STUDY OF ENERGY STORAGE USING PHASE CHANGE MATERIAL (PCM) AND ITS PERFORMANCE ON SOLAR WATER HEATING AFTER SUNSET

WONG JUN XIAN

A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechanical Engineering

Lee Kong Chian Faculty of Engineering and Science
Universiti Tunku Abdul Rahman

April 2019

DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

Signature : _________________________

Name : Wong Jun Xian

ID No. : 14UEB01928

Date : _________________________

APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STUDY OF ENERGY STORAGE USING PHASE CHANGE MATERIAL (PCM) AND ITS PERFORMANCE ON SOLAR WATER HEATING AFTER SUNSET"** was prepared by **WONG JUN XIAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Hons.) Mechanical Engineering at Universiti Tunku Abdul Rahman.

Approved by,

Signature : _________________________

Supervisor : _________________________

Date : _________________________

Signature : _________________________

Co-Supervisor : _________________________

Date : _________________________

ACKNOWLEDGEMENTS

I would like to thank Ho Zhi Yong and Vincent who had contributed to the successful completion of this project. I would like to express my gratitude to my research supervisor, Dr. Rubina Bahar for her invaluable advice, guidance and her enormous patience throughout the development of the research.

In addition, I would also like to express my gratitude to my loving parents and friends who had helped and given me encouragement throughout this research.

ABSTRACT

The conventional solar still is unable to provide sufficient volume of fresh water as the water productivity of device is highly dependent on the solar irradiation. Thus, aim of this study is to maximize the water productivity of conventional solar still by using thermal energy storage. Phase change material is used as the storage material because it is capable to absorb and release heat energy when it undergoes heating, cooling and phase transition process. Paraffin based phase change materials (paraffin wax and petroleum jelly) were selected to be used as the storage material in this study because they are able to fulfil most of the criterion to be used as thermal energy storage. However, they possess low thermal conductivity characteristic which leads to poor performance in energy charging and discharging process. In this study, aluminium scrap from machining process was mixed into pure paraffin based phase change material and acts as additive to improve its thermal conductivity. Different types of phase change material were tested in experiment and the water productivity of solar still integrated with thermal energy storage using different phase change material was compared and discussed. In the end, the water productivity of solar still was improved due to thermal energy storage using phase change material. Petroleum jelly mixed with aluminium scrap was found to have the best performance among the phase change materials used in this study due to its enhanced thermal conductivity characteristic.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS / ABBREVIATIONS

c_p	specific heat capacity, J/kg·K
m	mass, kg
A	surface area, m^2
T	temperature, K
h	heat transfer coefficient, $W/m^2 \cdot K$
k	thermal conductivity, $W/m^2 \cdot K$
I	solar irradiation, W/m^2
h_{fg}	vaporization heat, J/kg
Q	rate of heat transfer, W
τ	time, s
α	absorption coefficient
ε	emissivity coefficient
σ	stefan-boltzmann constant, $W/m^2 \cdot K^4$
PCM	phase change material
SW	saline water
ABP	absorber basin plate

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Water plays a vital role in our lives. Human life, as with all animal and plant life on the planet, is highly dependent upon water. Water is a basic part of our daily lives as we need to drink water every day in order for our bodies to continue functioning. Water is so important because approximately 2/3 of our bodies are water. All chemical processes inside our bodies such as carrying nutrient into and through the body, regulating body temperature and elimination of waste require water to occur. Therefore, human being will not survive for more than a few days without water.

However, there is more than 1.2 billion people worldwide lack access to fresh water that is safe to drink (Water Scarcity | Threats | WWF, 2018). According to Mekonnen and Hoekstra, they concluded that there are at least five hundred million people facing extreme water scarcity throughout the entire year. Two-third of world population experience severe water scarcity for part of the year. The statistic shows that the people who face the severe water scarcity mostly live in rural regions. Of those people, 180 million live in India, 27 million in Egypt, 73 million in Pakistan, 20 million in Saudi Arabia, 20 million in Mexico and 18 million in Yemen (Mekonnen and Hoekstra, 2016). Thus, the fresh water scarcity issue must be solved immediately as more and more population are expected in the future.

In order to solve the fresh water scarcity issue, numerous studies and researches in fresh water production were conducted in recent years. There are many methods can be used to purify the contaminated water such as filtration, sedimentation, disinfection and distillation. These methods remove the salts and impurities in the water so that the purified water is safe to drink. Among these methods, solar distillation is the most popular and most commonly used water purification method in the countries facing fresh water scarcity issue due to its low operating cost as it only requires heat energy provided in sun irradiation to operate.

The device used in solar distillation process to provide fresh water is called solar still. It is widely employed in rural regions because the cost needed to build this device is low as it can be built by using cheap and abundant materials. However, the conventional solar still cannot provide sufficient volume of fresh water due to its poor performance because it is very dependent on solar irradiation. Thus, this problem has leads to limitations in low solar-lit areas.

Rapid development of science and technology nowadays has provided a solution to the poor performance of conventional solar still. The solution is to use phase change material as thermal energy storage and integrate it into solar still to store the solar heat energy during day time and to release the energy stored after sunset so that the solar still can running for 24 hours.

However, most of the phase change material possesses low thermal conductivity characteristic and this undesirable property has significantly affected the performance of thermal energy storage. Thus, it is essential to apply engineering knowledge to increase the thermal conductivity of phase change material.

In this study, thermal energy storage using phase change material and its impact on water productivity of solar still was investigated. Improvement of thermal conductivity of phase change material was focused as well in order to improve the performance of thermal energy storage.

1.2 Importance of the Study

The outcome of this present study is expected to provide a solution to maximize the water productivity of conventional solar still by using thermal energy storage. It is expected that the poor performance of solar still can be improved by integrate thermal energy storage into the device. Moreover, it may contribute to a better understanding on thermal energy storage using phase change materials.

In addition, it also aims to investigate how improvement of thermal conductivity of phase change material affects the performance of thermal energy storage in solar still.

1.3 Problem Statement

The existing conventional solar still device is unable to provide sufficient volume of fresh water for people facing severe water scarcity issue at rural regions due to its poor performance.

A conventional solar still is very dependent on solar irradiation and therefore it is only able to produce fresh water during sunny day time when the sun is providing abundant solar heat energy to heat and evaporate the saline water. The solar still stop working after sunset as there is no heat energy supplied to it anymore and this is the main issue which leads to the poor performance of solar still.

Moreover, most of the phase change materials are low at thermal conductivity and this undesirable characteristic of phase change material has led to poor performance of thermal energy storage.

1.4 Aims and Objectives

The aim of this study is to use phase change material as thermal energy storage to increase water productivity of solar still. Thermal conductivity of phase change material will be enhanced and test in solar still in order to maximize the water productivity. Thus, the objectives of this study are to:

- Design and fabricate phase change material storage in solar still.
- Enhance the thermal conductivity of phase change material by adding additives with high thermal conductivity.
- Investigate the impact of thermal energy storage on water productivity of solar still.

1.5 Scope and Limitation of the Study

The phase change materials used in this study are paraffin wax and petroleum jelly. Aluminium scrap from machining process was mixed into petroleum jelly in order to increase the thermal conductivity of petroleum jelly. Water productivity of solar still using pure paraffin wax, pure petroleum jelly and petroleum jelly mixed with aluminium scrap was compared and discussed.

Cost is the biggest limitation in this study because it has put a limit on the selection of phase change materials as the phase change material used must be low at cost and at the same time possess the desirable properties to be used as thermal energy storage. Besides that, it is hard to search for phase change material supplier in Malaysia as phase change material is not a popular material in Malaysia.

Moreover, there is no external device used to feed heat energy to the solar still in the experiment. Sun is the only heat source to the solar still and therefore the water productivity of solar still is highly dependent on the solar irradiation.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The current chapter focuses on the researches conducted on the thermal energy storage using Phase Change Material (PCM) and its performance on solar still after sunset with references of existing scientific journals, theoretical and experimental studies and research papers published on internet.

2.2 Literature Review

The principle of thermal energy storage is to use storage material to store energy when it goes through heating, melting or vaporizing process and release energy stored when the process is reversed to cooling or solidifying. Thermal energy storage can be categorized into 2 types which are sensible heat storage and latent heat storage (Pielichowska and Pielichowski, 2014).

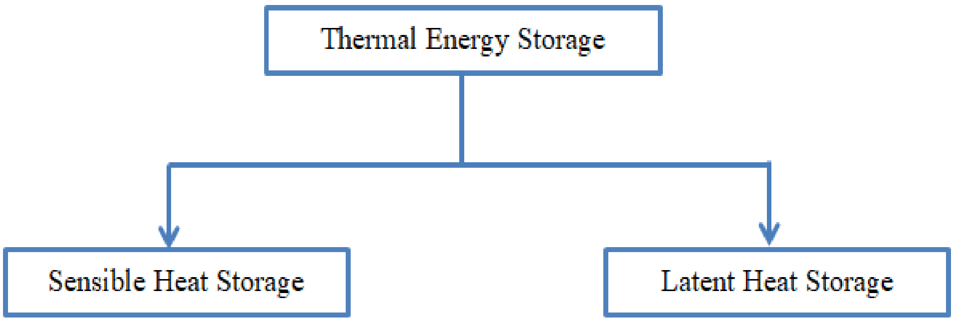


Figure 2.1: Type of Thermal Energy Storage

Thermal energy storage has made a significant impact to the world nowadays due to its effective utilization of energy. It is extensively implemented in the field of industrial waste heat recovery, building, medical, heat exchanger, textile, solar energy, etc. For example, application that integrates thermal energy storage into system includes cooling of electronic devices, cooling vest for athletes, solar water heating system, building temperature regulating system, etc.

