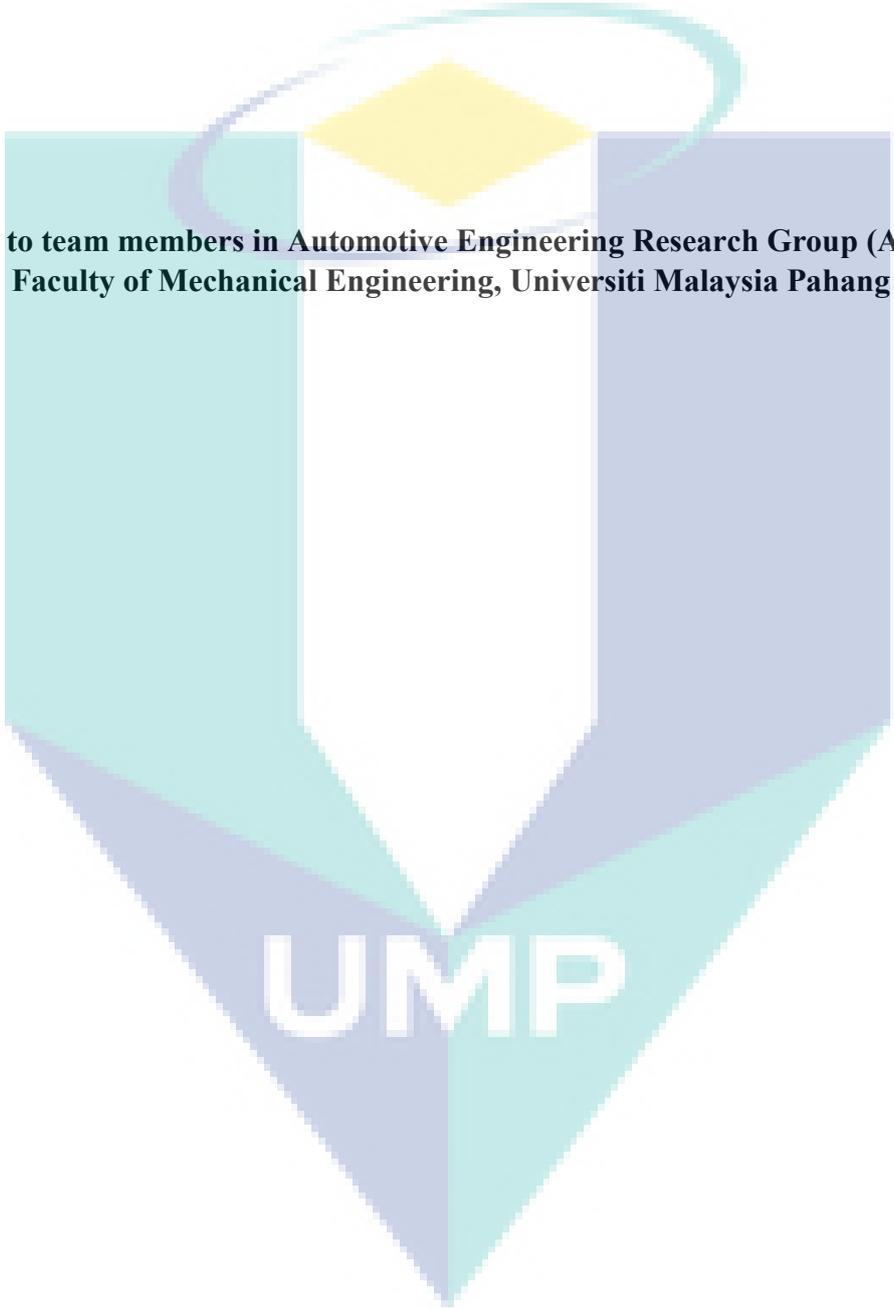
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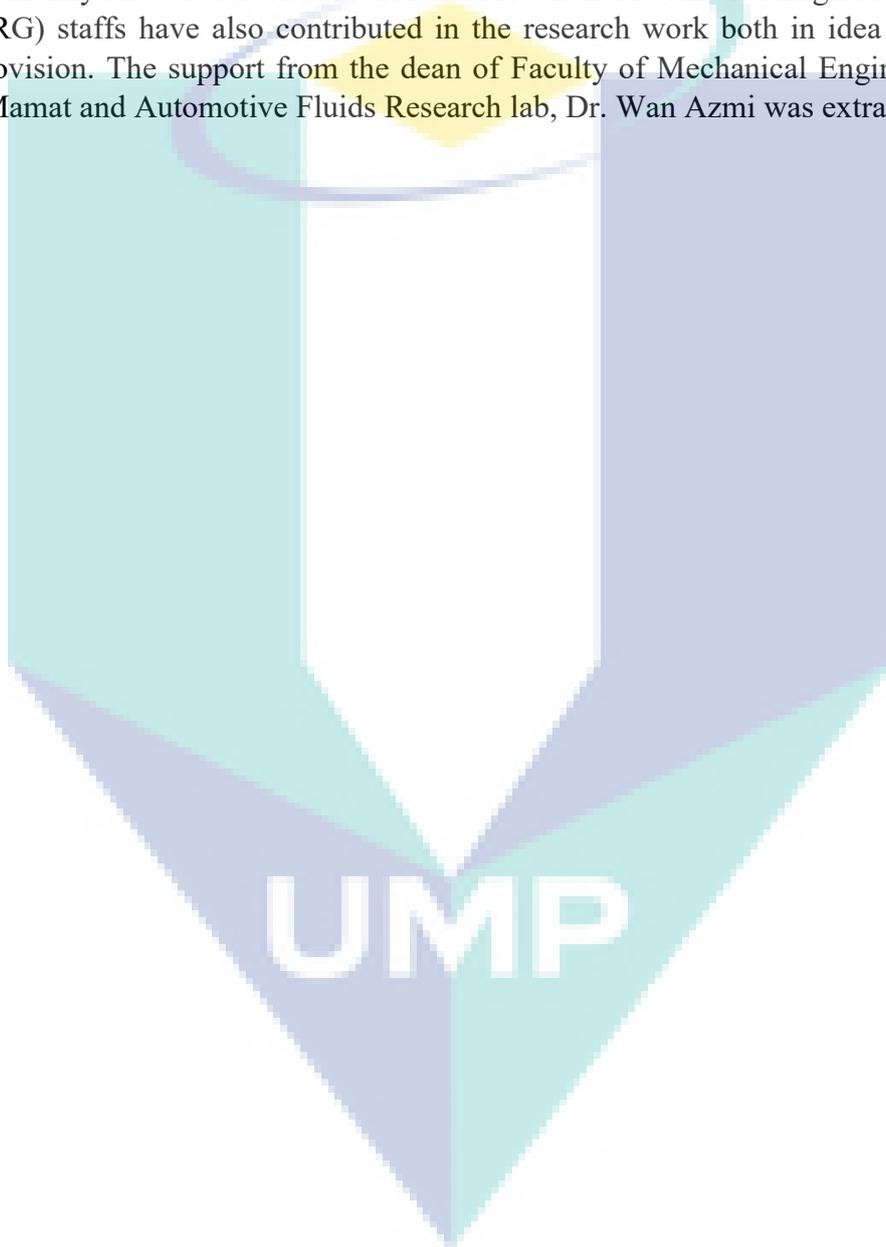
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**Dedicated to team members in Automotive Engineering Research Group (AERG) and  
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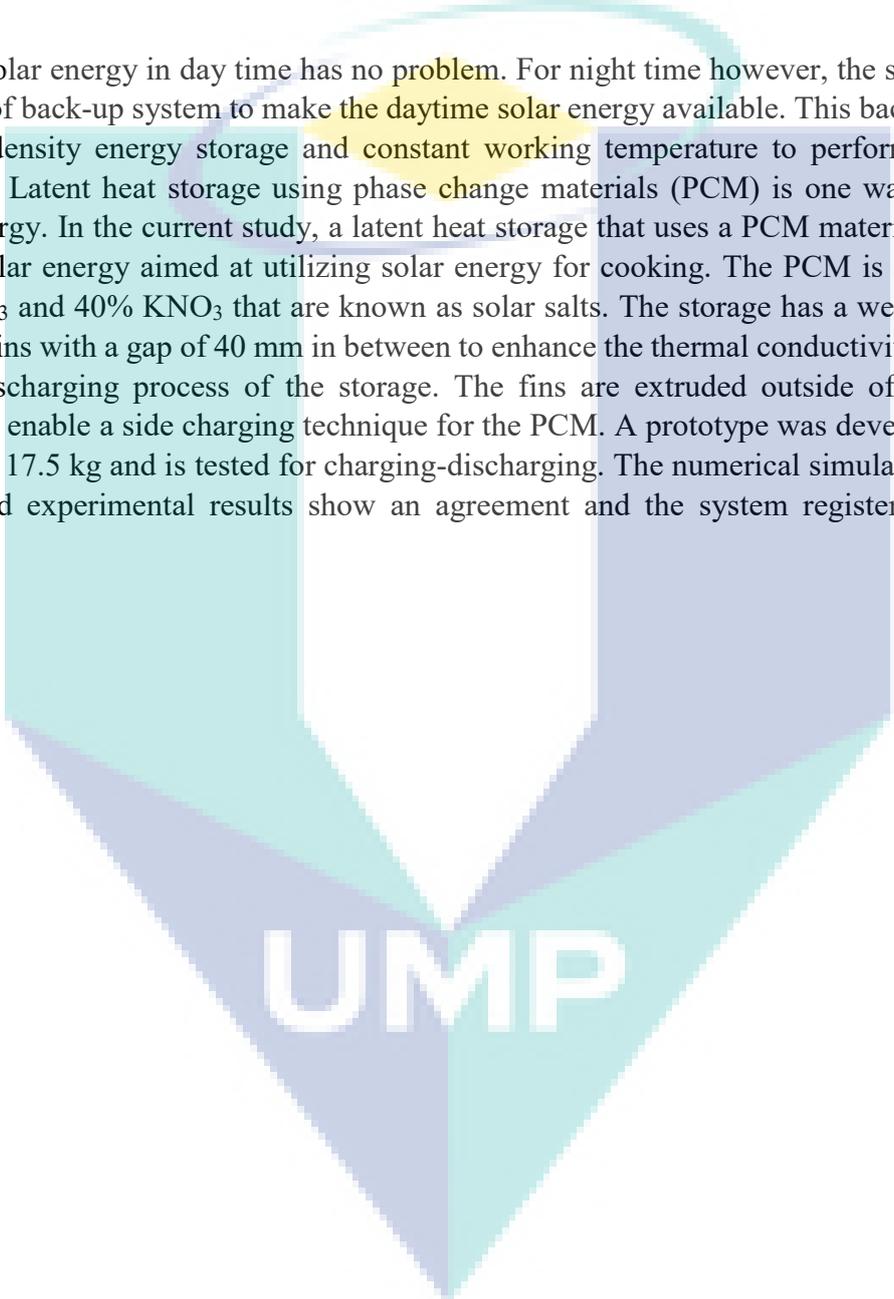


## ABSTRACT

### EXPERIMENTAL AND NUMERICAL INVESTIGATION OF PHASE MATERIAL AS HEAT STORAGE FROM A CONCENTRATING SOLAR COLLECTOR

(Keywords: Thermal storage; Latent heat; PCM; Side charging; Solar cooker)

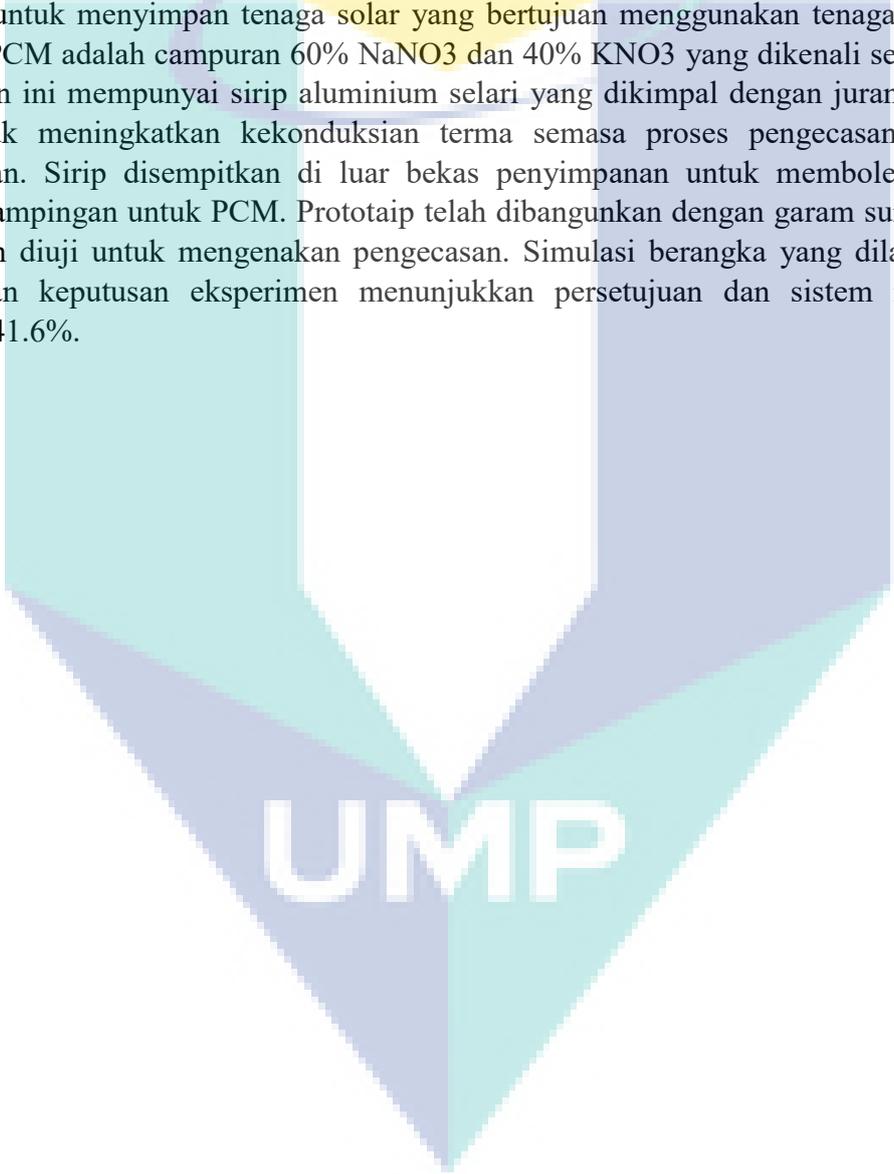
Using the solar energy in day time has no problem. For night time however, the system needs some kind of back-up system to make the daytime solar energy available. This back-up should have high-density energy storage and constant working temperature to perform a specific application. Latent heat storage using phase change materials (PCM) is one way of storing thermal energy. In the current study, a latent heat storage that uses a PCM material is used to store the solar energy aimed at utilizing solar energy for cooking. The PCM is a mixture of 60%  $\text{NaNO}_3$  and 40%  $\text{KNO}_3$  that are known as solar salts. The storage has a welded parallel aluminum fins with a gap of 40 mm in between to enhance the thermal conductivity during the charging-discharging process of the storage. The fins are extruded outside of the storage container to enable a side charging technique for the PCM. A prototype was developed with a solar salt of 17.5 kg and is tested for charging-discharging. The numerical simulation done on ANSYS and experimental results show an agreement and the system registered a 41.6% efficiency.



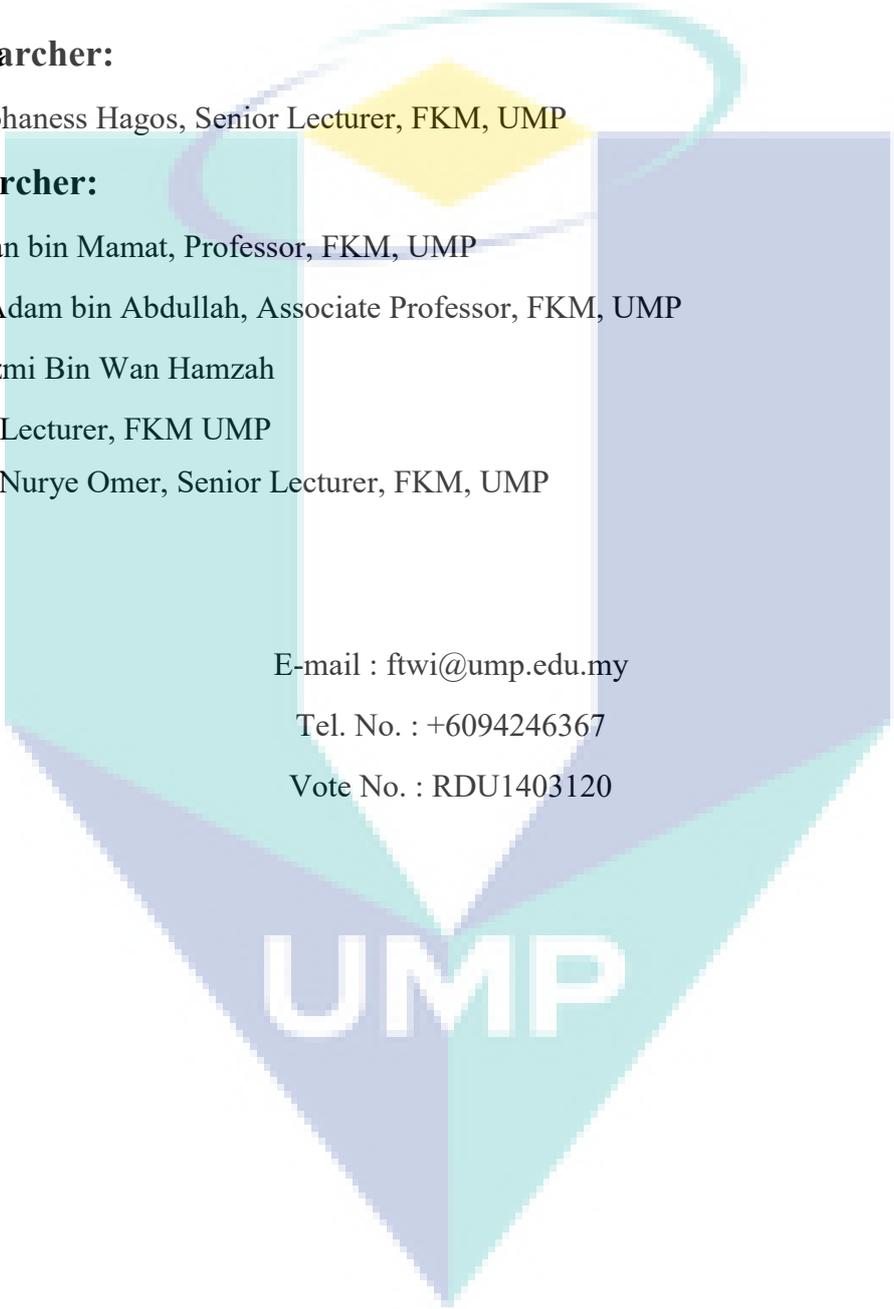
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## ABSTRAK

Menggunakan tenaga suria pada waktu siang tidak mempunyai masalah. Untuk waktu malam bagaimanapun, sistem memerlukan beberapa jenis sistem sokongan untuk menjadikan tenaga suria siang hari tersedia. Cadangan ini harus mempunyai penyimpanan tenaga berkepadatan tinggi dan suhu kerja malar untuk melaksanakan aplikasi tertentu. Penyimpanan haba laten menggunakan bahan perubahan fasa (PCM) adalah salah satu cara untuk menyimpan tenaga terma. Dalam kajian semasa, penyimpanan haba terpendam yang menggunakan bahan PCM digunakan untuk menyimpan tenaga solar yang bertujuan menggunakan tenaga solar untuk memasak. PCM adalah campuran 60%  $\text{NaNO}_3$  dan 40%  $\text{KNO}_3$  yang dikenali sebagai garam suria. Storan ini mempunyai sirip aluminium selari yang dikimpal dengan jurang 40 mm di antara untuk meningkatkan kekonduksian terma semasa proses pengecasan-pengecasan penyimpanan. Sirip disempitkan di luar bekas penyimpanan untuk membolehkan teknik pengisian sampingan untuk PCM. Prototaip telah dibangunkan dengan garam suria sebanyak 17.5 kg dan diuji untuk mengenakan pengecasan. Simulasi berangka yang dilakukan pada ANSYS dan keputusan eksperimen menunjukkan persetujuan dan sistem mencatatkan kecekapan 41.6%.



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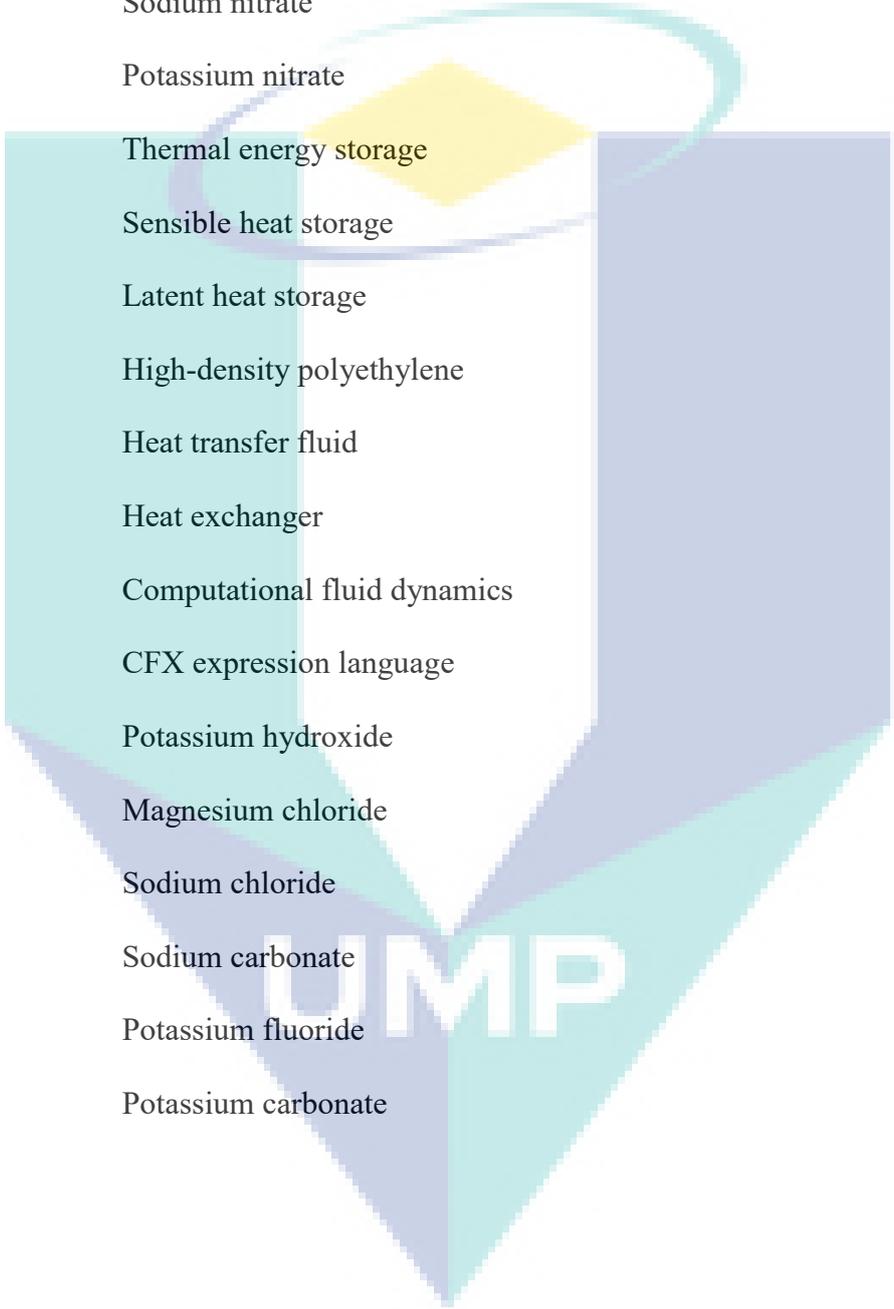
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## LIST OF ABBREVIATIONS



PCM	Phase change material
NaNO <sub>3</sub>	Sodium nitrate
KNO <sub>3</sub>	Potassium nitrate
TES	Thermal energy storage
SHS	Sensible heat storage
LHS	Latent heat storage
HDPE	High-density polyethylene
HTF	Heat transfer fluid
HE	Heat exchanger
CFD	Computational fluid dynamics
CEL	CFX expression language
KOH	Potassium hydroxide
MgCl <sub>2</sub>	Magnesium chloride
NaCl	Sodium chloride
Na <sub>2</sub> CO <sub>3</sub>	Sodium carbonate
KF	Potassium fluoride
K <sub>2</sub> CO <sub>3</sub>	Potassium carbonate

# CHAPTER 1

## INTRODUCTION

### 1.1 BACKGROUND OF STUDY

Energy can be defined as the capability of a system to do work. It can be in the form of electrical energy, chemical energy, potential energy, kinetic energy, latent heat energy and the list goes on. Energy storage is a device or object that store and keep the energy for later use. Thermal energy storage (TES) can be divided into three types, which are the sensible heat, latent heat and the thermo-chemical energy storage. All of these above also functioned as the medium to absorb thermal energy. In this case is heat from the sun and then keep the energy for later use.

Sensible heat is meaning that when heat is applied to the material, and the increase in temperature can be felt. Meanwhile, it can be sense that material becomes cool if the heat source was taken away (Hesaraki, A. et al., 2012). Using the same concept in the sensible heat storage (SHS), thermal energy is stored by applying heat to the material. During the charging and discharging of the SHS, it uses the change in temperature according to its heat capacity of the storage material. The amount of the thermal energy stored depends on the specific heat capacity, difference of temperatures and amount of the material (Milisic, E., 2013).

Latent heat storage is whenever a material changes its state from solid to liquid or liquid to gas, it will absorb heat energy at nearly constant temperature until it completely changed its state. On the other hand, if the material change from gas back to liquid or liquid back to solid, thermal energy can be released at about the same temperature. Normally this phenomenon is called as the phase changing process. The heat energy required for the material to completely change its state called latent heat. Compared to the sensible heat storage, latent heat storage can store a few times more heat to volume ratio (Sharma, A. et al., 2009). One of the examples of latent heat storage material is phase change material (PCM).

Thermo-chemical heat is when the material is forming or breaking its molecular bond, it will release or absorb energy during its chemical reaction. The chemical reaction is completely reversible and the amount of heat depends on the difference in enthalpy or called as heat of reaction (Milisic, E., 2013). Heat of reaction can be absorbed during endothermic reaction and the other way round for exothermic reaction and that is why it is used as heat storage system.

Heat exchanger is needed to transfer heat from the solar collector to store in the PCM. Heat exchanger is a device that allows two fluids at different temperatures to undergo heat exchanging process without mixing each other (Cengel, Y.A. and Ghajar, A.J., 2011). There are walls in the heat exchanger that separating the heat transfer fluids. Usually during the heat transfer in the heat exchanger involves convection in the fluid followed by conduction through the wall, lastly the heat transferred to another fluid by convection. There are a few types of heat exchanger which are the double-pipe, cross-flow, shell-and-tube, plate-and-frame, and regenerative heat exchanger. Heat exchanger often used as the radiator or condenser to cool fluid and as a boiler to heat or vaporize fluid.