2.2.1 Sensible Heat Storage

In sensible heat storage, the thermal energy is stored by heating of the storage material and released by cooling of the storage material without undergoing phase transition process. The storage material store the heat supplied through heat transfer mechanism such as conduction, convection and radiation. When the material cools at night, the stored heat energy is released back to the surrounding in the same modes.

The most commonly used storage material for sensible heat storage is rock, brick, concrete, water, etc. The amount of heat stored in the storage material can be determined by equation 2.1 (Pielichowska and Pielichowski, 2014).

$$Q = mC_{ap}(T_f - T_i) \tag{2.1}$$

where,

Q = Heat energy stored, J

T_f = Final temperature, K

T_i = Initial temperature, K

m = Mass of storage material, kg

C_{ap} = Average specific heat capacity between T_i and T_f, J/kg·K

2.2.2 Latent Heat Storage

The working principle of latent heat storage is similar with sensible heat storage. The only difference is that charging and discharging process of heat energy for latent heat storage involves phase transition of the storage material.

The storage materials used for latent heat storage are called Phase Change Materials (PCM). The amount of heat stored in the storage material can be determined by equation 2.2 (Pielichowska and Pielichowski, 2014).

$$Q = m\left[C_{sp}(T_m - T_i) + a_m \Delta H_m + C_{lp}\left(T_f - T_m\right)\right] \tag{2.2}$$

where,

Q = Heat energy stored, J

T_f = Final temperature, K

T_f = Melting temperature, K

T_i = Initial temperature, K

m = Mass of storage material, kg

C_{sp} = Average specific heat capacity between T_i and T_m, J/kg·K

C_{lp} = Average specific heat capacity between T_m and T_f, J/kg·K

a_m = Fraction melted

ΔH_m = Heat of fusion per unit mass, J/kg

According to Sharma et al., they concluded that latent heat storage provides a number of advantages over sensible heat storage, particularly its capability to store heat at constant temperature that corresponding to the phase transition temperature of the storage medium and its high energy storage density (Sharma et al., 2009).

2.3 Phase Change Material

Phase change material (PCM) is introduced here as a storage material for latent heat storage. It is also called as latent heat storage material. It is capable to store and release thermal energy when it undergoes heating, cooling and phase transition process.

Latent heat storage materials perform like sensible heat storage materials at the initial stage as they absorb heat in solid state when the temperature rises. But, when the temperature of materials reaches the melting point, they will absorb heat at a constant temperature corresponding to the melting point of the material. After the materials turn completely from solid into liquid, they continue to absorb heat at liquid state. Thus, latent heat storage is able to store more heat per unit volume than sensible heat storage.

PCMs are being used in various fields and act as thermal energy storage. Several studies have proved that employment of PCM has aided the performance of various applications. Khan, Saidur and Al-Sulaiman inferred that the use of PCMs has improved the performance of solar absorption refrigeration system (Khan, Saidur and Al-Sulaiman, 2017). Kenisarin and Mahkamov reviewed on residential building with passive thermal control by using PCMs and concluded that the PCMs has brought many benefits to the system (Kenisarin and Mahkamov, 2016). Akeiber, et al. studied the sustainable passive cooling in buildings using PCMs and concluded that PCMs has improved the performance of system (Akeiber et al., 2016).

2.3.1 Classification of Phase Change Material

There are various types of PCM available in the world and they are generally classified based on the physical state of material before and after the phase transition process. Therefore, PCMs are classified into solid-liquid PCMs, liquid-gas PCMs and solid-gas PCMs.

Among the types of PCM, the most commonly used PCMs in various engineering applications are solid-liquid PCMs. They possess the advantages of low change in volume during phase transition process and high latent heat capacity when compared with other class of PCMs. Although phase transition process involving gas can release large value of heat energy but containing a large mass of gas requires a pressure vessel which is costly and potentially dangerous (Lin et al., 2018).

Besides that, there is another way to classify the PCMs which is based on their chemical nature. Figure 2.2 shows the classification of phase change material. They are classified into 3 categories which are organic PCMs, inorganic PCMs and eutectic PCMs.

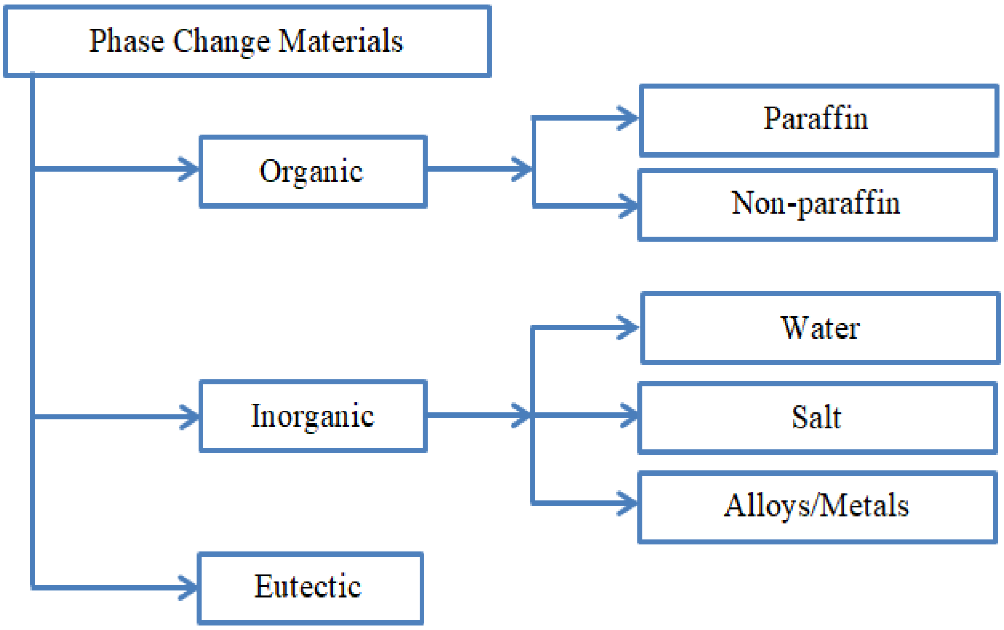


Figure 2.2: Classification of PCM

The organic PCMs can be further classified into paraffin type and non-paraffin type and they possess the advantages of non-toxic, non-corrosive, high chemical stability, congruent melting, no super cooling, etc. However, most of the organic PCMs are flammable and low at thermal conductivity.

Inorganic PCMs such as water, salt and alloy or metal carry the advantages of low cost, non-flammable and high latent heat when compared to organic PCMs. However, there are several drawbacks which include large change of volume during phase transition process, low thermal stability and corrosive.

On the other hand, eutectic PCMs are PCM with two or more soluble substances mixed together. They are generally better than organic PCMs and inorganic PCM as they have the features of high thermal conductivity, solidification without material's separation and simultaneous melting. However, the cost of eutectic PCMs is high.

2.3.2 Selection Criteria of Phase Change Material

The selection of PCM for latent heat storage mainly depends on the target application because each of the materials possesses different material properties. But, the most important criterion that must be focused when choosing the proper PCM for latent heat storage is the thermal properties of PCM.

First, the phase transition temperature of the material. The operating temperature of heating and cooling in system should match with the phase transition temperature of PCM (Wang et al., 2015).

Moreover, the PCM should have high value of latent heat and high specific heat capacity in both liquid and solid state in order to store more energy since the purpose of PCM is to act as thermal energy storage and store heat energy. Therefore, the more amount of heat energy stored the better the performance of thermal energy storage.

Thermal conductivity of PCM is also an important criterion in the selection of material. The material should have high thermal conductivity because the thermal conductivity plays a vital role in the energy charging and discharging process of thermal energy storage and therefore a high thermal conductivity material will be favoured as it will leads to better performance of the thermal energy storage.

Other than the thermal properties mentioned above, the physical, chemical, and kinetic properties as well as economic and market availability should also be taken into account when comes to the selection of material (Ibrahim et al., 2017). Table 2.1 summarize the desirable properties of PCMs to be used as latent heat storage.

Table 2.1: Desirable Properties of PCM

Thermal Properties	• High specific heat capacity • High thermal conductivity • Suitable phase transition temperature • High latent heat of transition
Physical Properties	• Small change in volume • Low vapour pressure • High density
Chemical Properties	• Non-flammable • Non-toxic • Non-corrosive • Long-term chemical stability
Kinetic Properties	• Sufficient crystallization rate • No or little super cooling
Economics	• Cost effective • Abundant • Available

2.3.3 Improvement of Phase Change Material

No single PCM can possibly fulfil all of the stringent requirements. The biggest barrier to the wide application of PCMs is their low thermal conductivity characteristic. However, engineering knowledge can be applied to enhance the thermal conductivity of PCM.

The thermal conductivity plays a vital role in the energy charging and discharging process of thermal energy storage. The low thermal conductivity characteristic of PCM has led to poor heat transfer performance between PCM and its system. Thus, the thermal conductivity of PCM should be as high as possible in order to enhance the charging and discharging process which will also improving the performance of thermal energy storage.

According to Lin et al., there are two methods can be used to enhance the thermal conductivity of PCMs. One is to add additives with high thermal conductivity into PCM and another one is to use encapsulated PCM. Several experiments have been conducted and the results have proven that the thermal conductivity was enhanced due to the methods mentioned (Lin et al., 2018).

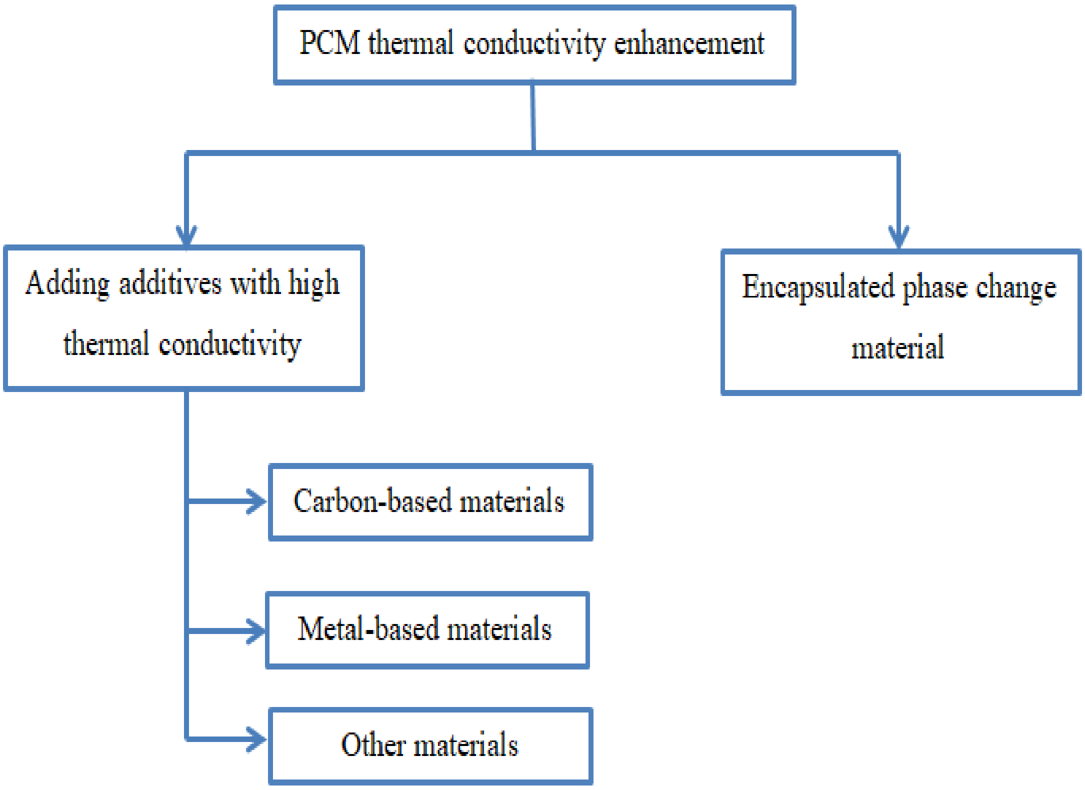


Figure 2.3: Enhancement of Thermal Conductivity of PCM

According to Xu et al., they performed a study by adding carbon-based material which is expended graphite (EG) into D-mannitol and produce a material called D-mannitol/EG composite PCM which was used in solar heat storage system. The composite PCM with 15 wt% EG has thermal conductivity of 7.31 W/m·K while the pure D-Mannitol has thermal conductivity of 0.60 W/m·K (Xu et al., 2016).

Sahan, Fois and Paksoy conducted an experiment to investigate the enhancement of thermal conductivity of PCM. In the experiment, dispersion technique was used to formula paraffin-nanomagnetite composites which consist of paraffin and Fe_3O_4. The thermal conductivity of pure paraffin wax is 0.25 W/m·K while the thermal conductivity measured for paraffin-nanomagnetite composites with 10 wt% and 20 wt% Fe_3O_4 is 0.37 W/m·K and 0.40 W/m·K respectively (Şahan, Fois and Paksoy, 2015).

Reyes et al. mixed paraffin wax with aluminium foils and produce paraffin-aluminium composites. The results proved that the thermal conductivity of paraffin wax was increased due to the addition of aluminium foils. The thermal conductivity of paraffin wax with aluminium is 0.63 W/m·K and it is higher than pure paraffin wax which has thermal conductivity of 0.31 W/m·K (Reyes et al., 2017).

Wang et al. performed a study by using encapsulated PCM. The thermal conductivity measured for encapsulated PCM was about 2-3 times higher. The results indicated that the shell has increase the thermal conductivity of the material due to the increased thermal contact area of PCM. Besides that, they also concluded that the change in volume of PCM during phase transition process is able to be controlled by the capsule shell (Wang et al., 2016).

2.4 Solar Still

During the last few decades, it has become a fact that the rapid increase in population has leads to an increasing demand of fresh water. The fresh water scarcity issue has proven to be a threat for human society in rural country in this world. Most of the available water cannot be used for drinking due to water contamination and drinking it could lead to several diseases. Thus, solar distillation is introduced here to produce fresh water that is safe to drink.

Solar distillation is the use of solar heat energy provided in solar irradiation as a heat source to evaporate saline water to produce water that is safe to drink. Solar still is the device used in the solar distillation process. It is widely used in rural country because it can be built by using abundant and cheap materials such as wood or plastic.

The overall concept of solar still is that saline water is stored in a basin which will be heated by solar energy collected through solar collector and causing the saline water to evaporate. The water vapour is then condenses on an inclined glass cover on top of solar still and the condensed water is allowed to flow into a collection unit. Impurities in the saline water will not evaporate but the pure water will and therefore distilling the water which allows it safe to drink (Al-harahsheh et al., 2018).

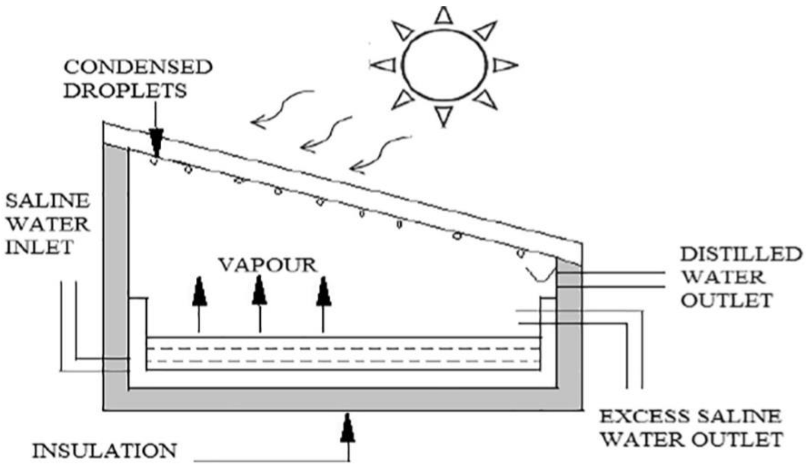


Figure 2.4: Single Slope Solar Still (Selvaraj and Natarajan, 2018)

2.4.1 Type of Solar Still

The solar still can be classified into active solar still and passive solar still. Active solar still is solar still that use external device to supply extra heat energy to evaporate saline water. They are normally integrated with solar heater or heat exchanger. On the other hand, passive solar still is solar still that evaporate saline water directly though sun without any external device (Selvaraj and Natarajan, 2018).

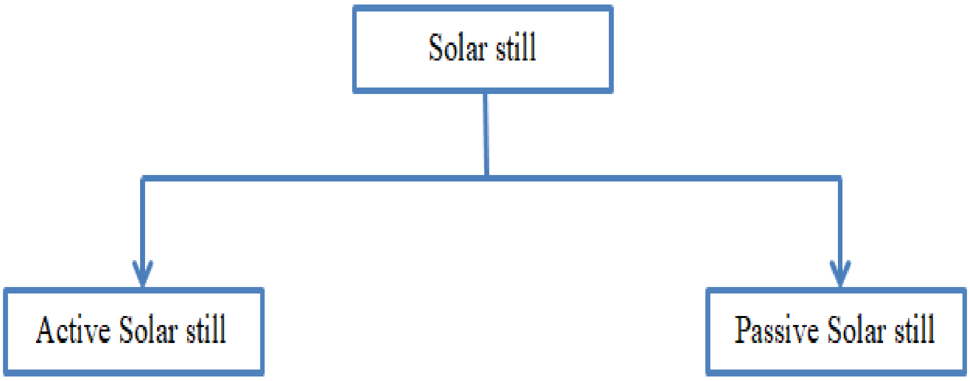


Figure 2.5: Type of Solar Still

There are various designs of solar still available nowadays such as double slope solar still, single slope solar still, wick type solar still, etc. However, different designs give different efficiency and water productivity. Therefore, numerous studies were conducted to study the performance of different design of solar still.

An experiment was conducted by Kumar and Tiwari to compare the performance of active solar still and passive solar still. Based on the result, the performance of active solar still is better than passive solar still as active solar still is able to produce more water than passive solar still (Kumar and Tiwari, 2008).