## **1.2 PROBLEM STATEMENT**

Phase change materials were sometimes used in latent heat storage. When reaching certain temperature, by changing its form from liquid to solid or vice versa, these latent heat storage materials can dissipate or absorb large amount of energy without significant change in temperature. However, energy storage using PCM was still in development and the heat transfer using different parameters require further study. In the present paper is to design and simulate the thermal energy storage for solar cooking application using phase change material (PCM).

## **1.3 SIGNIFICANCE OF THE STUDY**

According to the second laws of thermodynamics, the heat transfer in the direction of decreasing quality (Cengel, Y.A. and Ghajar, A.J., 2011). Energy is always transferred from high energy content to low energy content region. Using this concept, thermal energy storage

(TES) was invented. TES absorb energy from higher energy content area and release energy to lower energy content area. For example when a stone has low energy content, it stores energy from the fire as the heat source. After the stone gained enough energy, it can transfer the energy absorbed and heat up other desired lower energy content area. Besides than using TES for heating purposes, the heat in the storage can be transferred away and leave cold in the TES. The cold TES can be used as air condition.

## **1.4 OBJECTIVE**

### **1.4.1 General Objective**

This project is to design and model a thermal energy storage tank using phase change material (PCMs) as a medium to store energy obtained from the solar thermal energy for cooking purposes.

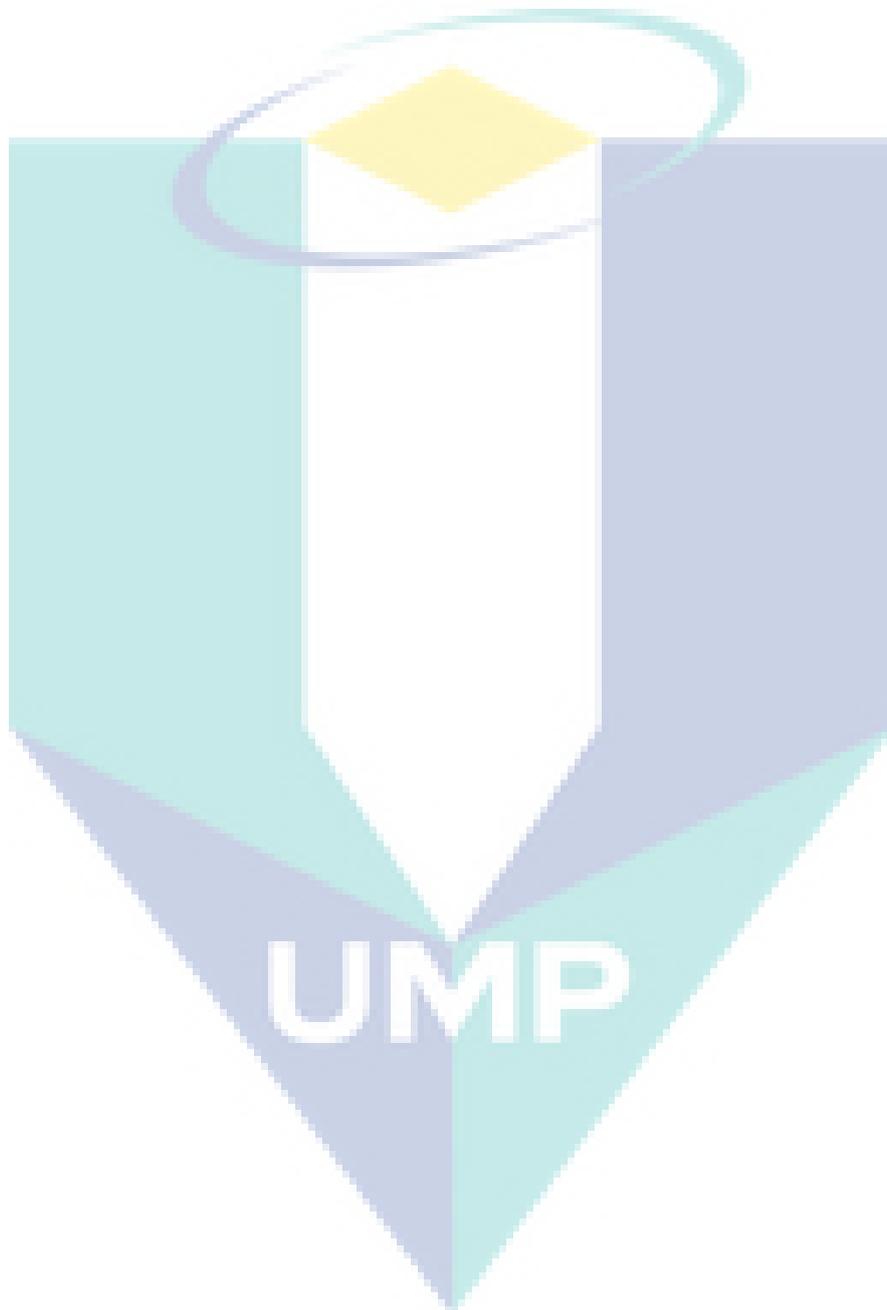
### **1.4.2 Specific Objectives**

- i. Design the thermal energy storage for solar cooking application with utilization of phase change material (PCM).
- ii. Find the most suitable PCM in terms of physical, thermal, chemical and economical for solar cooking stove.
- iii. Do simulation on the thermal energy storage for solar cooking stove or thermal energy storage using PCM for the evaluation of loading of heat.

## **1.5 SCOPE OF STUDY**

The path of study of this project involves the modeling and design of the thermal energy storage and choosing the right PCM. The design of the model was using uniform fin spacing. Furthermore, the model is being simulated using Ansys to find the most suitable type of PCM

energy storage. The heat transfer of the thermal energy storage was studied using temperature distribution. The fluid velocity was assumed to have Reynolds number of less than 2300 or called as laminar state. The molten PCM was assumed to be Newtonian fluid However, this project mostly does not deal with the processes and manufacturing.



## CHAPTER 2

### ISI JOURNAL

**Title:**

Corrosion effect of phase change materials in solar thermal energy storage application

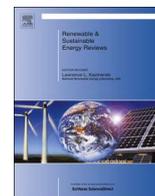
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## Corrosion effect of phase change materials in solar thermal energy storage application



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### ABSTRACT

The thermal energy storage (TES) system using phase change materials (PCMs) has been studied since past three decades. PCMs are widely used in heat storage applications due to their high storage density, as well as the wide range of melting and solidifying temperatures. Nevertheless, the main disadvantage of PCMs, especially salt hydrates, is their corrosive behavior with container materials. PCMs are normally encapsulated in containers, hence the compatibility of the container materials with PCM plays an important role. As such, this paper summarizes the investigations made on the corrosion behavior of PCM in various applications, besides suggesting ways to reduce (or rectify) the effect for long term successful energy storage. Moreover, PCM-storage material interaction in the latent heat TES system is important as the issue of corrosion affects the life of the container, as well as the performance of TES. The compatibility of the most commonly used PCMs with several major container materials was reviewed and it was revealed that stainless steel has emerged as the most compatible storage container material among others. On the other hand, aluminum was found to be corrosive when it is used with salt hydrates. Nonetheless, some contradictory articles are reported that several salt hydrates demonstrated compatibility with container materials. Corrosion causes thinning of cross sectional area of materials, making it brittle thus leading to an easy collapse. This situation is even more critical mainly in large scale concentrating solar thermal power plants. Hence, with the fact that there are currently large scale power plants employing TES under operation and under construction; issues pertaining to PCM-storage material compatibility should be properly and accurately addressed. Therefore, more research work is recommended in the area of finding new eutectics and less corrosive container material(s).

### 1. Introduction

Energy is becoming more and more important at this present age for survival of mankind, making energy a basic need [1–3]. Since the time wheel rolled from the Stone Age, humans needed more energy to overcome their survival problems, such as cooking, heating, lighting, hunting, transportation, and so on. With evolution, fellow humans began using other forms of energies like wind and water [4,5]. Obviously, the primitive humans either directly or indirectly, used only renewable energy sources. After the industrial revolution (1700 AD), people began making use of fossil fuels (coal, natural gas, and petroleum) to satisfy their energy needs in domestic, agriculture, and transportation fields. In fact, the two broad categories of available energy resources are non-renewable energy sources (fossil fuels) and renewable energy sources (nuclear fission and fusion, hydro power, wind power, solar energy, biogas, tidal, geothermal energy, and ocean

thermal energy) [2,5–7]. Non-renewable energy sources approximately satisfy 81% of energy requirement of the world, while renewable energy sources contribute only 19% [8–10]. Thus, it is obvious that non-renewable energy sources are further depleting at an alarming rate and such usages badly pollute the atmosphere by emitting CO<sub>2</sub> and NO<sub>2</sub>, leading to greenhouse effect. So, the world is in dire need of finding alternate sources of energy for further use and to slow down the depletion rate of fossil fuels.

As portrayed in Table 1, there is vast potential for utilization of renewable energy as the current total utilization at 19% can further increase. This notion can definitely decrease the percentage of non-renewable energy utilization, and thereby, diminishing their associated challenges. Solar energy is a type of vast, clean, and renewable energy source. Besides, estimated to be  $1.8 \times 10^{11}$  MW, it is many thousand times larger compared to the total energy consumption on earth from all other energy sources. This estimation confirms that solar energy

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**Table 1**  
Global energy potential and their current utilization of some renewable energies [11,12].

Renewable Energy sources	Global Potential TWy/Year	Global utilization TWy/Year	Challenges
Solar energy	23,000	0.0385	Intermittent, high cost of production
Wind	25–70	0.0624	Intermittent, high cost of production
Ocean Thermal Energy Conversion (OTEC) and Tides	3–11	$1.248 \times 10^{-4}$	High initial cost, a few locations for installation
Biomass	2–6	1.9744	High cost of production, inefficient, requires more land
Hydro	3–4	0.608	High initial cost, reliability of supply
Geothermal	0.3–2	0.0176	High initial cost, limited to some locations, lack of skilled manpower

could supply all the energy needs of the world continuously [1]. Its cleanliness, size, and free-of-cost attributes have always sparked interest among researchers worldwide. However, the main problem related to this energy source is its dependence on availability of time (daily and seasonally). Solar energy is available only during the day, and this unavailability of the energy source during the night time increases the gap between the wasted heat availability and the utilization period. Therefore, it is deemed necessary to identify an efficient way to store the thermal energy for later usage.

In addition, developing energy storage methods has equal importance to finding new energy source. The challenge, nonetheless, only starts when storing energy in its suitable form and converting it to the required form. Storing energy reduces the wastage of plenty of available energy that can be used later when it is needed. Energy storage in the field of power generation increases efficiency and leads to energy conservation [13–17]. Moreover, energy storage (ES) has its own impact on modern technology when it meets energy demand. Thus, the ES systems contribute significantly in utility (charging ES system using inexpensive base load electricity), industry (heat released during various industrial processes are stored in ES), co-generation (electricity and heat are produced together and stored), wind and run-of-river hydro (stored as electricity when available throughout the year), and solar energy (storing solar energy during sunny days at all time) applications [18,19].

In fact, several methods of ES systems have been continuously utilized in different areas, such as mechanical energy storage, chemical energy storage, biological storage, magnetic storage, and thermal energy storage (TES). Mechanical energy storage systems are comprised of three types: the hydro storage, the compressed air storage, and the flywheel energy storage systems. In the hydro storage, water is pumped from the river and stored in the reservoir at a higher level, whereby the water in the reservoir can be used to generate electricity if there is need for energy. Meanwhile, in the compressed air ES system, air is compressed using conventional gas turbine and stored in man-made or natural caverns, used oil or gas wells, or porous rock formations [20]. When energy need arises, electricity is generated using the similar method employed for hydro storage. On the other hand, the flywheel stores rotational kinetic energy and used for transportation, as well as electricity production [21]. Besides, reversible chemical reaction can be used to store energy. The absorption and release of heat during chemical reaction confirms its application in the field of TES. Additionally, energy stored in batteries is called electrochemical storage. In batteries, energy is stored in the form of chemical energy, but released in the form of electrical energy, such as lead-sulphuric acid battery [22]. Biological storage is another form of storing energy in chemical form using biological processes [23,24]. At absolute zero temperature, certain metals have no resistance against electricity, which helps to store direct current (DC) in the magnetic field, experiences energy loss during its conversion to alternating current (AC). Energy storage is also possible by using hydrogen. Hydrogen can be produced via electrolysis and stored as chemical energy. In fact, hydrogen can be used to generate electricity in fuel engines [22,25–28]. Even though many types of ES systems are available, they are limited by cost, volume of storage, low density,

and limited efficiency [22]. Furthermore, the world needs low cost, environmental-friendly, and abundant source with comfortable storage facilities. As for solar thermal energy utilization, the most common energy storage system is the TES system that collects the excess heat energy during sunshine hours and stores it in the form of thermal energy for night usage [18].

The two commonly used TES methods are sensible heat storage (SHS) and latent heat storage. ES in the sensible heat method is based on the temperature change that takes place in the material. Meanwhile, in the liquid based systems, water is used as the heat storage material, whereas rock bed is employed in air based system [18,29]. Besides, sensible heat is cheaper compared to latent heat storage (LHS); but its energy density is lower, thus requires bigger storage volume and its usage is limited by the gliding discharge temperature [18]. Unlike the SHS, the LHS, which is also called PCM, changes its phase at a particular temperature (melting temperature), in which further heating allows the heat energy to be stored in the phase change. However, the heat dissipates when it is cooled again. Latent heat storage system has higher storage density compared to sensible heat storage system of about five to ten times. The volume of storage of LHS is two times lower than SHS [30]. LHS has materials with wide range of melting temperature so, can be used for all type of applications. Moreover, the problems faced during latent heat storage methods are low thermal conductivity, density change, stability of properties during long term cycling, phase segregation, sub cooling [18], and corrosion [31]. Nonetheless, all these problems can be solved using appropriate methods. Various performance factors of different TES is given in Table 2.

The main challenge faced in the TES by the LTS method is the incompatibility of phase changing materials with the storage containers. Moreover, only a handful studies have looked into the corrosion effect of phase change material on the storage containers. This review paper mainly concentrates in this area. Besides, no complete data is available in relation to the list of PCM and compatible materials that can be used for storage containers. This review paper presents the work performed on that task as well. As such, this review paper consists of four sections. Section 1 discusses the different kinds of energy sources and the methods of storing them. This section gives information about the importance of solar energy and the methods of storing it. The problems faced during the storage of solar energy using PCM are listed in this section as well. Next, Section 2 details the types of PCM, their classification, and their application areas. Meanwhile, Section 3 discusses the corrosion effect of PCM on storage container and heat transfer fins. Finally, the concluding remark is provided in Section 4.

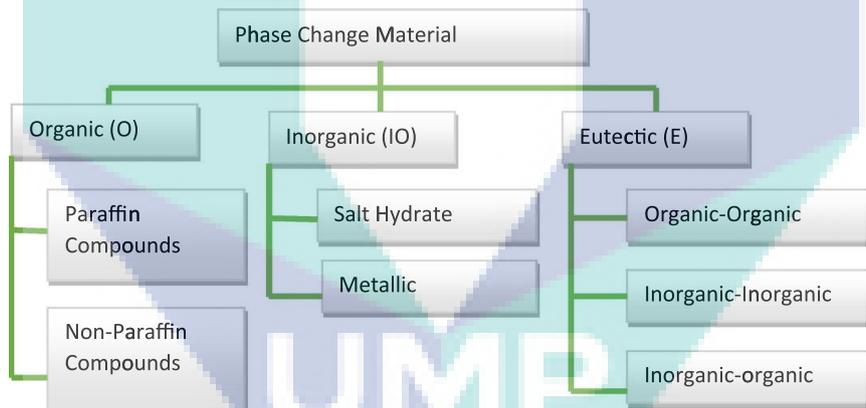
## 2. Different phase change materials (PCM) used in thermal energy storage (TES)

### 2.1. Classification of PCM

Phase change materials are substances that undergo phase change during the absorption/release of energy from/to the surroundings. The temperature of the material remains constant until the phase changing process is complete, thus a large amount of energy is stored.

**Table 2**  
Comparison of different types of TES based on various performance factors [30,32].

Performance Parameter	Type of Thermal Energy Storage		
	Sensible TES	Latent TES	Chemical TES (Sorption and Thermochemical)
Temperature range	Up to: 110 °C (water tanks)  50 °C (aquifers and ground storage) 400 °C (concrete)	20–40 °C (paraffin) 30–80 °C (salt hydrates)	20–200 °C
Storage density	Low (with high temperature interval): 0.2 GJ/m <sup>3</sup> (for typical water tanks)	Moderate (with low temperature interval): 0.3–0.5 GJ/m <sup>3</sup>	Normally high: 0.5–3 GJ/m <sup>3</sup>
Lifetime	Long	Often limited due to storage material cycling	Depends on reactant degradation and side reactions
Technology status	Available commercially	Available commercially for some temperatures and materials	Generally not available, but undergoing research and pilot project tests
Advantages	Low cost Reliable  Simple application with available materials	Medium storage density Small volumes  Short distance transport possibility	High storage density Low heat losses (storage at ambient temperatures) Long storage period Long distance transport possibility Highly compact energy storage
Disadvantages	Significant heat loss over time (depending on level of insulation) Large volume needed	Low heat conductivity  corrosiveness of materials Significant heat losses (depending on level of insulation)	High capital costs  Technically complex



**Fig. 1.** Classification of PCMs [22,23].

Furthermore, during the solidification process, the stored energy is released. This process of absorbing and releasing of heat energy during melting and solidification is called latent heat of fusion [33,34]. Latent heat storage can be made possible through solid-solid [35], solid-liquid, liquid-solid, solid-gas, and liquid-gas phase changing transitions [22,36]. Among these transitions, the solid-liquid phase change is commonly used because it occupies smaller volumes during the transition and besides, it increases energy density. However, the use of other types of transitions is limited due to their low heat transformation and large storage volume requirement [37,38]. PCMs are broadly classified as organic, inorganic, and eutectic. Fig. 1 shows the classification of PCMs.

Based on the Handbook of Phase Change Materials written by Hale et al., [36], an ideal PCM should provide high heat fusion, good reversible from solid to liquid transition, high thermal conductivity, high specific heat capacity and density, capacity to withstand for many repeated cycles, acceptable freezing behavior, low volume change when phase transition takes place, and low vapor pressure [36]. At present

times, many other factors should also be considered in selecting PCM. Table 3 lists the necessary characteristics for a PCM to be selected as the ideal candidate for latent heat storage. Unfortunately, no ideal candidate is available for easy application.

Considering organic PCMs, paraffin compounds possess excellent merit quality to be a candidate for low temperature applications. Organic PCMs are recyclable, melt congruently, exhibit little or no super cooling, i.e. they do not need to be cooled below their freezing point to initiate crystallization [39], non-corrosive except for some PCMs, as stated by Abhat [40], and chemically stable. Furthermore, organic PCMs have low thermal conductivity [41] and low volumetric energy storage [42]. The low conductivity problem can be reduced by adding nucleating agents [41]; however, almost all organic PCMs are flammable. Therefore, care should be taken when handling them during high temperature applications because at high temperature, these types of PCMs undergo decomposition and turn toxic [43].

On the other hand, inorganic PCMs are salt hydrates. They too possess good merit qualities, such as high thermal conductivity, high

**Table 4**  
Most common PCM materials and their application areas against their limitation.

List of PCM	Classification	Melting Temp. (°C)	Heat of Fusion (Kj/Kg)	Thermal Conductivity (W/mK)	Density Solid/liquid (Kg/m <sup>3</sup> )	Application/purpose	Limitation/remark	Ref.
CaCl <sub>2</sub> · 6H <sub>2</sub> O	IO	29	-	1.09	0.71/1.50	Roof integrated solar heating	Mathematical model in two-dimensional	[52]
75.6% paraffin and 53.1% cetyl alcohol	E	53–55	-	-	-	All applications where macro encapsulation of PCM is needed	Method of preparing PCM capsule	[53]
Commercial grade Erythritol (C <sub>4</sub> H <sub>10</sub> O <sub>4</sub> )	O	118	339	2.64/1.17	1.48/1.30	Solar cookers based on an ETSC with a PCM storage unit	- The PCM did not melt in (winter) - Expensive system - Density for solid at 20 °C, while liquid at 140 °C	[47]
Sodium sulphate + Diatomite	IO	880	87.09	-	-	High temperature thermal storage	Failures occur due to the composite materials at temperatures above 1000 °C.	[54]
Technical grade of octadecaneparaffin from Roper Thermals (Lot #C0036824)	O	-	240.7	-	-	Energy storage in building:	Leakage of the bulk PCM	[55]
Extrusion grade poly-ethylene	IO	-	293	-	-	-Waste energy management in the industry	Waste energy management is the next milestone to stop the depletion of fossil fuel	[56]
KNO <sub>3</sub>		330	266	-	-			
KOH		380	150	-	-			
K <sub>2</sub> CO <sub>3</sub> /Na <sub>2</sub> CO <sub>3</sub> /Li <sub>2</sub> CO <sub>3</sub> (35/33/32)		397	276	-	-			
LiOH/KOH (40/60)		341	341	-	-			
Raw vermiculite (VM-Raw) Paraffin	O	27.5	201.5	-	-	Incorporation of the composite PCM instead of sand leads to lightweight	Vermiculite was calcined at 800 °C	[57]

(continued on next page)

volumetric energy storage, and less expensive compared to organic PCMs [39]. Super cooling and incongruent melting have been noted, but these can be reduced by using nucleating agents [39,42]. In addition, thickening agent is believed to reduce the phase segregation problem [44]. A few salts, nonetheless, have irreversibility problem due to reduction of water content in the material [45]. These problems limit its applications up to some extent [13]. However, the major problem associated with salt hydrates is corrosiveness. The advantages and disadvantages of different categories of PCMs are analyzed before selecting a suitable candidate for specific applications. The advantages and disadvantages of PCMs are detailed in [45] to select the ideal choice.

### 2.2. Application of PCM

Within these recent years, there has been an increasing amount of PCM usage as TES, conditioning of buildings such as space cooling, cooling heat engines, storing food in cool place (refrigerator), air-condition in transport [46], transporting biological samples from one space vehicle to another, human body cooling by clothing, waste energy conversion to reusable energy [46], thermal control system, thermal capacitors [36], solar cooking [47], concentrating solar power (CSP) [14,31], and information storage (phase change memory) [35,48]. On the other hand, more recent studies have confirmed that the usage of PCM has very high potential in almost all fields where heat energy is required during off peak hours. On top of that, researchers are mostly interested in testing thermos-physical properties of PCM [41,49] and developing new Eutectic PCM by mixing two or more organic or inorganic compounds for application in many fields. This review paper lists the main PCMs used in recent experimental research and development works in different fields, as shown in Table 4. Furthermore, literature reviews indicate that very few research works have investigated the occurrence of corrosion in conjunction to PCM. While salt hydrates (widely believed to be corrosive in nature) are used as PCM, no corrosion-related data is available in the literature probably because these salts were utilized in the absence of water [50]. Even so, the corrosion data availability is indeed necessary for usage of PCM as TES. The following chapter summarizes the research works of the field. The compatible pairs are listed for the sake of future users in the field of latent energy storage.

### 2.3. Global use of PCM as TES

Inorganic PCMs are used as HTF and storage material in CSP application globally in many countries. They are proven and matured technologies where generated electricity can be easily integrated in to the grid. According to Greenpeace International Solar thermal electricity global outlook for the year 2016, a total of 6154 MW capacity solar thermal electricity operational globally with North America and Europe taking the bigger share. In the next 13 years, it is moderately projected with a generation capacity of 130,968 MW where the technology will expanded to all directions [65]. In the Gulf alone, Dubai has launched a big project of building world's biggest CSP with capacity of 1000 MW by 2020 and aims to attain 5000 MW by 2050. Table 5 shows list of countries where PCM is used in CSP applications.

### 2.4. Economic review

The success of latent heat thermal energy system mainly depends on the cost effectiveness of the storage materials used. In the low temperature applications like space cooling and heating in buildings, total life span analysis of the system will be considered in cost calculation. In high temperature application like power generation, Levelized Cost of Energy (LCOE) framework is used for cost evaluation. Estimation of the cost and operational cost of CSP with TES could be done using LCOE models published by U.S. Department of Energy

Table 4 (continued)

List of PCM	Classification	Melting Temp. (°C)	Heat of Fusion (KJ/Kg)	Thermal Conductivity (W/mK)	Density Solid/liquid (Kg/m <sup>3</sup> )	Application/purpose	Limitation/remark	Ref.
Mortars (HPCMM or SPCMM) with nearly 20% of PCM (three PCMs)	O	5, 21 and 23	-	-	-	concrete. Reduces indoor air temperature fluctuations. For building applications and Energy-saving hybrid PCM mortar in assessing energy efficiency gains for space heating Low temperature TES applications	Simulation method was employed	[58]
Sodium sulphate decahydrate (Na <sub>2</sub> SO <sub>4</sub> ·10H <sub>2</sub> O, analytical grade) and sodium phosphate dibasic dodecahydrate (Na <sub>2</sub> HPO <sub>4</sub> ·12H <sub>2</sub> O analytical grade) Paraffin wax	E	-	-	-	-	Successful discovery of new eutectic PCM	Cost of developing a new PCM is not mentioned. Thermo physical properties are not mentioned.	[59]
n-hexane Salt hydrate PYCO-PCM-1 aluminum sulphate octa decahydrate Al <sub>2</sub> (SO <sub>4</sub> ) <sub>3</sub> ·18H <sub>2</sub> O(AISH)	-	50–60	-	-	-	Innovation of a new PCM with melting temp. at 100 °C. Industrial application for waste heat management	Difficult to replicate Thermo-physical properties are not mentioned. Difficult to replicate	[38]

(continued on next page)

National Renewable Energy Laboratory. LCOE is expressed in \$ / MWh. The cost of any latent heat thermal energy storage system depends on many factors such as storage material cost, container material cost, encapsulation cost, construction cost (depends on the capacity factor and life time of LHTES), operation and maintenance cost [68,69]. The U.S. Department of Energy launched the Sun Shot Initiative to make the thermal energy storage electricity production more cost competitive. The goal of the sun shot Initiative is to attain the LCOE of solar plant to be less than 6 ¢/kWh (lowering from the starting 21 cent/kWh in 2010) and the cost of storage is \$15/kW ht with energetic efficiency 95% by 2020. This goal is achieved by Nithyanandam and Pitchumani by conducting cost analysis for two different types 2D models of latent thermal storage system, namely EPCM-TES (encapsulated phase change material thermal energy storage) and HP-TES (latent thermal storage system with embedded Heat Pipes) systems. The minimum LCOE for these two systems are calculated as 5.37 ¢/kWh which is less than the target of Sun Shot Initiative. This information opens the gate for LHTES in the TES industry [69]. Cost per unit mass of different thermal energy materials are listed in the Table 6.

Materials having high density and high specific heat capacity have high energy density, which occupies less space with high latent heat fusion. So, selecting storage materials with efficient thermo-chemical properties will reduce the capital cost. Reduced dimension of the container plays an important role in the overall cost. The compatibility of the container with storage material selection is another factor that reduce the capital and maintenance cost. Selection of storage materials with high stability for life time cyclic process of charging and discharging is a main factor for cost effective latent heat thermal storage system in long term basis. Encapsulation of PCM to increase the thermal conductivity and reduce the leakage of composite material Increase the encapsulation cost hence the capital cost [70]. This area is still under current investigation and as a result it is not yet fully commercialized.

2.5. Environmental assessment

Energy saving and thermal energy storing are the important factors involved in solving energy challenges. Latent heat thermal energy system is globally recommended for low, medium and high temperature applications because of its energy storing capacity and for its non-toxicity nature. However, environmental concern due to the stored energy should be taken in to account in the TES technology. Considering the energy consumption cost, energy conservation, applications and GHGs emission like CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>2</sub>, CFCs of other energy sources like fossil fuels, thermal energy storage is promising [46]. Even though nuclear energy is economically cheap, it is threatening the world through its radiation and the waste disposal is another major expensive problem. Therefore, leaving the world secured and green for the future generation is the main challenge faced by the human being. Latent heat thermal energy storage system always dominates the sensible heat storage system by its own way (Section 2.1). However care must be taken during the selection of the materials used to store the solar energy. The phase change materials used for this purpose must be eco-friendly and bio-degradable.

Paraffin is an extraction from the petroleum which is grey in color but treated with bleaching agents to convert it into paraffin wax. Food grade paraffin waxes are approved by US Food and Drug Administration to be used in food, cosmetic and medical industry but commercial paraffin contains chemicals like formaldehyde and vinyl chloride which are volatile and cariogenic in nature so care must be taken while using this materials in building applications. The U.S. Environmental protection agency (EPA) and the State of California have identified seven toxic materials among that benzene, toluene, naphthalene and methyl ethyl ketone are non-degradable and non-renewable so, disposing these materials are the big deal for the

**Table 5**  
Examples of PCM usage in TES in some countries [66,67].

Country/ Location/ Name	Thermal storage details			Cold tank Temp. (°C)	Hot tank Temp. (°C)	Storage capacity (h)	Electricity generation (MW/ year)	Remarks
	Technology	Storage material	Heat transfer fluid					
Tonopah USA	Power tower	Salt	Molten salt	550	1050	10	500,000	Out of twenty for solar thermal energy power plants only two use inorganic PCM as TES
Phoenix USA	Parabolic trough	Molten salt	Molten salt	293	393	6	944,000	
Adansol 1Aldeire Spain		Molten salt	Solar oil	293	393	7.5	158,000	Among forty CSP plants, 19 plants use both HTF and storage material as inorganic salts
Postmasburg South Africa	Power tower	Molten salt	Molten salt	288	566	12	480,000	It is a developing country of CSP
Chabei China	Parabolic trough	Molten salt	Molten salt	–	–	16	–	This plant is under construction
Delingha China	Power tower	Molten salt	Water/steam	–	–	3.7	628,448	Fast developing country in CSP technology
Kutch India	Parabolic trough	Molten salt	Diphyl	293	393	9	130,000	India joined with countries using CSP list in 2012
Ouarzazate, Morocco	Parabolic trough	Molten salt	Dowtherm A	293	393	3	–	Having three plants using inorganic PCM

environment. Generally Glauber's salt is considered nontoxic but its dust brings eye irritation and temporary respiratory problem like asthma so care must be taken when handling the salt. Calcium chloride hex hydrate causes severe health problem if swallowed. Eye irritation and inflammation problem occur during the possibility of eyes and skin contacts. Sodium carbonate cause mouth and throat irritation. It is non-flammable but it is non-biodegradable [71]. Until now, very few works have analyzed the carbon footprint (equivalent to CO<sub>2</sub> emission) of PCM application. After the success usage of PCM, it is important to evaluate the waste because there is always a possibility of new material formation that affect the environment so necessary treatment must be done before the disposal if necessary [72]. Future researches in these field are encouraged.

### 3. Corrosion effect of PCM in thermal energy storage (TES)

The effect of chemical or electro-chemical reactions between a material and its surroundings leads to degradation in the properties of the materials. Unfortunately, this natural happening is unavoidable [73]. The degradation causes thinning of cross sectional area of the materials, making it brittle, thus leading to easy collapse condition. Some of the major drawbacks of corrosion are summarized in Fig. 2, as generally explained elsewhere [74].

The harmful effects depicted in Fig. 2 conform that corrosion effect is, beyond doubt, an economic attack towards the world (for more details, refer [75]). This corrosion effect resembles a natural disaster that is unavoidable, but can be prevented or reduced. In fact, many fields are affected by this corrosion, for example, power stations (turbine engine failure), constructions, transportation (failure of break system), industries, economics, and TES. As such, this paper focuses on the corrosion effect of PCM in storage tank materials. Furthermore, PCMs have very high potential to function as a storage material in latent heat storage. Storage containers are designed to encapsulate the PCM during energy storage process through the phase change of material from solid to liquid. Generally, organic PCMs are not corrosive in nature, except a few, as revealed by Abhat [40]. On the other hand, inorganic compounds are highly corrosive. Thus, it is necessary to conduct the corrosion test in different temperature ranges to ensure the container materials for their compatibility with their PCM counterparts

for long-term usage. As such, many researchers have investigated the optimization of storage material usage in adverse PCM-storage material interaction since these past three decades. The fact that the research in the area of PCM is still active and periodically new material(s) or mixture(s) of materials are being proposed, the review work concerning PCM-storage material interaction must be continuously carried out. The summary of their works are tabulated chronologically. The work prior in 1982 was reviewed by Abhat [40]. The author also reviewed the work of other researchers regarding the aspect of compatibility among storage materials with container materials and noted the corrosion test procedures. The test referred to immersing the sample of container material into PCM filled in airtight bottles. After a certain time interval, the samples are taken out and cleaned to measure their mass loss to calculate the corrosion rate. Gravimetric, scanning electron microscope, and microscopic analysis have been performed to test the corrosive effect on the material. Besides, the thickness of the material is measured to determine the extent of surface corrosion. Other than that, chemical analysis is carried out to identify the chemical changes that might have taken place in both PCM and container material. With that, the author could summarize several materials and their compatibility. As a result, the stainless steel emerged as the only material compatible to all phase change materials tested. Meanwhile, mild steel exhibited good terms with all the PCMs, except Zn(NO<sub>3</sub>)<sub>2</sub>·6H<sub>2</sub>O and Mg(NO<sub>3</sub>)<sub>2</sub>·MgCl<sub>2</sub>·Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>·5H<sub>2</sub>O, which displayed heavy corrosion with copper. On the other hand, aluminum was found compatible with Na<sub>2</sub>S<sub>2</sub>O<sub>3</sub>·5H<sub>2</sub>O.

In a similar vein, Porisini (1988) [76] selected salt hydrates of melting range from 15 to 32 °C (refer to Table 4). The container materials selected in this work were stainless steel, carbon steel, aluminum alloys, and copper. Each PCM was encapsulated with all the materials selected for the research, and later, all the samples were placed in a 100 °C thermostatic chamber associated with thermal program to test its thermal stability. The thermal cycle was set between 4 and 40 °C for 202 min' duration. Then, the samples were removed from the chamber, and the reference samples were weighed after removing PCMs. After that, metallographic examinations were conducted to detect any structural damage in the inner surface before the containers were filled with new PCM and the cycle was continued. The results obtained from this study are summarized in Table 5. The author

**Table 6**  
Cost per unit mass of thermal energy storage materials [68,69].

Type	Storage Material	Unit Mass Cost (\$/Kg)
Nitrate salts	NaNO <sub>3</sub>	0.40
	KNO <sub>3</sub>	0.90
	Ca(NO <sub>3</sub> ) <sub>2</sub>	0.25
Hydroxide salts	NaOH	0.35
	KOH	0.35
Chloride salts	NaCl	0.10
	KCl	0.50
	MgCl <sub>2</sub>	0.10
	LiCl	10.00
	CaCl <sub>2</sub>	0.15
	BaCl <sub>2</sub>	0.41
	SrCl <sub>2</sub>	0.80
	ZnCl <sub>2</sub>	0.98
Carbonate salts	Li <sub>2</sub> CO <sub>3</sub>	5.71
	K <sub>2</sub> CO <sub>3</sub>	1.00
	Na <sub>2</sub> CO <sub>3</sub>	0.10
Fluoride salts	LiF	0.50
	NaF	0.90
	KF	0.10
	CaF <sub>2</sub>	0.35
	MgF <sub>2</sub>	0.01
	MgF <sub>2</sub>	0.26
Solid materials	Sand-rock-mineral oil Cast steel	0.15
	steel	5.00
	Concrete	0.05
Paraffin	Paraffin wax	1.00
	n-Pentadecane	0.59
	n-Hexadecane	4.00
Fatty acids	Caprylic acid	5.00
	Capric acid	4.00
	Lauric acid	1.00
	Myristic acid	1.89
	Palmitic acid	1.00
Easters	Methyl palmitate	100.00
	Methyl stearate	10.00
Glycols	(Poly Ethylene Glycol)	
	PEG400	2.00
	PEG 600	2.00
	PEG 1000	2.00
salt mixtures	42Ca(NO <sub>3</sub> ) <sub>2</sub> –15NaNO <sub>3</sub> –43KNO <sub>3</sub>	0.53
	61KCl–39MgCl <sub>2</sub>	0.30
	54KCl–46ZnCl <sub>2</sub>	0.59
	25KCl–27CaCl <sub>2</sub> –48MgCl <sub>2</sub>	0.27
	48NaCl–52MgCl <sub>2</sub>	0.21
	5KCl–29NaCl–66CaCl <sub>2</sub>	0.12
	32KCl–68MgCl <sub>2</sub>	0.32
	28KCl–19NaCl–53BaCl <sub>2</sub>	0.31
	33NaCl–67CaCl <sub>2</sub>	0.11
	1 24KCl–47BaCl <sub>2</sub> –29CaCl <sub>2</sub>	0.30
	37MgCl <sub>2</sub> –63SrCl <sub>2</sub>	0.63
	32Li <sub>2</sub> CO <sub>3</sub> –35K <sub>2</sub> CO <sub>3</sub> –33Na <sub>2</sub> CO <sub>3</sub>	2.21
	47Li <sub>2</sub> CO <sub>3</sub> –53K <sub>2</sub> CO <sub>3</sub>	3.21
	40KCl–23KF–37K <sub>2</sub> CO <sub>3</sub>	0.16
	44Li <sub>2</sub> CO <sub>3</sub> –56Na <sub>2</sub> CO <sub>3</sub>	2.57
	17NaF–21KF–62K <sub>2</sub> CO <sub>3</sub>	0.65
	28Li <sub>2</sub> CO <sub>3</sub> –72K <sub>2</sub> CO <sub>3</sub>	2.32
	35Li <sub>2</sub> CO <sub>3</sub> –65Na <sub>2</sub> CO <sub>3</sub>	2.06
	51K <sub>2</sub> CO <sub>3</sub> –49Na <sub>2</sub> CO <sub>3</sub>	0.56
22Li <sub>2</sub> CO <sub>3</sub> –16Na <sub>2</sub> CO <sub>3</sub> –62K <sub>2</sub> CO <sub>3</sub>	1.89	

further indicated that stainless steel was compactable with all the PCMs, whereas steel C20 and copper were covered with a thin layer of corrosion in the starting, which remained so for a long time. Other than

that, the aluminum alloys were deeply pitted and this was proven from the optical microscopic results. Thus, the author concludes that Calcium chloride hex hydrate demonstrated excellent thermal stability after 5650 cycles.

Meanwhile, Groll et al., (1990) [77] selected two batches of salts for the corrosion research; Batch 1: pure eutectic salt mixtures (AlCl<sub>3</sub>-NaCl, LiCl-LiNO<sub>3</sub>-NaNO<sub>3</sub>, NaCl-NaNO<sub>3</sub>, KCl-LiCl), and Batch 2: technical salt grades with impurities + water (LiCl-LiNO<sub>3</sub>-NaNO<sub>3</sub>, NaCl-NaNO<sub>3</sub> and KCl-LiCl). The study tested mild steel (St 35.8), boiler steel (13CrMo44), and austenitic steel (X10CrNiMoNb1810) to determine corrosive resistance with Batch 1 salts. The metal pieces with the dimension of 15 mm×11 mm×2 mm were placed in cylindrical containers that had the following measurement: diameter, length, and wall thickness of 25 mm, 80 mm and 2 mm, respectively, containing salt eutectics in a glove box under pure argon gas. On the other hand, mild steel (St37), boiler steel (13CrMo44), and austenitic steels (X8CrNiMoTi1811, X10CrNiMoNb1810, X22CrMoV121) were tested for Batch 2 salts. The testing specimens using LiCl-LiNO<sub>3</sub>-NaNO<sub>3</sub>-eutectics, NaCl-NaNO<sub>3</sub> eutectics (filled as liquid), NaCl-NaNO<sub>3</sub>-eutectics (added water), KCl-LiCl eutectics (filled dry), and AlCl<sub>3</sub>-NaCl salt (special case) were sized and prepared in a similar way as mentioned above, except that the filling of salt was carried out in the air. As for construction material X22CrMoV121, the dimensions were 16 mm diameter x 1.5 mm wall thickness×86 mm length; whereas the container had 15 mm×11 mm×2 mm for metal sheet (special case), respectively. Metal sheets and lids of tube were ground with silicon carbide paper and cleaned with acetone. The lids were further welded with Argon gas arc. Moreover, the automatic melting and freezing were controlled as a cycle for 6 h (2 h heating and 2 h freezing). The number of cycles carried out were 42, 84, 168, 336, and 672. After testing, chemical analysis was carried out on the salts, in which mass gain of the samples were calculated, surface of the samples were tested via metallographic investigation to detect the damages occurred due to corrosion. The author, hence, concluded that after 2016 h, all steels with LiCl-LiNO<sub>3</sub>-NaNO<sub>3</sub>-eutectics of technical grade mostly gained mass and showed evidence of surface corrosion. Meanwhile, NaCl-NaNO<sub>3</sub> showed better results with all the salts, but 13CrMo44 corroded after 4032 h. Other than that, the KCl-LiCl salt mixtures had been very aggressive with all the steels tested. KCl-LiCl showed corrosion for samples filled in air, whereas samples filled in argon had been compatible. Besides, salts with addition of water showed pitting corrosion in St37, 13CrMo44, and X22CrMoV121; while the austenitic steel X8CrNiMoTi1811 was recommended in this case. The results are tabulated in Table 5.

Furthermore, according to Cabeza et al., [78], researches were conducted for latent heat storage to rectify the low heat flux problem due to low thermal conductivity, but the issue of corrosion in relation to PCM has always been disregarded. Corrosion implies negative effects when one tries to store PCM in containers due to insufficient long-term stability. Aluminum (EN AW-2007 or AlCuMgPb), Brass (Ms58 Flach or CuZn<sub>39</sub>Pb<sub>3</sub>), Copper (E-Cu57), Steel (St37 K or Mat. No. 1.0345), and stainless steel (Mat. No.1.4301) were selected for the investigation. The chemical composition of the above mentioned metals are (for more details, refer to the authors' original article) clearly depicted in the text. Zinc nitrate hexahydrate (Zn(NO<sub>3</sub>)<sub>2</sub> 6H<sub>2</sub>O), sodium hydrogen phosphate dodehydrate (NaHPO<sub>4</sub> 12H<sub>2</sub>O), and calcium chloride hexahydrate CaCl<sub>2</sub> 2H<sub>2</sub>O are the salt hydrates used in this investigation and their thermo-physical properties are well provided by the authors. The melting temperature of salt hydrates had been in the range of 32–38 °C. The metal samples were cleaned with acetone in an ultrasonic bath and then immersed in test tube filled with molten salt hydrates. The whole arrangement was kept in 50–60 °C water bath. The conditions of the metals were evaluated after 3 days, 1 week, and 3 weeks' time interval. The PH value and the appearance of the solution were further noted. After observing the nature of the surface (cleaned with water), the metal samples were polished with 150 g abrasive paper

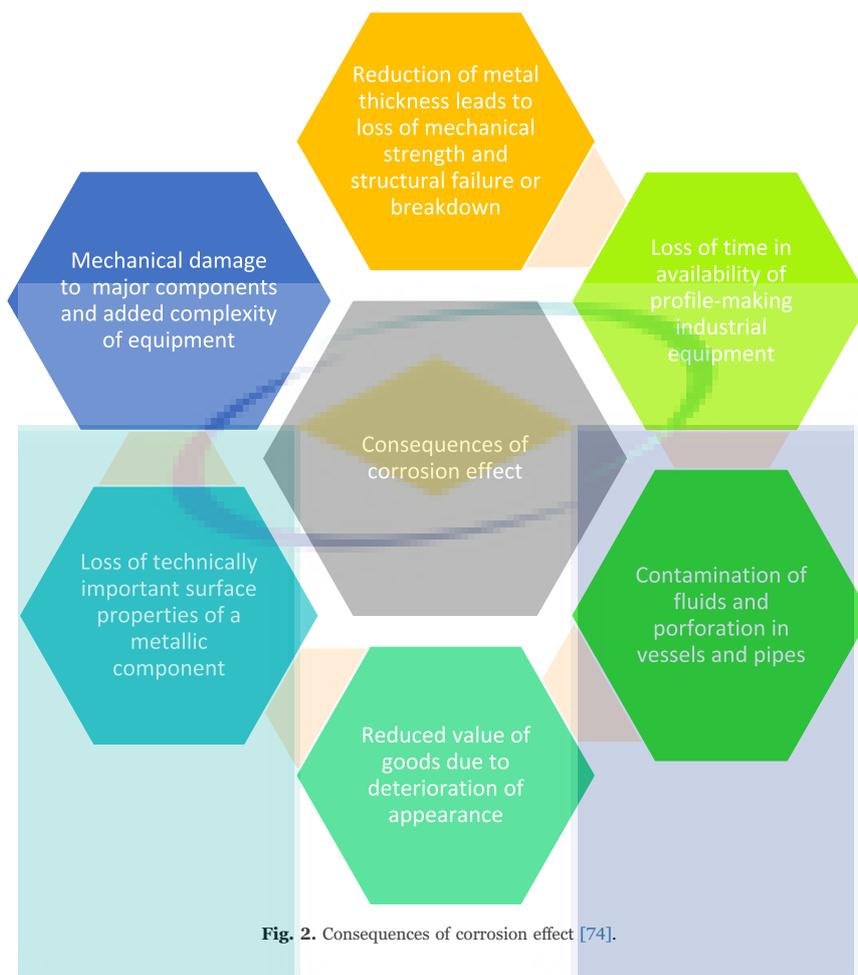


Fig. 2. Consequences of corrosion effect [74].

Table 7 Cabeza et al., [78] Guide for corrosion weight loss used in industry.

mg/cm <sup>2</sup> year	mm/year	Recommendation
> 1000	2	Completely destroyed within days
100–999	0.2–1.99	Not recommended for service greater than one month
50–99	0.1–0.19	Not recommended for service greater than one year
10–49	0.02–0.09	Caution recommended based on the specific application
0.3–9.9	–	Recommended for long-term service
< 0.2	–	Recommended for long-term service, no corrosion, other than as a result of surface cleaning was evidenced

and weighed to determine the mass loss. In addition, the corrosion rate was calculated by applying the mass loss per square meter method. The authors used Table 7 as reference for the analysis.

The study by the author suggests that the combination of chloride with stainless steel and nitrates with steel has to be avoided. The results of the deep immersion corrosion test are presented in Table 5. The study reveals that copper and brass can be used with calcium chloride hex hydrate, whereas aluminum, steel, and stainless steel cannot be used due to their corrosive nature. However, these results contradict from those of other studies [76,79]. Aluminum is an unfit candidate to all the salts tested. Brass, copper, and stainless steel, on the other hand, are good selectable options for container material with Sodium hydrogen phosphate do dehydrate. In addition, only zinc nitrate can be used with stainless steel. Meanwhile, copper and brass can be used for short term applications. Another research work by the same author in 2002 [80] investigated the corrosion resistance of aluminum, brass, copper, steel, and stainless steel with two salt hydrates named sodium acetate trihydrate (C<sub>2</sub>H<sub>9</sub>NaO<sub>5</sub>) and Sodium thiosulphate pentahydrate

(H<sub>10</sub>Na<sub>2</sub>O<sub>8</sub>S<sub>2</sub>) of which had a melting temperature range of 48–58 °C. The metals tested were cut in 30 mm by 10 mm size. The thickness of brass and steel, copper and stainless steel, as well as aluminum were 2 mm, 3 mm, and 5 mm, respectively. All the samples were cleaned with acetone and ultrasonic bath. Later, the samples were immersed into PCM-filled glass tubes and then, all the test tubes were placed in the water bath at 80 °C for 70 continuous days. In this research work, metal samples alone and samples in contact with graphite were also tested. The graphite in contact with metals had been expected to increase the thermal conductivity of PCM. The specimens were taken out at the end of 1st, 4th, and 12th week and their corrosion rates were calculated using the mass loss per square meter method. The same procedure was adhered to, as mentioned in [78]. Based on the results, aluminum, steel, and stainless steel demonstrated very good compatibility with both salts. Brass and copper corroded after 70 days in sodium acetate trihydrate, but brass with graphite increased the corrosion rate with time. Copper also hinted signs of corrosion; but with the addition of graphite, the corrosion rate began to decrease after 70 days. Other than that, brass and copper with sodium thiosulphate landed in severe corrosion and caused heavy mass loss. The results of the investigations are summarized in Table 8.

On the other hand, the research work of Cabeza and coworkers was continued by employing a low temperature range of 24–29 °C in 2005 [81]. PCMs with lower melting temperature are usually used for space cooling purposes, whereas PCM with higher melting temperature (above 30 – 100 °C) are used for heating purposes. Furthermore, commercial PCMs with melting temperature in the range of 20 °C is not available, thus the author mixed two different PCMs to achieve that range of temperature. Two PCMs TH29 from TEAP (Australia), CaCl<sub>2</sub> 6H<sub>2</sub>O and MgCl<sub>2</sub> 6H<sub>2</sub>O, were mixed to generate eutectic PCM with desired melting temperature (23 °C). The authors selected those two

**Table 8**  
Summary of the suitability of different PCMs with that of container materials.

Heat storage containers	Recommended type of PCM	Not recommended type of PCM	Recommended with caution type of PCM	Remark
Stainless steel	MgCl <sub>2</sub> [79] MgSO <sub>4</sub> [79] Ca(OH) <sub>2</sub> [79] Na <sub>2</sub> S [79] CaCl <sub>2</sub> 6H <sub>2</sub> O [76,79] [40] Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [40,78] Na <sub>2</sub> HPO <sub>4</sub> 12H <sub>2</sub> O [40,78] NaOAc 3H <sub>2</sub> O [80] Na <sub>2</sub> SO <sub>4</sub> 5H <sub>2</sub> O [80] SiO [50] ClO [50] ZnCl <sub>2</sub> 3H <sub>2</sub> O [50] NaOH 5H <sub>2</sub> O [50,76] K <sub>2</sub> HPO <sub>4</sub> 6H <sub>2</sub> O [50] S46 [50] C48 [50] Na <sub>2</sub> SO <sub>4</sub> 10H <sub>2</sub> O [40,76] Na <sub>2</sub> SO <sub>4</sub> 1/2 NaCl 10H <sub>2</sub> O [76] PCM-A ( (C-18): NaNO <sub>3</sub> + H <sub>2</sub> O + additives Climator) [85] PCM-B ( (E-21): NaCl + H <sub>2</sub> Oa Cristopia) [85] PCM-C (NaCl + H <sub>2</sub> Oa Cristopia + 1% CMC Modified from Cristopia) [85] PCM-D ( 19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation) [85] PCM-E (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 1% CMC Own formulation) [85] PCM-F (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% AIF3 Own formulation) [85] PCM-H (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% NaCl Own formulation) [85] PCM-I 19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% NaCl Own formulation+ 1% CMC Own formulation) [85] Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> 5H <sub>2</sub> O [85] SP21E [86] Capric acid 75.2%+ palmitic acid 24.8% [86] Capric acid 73.5%+ Myristic acid 26.5% [86] Pure Temp 23 [86] SP21E [86] Capric acid 75.2%+ palmitic acid 24.8% [86] Capric acid 73.5%+ Myristic acid 26.5% [86] Pure Temp 23 [86]	CaCl <sub>2</sub> 6H <sub>2</sub> O [78] PCM-G (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation ++ 3% AIF3 Own formulation + 1% CMC Own formulation) [85]	T29 [81] CaCl <sub>2</sub> 6H <sub>2</sub> O + MgCl <sub>2</sub> 6H <sub>2</sub> O [81]	Chloride salts showed contrary results with stainless steel. Caution must be taken when one encapsulates it using stainless steel. Further tests on CaCl <sub>2</sub> 6H <sub>2</sub> O with stainless steel are recommended to ensure its compatibility.
Stainless steel 304	NaOAc 3H <sub>2</sub> O [80] Na <sub>2</sub> SO <sub>4</sub> 5H <sub>2</sub> O [80]	Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [78] NaHPO <sub>4</sub> 12H <sub>2</sub> O [78]		Research works with chloride, nitrate, and Glauber's salts are encouraged
Stainless steel 316	Lithium potassium nitrate [84]			Research works with chloride, nitrate, and Glauber's salts are encouraged
Steel				Tests with a variety of eutectics are recommended because low number of salts are tested with steel.
Steel SS304				These container materials must be tested with easily available salts like calcium chloride and Glauber's salt. (continued on next page)

Table 8 (continued)

Heat storage containers	Recommended type of PCM	Not recommended type of PCM	Recommended with caution type of PCM	Remark
Stainless steel AISI 403	Mg(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O 53%+MgCl <sub>2</sub> 6H <sub>2</sub> O 47% [40]			Eutectic of nitrate and chloride showed good results with this steel, hence, other salts with economic value should be tested.
Mild steel	CaCl <sub>2</sub> 6H <sub>2</sub> O [40] Na <sub>2</sub> HPO <sub>4</sub> 12H <sub>2</sub> O [40] Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> 5H <sub>2</sub> O [40] CH <sub>3</sub> COONa 3H <sub>2</sub> O [40] Mg(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O 53%+ MgCl <sub>2</sub> 6H <sub>2</sub> O 47% [40] Ca(NO <sub>3</sub> ) <sub>2</sub> 4H <sub>2</sub> O 67% +Mg(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O 33% [40]	Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [40] Mg(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O 53%+MgCl <sub>2</sub> 6H <sub>2</sub> O 47% [40]		Eutectic of nitrate and chloride is incompatible, but eutectic of nitrates showed good result, thus usage of Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O must be avoided
Tin plated mild steel	LiClO <sub>3</sub> 3H <sub>2</sub> O [40] CH <sub>3</sub> COONa 3H <sub>2</sub> O [40] Mg(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [40] Ca(NO <sub>3</sub> ) <sub>2</sub> 4H <sub>2</sub> O 67% +Mg(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O 33% [40]			Showned very good results with all the salts tested. More salts can be tested for compatibility.
Carbon steel	Capric acid 73.5%+ Myristic acid [86] Pure Temp 23 [86] C48 [50] K <sub>3</sub> PO <sub>4</sub> 7H <sub>2</sub> O [50]	MgCl <sub>2</sub> (> 1year) [79] MgSO <sub>4</sub> (> 1 year) [79] Ca(OH) <sub>2</sub> [79] Capric acid 75.2% + palmitic acid 24.8% [86] S10 [50] C10 [50] (low term service) ZnCl <sub>2</sub> 3H <sub>2</sub> O [50] (low term service) K <sub>2</sub> HPO <sub>4</sub> 6H <sub>2</sub> O [50] MgSO <sub>4</sub> 7H <sub>2</sub> O [50] Zn(NO <sub>3</sub> ) <sub>2</sub> [50] PCM-A (C-18): NaNO <sub>3</sub> + H <sub>2</sub> O + additives Climator [85] PCM-D ( 19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation) [85] PCM-E (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 1% CMC Own formulation) [85] PCM-F (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% AIF3 Own formulation) [85] PCM-G (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% AIF3 Own formulation+ 1%CMC Own formulation) [85] PCM-H (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% NaCl Own formulation) [85]	CaCl <sub>2</sub> 6H <sub>2</sub> O [76,79]  Na <sub>2</sub> S [79] SP21E [86] NaOH 5H <sub>2</sub> O [50] S46 [50] Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> 5H <sub>2</sub> O [50] Na <sub>2</sub> SO <sub>4</sub> 10H <sub>2</sub> O [76] Na <sub>2</sub> SO <sub>4</sub> 1/2 NaCl 10H <sub>2</sub> O [76] NaOH 5H <sub>2</sub> O [76] PCM-B (E-21): NaCl + H <sub>2</sub> Oa Cristopia [85] PCM-C (PCM-B + 1% CMC Modified from Cristopia) [85] PCM-I (PCM-H 1% CMC Own formulation) [85]	Carbon steel is not a good choice for many salts in long term services.
Brass	NaHPO <sub>4</sub> 12H <sub>2</sub> O [78] CaCl <sub>2</sub> 6H <sub>2</sub> O [78] TH29 [81] CaCl <sub>2</sub> 6H <sub>2</sub> O +MgCl <sub>2</sub> 6H <sub>2</sub> O [81] NaOAc 3H <sub>2</sub> O [80] Na <sub>2</sub> SO <sub>4</sub> 5H <sub>2</sub> O [80] Capric acid 75.2%+ palmitic acid 24.8% [86] Capric acid 73.5%+ Myristic acid 26.5% [86]	Na <sub>2</sub> SO <sub>4</sub> 5H <sub>2</sub> O [80]  Na <sub>2</sub> S [79] CaCl <sub>2</sub> 6H <sub>2</sub> O [76,78] Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [78] NaHPO <sub>4</sub> 12H <sub>2</sub> O [78]	Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [78] (short term usage) NaOAc 3H <sub>2</sub> O [80] (short term usage) MgCl <sub>2</sub> [79] MgSO <sub>4</sub> [79] Ca (OH) <sub>2</sub> [79] CaCl <sub>2</sub> 6H <sub>2</sub> O [79]	Chloride and eutectics of chloride are strongly recommended. More tests are to be conducted with varied salts.
Aluminium				A few eutectics can be used but, chloride salts do not show good compatibility. Sulphate salts are a notable pair with aluminium. Better avoid pure Al for long term usage.