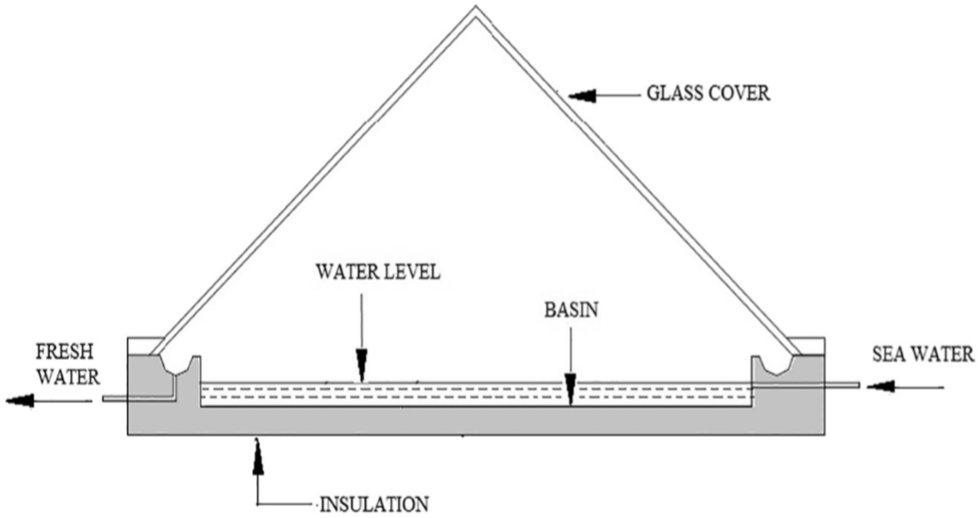


Figure 2.6: Double Slope Solar Still (Selvaraj and Natarajan, 2018)

Badran et al. conducted an experiment on solar still coupled with flat plate collector. The result obtained showed that the solar still without flat plate collector produces 1.51 l/m^2 while the solar still coupled with flat plate collector produces 2.31 l/m^2 (Badran et al., 2005).

Abdel-Rehim and Lasheen conducted an experiment by integrate heat exchanger into solar still. The results obtained showed that the water productivity of active solar still is 18% higher than the passive solar still (Abdel-Rehim and Lasheen, 2007).

It can be concluded that active solar still is said to have higher efficiency and water productivity than passive solar still because of the extra thermal energy supplied but the biggest drawback is its high capital cost investment.

2.4.2 Parameter Affecting Performance of Solar Still

The aim of this study is to use PCM as thermal energy storage to enhance the water productivity of conventional solar still. But, the solar still design also significantly affects the water productivity. Thus, the solar still has to be well designed so that PCM can further improve its water productivity. According to Selvaraj and Natarajan, they concluded that performance of solar still is strongly depends on parameters like solar irradiation, basin water depth, solar collector area, insulation material, glass cover plate thickness and glass cover plate inclination (Selvaraj and Natarajan, 2018).

However, the performance of solar still varies with uncontrollable parameters such as atmosphere humidity, weather condition, wind speed and solar irradiation. These parameters are called meteorological parameters and they cannot be controlled during the operation. Therefore, the controllable design parameters such as insulation material, basin water depth, solar collector area, etc. should be designed appropriately in order to improve the performance of solar still.

2.4.2.1 Solar Irradiation

The performance of solar still is strongly relying on the heat energy supplied and several researches have concluded that the performance of solar still has a positive relationship with solar irradiation. Thus, a high intensity solar irradiation will be favoured as it is able to provide high heat energy to solar still and more water will be evaporated and hence increase the water productivity.

Badran and Abu-Khader performed an experiment to study how solar irradiation affects the performance of solar still. In the experiment, the highest water productivity was obtained at early afternoon which is the time with the highest solar irradiation. Thus, they inferred that the performance of solar still is strongly affected by the solar irradiation (Badran and Abu-Khader, 2007).

2.4.2.2 Basin Water Depth

Several researches have proved that the increase in depth of basin water will lead to decrease in the water productivity of solar still.

Experiments were performed to study the impact of water depth on water productivity of solar still and all of the researchers agreed that the water productivity of solar still will be reduced when the basin water depth was increased (Abdul-Wahab and Al-Hatmi, 2013) (Rajamanickam and Ragupathy, 2012).

2.4.2.3 Solar Collector Area

Solar collector is usually coated with black paints to have better absorption of solar irradiation. It is found that the solar collector area has a proportional relationship with performance of solar still as the heat transfer rate is directly proportional to the surface area available for heat transfer and therefore increase in solar collector area will increase the water productivity of solar still.

Velmurugan and Srithar conducted an experiment and they agreed that the increase in solar collector area is able to improve the water productivity of solar still due to the enhanced heat transfer process (Velmurugan and Srithar, 2011).

2.4.2.4 Insulation Material

Insulation material is used to minimize the heat loss from the system to the surrounding and hence improve the performance of solar still. Insulation material such as wood, sawdust, polyurethane and styrofoam were commonly used.

Alaudeen et al. employed saw dust as insulation material in his stepped solar still to reduce heat loss from system to surrounding. The result showed that the water productivity of solar still unit with insulation material is higher than the solar still unit without insulation material (Alaudeen et al., 2014).

2.4.2.5 Glass Cover Plate Thickness

Typical solar still will place a high transmissivity material such as glass plate on top. Glass has the property of selectively allowing higher energy irradiation to pass through. This property allows the solar still to capture heat energy provided in solar irradiation and retain it to heat the saline water in basin. The glass cover plate is also the place where the condensation process happens.

However, the glass cover plate thickness will makes an impact on the water productivity of solar still. 3 mm and 4 mm thick glass cover plate were typically used by researchers in their solar still.

Selvaraj and Natrajan conducted an experiment by using glass cover plate with different thickness in their solar still. The results obtained showed that the set up with 3 mm thick glass cover plate has the highest fresh water production (Selvaraj and Natarajan, 2018).

2.4.2.6 Glass Cover Plate Inclination

Several experiments were conducted and all of the results have proved that the water productivity of solar still was affected by the angle of inclination of glass cover plate.

Akash, Mohsen and Nayfeh, Singh and Tiwari, Panchal and Shah and Fath et al. conducted experiment by setting different angle of inclination of glass cover plate and the optimum angle for maximum production is the angle which is about the same with the latitude angle of the place where they conducted the experiment (Akash, Mohsen and Nayfeh, 2000) (Singh and Tiwari, 2004) (Panchal and Shah, 2012) (Fath et al., 2003).

2.5 Solar Still with Phase Change Material

In order to improve the water productivity of conventional solar still, the solar still device is integrated with thermal energy storage using PCM mentioned in previous discussion. Performance of solar still is strongly dependent on solar irradiation and solution to the low water productivity of solar still is thermal energy storage.

The solar still without PCM produces fresh water only during sunny day time when the sun is able to provide sufficient heat energy to evaporate the saline water. However, the solar still stop producing fresh water during night time or even cloudy day time. Therefore, PCM is integrated into solar still and act as thermal energy storage in order to supply continuous heat to evaporate the water and produce fresh water in a more efficient way. Theoretical and experimental studies were performed and all of the results have showed that employment of PCM is able to improve the performance of solar still.

Dashtban and Tabrizi conducted an experiment by using paraffin wax as thermal energy storage in their solar still. They found that the water productivity of solar still was enhanced by 31 % due to the PCM employed (Dashtban and Tabrizi, 2011).

Kabeel and Abdelgaied performed a study to investigate the impact of thermal energy storage using PCM on performance of solar still. The results showed that the PCM has improved the water productivity of solar still up to 68.8% (Kabeel and Abdelgaied, 2016).

Asbik et al. conducted an analysis on solar still utilizing paraffin wax as thermal energy storage in the system. They inferred that the thermal energy storage is able to increase the water productivity of solar still (Asbik et al., 2016).

Shalaby, El-Bialy and El-Sebaii performed an experiment to study the impact of thermal energy storage using PCM on performance of solar still. Paraffin wax with melting point of 56 ºC was used in the experiment. They found that the water productivity of the solar still was increased by 12 % due to the thermal energy storage (Shalaby, El-Bialy and El-Sebaii, 2016).

2.6 Summary

This literature review was conducted in order to have a better understanding on thermal energy storage using PCM. Moreover, it provides explanations on how PCM enhances the water productivity of solar still. Based on this literature review, parameters affecting the water productivity of solar still were identified. On the other hand, it also helps in providing knowledge on how to enhance the thermal conductivity of PCM in order to improve the performance of thermal energy storage integrated in solar still.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

The current chapter focuses on methodology and work plan for the research. Information obtained in literature review was used to establish methodology for this particular research. The work plan for the entire research is presented in Figure 3.1.

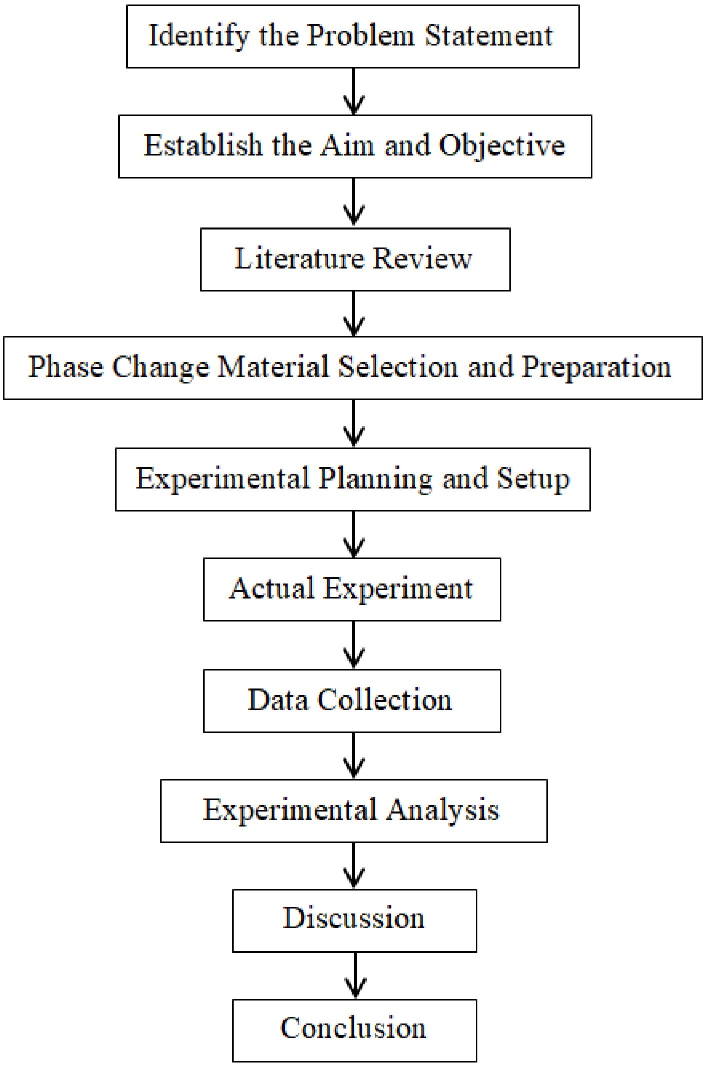


Figure 3.1: Research Flow Chart

3.2 Methodology

The relevant theories, formula, material and experiment setup were examined in depth in order to satisfy the aim of this research.