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Table 8 (continued)

Heat storage containers	Recommended type of PCM	Not recommended type of PCM	Recommended with caution type of PCM	Remark
Aluminum alloy	Pure Temp 23 [86] C10 [50] C48 [50] MgSO <sub>4</sub> 7H <sub>2</sub> O [50] PCM-I ( PCM-H 1% CMC Own formulation) [85]	CaCl <sub>2</sub> 6H <sub>2</sub> O + MgCl <sub>2</sub> 6H <sub>2</sub> O [4] SP21E [86] ZnCl <sub>2</sub> 3H <sub>2</sub> O [50] NaOH 5H <sub>2</sub> O [50] K <sub>2</sub> HPO <sub>4</sub> 6H <sub>2</sub> O [50] Zn(NO <sub>3</sub> ) <sub>2</sub> [50] K <sub>3</sub> PO <sub>4</sub> 7H <sub>2</sub> O [50] Na <sub>2</sub> SO <sub>4</sub> 10H <sub>2</sub> O [76] Na <sub>2</sub> SO <sub>4</sub> 1/2 NaCl 10H <sub>2</sub> O [76] NaOH 5H <sub>2</sub> O [76] PCM-A ((C-18): NaNO <sub>3</sub> + H <sub>2</sub> O + additives Climator) [85] PCM-B ((E-21): NaCl + H <sub>2</sub> Oa Cristopia) [85] PCM-C (NaCl + H <sub>2</sub> Oa Cristopia + 1% CMC Modified from Cristopia) [85] PCM-D (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation) [85] PCM-F (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% AlF <sub>3</sub> Own formulation) [85] PCM-G (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 1% CMC Own formulation) [85] PCM-H (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% NaCl Own formulation) [85]	Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> 5H <sub>2</sub> O [50] S10 [50] S46 [50] PCM-E ( PCM-D + 1% CMC Own formulation) [85]	Aluminum alloys with copper trace must be avoided i.e. 2000 series. Mostly aluminum alloys showed good compatibility with sulphate salts.
	(3003,6063, 1050+2024 1050+3003) 2024----- 1050+2024-- Al 99.5	Glauber's salt [83] -- Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> 5H <sub>2</sub> O [40]	Glauber's salt [83] -- CaCl <sub>2</sub> 6H <sub>2</sub> O [40] Na <sub>2</sub> HPO <sub>4</sub> 12H <sub>2</sub> O [40] Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [40] CaCl <sub>2</sub> 6H <sub>2</sub> O [40] Na <sub>2</sub> HPO <sub>4</sub> 12H <sub>2</sub> O [40] Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [40]	Glauber's salt [83]
Al Mg <sub>3</sub>	Na <sub>2</sub> SO <sub>4</sub> 10H <sub>2</sub> O [40] Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> 5H <sub>2</sub> O [40]			
Copper	CaCl <sub>2</sub> 6H <sub>2</sub> O [40,78] Na <sub>2</sub> HPO <sub>4</sub> 12H <sub>2</sub> O [2] [40] TH29 [81] CaCl <sub>2</sub> 6H <sub>2</sub> O + MgCl <sub>2</sub> 6H <sub>2</sub> O [81] SP21E [86] Pure Temp 23 [86] ZnCl <sub>2</sub> 3H <sub>2</sub> O [50] Na <sub>2</sub> SO <sub>4</sub> 10H <sub>2</sub> O [40] Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O [40]	Na <sub>2</sub> S [79] Ca (OH) <sub>2</sub> (> 1year) [79] (MgSO <sub>4</sub> (> 1year) [79] Na <sub>2</sub> SO <sub>4</sub> 5H <sub>2</sub> O [80] Capric acid 75.2% + palmitic acid 24.8% [86] S10 [50]C10 [50] NaOH 5H <sub>2</sub> O [50] S46 [50] C48 [50] MgSO <sub>4</sub> 7H <sub>2</sub> O [50] Zn(NO <sub>3</sub> ) <sub>2</sub> 4H <sub>2</sub> O [50]	CaCl <sub>2</sub> 6H <sub>2</sub> O [79] MgCl <sub>2</sub> [79] Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O (short term usage) [78] NaOAc 3H <sub>2</sub> O [80] Capric acid 73.5% + Myristic acid 26.5% [86] K <sub>2</sub> HPO <sub>4</sub> 6H <sub>2</sub> O [50] PCM-I (PCM-H 1% CMC Own formulation) [85]	Many contrary results related to CaCl <sub>2</sub> 6H <sub>2</sub> O Zn(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O so, further tests related to their compatibility are necessary. Only a few salts are good candidates to be with copper.

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salts because they are inexpensive, available in abundant, possess good storage capacity, and besides, their density and conductivity are acceptable. Sources of the availability of the two salt hydrates are mentioned clearly in the article published by [81]. Two PCMs, TH29 from TEAP (Australia), as well as CaCl<sub>2</sub> 6H<sub>2</sub>O and MgCl<sub>2</sub> 6H<sub>2</sub>O mixture (eutectic PCM), had been selected in this research. Aluminum (EN AW-2007 or AlCuMgPb), brass (Ms58 Flach or CuZn39Pb3), stainless steel (Mat. No. 1.4301), copper, and steel had been selected to determine their resistivity against corrosion. The metals test specimens were prepared in the same size and adhered to the similar sample preparation methodologies employed by past authors in prior work [80]. The samples were immersed into the PCM-filled glass tubes, and then, all the test tubes were placed in the water bath at 80 °C. The samples were taken out from the water bath at the end of 3rd, 6th, 14.5th, 40th, and 71.5th weeks to determine the measurements (by adhering to the methodology employed in previous research works) [80]. The metals with and without in contact with graphite samples had been subjected to corrosion test. From this investigation, the authors have concluded that all the metals, except aluminum and steel, are indeed compatible with PCMs. Stainless steel, nonetheless, is not recommended because of their incompatibility with chloride and stress corrosion cracking. The results of the investigations are portrayed in Table 5.

Metal corrosion, inclusive of pitting, erosion, hydrogen embrittlement, oxidation, fretting, fatigue, dealloying, and galvanic erosion, are studied by Schweitzer and Shreir, as cited by Farrell et al., (2006) [82]. In fact, Farrell et al., focused on galvanic erosion. Galvanic erosion is the potential difference of metal to the standard reference of hydrogen electrode. Galvanic series is based on the immersion tests using sea water as electrolyte and thus, corrosion rates are noted. Galvanic series of metals is given in detail by the author. Hence, for further details, do refer to the original article [82]. Other than that, sodium sulphate dehydrate and sodium chloride Plus (ICE E17), ClimSel C18 Sodium acetate + additives (ClimSel C18) with melting points at 17 °C and 18 °C were the PCMs selected for this investigation. Copper and aluminum metals were also considered in this work. Conventional heating/cooling arrangement with heat exchanger was employed with two chambers; one was open to the atmosphere, while the other was filled with PCM and sealed. PCM acted as both heat source/cold sink and they are interconnected with heat exchanger pipes made up of copper coated with aluminum, which also had aluminum fins. Two horizontal pipes with vertical distance of 50 mm were integrated to avoid incongruent melting. The sample metals were cleaned and encapsulated with reference PCM separately, and both metals together for both PCMs. These samples were heated up to 70 °C and cooled down to 40 °C without air contact and were kept for 17 h. The samples were removed, cleaned (copper with nitric acid, aluminum with diluted hydrochloric acid), and weighed using a precision balance to determine the mass in four decimal places. In addition, the corrosion rate was calculated as well. The surface of the metal was studied under a microscope. Corrosion was observed in copper, whereas pitting was noted in aluminum when they were tested separately. On the other hand, copper was found to be clean, while all aluminum samples displayed severe pitting when coupled with copper in both the samples. Moreover, the galvanic corrosion copper was safe because aluminum acted as sacrificing material. From this, the author concludes that aluminum coated copper pipes in the heat chamber can severely corrode when filled with PCMs. However, in order to avoid such scenario, zinc plates can be immersed in the PCM or inner walls of the chamber can be coated with zinc. The compatible and non-compatible storage materials against respective PCMs are summarized in Table 5.

Other than that, Romero et al., (2009) [83] were strongly attracted by the results obtained by Abhat [40] and Porisini [76] in relation to the compatibility of aluminum with PCM. All other researchers, including Cabeza [78,80,81], concluded that aluminum cannot be a container tank material because of its severe corrosive nature against

Table 8 (continued)

Heat storage containers	Recommended type of PCM	Not recommended type of PCM	Recommended with caution type of PCM	Remark
		K <sub>3</sub> PO <sub>4</sub> 7H <sub>2</sub> O [50] Na <sub>2</sub> S <sub>2</sub> O <sub>3</sub> 5H <sub>2</sub> O [40,50] PCM-A (C-18): NaNO <sub>3</sub> + H <sub>2</sub> O + additives Climator) [85] PCM-B (E-21): NaCl + H <sub>2</sub> Oa Cristopia) [85] PCM-C (NaCl + H <sub>2</sub> Oa Cristopia + 1% CMC Modified from Cristopia) [85] PCM-D (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation) [85] PCM-E (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 1% CMC Own formulation) [85] PCM-F (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% AlF <sub>3</sub> Own formulation) [85] PCM-G (PCM-F + 1% CMC Own formulation) [85] PCM-H (19% NH <sub>4</sub> Cl + H <sub>2</sub> O Own formulation + 3% NaCl Own formulation) [85] Mg(NO <sub>3</sub> ) <sub>2</sub> 6H <sub>2</sub> O 53%+ MgCl <sub>2</sub> 6H <sub>2</sub> O 47%(tests with 1% carbon steel) [40]		

almost all PCMs. In fact, a few thousand series of aluminum alloy have been made available with lower cost, leading the author to conduct corrosion tests for certain series of aluminum alloy with commonly used Glauber's salt (Mirabilite,  $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ), which is a mixture of (anhydrous disodium sulphate Thenardite,  $\text{Na}_2\text{SO}_4$ ) and disodium sulphate decahydrated. Aluminum alloys 2024, 1050, and 3003 were selected to meet the research purpose. These specimens were cleaned in a way similar to that of Cabeza et al., [78,80,81] and were partially immersed in the molten PCM of melting temperature at 45 °C. Aluminum alloy 1050 was immersed partially together with 3003 and 6063 separately in such a way they were not in contact with each other. The whole arrangements were covered with a plastic sheet to avoid evaporation and PCM degradation. The samples then were taken out in 30, 60, and 90 days interval to determine the corrosion rate. The surface of the samples were tested using scanning electron microscope (SEM) to observe the surface damages. Besides, the PH value of the solution was measured using PH paper. The authors concluded that the parts immersed in the PCM did not corrode for all samples. However, the corrosion rate was very high for 2024 because Al and Na formed a thick layer of carbonate precipitate, thus pitting went unnoticed. The authors also strongly doubt that all 2000 series would face the issue of corrosion due to the presence of copper trace. The corrosion action was further intensified by Cu; thus, it is advisable to use Al alloy without copper. All other 3003 and 6063 separately and those combined with 1050 also showed strong resistance against corrosion. The summary of the performance of the metals and metal alloys is presented in Table 5.

In a similar note, Aswin (2011) [84] chose SS304 (the steel used to design the storage container in CSP) as the sample material and Lithium-potassium carbonate eutectics (prepared using aqueous method) as salt for a research work. The sample material was cut into 20 mm×5 mm×0.6 mm in size and placed in an arrangement called bomb. A total of 45 bombs were prepared carefully with a particular size so that the sample metal can be encapsulated. Empty metal, metal with eutectics, and metal in eutectics with silicon nanoparticles (1%) were marked as one family. In fact, a total of nine families were arranged vertically inside the furnace at 520 °C statically. The samples were removed from the tank at the end of 2nd, 4th, and 6th week for further observation. Besides, the corrosion rate was calculated in a standard way via mass loss method. From the results, the author concluded that adding silica nanoparticles to eutectics reduced the corrosion rate of SS304. SS304 and it was recommended as TES with carbonate salts.

Furthermore, Oro et al., (2012) [85] analyzed nine PCM formulations with four metals and four polymers for cold storage. The PCMs tested were PCM-A (C-18):  $\text{NaNO}_3 + \text{H}_2\text{O} + \text{additives}$  a Climator, PCM-B (E-21):  $\text{NaCl} + \text{H}_2\text{O}$  a Cristopia, PCM-C: PCM-B +1% CMC Modified from Cristopia, PCM-D: 19%  $\text{NH}_4\text{Cl} + \text{H}_2\text{O}$  Own formulation, PCM-E: PCM-D +1% CMC Own formulation, PCM-F: PCM-D +3%  $\text{AlF}_3$  Own formulation, PCM-G: PCM-F +1% CMC Own formulation, PCM-H: PCM-D +3%  $\text{NaCl}$  Own formulation and PCM-I: PCM-H 1% CMC Own formulation (the exact compositions are unknown). The four metals and the four polymers tested had been copper, aluminum, stainless steel, carbon steel, poly propylene (PP), high density polyethylene (HDPE), poly ethylene terephthalate (PET), and polystyrene (PS). All the metals of size 50 mm×10 mm×0.5 mm were cleaned with acetone, whereas polymers with a dimension of 12 mm×75 mm×2 mm were not cleaned, but weighed using precision balance. All the samples were immersed in glass tubes filled with all the PCMs separately. All the PCMs used were in liquid form at the room temperature because their melting point is 18 °C. The test tubes were closed with plastic paraffin to avoid contact with atmosphere. After 1st, 4th, and 12th week, the samples were weighed and the corrosion rate was calculated by adhering to that suggested by Cabeza et al., [78,80,81]. In the case of polymers, the mass change was calculated by using Eq. (1).

$$\Delta m(\%) = \frac{m(t) - m(t_0)}{m(t_0)} \times 100\% \quad (1)$$

where  $\Delta m$  is difference in mass in percent,  $m(t)$  is mass at time  $t$ , and  $m(t_0)$  is the initial mass. The authors discarded PCM-G due to the experience of phase segregation during the experiment. Moreover, crystal formation was noted in copper in contact with PCM-D. As for PCMs C, E, and G with copper, color change (blue) in the solution was observed; but for others, they thickened. At the start of the experiment itself, bubble formation was noted, while PCMs D, C, and I displayed pitting, which confirmed that aluminum did show corrosion behavior with all the PCMs analyzed. In addition, orange shaded precipitate was formed for carbon steel with all PCMs, thus indicating corrosion. After analyzing all the results, the authors have concluded that stainless steel is the only candidate that has shown compatibility with all PCMs, as presented in Table 8. Other than that, polymers PP, PS, PET, and ADPE did not display any corrosion with any of the PCM formulations used. Therefore, they can be used as storage container to all the PCM formulations.

Meanwhile, in a study conducted by Moreno et al., (2014) [50], copper, aluminum, stainless steel 316, and carbon steel were chosen as sample metals. The samples of size 50 mm×and 10 mm×0.5 mm were cleaned in a standard way and immersed in the eleven selected PCMs. The melting point of five PCMs are 10 °C, while the other six are 46 °C. The temperature bath was maintained as 22 °C and 60 °C for low and high temperature requirement PCMs, respectively. The test tubes of PCM at room temperature were covered with plastic sheets to avoid contact with the environment. In the time interval of 1st, 4th, and 12th week, the samples were taken out, polished, and weighed to measure the mass loss into 4 decimal places to calculate the corrosion rate. Additionally, the PH value of PCMs were tested to determine the nature of the solution. After that, using scanning electron microscope (SEM), the surface nature of the samples were observed. Stainless steel looked clean with all the PCMs throughout the experiment, while copper is not affected by C10, but blue salt deposition is noted, and others did not exhibit any significant corrosion. Carbon steel displayed corrosion in the first week, but the rate of corrosion decreased until 12th week. Only S10 showed a high corrosion rate. The commercial PCMs, on the other hand, showed very low corrosion rate, but the other two;  $\text{ZnCl}_2 \cdot 3\text{H}_2\text{O}$  and  $\text{NaOH} \cdot 5\text{H}_2\text{O}$ , had underwent severe corrosion, which end up with degradation.  $\text{Na}_2\text{S}_2\text{O}_3 \cdot 5\text{H}_2\text{O}$ , C48, and  $\text{Zn}(\text{NO}_3)_2 \cdot 4\text{H}_2\text{O}$  also showed high corrosion after 1st, 4th, and 12th week, respectively; but the corrosion rate decreased after that. Other salts also corroded, but the corrosion rate decreased as time passed. Based on the results presented in Table 8, the authors have recommended metals and metal alloys studied PCMs for heat pump and cooling applications.

In a similar vein, Solé et al., (2014) [79] studied the compatibility of  $\text{Na}_2\text{S}$ ,  $\text{MgSO}_4$ ,  $\text{MgCl}_2$ ,  $\text{Ca}(\text{OH})_2$  and  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  with metals, such as copper, aluminum, stainless steel 316, and carbon steel. Information about the suppliers of the above mentioned salt hydrates and their purity can be referred from authors' original article [79]. The corrosion test was conducted by dipping the samples in the salt hydrates. The whole arrangement was kept in a humidity chamber at 60 °C. The samples were removed from the chamber at the end of 1st, 4th, and 12th week, similar to the research conducted by Moreno et al., [50]. The nature of the surface was evaluated and compared with other samples every time they were removed from the chamber. By measuring the mass lost, corrosion rate was calculated by using Eq. (2).

$$CR = \frac{\Delta m}{A(t_o - t)} \text{mg/cm}^2\text{year} \quad (2)$$

where  $CR$  is corrosion rate ( $\text{mm/cm}^2$ ),  $\Delta m$  is the change in mass flow rate ( $\text{mg/s}$ ),  $A$  is area in  $\text{cm}^2$ , while  $t$  and  $t_o$  are final and initial time in second. The compatibilities of each container material with the salt hydrates are tabulated in Table 8. It is noted that stainless steel 316 is unaffected by any of the salts tested. Nonetheless, carbon steel is not

recommended for  $\text{MgCl}_2 \cdot \text{Ca}(\text{OH})_2$  and  $\text{MgSO}_4$ . Copper and aluminum, on the other hand, were completely destroyed by  $\text{Na}_2\text{S}$ .  $\text{MgCl}_2$ , which was compatible with aluminum, copper, and stainless steel. Besides, copper is not recommended for more than a year service for  $\text{Ca}(\text{OH})_2$  and  $\text{MgSO}_4$ . As such,  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  is the only salt that could be used with all the four metals, but care must be taken for carbon steel and aluminum.

Ferrer *et al.*, (2015) [86] concentrated in the corrosive study of five selected metals (Stainless steel 316, stainless steel 304, carbon steel, copper, and aluminum) with four PCMs (one organic mixture - SP21E, one ester- pure temp, and two fatty acids eutectics - Capric 75.2% + Palmitic 24.8%, and Capric 73.5% + Myristic 24.5%). Among the four PCMs, two are commercial, named as SP21E (by Ruby Therm) and Pure Temp 23 (by pure temp), respectively. The size of the specimens is set at 5 cm×1 cm×0.1 cm and were cleaned with acetone to remove oil and impurities, then weighed by using a Mettler Toledo Precision Balance (up to 4 decimals). All the specimens were placed inside glass test tubes filled with PCM. Each metal specimen was immersed in four different PCMs. All the test tubes were covered with plastic lids to avoid environmental contact. All the PCMs used had melting temperature at around 22 °C, therefore, all the 20 test tubes were kept on a stove at 38 °C to retain the PCMs in its liquid form. Later, the samples were taken out at the end of 1st, 4th, and 12th week and the corrosion rate was calculated via mass loss method. The investigators regularly examined the color, the PH of the molten PCM, and the nature of the surface of the metal samples. The compatibility of the metal specimens with the PCMs is summarized in Table 8. The authors further explained that when the carbon steel was immersed in SP21E. The color of PCM changed to yellow in the first week and the shade of the color darkened with time. At end of the 12th week, surface degradation was noted. Capric + palmitic acid and capric + myristic eutectics with copper showed nil corrosion, but the color of the solution changed to blue and the effect increased in the following weeks. Furthermore, the luminous of the metal was lost in the first week itself, so caution must be taken for long term usage. Other than that, aluminum in SP21E changed the color of the solution to grey. Bubbles were noticed at the end of 4th week. Finally, at the 12th week, corrosion and pitting were observed and solidification of PCM occurred, hence suggesting that the usage of aluminum must be avoided.

In summary, all the salts, including  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$ , have been found compatible with stainless steel, based on the articles published by Solé *et al.*, [79], Porisini [76], and Abhat *et al.*, [40]. However, interestingly, this is on contrary to a study conducted by Cabeza [78]. Since the experimental results are controversial, further research works regarding this are encouraged to confirm the compatibility of  $\text{CaCl}_2 \cdot 6\text{H}_2\text{O}$  with stainless steel. Besides a few eutectics did display very good compatibility with steel and steel alloys, as noted in [40,86]. It should be recognized, however, all the studies of aluminum with salt hydrates reported cases of corrosive [50,76,78,79,85,86], while alloys of aluminum showed good compatibility with sulphate salts, except 2000 series [83]. Thousands of aluminum alloys are available in the market and they are very cheap [83]. Therefore, researchers should be motivated in this type of research in future. Glauber's salt is a commonly used salt in latent heat storage and it has compatibility with aluminum alloys. As a result, potential approach towards the suitability of its usage with a variety of storage container materials is also encouraged. Even though only a handful candidates are compatible with copper; galvanic coatings can overcome this limitation and ensure safe usage of this metal [82]. Further summary of the suitability of different PCMs with that of container materials is stated in Table 8.

#### 4. Conclusion

Renewable energy usage can keep the world clean and green. Global warming increases the usage of air-conditioning and this worsens the problem. Thus, latent heat storage is necessary to make use of solar

energy in an effective way. Furthermore, PCM plays an important role in latent heat storage. Organic PCMs are mostly non-corrosive, but inorganic PCMs are corrosive. Since the inorganic PCMs are comparatively good in heating applications, researches on corrosiveness of salt hydrates with storage tank materials have been conducted since past four decades.

From the results, stainless steel is compatible with almost all the salt hydrates tested. However, some contradicting results in this regard demand further research studies. Besides, Glauber's salts are compatible with all the aluminum alloys tested. Nevertheless, aluminum alloys with carbon trace showed corrosion; hence needs to be avoided. Meanwhile, eutectics demonstrated good results with steel and steel alloys, so determination of new eutectics will unfold a new era in the latent heat storage. However, only a handful of research works have been carried out to date in relation to the corrosion field of salt hydrates. Thus, more work related to this must be continued in full force until a non-corrosive, more economic, and easily available compatible pair is discovered. As such, many more applications are just waiting for this valuable discovery.

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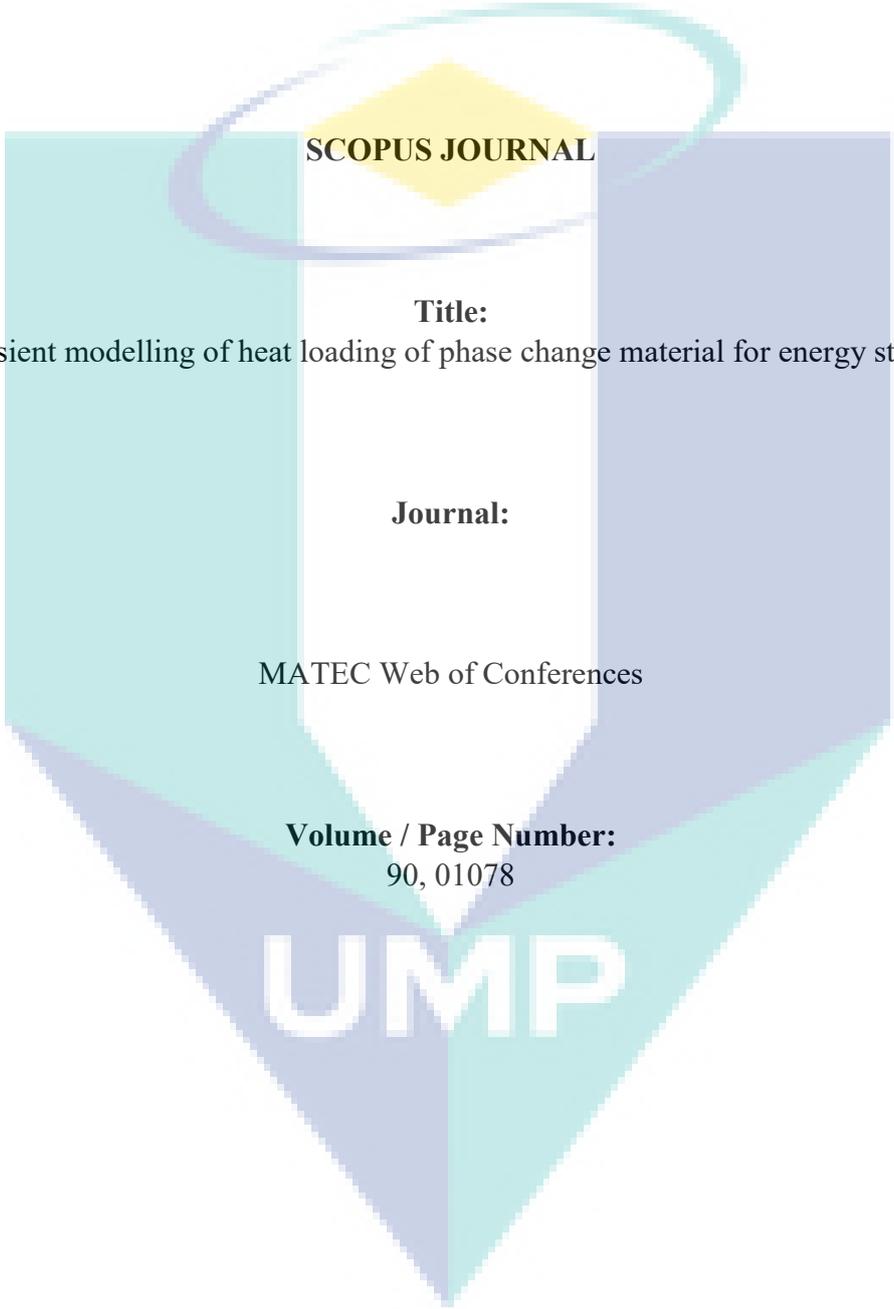
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## CHAPTER 3



**SCOPUS JOURNAL**

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Transient modelling of heat loading of phase change material for energy storage

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**UMP**

# Transient modelling of heat loading of phase change material for energy storage

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**Abstract.** As the development of solar energy is getting advance from time to time, the concentration solar technology also get the similar attention from the researchers all around the globe. This technology concentrate a large amount of energy into main spot. To collect all the available energy harvest from the solar panel, a thermal energy storage is required to convert the heat energy to one of the purpose such as electrical energy. With the idea of energy storage application that can be narrow down to commercial application such as cooking stove. Using latent heat type energy storage seem to be appropriate with the usage of phase change material (PCM) that can release and absorb heat energy at nearly constant temperature by changing its state. Sodium nitrate ( $\text{NaNO}_3$ ) and potassium nitrate ( $\text{KNO}_3$ ) was selected to use as PCM in this project. This paper focus on the heat loading process and the melting process of the PCM in the energy storage using a computer simulation. The model of the energy storage was created as solid three dimensional modelling using computer aided software and the geometry size of it depend on how much it can apply to boil 1 kg of water in cooking application. The materials used in the tank, heat exchanger and the heat transfer fluid are stainless steel, copper and XCEL THERM MK1, respectively. The analysis was performed using a commercial simulation software in a transient state. The simulation run on different value of velocity but kept controlled under laminar state only, then the relationship of velocity and heat distribution was studied and the melting process of the PCM also has been analyzed. On the effect of heat transfer fluid velocity, the higher the velocity resulted in higher the rate of heat transfer. The comparison between the melting percentages of the PCMs under test conditions show that  $\text{NaNO}_3$  melts quite faster than  $\text{KNO}_3$ .

## 1 Introduction

From day to day, the dependence on fossil fuel energy is quite distressing. Fossil fuel energy will face depletion due to the drastic increase in world energy consumption. The non-renewable energy usage is also one of the leading reasons for the production of greenhouse gases. In recent decades, researchers have been studying the usage of

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environmental friendly and renewable energy that could be harvested around the globe with no cost [1, 2]. Solar energy is one of the clean and abundantly available renewable energy resources that can replace the non-renewable energy resources [3]. In the application of solar cooking using concentrated solar power, thermal energy storage (TES) medium is required to store the heat energy obtained from solar energy [4]. Phase change material (PCM) that can store and release heat energy according to necessity by changing its state from solid to liquid or vice versa is likely to be the most suitable type of material that can be used as TES. Heat loading process of the PCM during absorption of heat energy that leads to the phase change from solid to liquid is to be analyzed in this paper.

Lewis et al.[5] have reported that there are three major components needed for solar energy utilization [5]. These include solar capture, conversion, and storage. Solar capture and conversion can be achieved by photo-voltaic cells (PVs). The solar energy utilization and storage are expected to be economical and affordable to enhance its usage. Unfortunately, the cost of material needed to utilize this renewable energy is very expensive compared to fossil fuels usage. There should be an advancement in the approach to utilize this very important sustainable energy in a more economical way. Finding new material for thermal capture during its availability as well as new thermodynamic cycle to harvest the solar energy to produce a useful fuel is necessary. Chwieduk [6] stated that there are two methods of utilizing solar energy available. The first method is indirect utilization method. In this case, renewable energy is used as a secondary effect of solar energy. Hydro energy, ocean energy, and wind energy are the examples of secondary effect of solar energy. These energies are accomplished by photosynthetic processes and is mostly related to biomass and biofuels. The second method is direct utilization of solar energy. In this case, there are two fundamental methods of energy conversion available. These includes photo-thermal conversion of energy and solar - photoelectric conversion of solar energy radiation. The photo-thermal conversion is applied in active low temperature solar water and air heating system, passive low temperature solar water heating, high temperature solar heating system with solar concentrator and electric power system.

Edina Milisic [7] stated that, thermal energy storage must be able to store and release a large amount of energy. Using PCM as a storage medium will completely depend on the latent heat energy for the energy storage system. Unlike sensible heat energy, latent heat type shows less temperature change during energy storage because when the material changes its phase, the combination of pressure and temperature leads to the aggregate state. In the aggregate state, the latent heat will be stored and released almost at constant temperature, thus even a small difference in temperature can be used to store a large amount of latent heat energy. In general, energy storage can be distinguished as sensible heat, latent heat and thermochemical or any combination of it. Atul Sharma et al. [8] investigated about how thermal energy storage works with the change in internal energy of the material. This article includes the sensible heat, latent heat, and thermochemical or any combination of these for further discussion. Sensible heat storage (SHS) is a thermal energy stored by raising the temperature of liquid or solid material. SHS will develop the heat capacity and change in temperature during the loading and unloading processes of heat transfer. The specific heat and temperature change in the storage medium will affect the amount of heat stored in SHS. Another approach is latent heat storage (LHS). In this case, the energy is stored when a material undergoes a change in state that is liquid-to-solid or gas-to-liquid or vice versa. Regin et al. [9] stated that developing a suitable containment for PCM will lead to a better utilization of PCM and heat transfer of fluid. The PCM storage containers with several geometric designs have their own pro and cons. PCM storage container material should meet the requirement of strength, flexibility, thermal stability and corrosion resistance to the PCM material. PCM capsules made of container material of characteristics as above enhance the latent heat storage and at the same time acts as a

barrier to protect the latent heat storage material from harmful interaction with environment. PCM capsules storage provides sufficient surface for heat transfer and structural stability for easy application.

Agyenim et al. [10] have reported that the most important factors need to be considered in PCM energy storage are the thermal and geometric parameters of the container material required for a fixed quantity of PCM. This criteria has a direct impact to heat transfer characteristic and has major influence to the melting time and performance of the PCM storage unit. The geometric parameters of the PCM container must correspond to the melting time and daily insolation process from a solar collector at specific location in order to ensure long term thermal performance of PCM storage systems. Cabeza et al. [11-15] highlighted a technique to encapsulate the PCM to avoid the liquid phase flow away from the specific location applied. The two principles of PCM encapsulation include micro-encapsulation and macro-encapsulation. Micro-encapsulation is a small, spherical, rod shaped particle that is covered in a thin, high molecular weight polymeric film. On the other hand, macro-encapsulation comprises the PCM in some form of tube, pouches, sphere or panel that serves directly as heat exchanger.

Arefeh Hesaraki [16] stated that PCM are widely used to store latent heat energy. This is due to PCM's ability to absorb a large amount of heat energy during its change in state at constant temperature. Hence, PCM changes its phase by absorbing or releasing heat energy without much change in temperature. The heat transfer enhancement and performance of the thermal energy system (TES) depends on the thermal conductivity of the PCM. To prevent heat loss, the PCM storage can be insulated but if the heat loss occurs through vaporization of materials, there is no clear method of preventing to avoid it. There are limited study on the high temperature TES employing PCM both experimental and numerical. The effect of heat transfer fluid velocity and fin spacing is conducted for medium temperature application (paraffin wax) by Ogoh and Groulx [17] in a cylindrical heat storage tank and the fins arranged horizontally. The same paraffin wax material is also utilized the study of heat transfer characteristics by Jesumathy et al. [18]. The general objective of this study is to develop a further understanding and modelling of loading process of phase change material (PCM). Therefore the current investigation is narrowed down to these specific objectives of analysis of the heat requirement for solar cooking applications, design and sizing of the thermal energy storage (TES) and execution of a transient simulation on heat energy distribution, heat loading process of thermal energy storage for solar cooking application using phase change material.

## **2 Methodology**

Solar cooking model required a solar collector that will absorb the heat and radiation energy from the sun. Then the absorber will transfer the heat energy to the heat transfer fluid (HTF). The heat transfer from the HTF will heat up the PCM in the thermal energy storage (TES). To minimize the heat lost to surrounding the TES should be well insulated. The focus of the current study is only the TES system. The problem definition consists of a thermal heat storage tank with its volume filled by PCM and a heat transfer fluid channel enters at the bottom center of the tank and leaves at the top center of tank. The work is progressed in such a way that the effect of heat transfer fluid in the exchanger tube is studied with different PCMs.

### **2.1 Geometry design**

The geometry of thermal energy storage is designed based on the application requirement to boil 1 kg of pure water. The heat requirement to boil 1 kg of pure water is calculated in

order to obtain the minimal volume of PCM needed in the TES. The law of calorimetric to determine heat energy needed to boil 1 kg of water based on Eq. (1),

$$Q = c \cdot m(100^\circ\text{C} - T) + \Delta h_{vap} \cdot m \quad (1)$$

where,  $c$ =specific heat of pure water,  $m$ =mass of water,  $T$ =initial temperature, and  $\Delta h_{vap}$ = specific enthalpy of vaporization of water. The heat energy calculated when the thermal efficiency of TES is assumed to be 70% is stated as total energy stored,  $E_{stored}$ . Using Eq. (2), the mass and volume of the PCM can be obtain.

$$m_{PCM,solid} = \frac{E_{stored}}{h_{PCM}}, \quad V_{PCM} = \frac{m_{PCM}}{\rho_{PCM}} \quad (2)$$

The value obtained from Eq. (2) is volume and mass of PCM in room temperature that is in solid state. PCM will change its state to liquid during heat loading process, thus the mass and volume of the PCM in liquid state also need to be considered and can be obtained using Eq. (3) [19].

$$\rho_{PCM,liquid} = 1000[2.112 - 0.0006891(\text{Melting temp } ^\circ\text{C})] \quad (3)$$

With the help of the above data, dimensional parameters of the TES design can be defined using CAD software. Based on the previous calculation from Eqs. (1) – (3), the volume of the TES should not be less than  $0.017 \text{ m}^3$ . Therefore, the cylindrical shape of TES can be designed using the volume equation given below. The heat transfer formula can yield the parameters such as TES length  $l = 0.25 \text{ m}$ , diameter =  $0.3 \text{ m}$  and heat exchanger tube length;  $l = 0.35 \text{ m}$ .

$$V_{cylinder} = \frac{\pi D^2 L}{4}, \quad V_{pipe} = \frac{\pi D^2 L}{4} \quad (4)$$

$$Q_{conv} = hA(T_s - T_\infty), \quad A = \pi D \quad (5)$$

where,  $h = 385 \text{ W/m}^2 \cdot \text{K}$ ,  $T_s$ = Surface temp $^\circ\text{C}$ ,  $T_\infty$ = Surrounding temp ( $^\circ\text{C}$ ) ,  $D= 0.015 \text{ m}$  (diameter of copper tube).



**Fig. 1.** Complete 3D model of TES with heat exchanger tube.

The geometrical structure considered for the present study is shown in Figure 1. It was created using Solid works modelling software. In this design, minimum dimensions and

parameters are considered in such a way it can boil only 1 kg of pure water to make it more simple and economic.

## 2.2 Boundary conditions

The main boundary condition of this experiment excludes any heat flux from other sources except heat from the heat transfer fluid (HTF) in the heat exchanger tube (HET). It was assumed that heat was carried out through the HTF at temperature of 500 to 600°C. All the walls are treated as adiabatic walls to avoid heat loss. To avoid material transfer between PCM and air, the interface domain is considered as a wall. The initial temperature was set to room temperature. The side wall of HET provide heat flux for HTF. The domain is simplified by cutting it into half by using the symmetry assumption between all four directions. The surface of the tank walls are considered insulated. This can be achieved by applying the heat flux value equals to zero. Located at the bottom of the HET, the HTF flows upwards in the tube. The temperature of HTF is maintained about 350°C. This is the highest melting point of the PCMs to be tested. The gauge pressure is considered as zero bar for outlet boundary for the temperature output of various rate of flow of HTF in the tube. The initial part of the process is conducted at room temperature and state of the PCM is solid. Stainless steel and pure copper are the metals used for TES and HET respectively. The materials used for PCM are  $KNO_3$  and  $NaNO_3$ . The mass, momentum and energy equation in the solution are monitored in such way the residuals are converged to a value not more than  $10^{-6}$ .

## 2.3 Governing equation

In a specific range of temperature, problems in solidification or melting can be solved using FLUENT simulation. FLUENT has the option to track the liquid-solid front explicitly and enthalpy-porosity formulation. In this closed system, the liquid-solid mushy zone or porous zone was neglected due to the fluid material of PCM being fixed in a closed energy storage. Therefore, there is no additional momentum equation added into the simulation. The flow domain is separated into discrete cells and analysis is done by finite volume method. Solving the governing equations are controlled in the point of discrete cells. The partial differential equations were evaluated as algebraic equations using the finite volume method.

The list of differential and algebraic equations can be written as in Eqs. (6) – (14):

Continuity Equation:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} [\rho u_j] = 0 \quad (6)$$

Momentum Equation:

$$\frac{\partial}{\partial t} (\rho u_i) + \frac{\partial}{\partial x_j} [\rho u_i u_j + p \delta_{ij} - \tau_{ij}] = 0 \quad (7)$$

Energy Equation:

$$\frac{\partial}{\partial t} (\rho e_0) + \frac{\partial}{\partial x_j} [\rho u_j e_0 + u_j p + q_j - u_i \tau_{ij}] = 0 \quad (8)$$

Stokes law was assumed for mono-atomic gases with Newtonian fluid. Hence, the viscous stress is as follows:

$$\tau_{ij} = 2\mu S_{ij} \quad (9)$$

The trace-less viscous strain-rate:

$$S_{ij} = \frac{1}{2} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{1}{3} \frac{\partial u_j}{\partial x_k} \delta_{ij} \quad (10)$$

Fourier's law heat-flux:

$$q_j = -\lambda \frac{\partial T}{\partial x_j} = -C_p \frac{\mu}{Pr} \frac{\partial T}{\partial x_j} \quad (11)$$

Laminar Prandtl number Pr is:

$$Pr = \frac{C_p \mu}{\lambda} \quad (12)$$

An equation of state is necessary to close these equations. An ideal gas was assumed so that the following equation to be valid:

$$\gamma = \frac{C_p}{C_v}, \quad P = \rho RT, \quad e = C_v T, \quad C_v - C_p = R \quad (13)$$

where,  $C_v$ ,  $C_p$  and R are constant.

Hence the total energy:

$$e_0 = e + \frac{U_k U_k}{2} \quad (14)$$

## 2.4 Numerical simulation

The 3D geometry is then exported into the simulation commercial computer software. It is used to simulate the mechanism of heat exchange and the melting distribution of PCM. This commercial simulation software provides a step-by-step workspace, so that the analysis cannot be proceeded if the previous step is not complete.

By using a tetrahedral mesh with independent on solid interface, the model is discretized. Solid works file is exported in SAT format to make it easier to edit in Ansys. The setting of Ansys Fluent for numerical solutions are listed in this section. The geometry of the setup has undergone various checks on the mesh through Fluent and the report has appeared in the console. This is done to make sure that the minimum value of the mesh is always positive and the values are selected in the specified range. Once checking the grid of mesh model is done, the required units are selected. The general setting shows the solver settings and discretization details such as equation required for solving the problem and additional physics applications required regarding the solution of the simulation. The Table 1 provides the basic solver settings.

**Table 1.** Basic solver settings.

Model	Settings
Space	3D
Solver	Pressure based
Time	Unsteady, 1st-Order explicit
Viscous	Laminar
Heat transfer	Enable
Solidification and Melting	Enable

Solidification and melting is enabled in order to satisfy phase change condition. The value of mushy zone is neglected assuming that the PCM is already in the TES.

The properties of the materials under test are specified including the thermo-physical properties. Stainless steel and copper are the metals used for TES container and heat exchanger tube, respectively.  $KNO_3$  and  $NaNO_3$  are the PCM materials tested in this work and air is used as forced convection fluid. The settings provide for PCM are given in Table 2.

**Table 2.** Thermo-physical properties of major material in the simulation.

Property	Units	Method	KNO <sub>3</sub>	NaNO <sub>3</sub>
			Value(s)	
Density	kg/m <sup>3</sup>	Piecewise continuous	$\rho = 2293.6 - 0.7497T$	
Specific Heat	J/kgK	Piecewise continuous	$C_p = 5806 - 10.8337T + 7.2413 \times 10^{-3}T^2$	
Thermal Conductivity	w/mK	constant	0.5	
Viscosity	kg/ms	Piecewise continuous	$\mu = 0.4737 - 2.297 \times 10^{-3} + 3.731 \times 10^{-6}T^2 - 2.019 \times 10^{-9}T^3$	
Melting Heat	kJ/kg	constant	116	174
Solidifying Temperature	K	constant	600	573
Liquefying Temperature	K	constant	610	583

XCEL THERM MK1 is a commercial liquid by Radco used as HTF in the heat exchanger tube. The setting and properties of the HTF are given in Table 3.

**Table 3.** Thermo-physical properties of XCEL THERM MK1 as HTF [2].

Property	Units	Method	Value(s)
Density	kg/m <sup>3</sup>	constant	695.3
C <sub>p</sub> (Specific Heat)	J/kg-K	constant	2.62
Viscosity	cSt	constant	0.146
Thermal Conductivity	w/m-K	constant	0.076

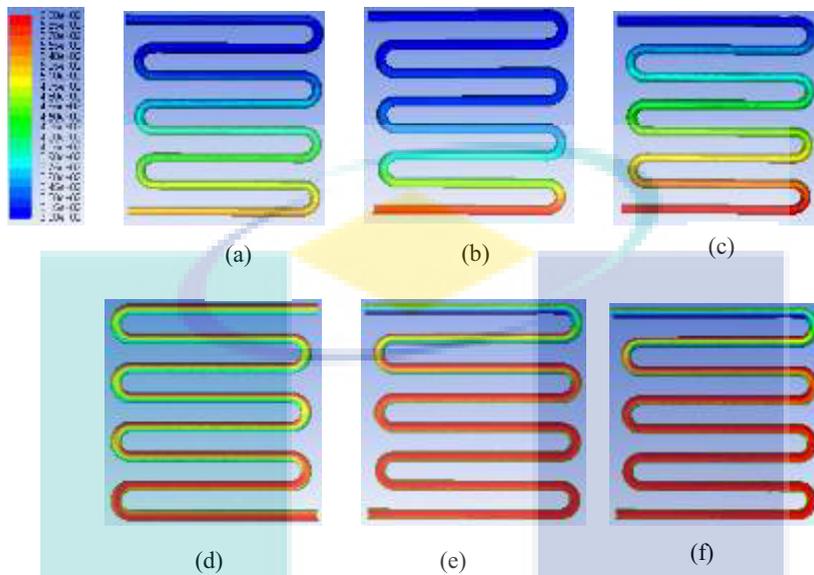
### 3 Results and discussion

This section discusses the results of the design and simulation using Ansys Fluent software. Besides, It also discusses the trend of the observation and the reason behind it. Simulation results will focus on the heat transfer fluid velocity, type of phase change material that may affect the heat transfer rate of the thermal energy storage tank, and the melting phase distribution of phase change material.

#### 3.1 Effect of heat transfer fluid velocity

The simulation of thermal energy storage is assumed to undergo a laminar fluid flow. The heat exchanger tube with diameter of 0.015 m is used in this work. Heat transfer fluid with density of 695.3 kg/m<sup>3</sup> (based on the online database) and dynamic viscosity of 6.88347 × 10<sup>-7</sup> kg/m·s is considered for this experiment [20]. For fluid flow to be laminar, the Reynolds number should be less than 2300, the Reynolds number in this simulation is therefore considered to be 2200. The highest velocity of the heat transfer fluid at laminar state is about 0.15 m/s. This is calculated using Reynolds number formula, Eq. (15). The maximum and minimum temperatures of the PCM are calculated at specific time interval of 30 min for particular fluid velocity. The simulation is carried out for different values of fluid velocities as follows 0.01 m/s, 0.035 m/s, 0.07m/s, 0.1 m/s, 0.15 m/s and 0.2 m/s. These values of velocities were inserted into the simulation to investigate the relationships.

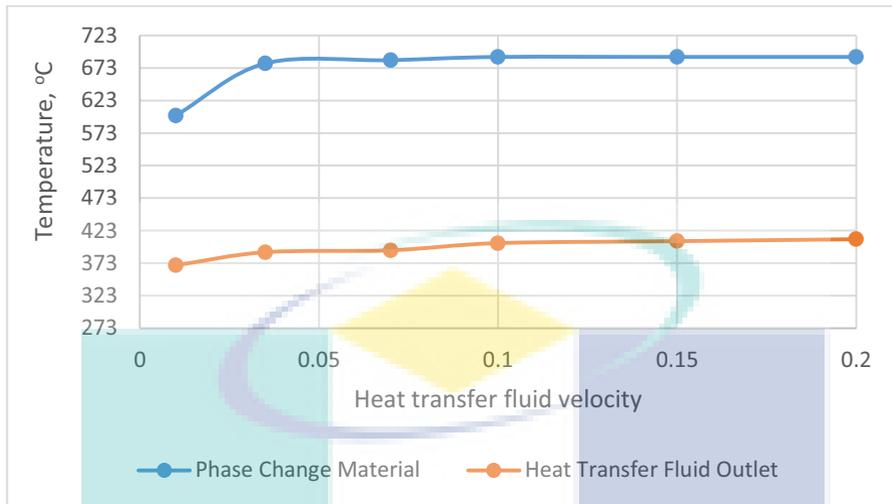
$$Re = \frac{\rho VD}{\mu} \quad (15)$$



**Fig. 2.** Temperature distribution in K for different heat transfer fluid velocities (a) 0.01 m/s; (b) 0.035 m/s; (c) 0.07 m/s; (d) 0.1 m/s; (e) 0.15 m/s; (f) 0.2 m/s.

The minimum and maximum temperature yields at specific time of 30 min are 300 K and 600 K, respectively. The effect of the heat transfer fluid velocity on the temperature of both the heat transfer fluid pipe and on the PCM are depicted in Figures 2 and 3. As shown in Figure 2, the temperature distribution contour is roughly almost the same for both fluid velocities (e) 0.15 m/s and (f) 0.2 m/s. This is probably because, the velocity of heat transfer fluid turns into turbulence state above 0.15 m/s. As stated earlier, the FLUENT simulation software was set to be in laminar model only, therefore the simulation will not proceed if the heat transfer fluid model enter the turbulence state. The results appeared to be roughly the same because the software will only simulate within laminar stage. The rate of heat transfer is directly proportional to mass flow rate. It also states that mass flow rate is directly proportional to fluid velocity. Thus, it can be accepted that the higher the heat transfer fluid velocity, the higher the rate of heat transfer. This happened because, when the fluid in tube is in high velocity, more new and hot fluid from solar collector flows into the tube that replaces comparatively cooler fluid in the tube. At the end, the temperature of the PCM will be higher as the heat transfer fluid transfers more heat to the PCM. Therefore, the fluid velocity at 0.15 m/s should be the optimum velocity for the thermal energy storage tank design.

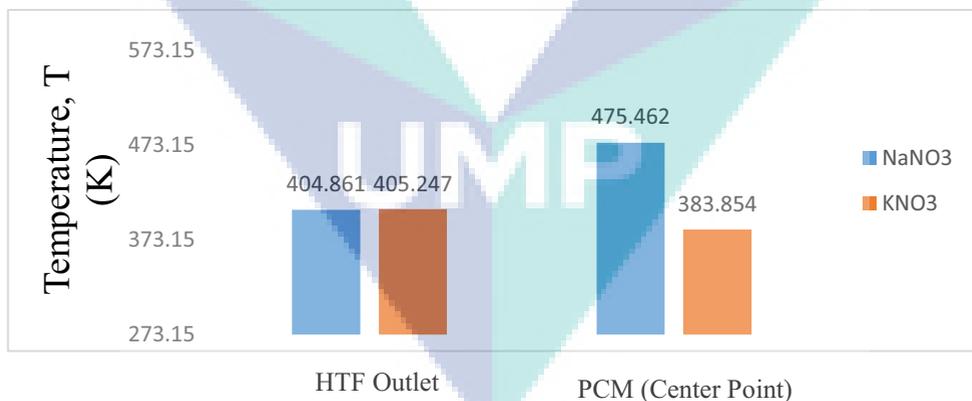
On the other hand, the temperature of the PCM is observed to be less effected with the heat transfer fluid velocity. The effect is only visible from 0.01-0.035 m/s. Then if become constant from 0.035- 0.2m/s. This is in contrary to the report by Ogoh and Groulx [17]. However, the report by Ogoh and Groulx is based on turbulent modeling and with various fin spacing and the PCM is medium temperature heat storage material. Therefore, the model should be extended to the turbulence so that full picture of the simulation could be seen.



**Fig. 3.** Effect of heat transfer fluid velocity on the temperatures of the phase change material and the HTF outlet.

### 3.2 Effect of phase change material type

In the current study, the effect of PCM types on the melting rate during the heat charging of the thermal energy storage is investigated by taking sodium nitrate salt ( $\text{NaNO}_3$ ) and potassium nitrate salt ( $\text{KNO}_3$ ). These two PCMs are selected to study the effect of temperature for different fluid velocity in HTF. Different types of PCMs have their own physical and thermal properties (Table 2) and those properties decide the rate of temperature distribution during heating process.