3.2.1 Mathematical Model of Solar Still

In order to have better understanding on the working principle of solar still integrated with thermal energy storage using PCM, it is important to understand the heat transfer mechanism behind it. According to the mathematical model presented by Kabeel, El-Samadony and El- Maghlany, they have solved the model of solar still integrated with thermal energy storage using principle of energy balance and the model is able to provide detailed explanations on the heat transfer mechanism in a solar still (Kabeel, El-Samadony and El-Maghlany, 2018).

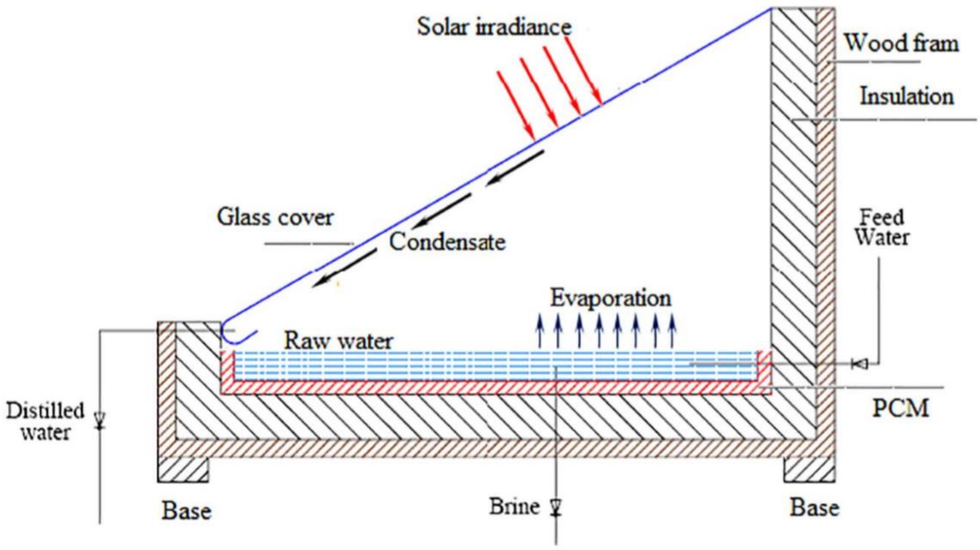


Figure 3.2: Solar Still with PCM (Kabeel, El-Samadony and El-Maghlany, 2018)

The energy balanced components consists of absorber basin plate, saline water, phase change material and glass cover plate. Some assumptions were made and listed as following:

- Solar still is vapour leakage proof
- Glass cover is assumed to be thin
- No temperature gradient through PCM thickness
- Phase change material is in perfect contact with absorber basin plate

Absorber basin plate energy balance:

$$m_{abp}C_{P_{abp}}\frac{dT_{abp}}{d\tau} = (\alpha_{abp})A_{abp}I - Q_{abp-sw} - Q_{abp-PCM} \tag{3.1}$$

Saline water energy balance:

$$m_{sw}C_{P_{sw}}\frac{dT_{sw}}{d\tau} = (\alpha_{sw})A_{sw}I + Q_{abp-sw} - Q_{r(sw-g)} - Q_{c(sw-g)} - Q_{evap} \tag{3.2}$$

Still cover glass energy balance:

$$m_{g}C_{P_{g}}\frac{dT_{g}}{d\tau} = (\alpha_{g})A_{g}I + Q_{r(sw-g)} + Q_{c(sw-g)} + Q_{evap} - Q_{c(g-a)} - Q_{r(g-a)} \tag{3.3}$$

Water productivity of solar still:

$$m_{prod} = \frac{Q_{evap}}{h_{fg}} \tag{3.4}$$

where,

m_{abp}= Mass of ABP, kg

m_{sw}= Mass of SW, kg

m_{g}= Mass of glass, kg

m_{prod} = Rate of production, kg/s

$C_{P_{abp}}$ = Specific heat capacity of ABP, J/kg·K

$C_{P_{sw}}$ = Specific heat capacity of SW, J/kg·K

$C_{P_{g}}$ = Specific heat capacity of glass, J/kg·K

$\frac{dT_{abp}}{d\tau}$ = Rate of change of temperature of ABP, K/s

$\frac{dT_{sw}}{d\tau}$ = Rate of change of temperature of SW, K/s

$\frac{dT_{g}}{d\tau}$ = Rate of change of temperature of glass, K/s

α_{abp} = Absorption coefficient of ABP

α_{sw} = Absorption coefficient of SW

α_g = Absorption coefficient of glass

A_{abp} = Surface area of ABP, m^2

A_{sw} = Surface area of SW, m^2

A_g = Surface area of glass, m^2

I = Solar irradiation, W/m^2

h_{fg} = Vaporization heat, J/kg

Q_{abp-sw} = Rate of heat transfer between ABP and SW, W

$Q_{abp-PCM}$ = Rate of heat transfer between ABP and PCM, W

$Q_{r(sw-g)}$ = Rate of heat transfer between SW and glass in radiation mode, W

$Q_{c(sw-g)}$ = Rate of heat transfer between SW and glass in convection mode, W

Q_{evap} = Evaporative heat transfer between SW and glass, W

$Q_{c(g-a)}$ = Rate of heat transfer between glass and ambient in convection mode, W

$Q_{r(g-a)}$ = Rate of heat transfer between glass and ambient in radiation mode, W

Equation 3.1, 3.2 and 3.3 show the energy balance for absorber basin plate, saline water and glass cover. Theses equations provide explanations on the entire heat transfer mechanism in a solar still. By solving the equations, the water productivity can be obtained by using equation 3.4.

The equations used to study the energy charging and discharging mode of PCM are listed in following:

Charging mode:

Solid sensible heat in charging mode, $(T_{abp} > T_{PCM})$, $(T_{PCM_{sat}} > T_{PCM})$

$$m_{PCM} C_{P_{PCM.S}} \frac{dT_{PCM}}{d\tau} = Q_{abp-PCM} - Q_{Lost} \tag{3.5}$$

Melting in charging mode, $(T_{abp} > T_{PCM})$, $(T_{PCM_{sat}} = T_{PCM})$

$$dT_{PCM} = 0 \tag{3.6}$$

Liquid sensible heat in charging mode, $(T_{abp} > T_{PCM})$, $(T_{PCM_{sat}} < T_{PCM})$

$$m_{PCM} C_{P_{PCM.L}} \frac{dT_{PCM}}{d\tau} = Q_{abp-PCM} - Q_{Lost} \tag{3.7}$$

Discharging mode:

Liquid sensible cooling in discharging mode, $(T_{abp} < T_{PCM})$, $(T_{PCM_{sat}} < T_{PCM})$

$$m_{PCM} C_{P_{PCM.L}} \frac{dT_{PCM}}{d\tau} = Q_{abp-PCM} - Q_{Lost} \tag{3.8}$$

Solidification in discharging mode, $(T_{abp} < T_{PCM})$, $(T_{PCM_{sat}} = T_{PCM})$

$$dT_{PCM} = 0 \tag{3.9}$$

Solid sensible cooling in discharging mode, $(T_{abp} < T_{PCM})$, $(T_{PCM_{sat}} > T_{PCM})$

$$m_{PCM} C_{P_{PCM.S}} \frac{dT_{PCM}}{d\tau} = Q_{abp-PCM} - Q_{Lost} \tag{3.10}$$

where,

m_{PCM} = Mass of PCM, kg

$C_{P_{PCM.S}}$ = Specific heat capacity of PCM in solid state, J/kg·K

$C_{P_{PCM.L}}$ = Specific heat capacity of PCM in liquid state, J/kg·K

$\frac{dT_{PCM}}{d\tau}$ = Rate of change of temperature of PCM, K/s

dT_{PCM} = Change of temperature of PCM, K

$Q_{abp-PCM}$ = Rate of heat transfer between ABP and PCM, W

Q_{Lost} = Heat transfer losses to surrounding, W

T_{abp} = ABP temperature, K

T_{PCM} = PCM temperature, K

$T_{PCM_{sat}}$ = PCM saturation temperature, K

3.2.2 Energy Stored in Phase Change Material

The function of PCM is to act as latent heat thermal energy storage. Therefore, the amount of energy stored inside PCM should be as much as possible. The thermal energy stored in PCM can be obtained by using following equation (Pielichowska and Pielichowski, 2014).

$$Q = m\left[C_{sp}(T_m - T_i) + a_m \Delta H_m + C_{lp}\left(T_f - T_m\right)\right] \tag{3.11}$$

where,

Q = Heat energy stored, J

T_f = Final temperature, K

T_m = Melting temperature, K

T_i = Initial temperature, K

m = Mass of storage material, kg

C_{sp} = Average specific heat capacity between T_i and T_m, J/kg·K

C_{lp} = Average specific heat capacity between T_m and T_f, J/kg·K

a_m = Fraction melted

ΔH_m = Heat of fusion per unit mass, J/kg

By looking into equation 3.11, it can be seen that the mass of PCM has a directly proportional relationship with the amount of heat energy stored. In short, it can be concluded that a larger mass of PCM can store more energy.