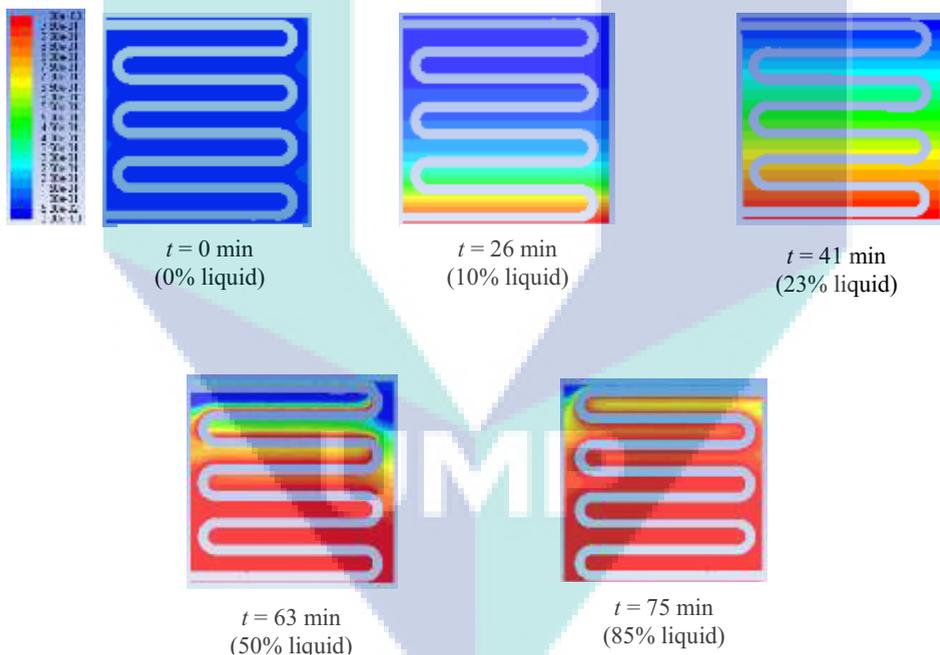
**Fig. 4.** Temperature of heat transfer fluid and PCM for different types of PCMs.

As shown in Figure 4, the temperature of heat transfer fluid outlet are about the same for both types of PCMs. However, if the analysis focuses on the center point of the PCM temperature, the temperature of the sodium nitrate salt was higher than potassium nitrate salt about  $92^\circ\text{C}$ . This result attributed to the latent heat of the sodium nitrate is higher than potassium nitrate salt. Thus, the sodium nitrate salt is better as compared to potassium nitrate salt to be used as phase change material in this thermal energy storage tank design.

### 3.3 Melting phase rate of PCM

From the result of simulation, the melting rate of the PCM was investigated. At the room temperature the initial condition of the PCM was solid. Minimum HTF inlet velocity of the laminar flow that has been considered for modelling was the fluid velocity in this case. The simulations provided detailed phase distributions of PCM. The liquid fraction is labelled from the scale 0 (blue contour) to 1 (red contour). In which '0' indicates the solid state and '1' indicates fully liquid state.

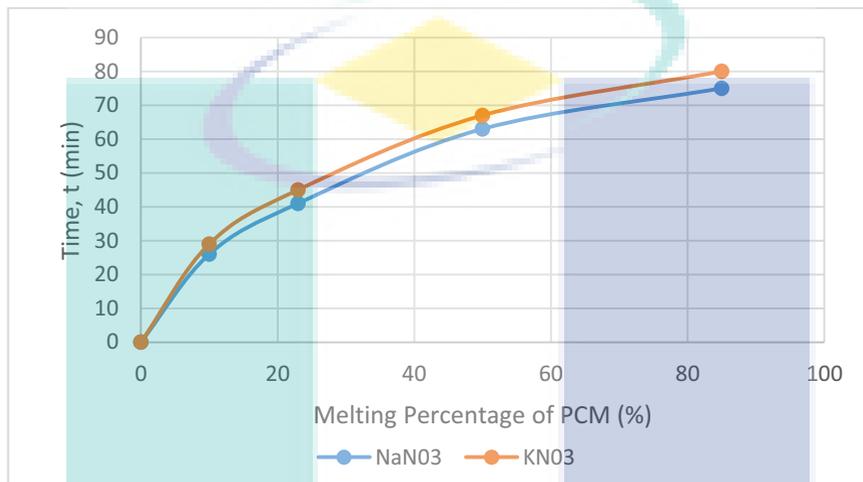
The liquid fraction contour phase distribution is non-uniform in PCM due to very low thermal conductivity and poor heat distribution of HTF in the heat exchanger tube. Heat is distributed non-uniformly along the heat exchanger tube from the bottom (inlet) to the top (outlet). When the temperature at the inlet is higher than the outlet, then the PCM is likely to melt from the inlet level. That is the starting zone of melting process. The conduction of heat transfer is prevailed in the system from the beginning of the process until PCM starts to change its phase. After the PCM starts melting then both heat conduction from HTF and natural convection in the liquid PCM is act in the system. The more progress in melting process is caused by natural convection. So, as the convection process increases then rate of melting also increases.



**Fig. 5.** Liquid fraction of PCM melting phase distribution.

Figure 5 shows the variation of liquid fraction contour phase distribution with time for  $\text{NaNO}_3$ . The variation of liquid fraction indicates that the PCM is completely solid in the starting point of simulation that is  $t=0$  min. Thermodynamic properties of the PCM showed variance with time in the simulation setup, hence the PCM starts phase change when having a high heat storage capacity. By comparing the melting phase of PCM with variance of time in Figure 5, it can be observed that the bottom part of PCM is melted easily and quickly but much time is required to melt the PCM that are close to the container wall. This may be attributed to the gravity effect. The contour is seems to be perpendicular to the heat

exchanger tube wall due to heated moving fluid in it. At  $t=63$  min, more than 50% of the PCM is melted. The PCM was melted about more than 85% when the time reached  $t=75$  min, but unfortunately due to the limitation of this simulation, the complete melting phase of PCM seems to be difficult to achieve, Figure 5. Therefore, the final results obtained does not include complete melting state of PCM. Some results displayed in the simulation happens to differ and disturbed due to quality of mesh that can be set under limitation of the simulation software.



**Fig. 6.** Time versus PCM Melting rate for both  $\text{NaNO}_3$  and  $\text{KNO}_3$ .

The comparison between the melting percentages of the PCMs under test show that sodium nitrate melts quite faster than potassium nitrate, Figure 6. This is because the melting temperature of potassium nitrate ( $336^\circ\text{C}$ ) is slightly higher than sodium nitrate ( $308^\circ\text{C}$ ). Sodium nitrate also has a higher latent heat energy compare to potassium nitrate that enable to absorb and store more heat energy. In fact, thermal conductivity of nitrate salt is very low, at the beginning of the simulation, however the melting process takes quite a long time but as the time increase, the PCM will be able to absorb and store more heat energy from the heat exchanger tube because of additional heat transfer from the melted layer of the PCM.

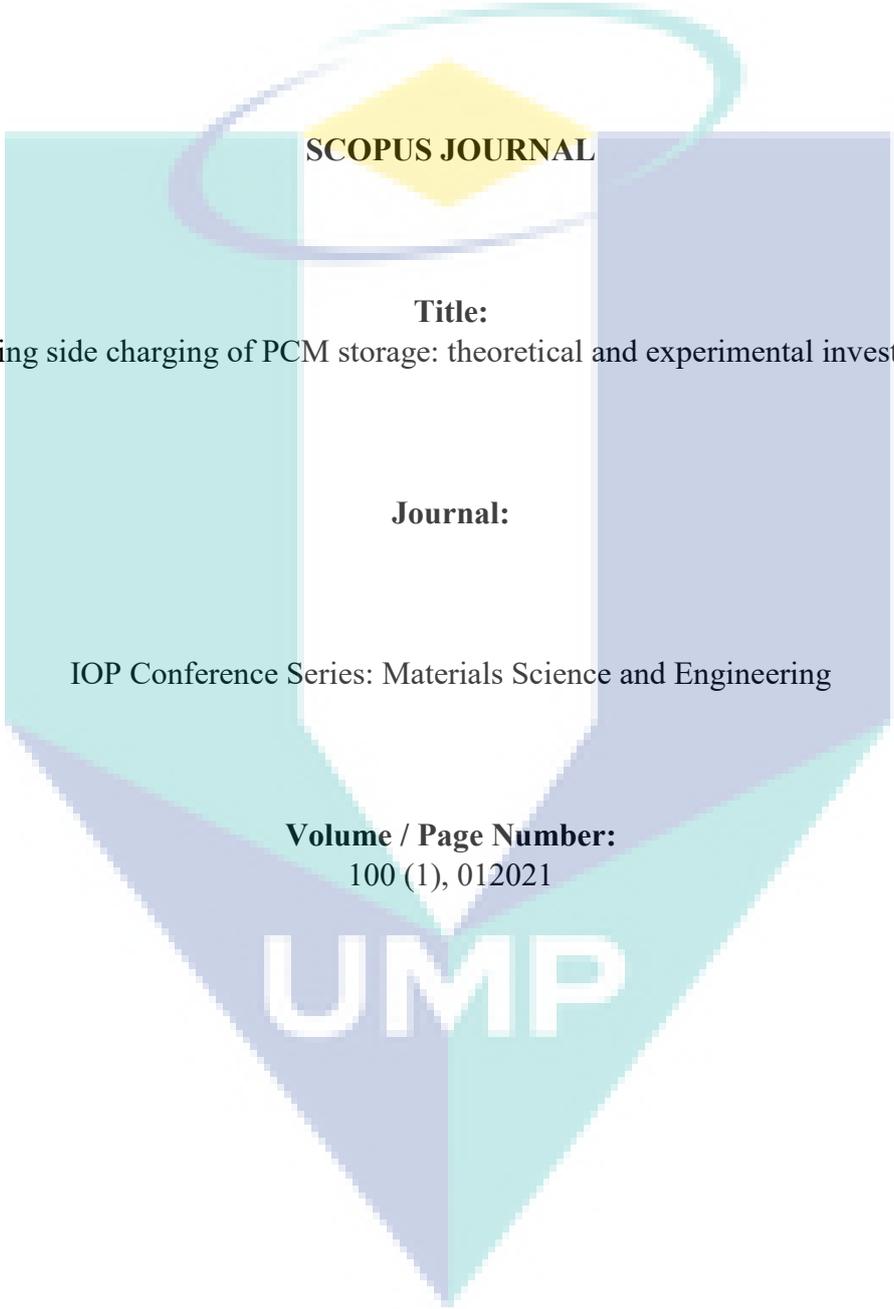
## 4 Conclusions

The PCM usage in medium range heat energy storage have a great potential in solar cooking applications. This work studied and analyzed the relationship between the HTF velocity, type of PCM and PCM heat loading process. Numerical analysis is done by using Ansys Fluent. The characteristics and applications of the PCMs are also included in this study. In this project PCMs are analyzed only during their melting process not in the solidification process (heat unloading process). This work concentrated in studying the time taken by the PCM to distribute temperature. Forced convection of air is included because the PCM is not completely filled up in the tank, thus the presence of air domain is considered in the application continuously. The maximum temperature reached, HTF velocity, melting fraction are computed in unsteady state transient analysis. PCMs of different range of temperatures can be tested in the same way for future usage in many solar applications like water heating etc.

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## CHAPTER 4



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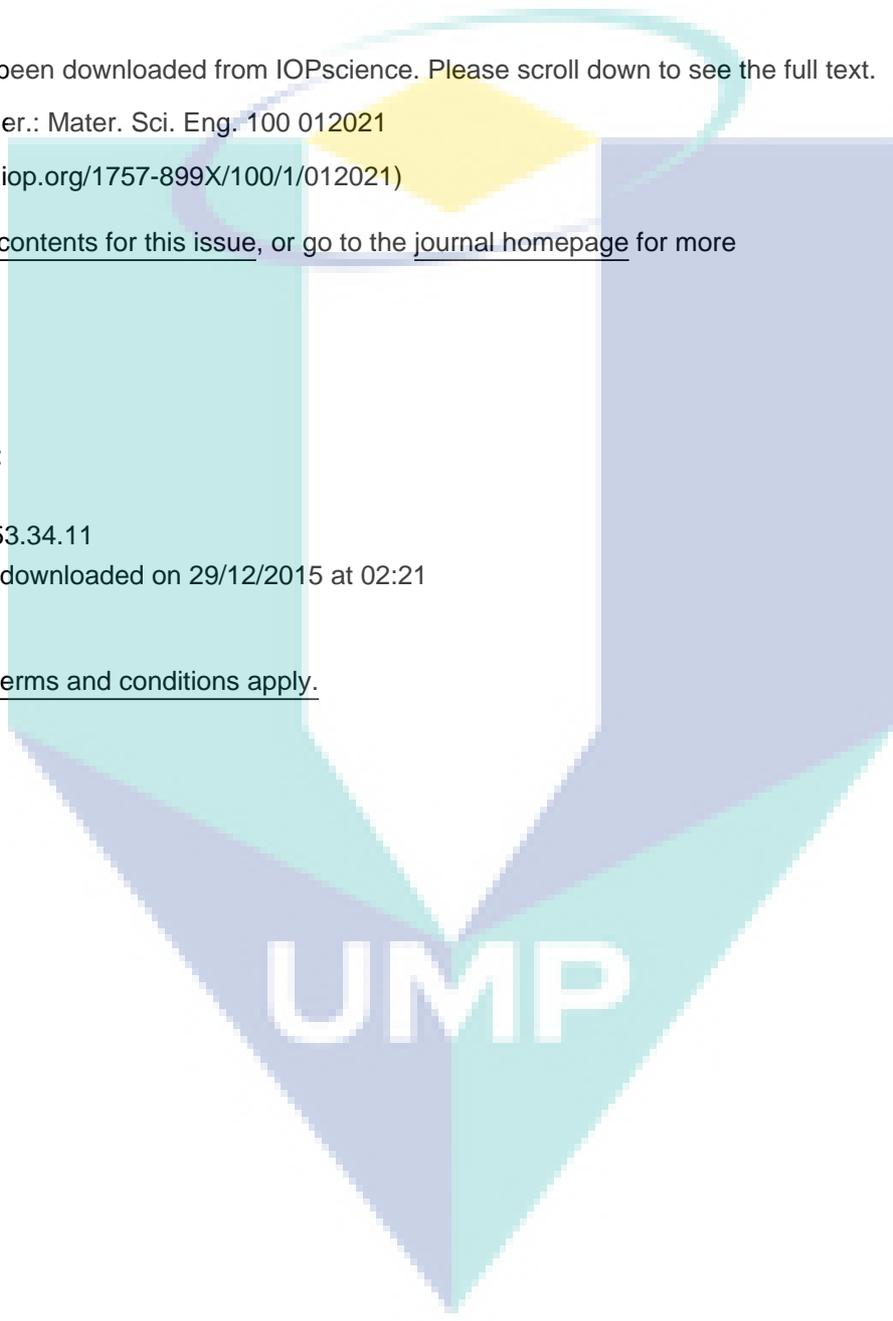
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# Preparing side charging of PCM storage: theoretical and experimental investigation

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**Abstract.** In Ethiopia, there is an abundant source of solar energy that is estimated to 5.3 kWh/m<sup>2</sup>/day. However, more than 90% of the society uses biomass as a main source of energy for cooking due to lack of technologies to convert this energy. Replacing these cooking activities by using renewable energy resources decreases pollution and reduces deforestation significantly. Using the solar energy in day time has no problem. For night time however, the system needs some kind of back-up system to make the daytime solar energy available. This back-up should have high-density energy storage and constant working temperature to perform a specific application. Latent heat storage using phase change materials (PCM) is one way of storing thermal energy. In the current study, a latent heat storage that uses a PCM material is used to store the solar energy aimed at utilizing solar energy for cooking Injera, main staple bread in Ethiopia. The PCM is a mixture of 60% NaNO<sub>3</sub> and 40% KNO<sub>3</sub> that are known as solar salts. The storage has a welded parallel aluminum fins with a gap of 40 mm in between to enhance the thermal conductivity during the charging-discharging process of the storage. The fins are extruded outside of the storage container to enable a side charging technique for the PCM. A prototype was developed with a solar salt of 17.5 kg and is tested for charging-discharging. The numerical simulation done on ANSYS and experimental results show an agreement and the system registered a 41.6% efficiency.

## 1. Introduction

Energy storage technologies have been in use for different purposes. Although, electro- chemical energy storage technologies are matured; majority of thermal energy technologies are still in their research stage. Since recently, there is a growing interest of solar thermal utilization. As a result, solar thermal storages got global attention. The two widely used heat storages in solar thermal applications are sensible and latent heat storages. These storages are used in different applications such as in drying, space heating, cooking, power generation. The temperature change in sensible heat storage comes as a result of the absorption of solar radiation by the material. On the other hand, latent heat is the energy absorbed and released by a substance during its phase change from solid to liquid, liquid to gas and vice versa.

Even though many developing countries are situated in in the solar belt (between 40° North to 40° South) that is endowed with huge solar energy potential, they are desperately in need of energy. Ethiopia, like other developing countries, is affected by shortage of energy. Consequently, biomass becomes the source of energy as the expense of deforestation and environmental impacts. The northern part of the country for example, has an average solar energy potential of more than 6.5 kWh/m<sup>2</sup>/day during the dry season and 4.634 kWh/m<sup>2</sup>/day during the rainy season [1, 2]. However, more than 90% of the region's community still depend on biomass for primary energy supply. Biomass took the lead in primary energy supply in most developing countries and majority of this primary energy is used for cooking. Cooking in biomass based energy affects children's' school time,



woman and girls health, and contributes to greenhouse gas emission, land degradation and deforestation.

The interventions of solar cookers assure safe and clean energy utilization. However, their acceptance remains limited due to their longer cooking time and dependence to the presence of the sun. The mismatch of the availability and demand for solar energy can be bridged by using thermal batteries. Naturally, cooking requires nearly isothermal heat supply. Therefore, latent heat storage using phase change materials (PCM) are ideal candidate in this regard. Although PCM materials are good solar energy batteries, their charging-discharging process is difficult due to their poor thermal conductivity nature. This paper, deals with charging-discharging of nitrate based thermal storage (mixture of 60%  $\text{NaNO}_3$  and 40%  $\text{KNO}_3$ ). This mixture has two phase change points, a solid-solid phase change at  $110^\circ\text{C}$  and a solid-liquid phase change at  $222^\circ\text{C}$ . The material absorbs solar thermal to undergo these phase changes and release the heat in the reverse process during the application. The liquid-solid phase change state gives nearly isothermal heat supply suitable for cooking.

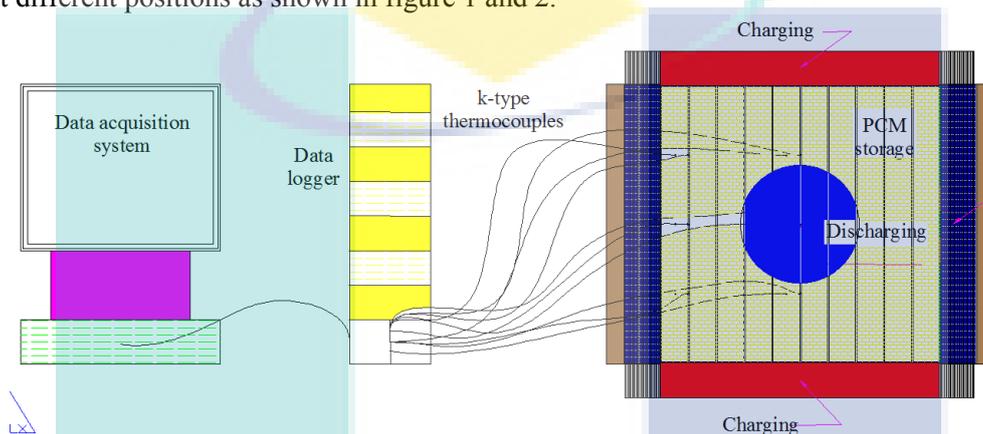
Phase change materials are good potentials to store solar energy, however, their charging-discharging techniques are premature for large-scale usage. Since recently many researches are undergoing on thermal properties of PCMs, heat transfer enhancement and design configurations of the heat storage for various end uses [3]. Cooking is one of the common applications particularly in developing countries, where it took the lion share of households energy share. Although many developing countries are found in the solar belt, there are only few solar cookers introduced in this region. The adoption and extension of solar cookers depends on its affordability, cooking speed, versatility, safety and cooking period. Although PCM materials have the potential to improve the utilization of solar energy, its technological status is at concept development and research level [4]. Some solar cookers with PCM storage enable cooking of family lunch while charging the storage and the stored heat has abled to cook dinner and the next day breakfast [5]. For example, many direct and indirect solar cookers with heat storage are installed in India and some African countries for family and community purpose [6]. Nitrate salts are suitable for high temperature isothermal applications. However, they have low thermal conductivity like other PCMs, which affects their charging-discharging process. For example, DLR test showed its usage for solar thermal power plants and process industry in the range of 2 to 100 kW at a melting temperature of  $142^\circ\text{C}$  and  $222^\circ\text{C}$  [7].

Some studies mainly focused on thermo physical properties of potential PCMs for high temperature latent heat storage [8]. Thermal reliability and stability of PCMs are the two most important factors to assure their latent heat storage. Manish and Jyotirmay have identified some of the most reliable PCMs for particular applications [9]. The solar salt PCM has a density of 1800 and 1700  $\text{kg/m}^3$  in its solid and liquid state, respectively. This density difference raises safety concerns and system challenge on how the storage charging-discharging technique was followed. Researchers by the Norwegian Science and Technology University (NTNU) have applied three different techniques to charge and discharge this PCM. While Foong used direct illumination of storage using double reflector collector, Maxim and Asfafaw used indirect charging by immersing the salt container in a hot oil bath and an aluminium block with salt cavities and steam channels, respectively [10-12]. These researches were focused to realize the use of stored solar energy for baking Ethiopia's Injera. Besides, the later author has able to bake Injera in a steam based solar stove [13]. Although, the literature shows that Injera baking is possible in the temperature range of  $180 - 220^\circ\text{C}$  [14], Asfafaw et al. [12] have shown Injera baking is possible in the range of  $130 - 150^\circ\text{C}$ . The charging time of PCMs can be improved by the thermal performance enhancement of solar collectors [15]. In addition, when a PCM is charged by using (heat transfer fluid) HTF, the inlet temperature of the HTF has greater influence over its mass flow rate in reducing the charging time [16].

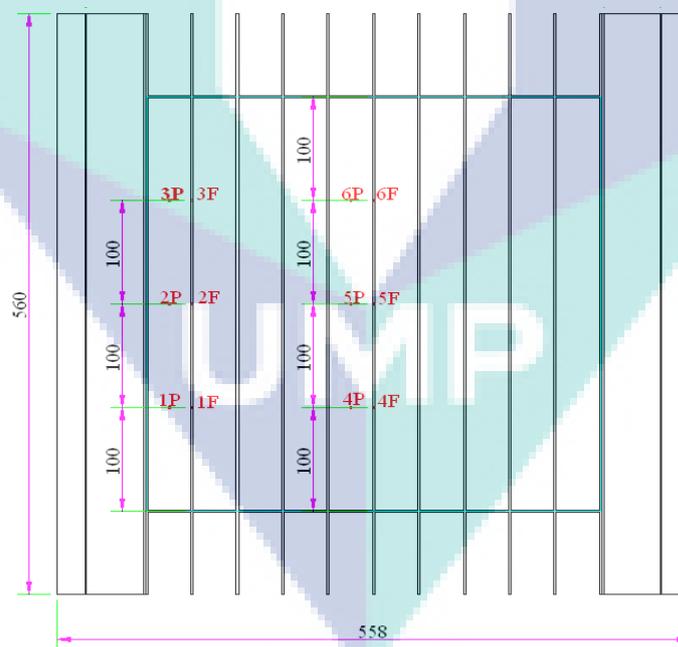
The interest of this paper lies on the design and experimentation of PCM storage capable of storing 4-5 kWh thermal energy when fully charged (up to  $250^\circ\text{C}$ ) by a side charging and top discharging technique. The outcome of this study will be implemented for solar thermal application using fixed focus offset parabolic dish concentrators. This charging technique will realize and simplify thermal system designs required for high temperature purpose.

## 2. Methodology and materials

Both theoretical and experimental methods are used to investigate the charging-discharging of the PCM Storage. The experiment is conducted in Mekelle University, Ethiopia. The geographical coordinate of the experimental location is  $13^{\circ}28.694'$  N latitude and  $39^{\circ}29.244'$  E longitude with 2,208 m above sea level [1, 2, 17]. ANSYS is used for the numerical analysis. In the experiment, about twelve K-type thermocouples are used to record continuous charging-discharging temperature of the storage at different positions as shown in figure 1 and 2.



**Figure 1.** Schematic drawing of the system set up.



**Figure 2.** Position of thermocouples.

The storage has symmetric feature on which the thermocouples are connected to twelve points. Six of them were attached to the PCM and the remaining six attached to the fins. Heat was supplied to both sides of the storage and the extruded fins conduct this heat to the PCM. The temperature development inside the storage was sensed by the thermocouples and continuously recorded every second using National Instrument's data logger and Lab view software. Lab view gives continuous

digital data and their graphical representation that help to understand how the charging-discharging process is undergoing. The simulated heat used in this study was obtained from charcoal.

### 3. System modeling

#### 3.1. Theoretical modelling

Generally, heat flows from a high temperature zone towards a lower temperature zone. In the current analysis, only conduction and radiation heat transfers are considered. The conduction and radiation heats can be calculated by using Fourier's law and Stefan-Boltzmann law as given in equation (1) and (2)

$$q = -kA \frac{dt}{dx} \quad (1)$$

$$q = \epsilon \sigma A (T_s^4 - T^4) \quad (2)$$

where  $q$  is the net rate of thermal energy,  $A$  is the radiating area,  $\sigma$  is the Stefan-Boltzmann constant ( $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2\text{K}^4$ ),  $\epsilon$  is the emissivity coefficient,  $T_s$  is surface temperature and  $T$  is the temperature of the surrounding.

The rule of conservation of energy is used to model the physical problem and analysing the heat transfer problems

$$E_{in} - E_{out} + E_{gen} = E_{stored} \quad (3)$$

where,  $E_{in}$  and  $E_{out}$  represent the amount of energy crossing into and out of the surfaces of a system,  $E_{gen}$  represents the rate of the conversion of energy from electrical,  $E_{stored}$  is the energy stored.

#### 3.2. Fin design

The fins in the current study are made from aluminium sheet of 2 mm thickness with extruded features. Consecutive fins have a gap of 38 mm, which is filled by the PCM material. Figure 3 shows the arrangement of the fins.

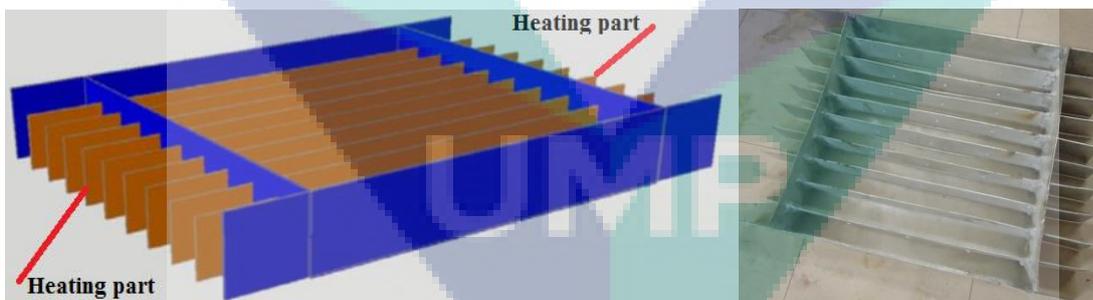


Figure 3. Aluminium fins inserted and welded to the storage.