However, not the entire material will be melted and used to store heat energy in real life situation if the heat energy supplied is not enough. A large size of PCM will increase the cost as well and it would be a waste if the water productivity of solar still does not have a significant improvement.

According to Kabeel, El-Samadony and El-Maghlany, they performed an experiment to study the impact of thickness of PCM on the water productivity of solar still. They concluded that the increase in thickness of PCM has insignificant impact on the water productivity of solar still compared to changing in type of PCM (Kabeel, El-Samadony and El-Maghlany, 2018).

Besides that, equation 3.11 also shows that the heat energy stored in PCM is a function of latent heat and specific heat capacity in solid and liquid state. Therefore, the PCM used should possess properties of high latent heat value and high specific heat capacity in solid and liquid state in order to store more energy.

3.2.3 Selection of Phase Change Material

Based on chapter 2.3.1, it is concluded that the PCM used should belongs to the category of solid-liquid PCMs due to their advantages over other type of PCM.

Once again, the solar still is aim to be used in rural region so the cost of PCM should be low. Thus, the material used should not contain any rare elements since this would unnecessarily increase the cost. The market availability also plays an important part in selection of PCM. Besides that, the PCM should also possess the desirable properties mentioned in table 2.1.

When comes to the selection of PCM, it is important to determine the suitable operating temperature of PCM. The temperature range of saline water attainable in solar still has to be determined because the PCM containers will be immersed in the saline water and the temperature of saline water and PCM will be similar as they will undergo heat exchange process all the time. Thus, the PCM should melt within the temperature range of saline water. Based on a previous project conducted by UTAR in Selangor, Malaysia, the result has showed that the saline water in solar still can be easily heated to temperature range of 55 ^{o}C – 65 ^{o}C. Thus, any PCM with melting point lower than 65 ^{o}C is suitable to be used in the solar still.

There are various types of PCM available in the world, but paraffin based PCM is the most commonly used PCM in solar distillation system due to cost consideration. It is a suitable material to be used as a latent heat storage material because it is capable to release large amount of latent heat during the solidification process. Most importantly, it is able to fulfil most of the desirable properties of storage material mentioned in table 2.1.

Figure 3.3: Paraffin Wax

Figure 3.4: Petroleum Jelly

By searching for suppliers through various online trading platforms, paraffin wax with melting point of 58 ^{o}C – 60 ^{o}C and petroleum jelly with melting point of 37 ^{o}C – 40 ^{o}C were found to be the most readily available paraffin based PCM in Malaysia. Therefore, they were used in this study.

3.2.4 Improvement of Phase Change Material

Thermal conductivity of PCM plays an important role in the heat transfer process between the solar absorber and PCM. In other word, the thermal conductivity of PCM will affects the charging and discharging process of PCM.

Heat transfer rate is important in determining the performance of thermal energy storage in solar still. A high thermal conductivity PCM can absorb heat from the solar absorber in a more efficient way and therefore it can store more heat energy compared to PCM with low thermal conductivity.

The rate of heat transfer between absorber basin plate and PCM can be obtained by using following equation (Kabeel, El-Samadony and El-Maghlany, 2018).

$$Q_{abp-PCM} = k_{PCM}A_{PCM}(T_{abp} - T_{PCM}) \tag{3.12}$$

where,

$Q_{abp-PCM}$ = Rate of heat transfer between ABP and PCM, W

k_{pcm} = Thermal conductivity of PCM, W/m^2·K

A_{PCM} = Surface area of PCM, m^2

T_{abp} = ABP temperature, K

T_{PCM} = PCM temperature, K

Based on chapter 2.3.3, there are two methods can be used to enhance the thermal conductivity of PCM. Among the two methods, adding additives with high thermal conductivity is the most commonly used and the most effective method to increase the thermal conductivity of PCM. The additives which have high thermal conductivity are normally metal based materials and carbon based materials. The most commonly used additives are metal particles, metal foam, carbon nanotube, carbon fiber, graphene, expended graphite, etc (Lin et al., 2018).

In this study, aluminium scrap from machining process was used as the additive in PCM. It is believed that by mixing metal scrap into pure PCM, the thermal conductivity can be increased and the energy charging and discharging process of PCM can be improved.

3.2.5 Design of Phase Change Material Storage

A container is needed to contain the PCM and it will be integrated into the solar still unit and act as thermal energy storage. Figure 3.5 shows the pyramid solar still with v-corrugated absorber plate designed by Kabeel, et al. and it was used as a benchmark in the design of storage of PCM (Kabeel et al., 2017).

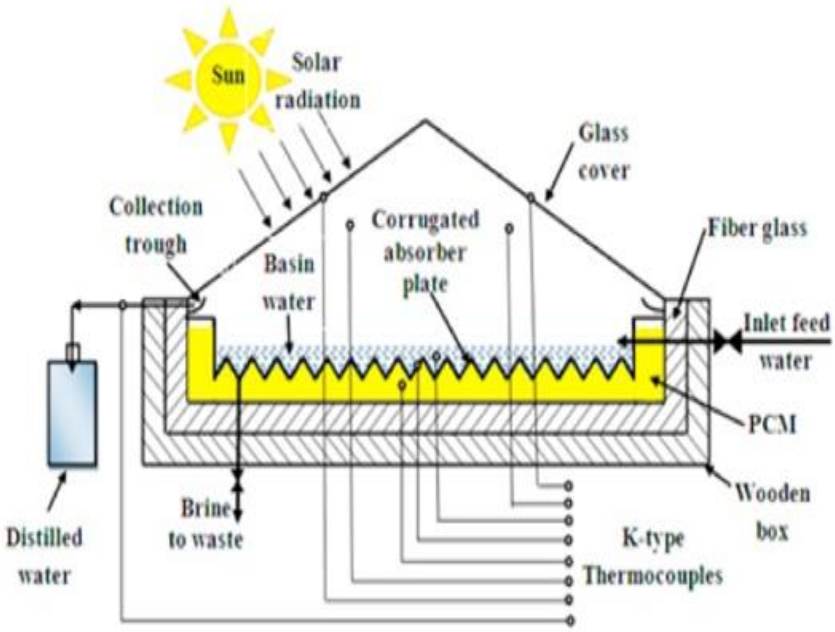


Figure 3.5: Pyramid Solar Still with V-Corrugated Absorber Plate (Kabeel et al., 2017)

Design 1

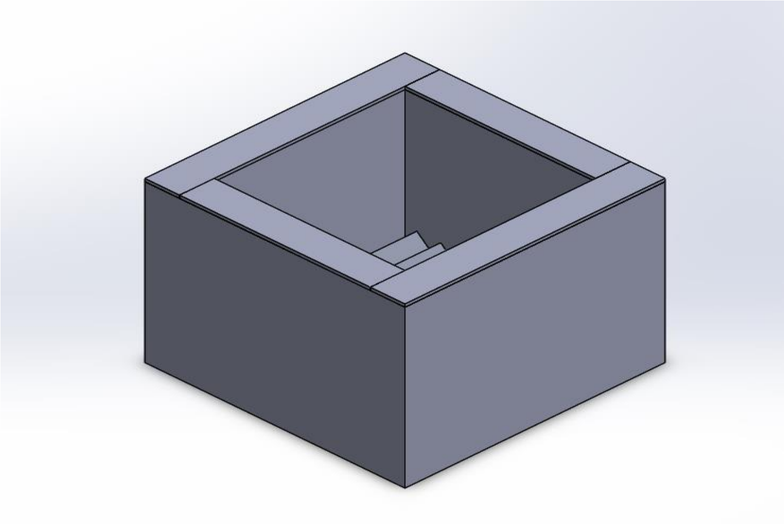


Figure 3.6: Design 1

Figure 3.6 shows the drawing of design 1. In this design, there will be special space designed to contain the PCM and it will be sealed properly after the melted PCM is poured into it to prevent any leakage. After that, the saline water will be poured into it from the top and it will act as the basin for saline water.

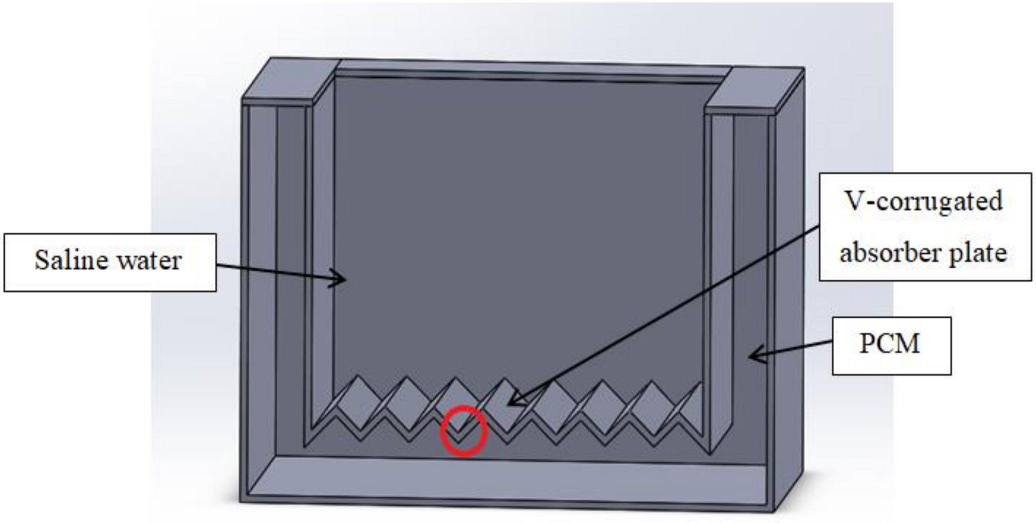


Figure 3.7: Section View of Design 1

Figure 3.7 shows the section view of design 1. The saline water will be poured into the basin and PCM will fills up the empty space. In this design, the absorber plate is designed to be v-corrugated which is similar with the benchmark model.

According to chapter 2.4.2.3, the solar collector area has a directly proportional relationship with the rate of heat transfer and affects the water productivity of solar still. The v-corrugated absorber plate has increased the surface area available for heat transfer. As a result, the rate of heat transfer between the saline water and PCM will be enhanced and lead to increase in water productivity of solar still.

However, it can be predicted that the impurities in saline water will trap at the red circle drawn on the figure 3.7 due to the v shape geometry. When the impurities built up over time, it will become a blockage in the heat transfer between PCM and saline water as it reduces the surface available for heat transfer. In this case, the performance of solar still will be affected and the users have to dismantle the solar still in order to remove the impurities trapped at the v-corrugated absorber plate.

Besides that, the sealant used to seal the opening of PCM container may fades off over times and the PCM might leak into the saline water. It is also difficult to remove PCM from the solar still as the users have to dismantle the entire set up to remove the PCM inside. Thus, this design requires regular maintenance and technical knowledge will be needed to dismantle the solar still.

Moreover, it needs certain technique to fabricate the v-corrugated absorber plate. Thus, fabrication cost will be increased due to the special geometry.

<u>Design 2</u>

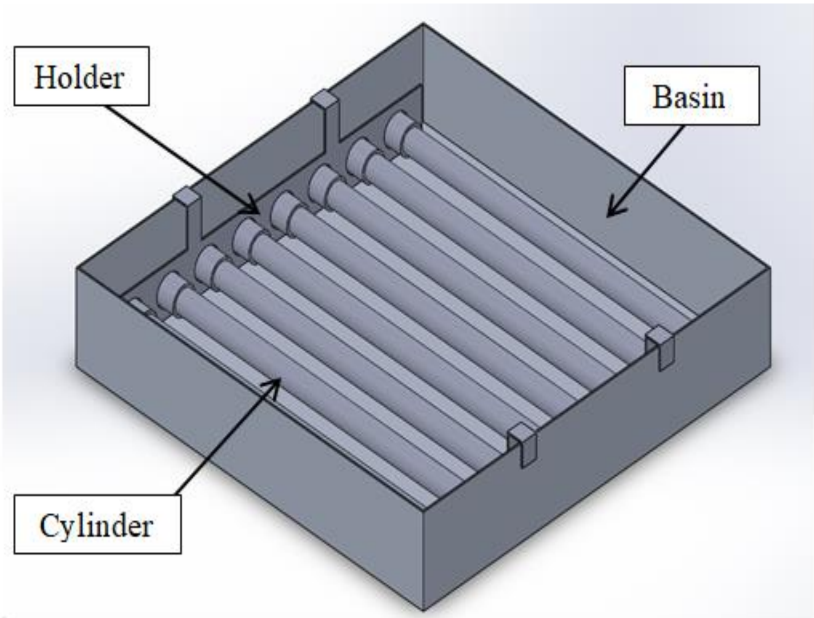


Figure 3.8: Design 2

Figure 3.8 shows the drawing of design 2. In this design, the melted PCM will be poured into the cylinders and the cylinders will be hold by the holders designed to fix them in place. After that, the saline water will be poured into the basin and the cylinders will be immerged in the saline water.

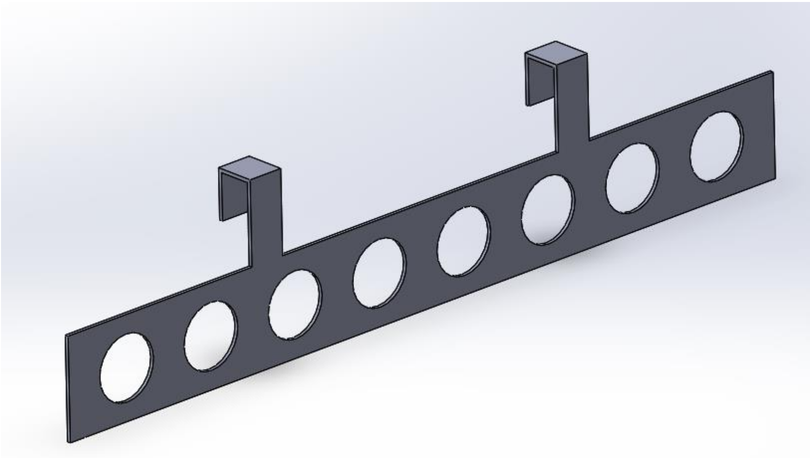


Figure 3.9: Cylinder Holder

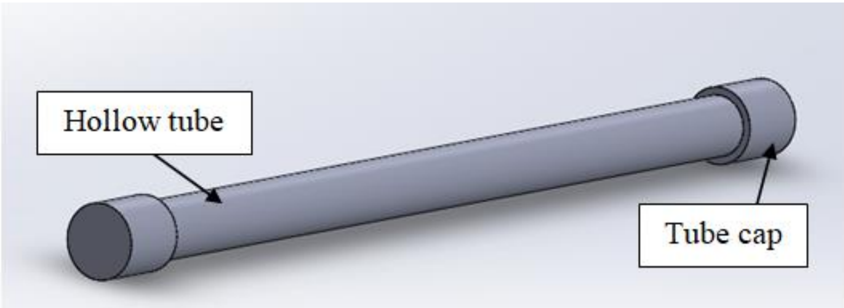


Figure 3.10: Cylinder

Figure 3.9 shows the holder designed to fix the cylinders in place while figure 3.10 shows the cylinder that will be used to contain PCM. The cylinder is a hollow tube which has thread on both ends. The melted PCM will be poured into the tube and tube caps will be used to close the opening. Thread seal tape will be used to seal the opening of tubes to prevent any leakage.

This design is easy to fabricate as it does not has any special geometry. The only machining process is to make thread on the tube. Thus, the fabrication cost is lower and it is able to fulfil the will of large scale implementation in rural region. Moreover, the problem of trapping impurities will not be a concern and therefore it does not need a regular maintenance compared to design 1.

This solar still is aim to produce fresh water in rural region and therefore the fabrication cost should be as low as possible. Moreover, people in rural region do not have any technical knowledge on maintenance of solar still. Thus, the design that is lower cost and requires lesser maintenance will be preferable. As a result, design 2 is selected over design 1.

3.2.6 Fabrication of Phase Change Material Storage

In this solar still, the PCM containers will be immersed in the saline water and therefore saline water will have direct contact with the surface of PCM containers. Thus, the material used to build the containers should possess high thermal conductivity characteristic in order to enhance the heat transfer process between saline water and PCM. Besides that, the material used to fabricate the container must be able to withstand the saline water environment as it is immerged in the saline water. Moreover, cost plays a vital role in selection of material and therefore a low cost material will be favourable. In this case, marine grade metal is selected. Table 3.1 shows the list of marine grade metal.

Table 3.1: Marine Grade Metal

Marine Grade Metal	
1	Carbon Steel / Alloy Steel
2	Aluminium
3	Stainless Steel
4	Copper
5	Bronze
6	Brass
7	Galvanized Steel

Aluminium is proposed here because making the container from aluminium is cheaper compared to other marine grade metal listed in the table 3.1. Moreover, aluminium tube can be easily found in market. Most importantly, the thermal conductivity of aluminium is considerable high and therefore it can be concluded that aluminium is the suitable material to be used in fabrication of PCM container.

3.2.7 Experiment Planning

Fabrication of experiment setup, delivery of PCM and preparation of additives material were completed prior to the experiment. Details of experiment setup can be referred to table A-1 in appendix A. Before the experiment, three types of PCM were prepared.

i) Pure paraffin wax
ii) Pure petroleum jelly
iii) Petroleum jelly mixed with aluminium scrap (10 wt% aluminium scrap)

The PCM was melted and poured into the cylinders. After that, the cylinders were installed into the basin using the holders and they were assembled together with a wooden frame to complete a solar still unit. In this setup, fresnel lens were installed on top of the solar still to act as a solar concentrator which helps to improve the water productivity of solar still.

In the experiment, 6 litres of saline water was poured into the solar still unit and it was put outdoor under the sun to collect thermal energy provided in solar irradiation and use the heat energy to evaporate the saline water inside the basin to produce fresh water that is safe to drink. At night, it is expected that the melted PCM with stored heat energy will release the energy to the saline water in basin to keep the unit running after sunset.