#### 3.3. Quantifying the amount of PCM

The PCM's melting temperature is  $222^\circ\text{C}$  and it has  $108 \text{ kJ/kg}$  heat of fusion. The amount of PCM is determined based on the average household energy requirement to bake one time Injera need (about 25 Injeras). The heat required to bake a single Injera is  $239.5 \text{ kJ}$  [18]. Assuming the efficiency of the storage to be  $33.8\%$ , then the amount of energy needed is  $17,714.5 \text{ kJ}$  and then the mass of PCM is found  $17.5 \text{ kg}$  from equation (4).

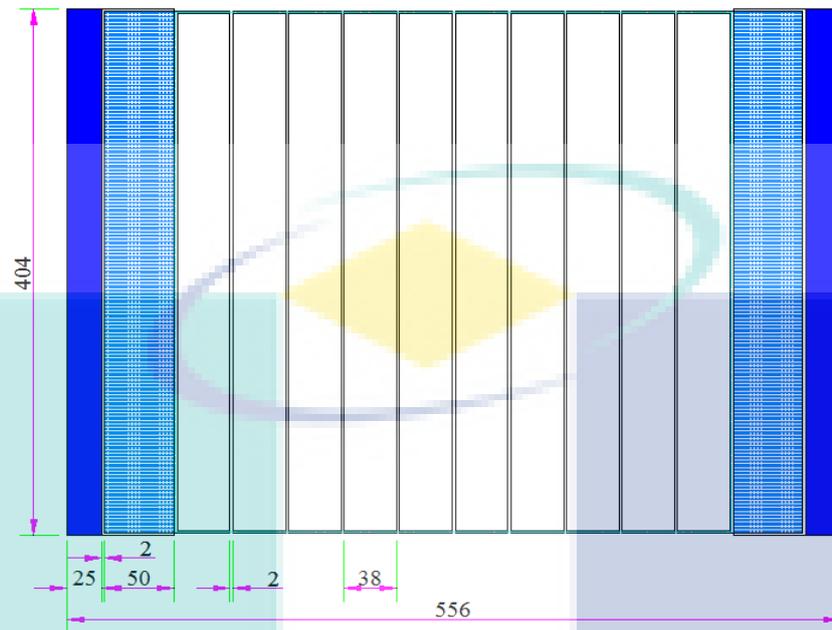
$$Q = \int_{T_i}^{T_f} m C_p dT \quad (4)$$

where  $m$  is the mass of PCM,  $dT$  is the temperature difference,

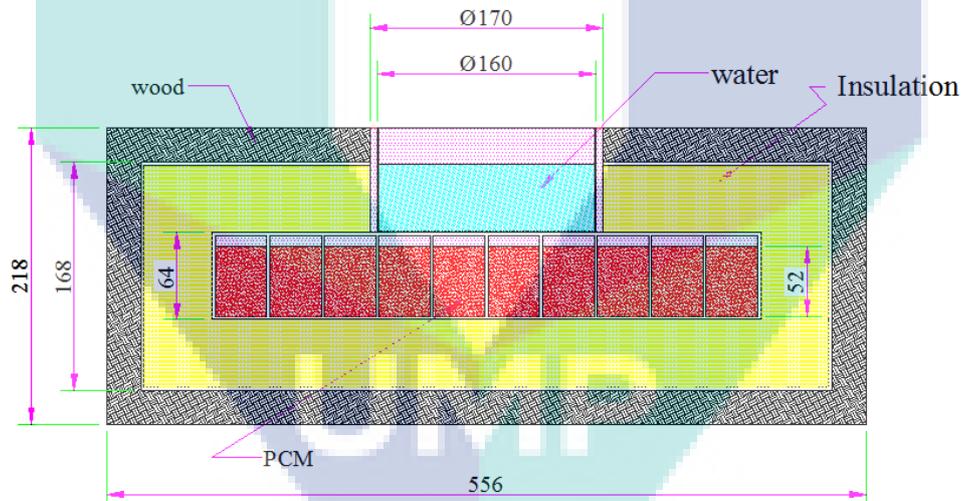
$$C_p \text{ (kJ/kg)} = \begin{cases} 0.75 & T < 110^\circ\text{C} \\ 4.2 & 110^\circ\text{C} \leq T \leq 120^\circ\text{C} \\ 1.4 & 120^\circ\text{C} < T < 210^\circ\text{C} \\ 12 & 210^\circ\text{C} \leq T \leq 220^\circ\text{C} \\ 1.6 & T > 220^\circ\text{C} \end{cases}$$

### 3.4. Modelling

The thermal behaviour of the system is simulated using ANSYS by formulating the linear thermal conduction problem using an element of plane 55 with temperature as a single degree of freedom variable at each node in the mesh and with the material properties model expressed deeply with temperature change to solve the nonlinear solution. Since transient thermal analysis uses the same elements as of the steady state thermal analysis. The nonlinear transient thermal analysis of the storage is simulated using ANSYS calculating the phase changing properties in two ways; the first one is by assigning the specific heat of the PCM at different temperatures and the second one is by giving enthalpy change through time. The phase changing properties of the solar salt is predicted by assigning specific heat of PCM versus temperature. The energy stored or released during phase change is considered by defining the enthalpy of the material as a function of temperature. Thermal conductivity, specific heat and density must be specified in thermal transient analysis. These inputs can be constant or temperature dependent. The material properties of each component are provided in the data base at different temperatures to make the analysis more accurate and are assigned from the database to the corresponding drawing of materials in the model. This transient analysis is arranged to give output with time steps until the steady state so that it can easily be compared with experimental values. The initial temperature of the PCM was assumed as 288 K for the transient analysis and heat begins to flow into the storage as soon as charging starts and after a period of time the temperature distribution throughout the PCM becomes steady. The element used in this analysis is Plane55 as shown in figure 4, an element description for a 2-D steady state or transient thermal analysis including phase change as shown in figure 4 and figure 5. The element can be used as a plane or ring element with a single degree of freedom, temperature at each node.



**Figure 4.** 2-D modeling for ANSYS charging analysis.

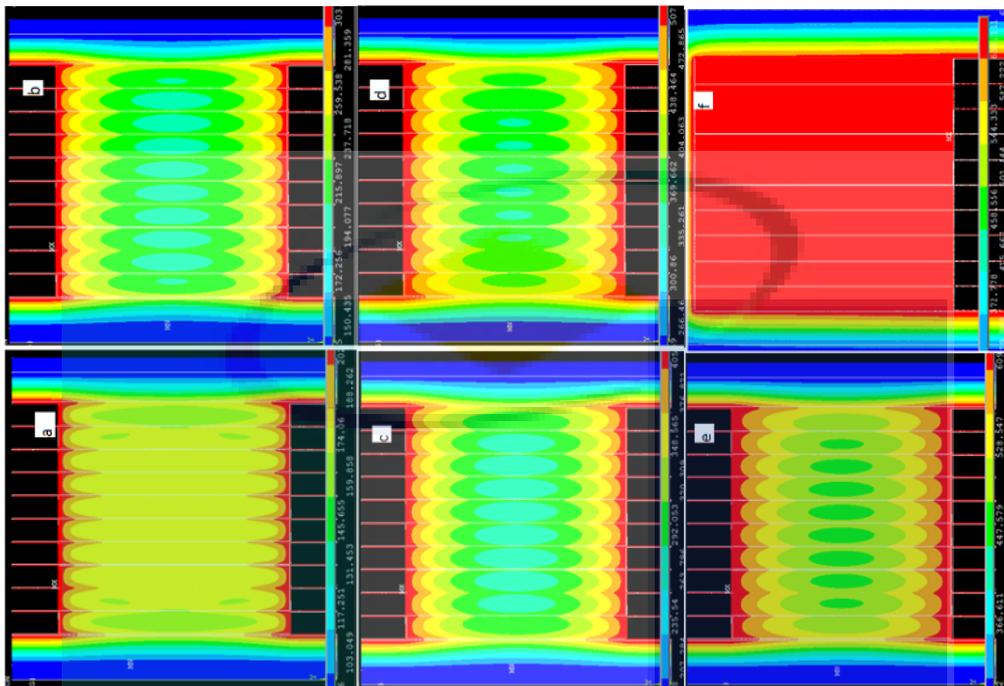


**Figure 5.** 2-D model for ANSYS discharging analysis.

## 4. Result and discussions

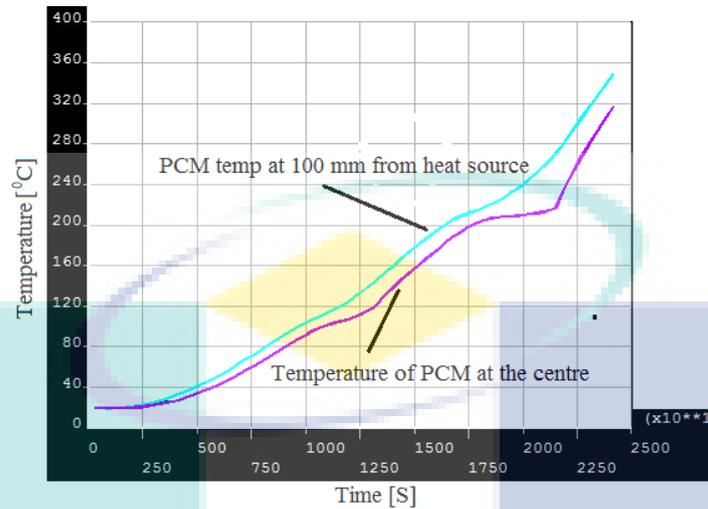
### 4.1. ANSYS results

Figure 6 shows the temperature development of the PCM during charging at a constant input temperature of 350°C. An optimized spacing between the fins gives best time in conserving the stored energy and helps to completely melt the PCM by fixing the charging temperature and time.



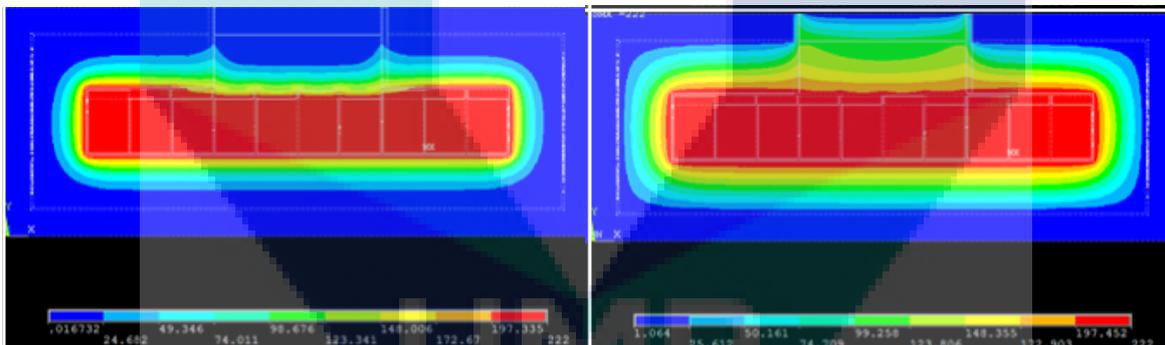
**Figure 6.** Results of ANSYS temperature contour during fin spacing design, (a) temperature contours at 2 hours of charging, (b) at 3 hours, (c) at 4 hours, (d) at 5 hours, (e) at 6 hours and (f) at steady state position.

The ANSYS result shows side charging is possible for solar collectors that can give an average temperature of  $350^{\circ}\text{C}$  at their receiver or charging sides of the storage for a consecutive eight hours. For less than  $350^{\circ}\text{C}$  input temperature to the storage charging side either it should get for more than 8 hours or there will not happen complete melting of the PCM. Optimizing the gap among the heat exchanger fins give the storage maximum efficiency by charging fully at the available time of solar energy and store for the whole night. If the gap is reduced to less than 40 mm the storage will be able to fully charged soon but the heat loss from the storage will increase due to high thermal conductivity of aluminium fins. During charging, it is expected to gain slightly higher temperature in the fins than the PCM. The PCM has zero slopes at about  $110^{\circ}\text{C}$  and  $222^{\circ}\text{C}$  where a solid-solid and solid-liquid phase change happens. Figure 7 shows results of ANSYS simulations while the storage is charging.

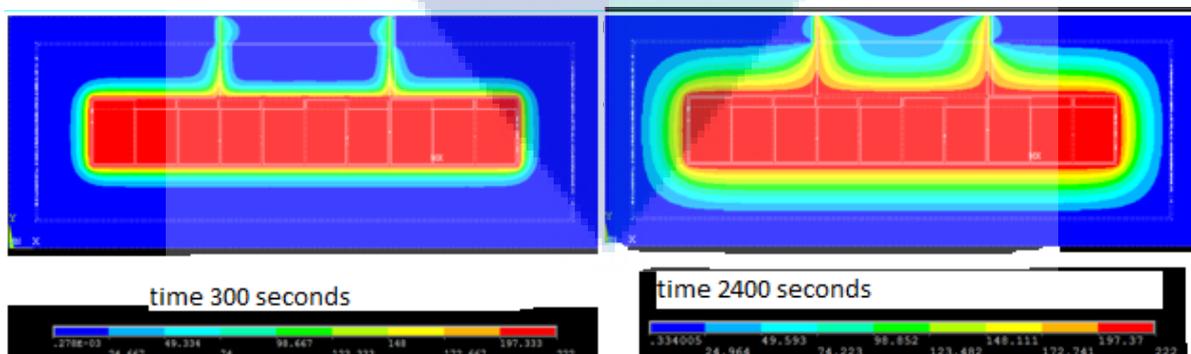


**Figure 7.** Temperature trend of PCM at the centre of the storage and 100 mm from the heat source.

Discharging of the stored heat is made using two cooking pots, which are aluminium and stainless steel pots. When the aluminium pot took 3,381 seconds to boil water to the temperature of 82.6°C, the stainless steel pot took 40,891 seconds to reach water temperature of 81.3°C. This difference happened due to the thermal conductivity of aluminium which is approximately 20 times greater than stainless steel. Figures 8 and 9 show the ANSYS simulation of water boiling on the two pots.



**Figure 8.** Temperature contour of water boiling using stainless steel pot, (a) at 300 seconds and (b) at 7200 seconds.



**Figure 9.** Temperature contour of water boiling using Aluminium pot, (a) at 300 seconds and (b) at 2400 seconds.

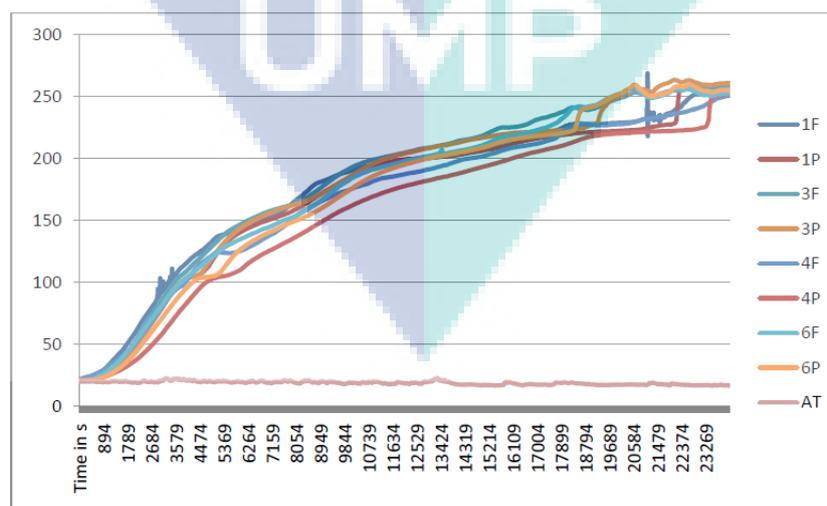
#### 4.2. Experimental results

The experiment is carried out having 7 and 10.5 kg of  $\text{KNO}_3$  and  $\text{NaNO}_3$ , respectively. The storage is a rectangular box with 400 mm length, 400 mm width and 60 mm height. The box has an allowance for expanding the PCM during melting. The storage can be considered as symmetric and representative temperature distribution can be taken from the first from left or right side and fifth fins at a distance of 100 mm from the charging side and 100 mm among the thermocouples. The thermocouples read temperatures of the fin and PCM. In order to prime a complete mixing of the two salt mixtures, the melting was performed using a digital electric furnace. After melting and mixing of the two salts pouring to the storage container is performed as shown in figure 10.

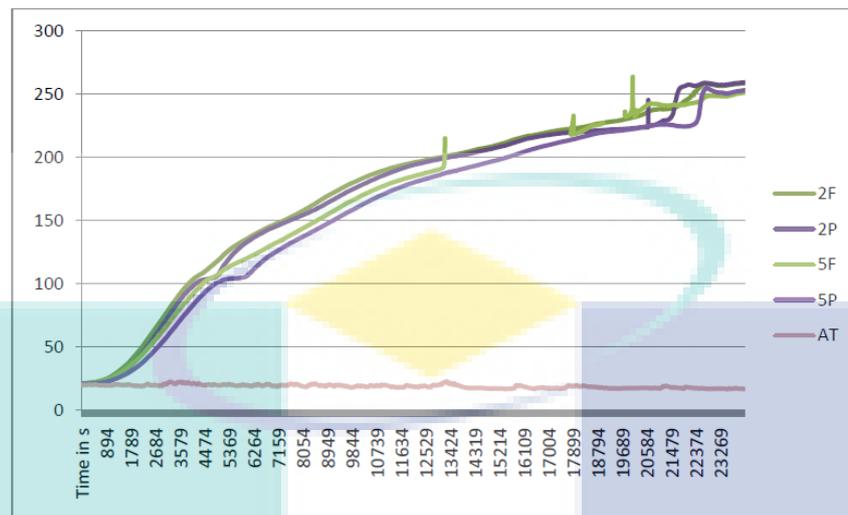
The temperature variation of the storage during charging is given in figure 11 and 12. The readings of 1F and 3F, 1P and 3P, 6P and 4P, and 4F and 6F, as given in figure 2, are expected to show the same temperature profile. In the ANSYS analysis, the same temperature contour is observed for these pairs. However, the temperature distribution of the heat source in the experimental investigation is not uniform. During ANSYS analysis a very small amount of temperature deviation is plotted between 1F and 4F, 1P and 4P, 3P and 6P, and 3F and 6F; even though these pairs are at the same distance from the heat source and are reading of the same material the slight difference comes due to the effect of insulation material.



**Figure 10.** PCMs melted and pouring.



**Figure 11.** Charging temperature distribution 100 mm from the heat source.

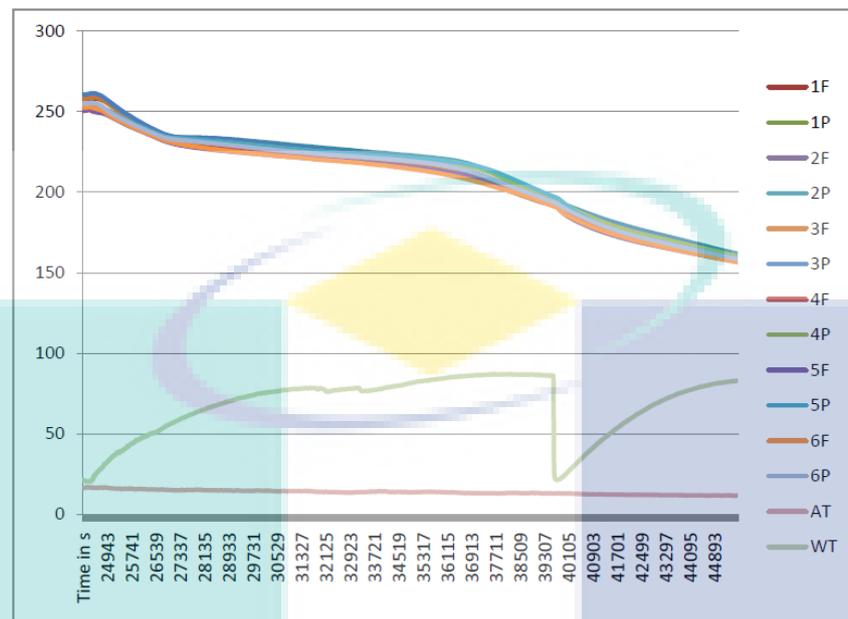


**Figure 12.** Temperature distributions at the centre of the storage during charging at a heat source of 490°C.

In the experimental study, the solid-solid phase transition temperature has happened in the range of 104 to 109°C and solid-liquid phase transition in the range of 217 to 228°C. The temperature variation from 228°C onward shows a sharp increase in its temperature. The maximum difference in temperature reading between the average readings of fins and PCM at 100 mm from heat source is 15°C and the average difference is calculated to be 7°C. Similarly, the maximum difference in average temperature reading between the fins and PCM at the centre or 200 mm away from charging side is 14°C and the average difference is calculated to be 5°C. The difference between average readings registered at PCM 100 mm away from heat source, PCM at the centre is 6°C, and the maximum temperature difference recorded is 11°C. On the other hand, the difference in the average reading between fins at 100 mm away from heat source and fins at the centre registered a maximum temperature of 17°C and the average difference is calculated to be 7°C. In all charging process the temperature of fins is greater than the PCM at the same position from the charging side.

#### 4.3. Discharging tests

During charging, there is a considerable temperature variation throughout the storage until the phase transition is completed. After this state, the temperature increases almost at the same rate in all nodes. During discharging the storage temperature decreases at constant rate and at very small difference between fin and PCM temperature. Figure 13 shows a uniform declination of the storage temperature. The temperature of water initially has increased but at about 32,123 seconds and 32,905 seconds, the cover of the pot is opened twice and it started to maintain a constant temperature. At 39,730 seconds, the water is replaced by cold tap water and at 45,665 seconds, the temperature raised to 82.94°C. The thermal degradation of the container is less than 10°C per hour. The storage is tested for thermal degradation without load and a temperature of 85-95°C is recorded after 12 hours of disconnection from heat source. Heat loss is directly proportional to the external surface area of the storage. Better heat conservation is expected if it is made in full size as the surface area to volume ratio decreases. If the storage is fully charged during day time, its temperature in the next early morning will be about 90°C which makes the storage applicable for the whole night. The thermal efficiency of the system from the experimental work is also calculated to be 41.62%.



**Figure 13.** Discharge temperature distributions of the storage during water boiling.

## 5. Conclusions

In the current study, a solar-salt with a chemical composition of 60%  $\text{NaNO}_3$  and 40%  $\text{KNO}_3$  is used to store solar thermal energy. The PCM melts at  $222^\circ\text{C}$ , which is suitable for cooking and baking applications. The charging and discharging process is investigated experimentally and numerically. Twelve K-type thermocouples were used to record continuous charging-discharging temperature of the storage at different positions. Six of them were attached to the PCM and the remaining six attached to the fins as the storage has symmetric features. The PCM charging time depends on the level of input steady heat supply (input temperature), when the input temperature changes from  $350$  to  $490^\circ\text{C}$  the charging time has reduced dramatically. The charging time difference observed in this study comes from the different natures of heat supply. The heat supply in the numerical work considers an ideal steady heat input, however, the charcoal heat was difficult to regulate. The practicality of side charging has many advantages to utilize solar energy efficiently. Hence, combination of this design concept with offset parabola will give side charging and top discharging simultaneously, which is an ideal feature for cooking and baking applications.

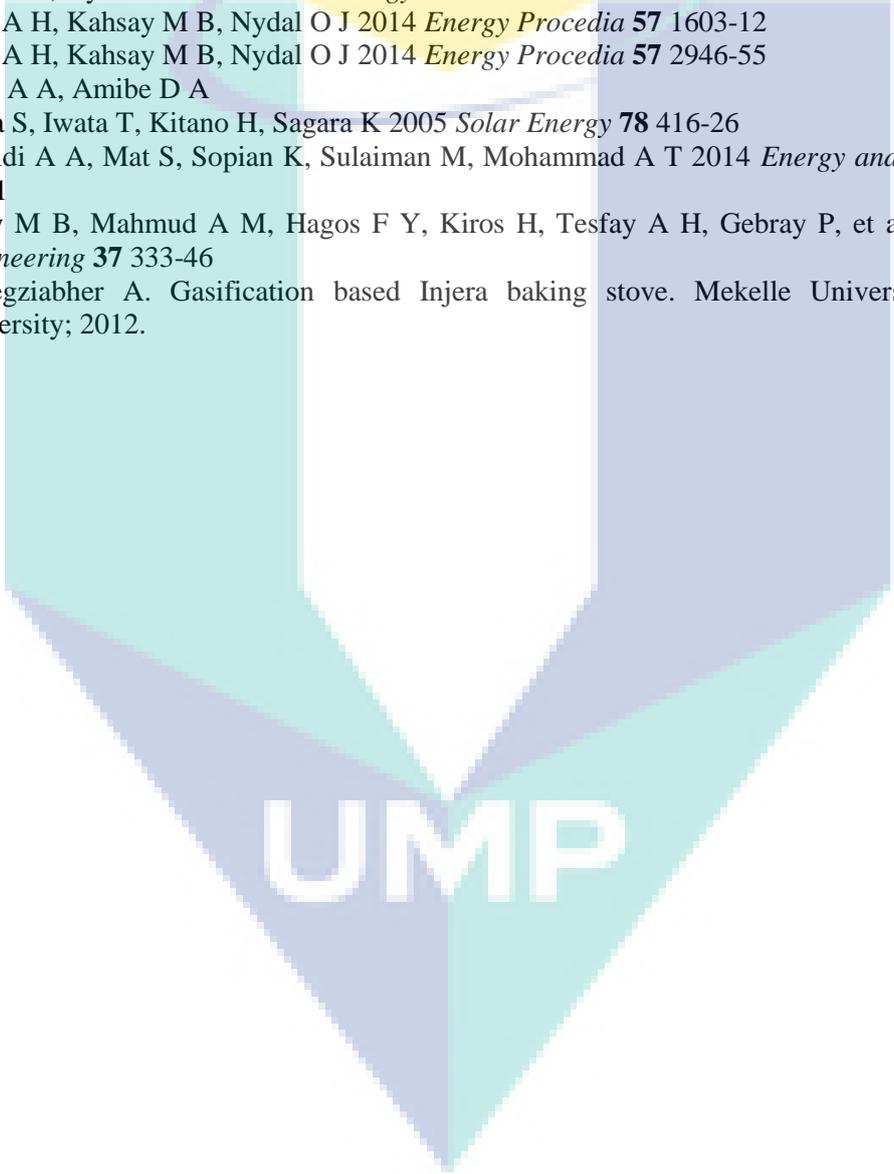
## Acknowledgments

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**CHAPTER 5**



**FINAL YEAR PROJECT**

**DESIGN AND SIMULATION OF SIDE CHARGED PHASE CHANGE  
MATERIAL FOR ENERGY STORAGE IN CONCENTRATING SOLAR  
THERMAL COOKING STOVE**

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MA11131**

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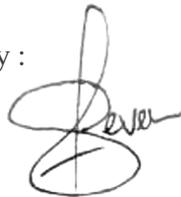
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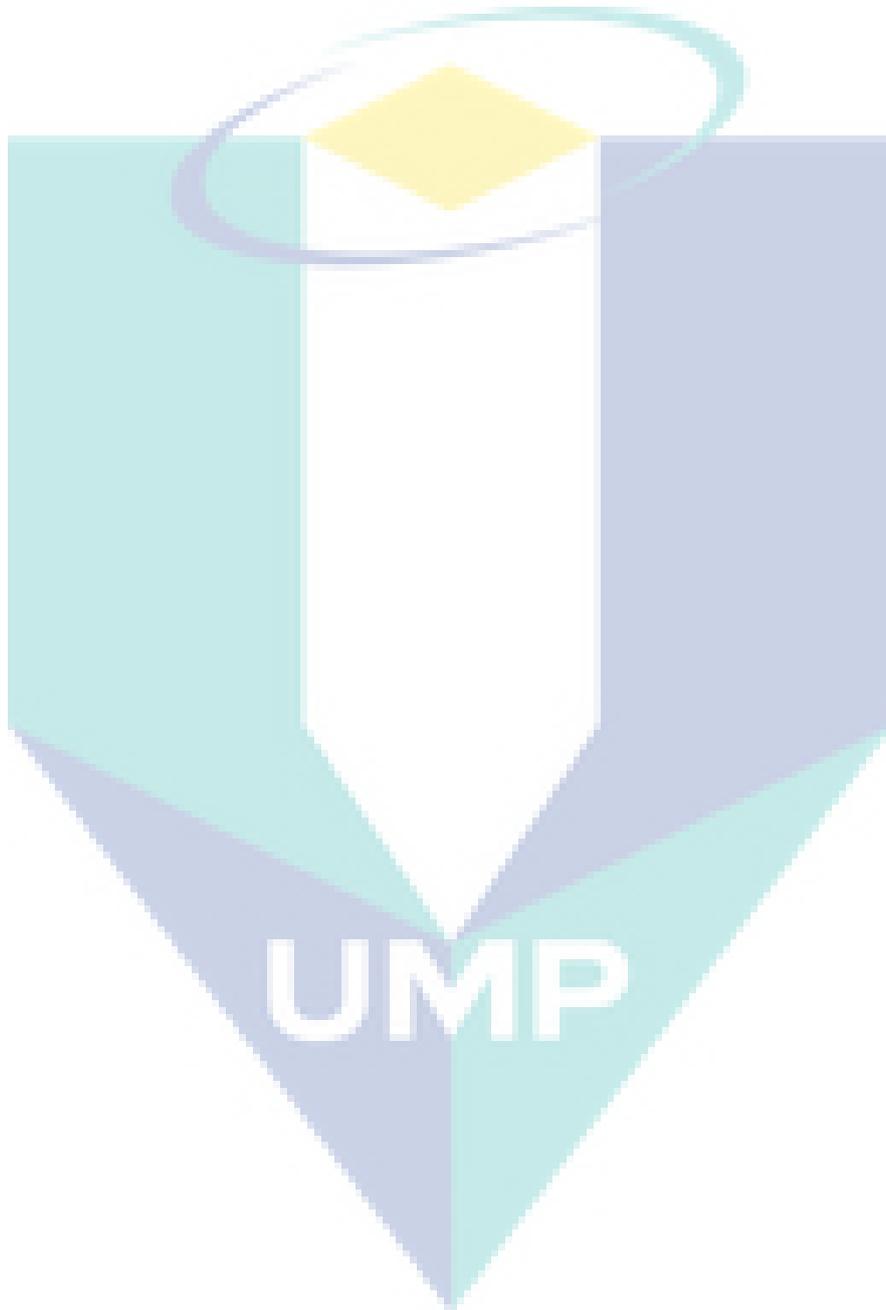


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DESIGN AND SIMULATION OF SIDE CHARGED PHASE CHANGE MATERIAL  
FOR ENERGY STORAGE IN CONCENTRATING SOLAR THERMAL COOKING

STOVE

ANG CHAN MUN

This thesis submitted in fulfillment of the requirements for the award of Bachelor degree of  
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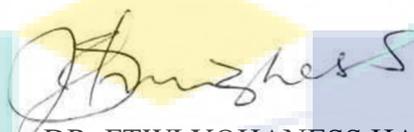
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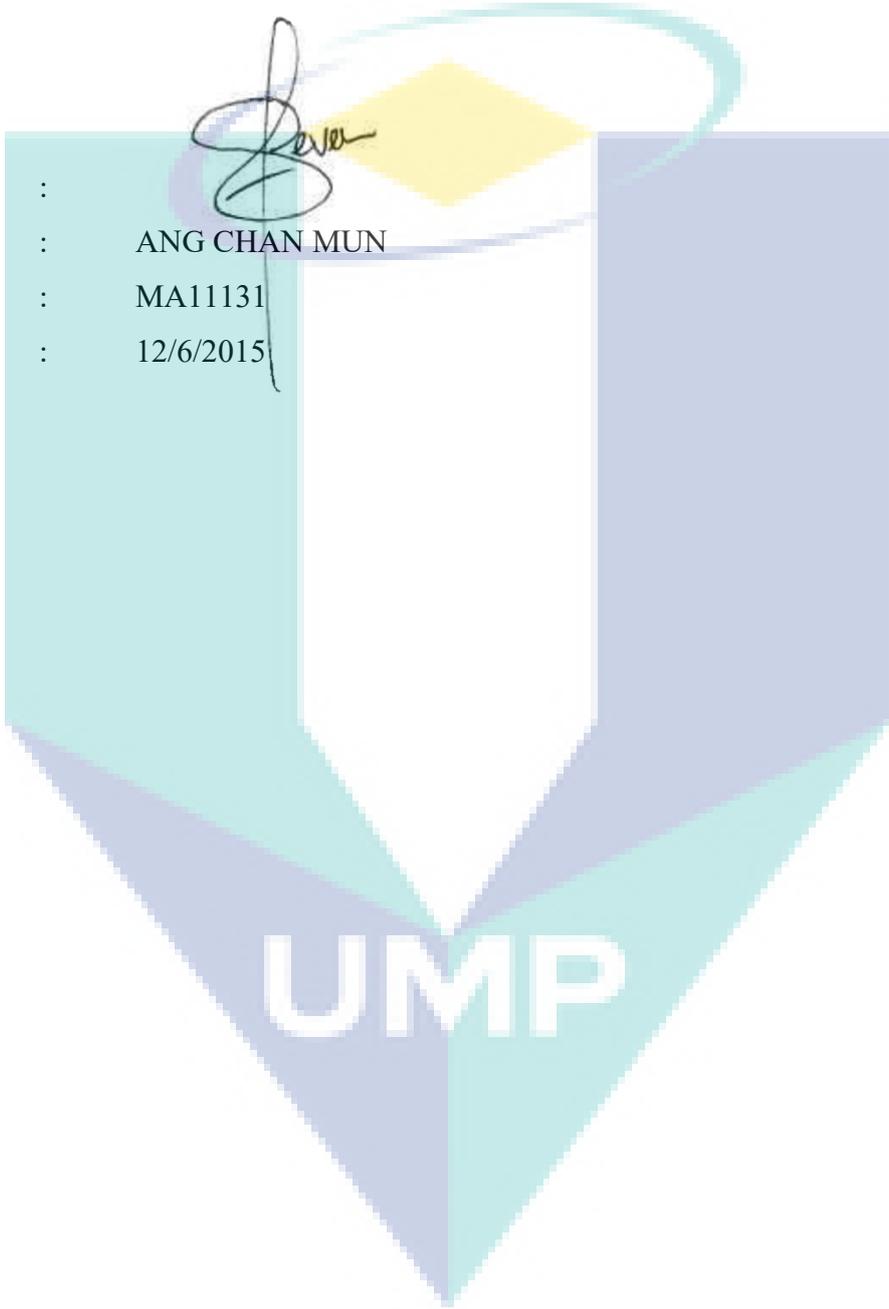
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## STUDENT'S DECLARATION

I hereby declare that that the work in this thesis is my own except for quotation and summaries which have been duly acknowledged. The thesis has not been accepted for any degree and is not concurrently submitted for award of other degree.

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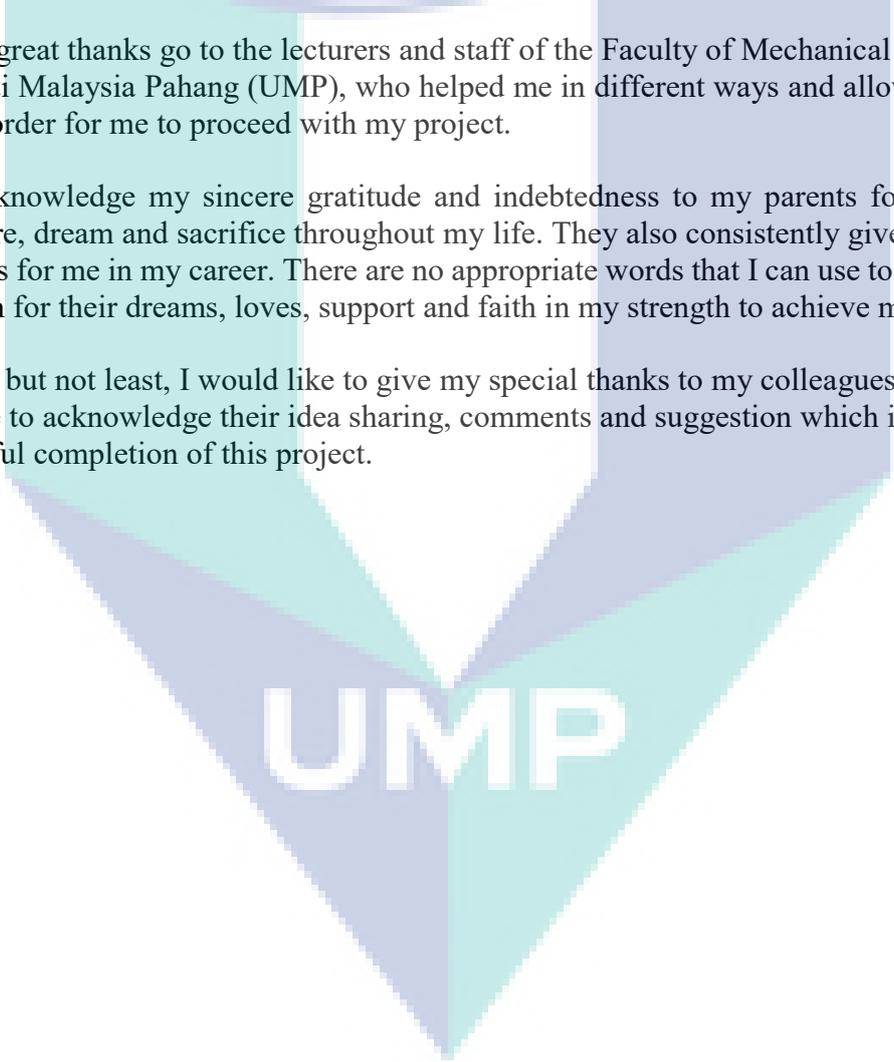
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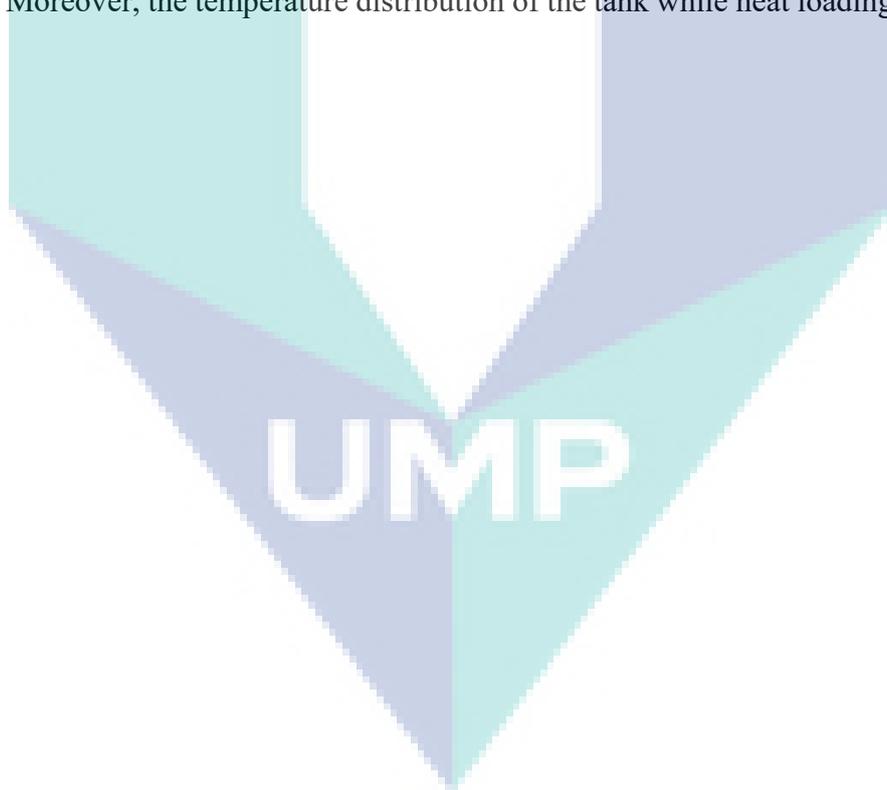
I acknowledge my sincere gratitude and indebtedness to my parents for their love, concern, care, dream and sacrifice throughout my life. They also consistently give encourages and supports for me in my career. There are no appropriate words that I can use to describe my appreciation for their dreams, loves, support and faith in my strength to achieve my goals.

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## ABSTRACT

A thermal energy storage using phase change material (PCM) is called as latent heat storage. PCM can absorb and release heat energy by changing its state. The latent heat can be stored for later used such as cooking in the evening. However, energy storage using PCM was still in development and the heat transfer using different parameters require further study. This project is focused on designing a thermal energy storage model using PCM as medium and apply simulation on it. The solid three-dimensional modeling of the tank was developed using computer aided drawing software. Tank materials such as stainless steel, aluminium and copper tube were used in thermal energy storage design. Heat transfer fluid was using XCEL THERM MK1 and types of PCM used was sodium nitrate and potassium nitrate salt. The analysis was then performed by ANSYS CFX simulation software. The simulation steps to study the temperature distribution using different tank configurations was shown. The simulation was run using different quality of meshes and obtained mesh dependency of 0.26%, meaning that the simulation is not mesh dependent. Based on the results, the design with 4 aluminium fins (90 mm fins spacing) got higher PCM temperature than other fin configurations. Among five different inlet fluid velocities, inlet fluid velocity of 0.168 m/s in the copper tube under laminar state was the optimum for this parameter. For PCM price and latent heat in this paper, it was found that sodium nitrate ( $\text{NaNO}_3$ ) has a lower cost and higher latent heat than potassium nitrate salt ( $\text{KNO}_3$ ). Therefore, the thermal energy storage was designed using suitable PCM as medium. Moreover, the temperature distribution of the tank while heat loading was studied.



## ABSTRAK

Penyimpanan tenaga haba yang menggunakan bahan perubahan fasa (PCM) dipanggil sebagai penyimpanan haba pendam. PCM boleh serap serta membebaskan tenaga haba dengan menukar keadaan. Haba pendam boleh disimpan untuk masa lain digunakan seperti memasak pada sebelah petang. Walau bagaimanapun, penyimpanan tenaga menggunakan PCM masih dalam pembangunan dan pemindahan haba menggunakan parameter yang berbeza memerlukan kajian lanjut. Projek ini memberi tumpuan kepada mereka bentuk model penyimpanan tenaga haba menggunakan PCM sebagai kandungan dan menggunakan simulasi di atasnya. Pepejal model tiga dimensi tangki dilukis dengan menggunakan perisian komputer lukisan. Bahan tangki seperti keluli tahan karat, aluminium dan tiub tembaga telah digunakan dalam reka bentuk penyimpanan tenaga. Cecair pemindahan haba telah menggunakan XCEL THERM MK1 dan jenis PCM yang digunakan adalah natrium nitrat dan garam kalium nitrat. Analisis ini kemudian dilakukan oleh perisian simulasi ANSYS CFX. Langkah-langkah simulasi untuk mengkaji taburan suhu menggunakan konfigurasi tangki yang berbeza ditunjukkan. Simulasi yang dijalankan menggunakan kualiti mesh yang berbeza dan memperolehi pergantungan mesh pada 0.26%, yang bermaksud bahawa simulasi itu tidak bergantung pada mesh. Berdasarkan keputusan yang didapati, reka bentuk dengan 4 sirip aluminium (90 mm sirip jarak) mendapat suhu PCM lebih tinggi daripada konfigurasi sirip lain. Antara lima halaju bendalir masuk yang berbeza, salur masuk halaju bendalir daripada 0,168 m / s dalam tiub tembaga di bawah keadaan lamina adalah optimum untuk parameter ini .. Harga PCM dan haba pendam dalam kertas ini, didapati bahawa natrium nitrat ( $\text{NaNO}_3$ ) mempunyai harga yang lebih rendah dan haba pendam yang lebih tinggi daripada garam kalium nitrat ( $\text{KNO}_3$ ).



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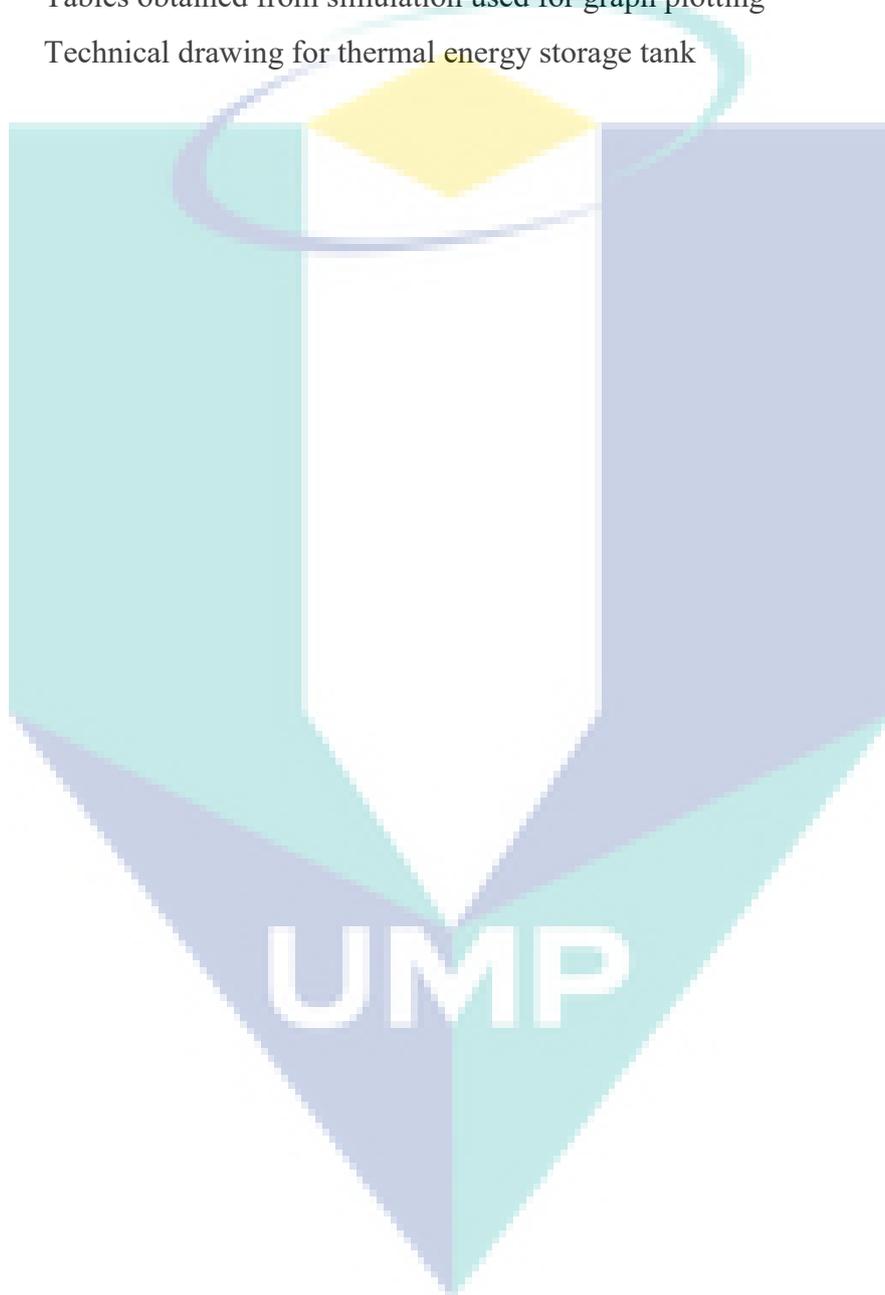
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## CHAPTER 6

### CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 CONCLUSIONS

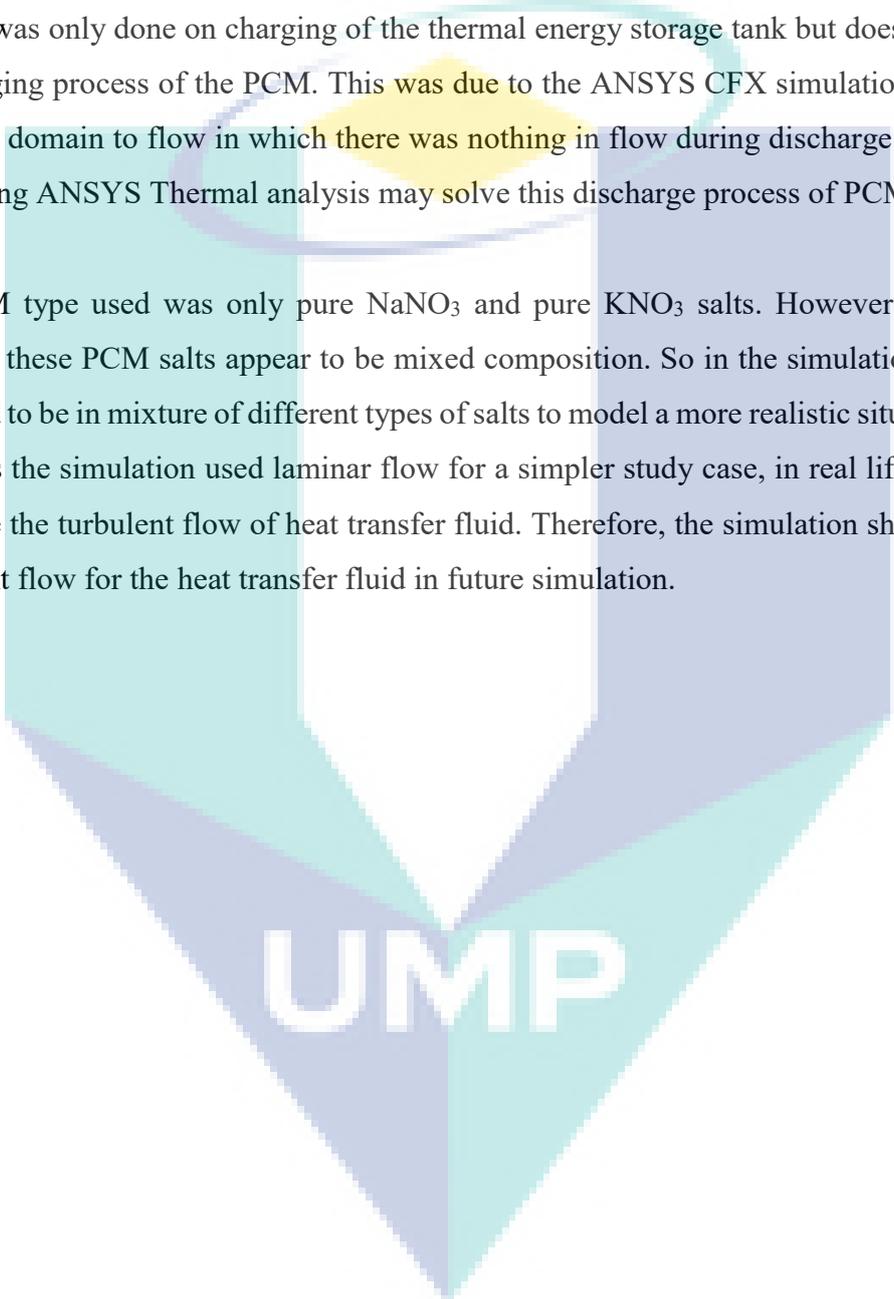
In designing a thermal energy storage, latent heat storage was selected instead of sensible heat storage in this project. This is because latent heat storage can store more energy per unit volume compared to sensible heat storage. Using PCM as energy storage medium was one of the latent heat storage methods. The types of PCM in this paper were using the sodium nitrate salt ( $\text{NaNO}_3$ ) and potassium nitrate salt ( $\text{KNO}_3$ ) to store the heat energy coming heat transfer fluid in copper tube. These  $\text{NaNO}_3$  and  $\text{KNO}_3$  salts contained in the steel tank has melting point of about  $308^\circ\text{C}$  and  $336^\circ\text{C}$  respectively which are the temperature range for the cooking purposes. However, these nitrate salts have a significantly low thermal conductivity about  $0.5 \text{ W/m}\cdot\text{K}$  in which the tank will take more time while charging and discharging. To solve this problem, aluminum fins of different space configurations were done. 3, 4, 5, 6 and 7 fins with gap of 100 mm, 90 mm, 70 mm, 60 mm, and 50 mm were inserted in order to improve the thermal conductivity of PCM.

A 3 dimensional model for thermal energy storage tank was designed using Solidworks. This model was tested in ANSYS CFX simulation at steady state to measure the temperature contour, find the optimum fin spacing, obtain suitable heat transfer fluid velocity and to find the best type of PCM. The charging method was done using side charged thin wall model for heat transfer type. Design with 4 fins got  $23^\circ\text{C}$  PCM temperature higher than other fin configuration. By flowing a  $0.168 \text{ m/s}$  heat transfer fluid in the copper tube under laminar state was the optimum for this simulation. Based on the reviews done on the PCM price and latent heat,  $\text{NaNO}_3$  has lower price and higher latent heat than  $\text{KNO}_3$ . In conclusion, the design for thermal energy storage in the temperature range for cooking application using PCM was obtained. The suitable type of PCM in term of physical, thermal, chemical and economical was found to be sodium nitrate salts. The simulation of heat loading for this model was done and the temperature distribution was studied.

## 5.2 RECOMMENDATIONS

The simulation was done under steady state heat transfer. The simulation will not be able to determine the time taken for the tank to be fully charged. By using ANSYS Transient Thermal analysis, the time taken for the charging process can be obtained. Besides, this simulation was only done on charging of the thermal energy storage tank but does not include the discharging process of the PCM. This was due to the ANSYS CFX simulation requires at least 1 fluid domain to flow in which there was nothing in flow during discharge stage in this project. Using ANSYS Thermal analysis may solve this discharge process of PCM.

PCM type used was only pure  $\text{NaNO}_3$  and pure  $\text{KNO}_3$  salts. However, in real life application, these PCM salts appear to be mixed composition. So in the simulation, the PCM is suggested to be in mixture of different types of salts to model a more realistic situation. Other than that, as the simulation used laminar flow for a simpler study case, in real life situation it will involve the turbulent flow of heat transfer fluid. Therefore, the simulation should include the turbulent flow for the heat transfer fluid in future simulation.

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