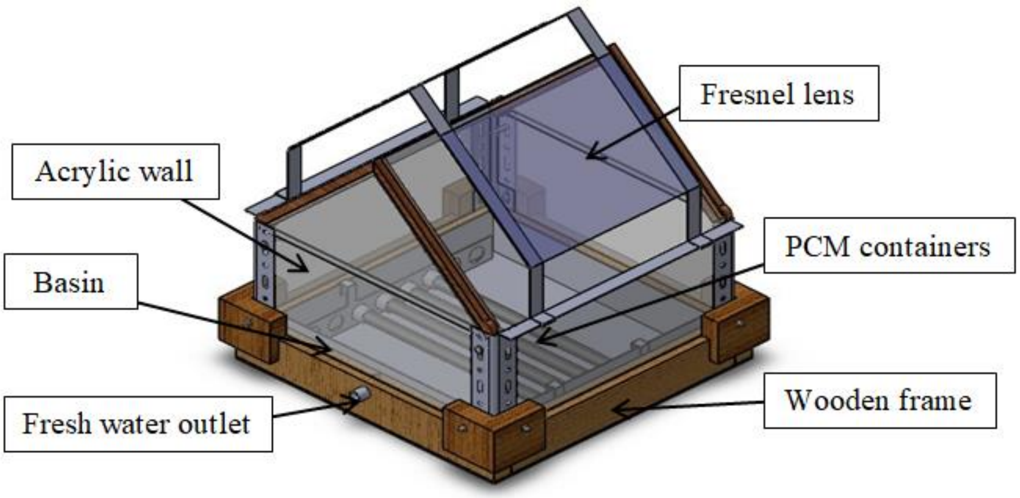


Figure 3.11: Experiment Setup Drawing

Experiments were conducted in Sungai Long, Selangor, Malaysia. Data measurements of solar irradiation, water yield and temperatures were taken in 1 hour interval from 8 am to 12 am. The water productivity of solar still integrated with thermal energy storage using PCM was determined at daily basis and the water productivity of solar still using different type of PCM was compared and discussed.

Nonetheless, conductivity test was conducted after the experiments to determine the value of part per million (PPM) for the water produced. PPM is a unit of measurement for the amount of particles in fluid. According to World Health Organization (WHO) standard, the value of PPM for drinkable water must locate below 500 PPM. The saline water poured into solar still is around 20000 PPM which is the average salinity of sea water. 20000 PPM value of saline water was synthesized by mixing 120 g of salt into 6 litres of tap water. The fresh water produced by solar still should be well below 500 PPM so that it is drinkable. Thus, conductivity test is necessary to prove that the water produced through this solar still is safe to drink.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 Introduction

The current chapter focuses on the results and discussions for this study. Experiment data collected were presented in this chapter and the data were analysed and discussed in depth to provide a better understanding on how PCM improve the water productivity of solar still.

4.2 Experiment

Three types of PCM as shown in figure 4.1 were tested in solar still to determine the impact of thermal energy storage using PCM on water productivity of solar still.

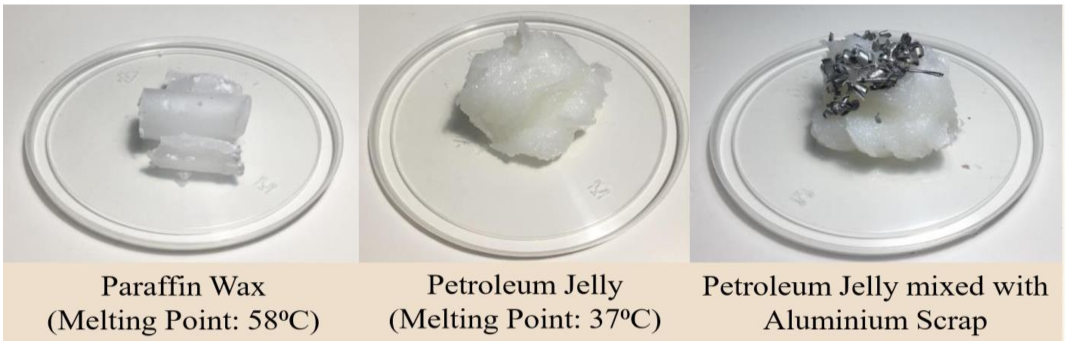


Figure 4.1: PCM Used in Experiment

PCM was melted and poured into PCM container as shown in figure 4.2. The container was painted black to have better absorption of solar irradiation as the PCM container is also the solar absorber in the solar still unit.

Figure 4.2: PCM Container

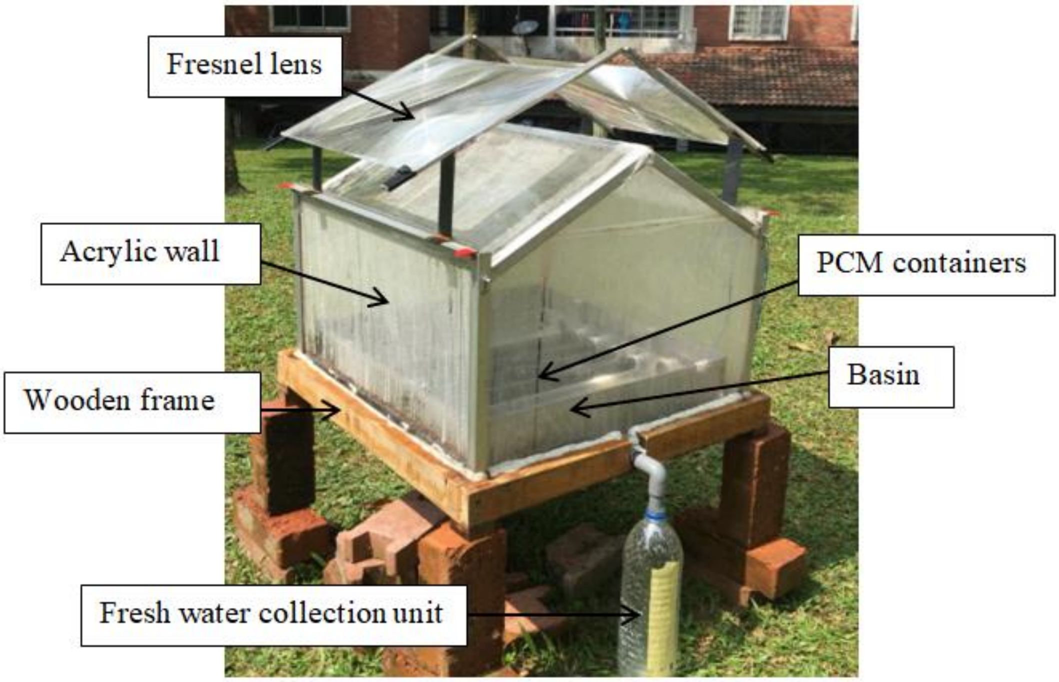


Figure 4.3: Solar Still Prototype

Figure 4.3 shows the solar still prototype used in this study. Referring to mathematical model in chapter 3.2.1, equation 3.5 to equation 3.10 state that the PCM in the containers will receives heat energy from the solar absorber which is also the PCM container in this study. The PCM containers were immersed in the saline water and the fresnel lens on top will concentrate the solar irradiation on the surfaces of PCM containers. Therefore, the PCM container which is also the solar absorber will receives solar heat energy provided in solar irradiation and transfer the heat energy to the PCM inside the containers.

4.3 Temperature

During low solar irradiation period, PCM with stored heat energy will release the energy to heat the saline water. The energy discharging process of PCM occurs when the temperature of saline water is lower than the temperature of PCM. Therefore, the temperature of saline water and PCM are important information which can be used to analyse the heat transfer mechanism between saline water and PCM to study the performance of latent heat energy storage using PCM in the solar still. Ambient temperature was plotted in the temperature graphs as well in order to study the interaction between solar still system and its surrounding. Multiple type K thermocouples were attached to several points inside the solar still to measure the temperature readings.

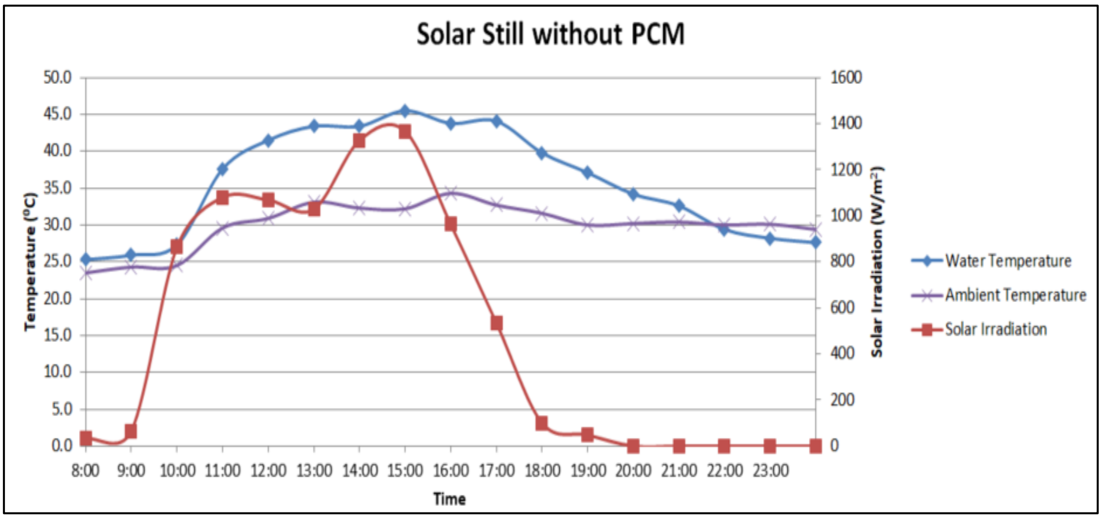


Figure 4.4: Temperature Graph of Solar Still without PCM

Based on figure 4.4, it can be seen that the temperature of saline water increase and decrease together with the solar irradiation. The temperature rises to a peak and starts to drop when the solar irradiation decreased. This result complies with the theory because this is the working principle of solar still as it retain heat energy provided in solar irradiation to heat up the saline water to produce fresh water that is safe to drink. The temperature of saline water drops after 15:00 because the solar heat energy input is low and the heat energy of saline water is loss to the surrounding over time.

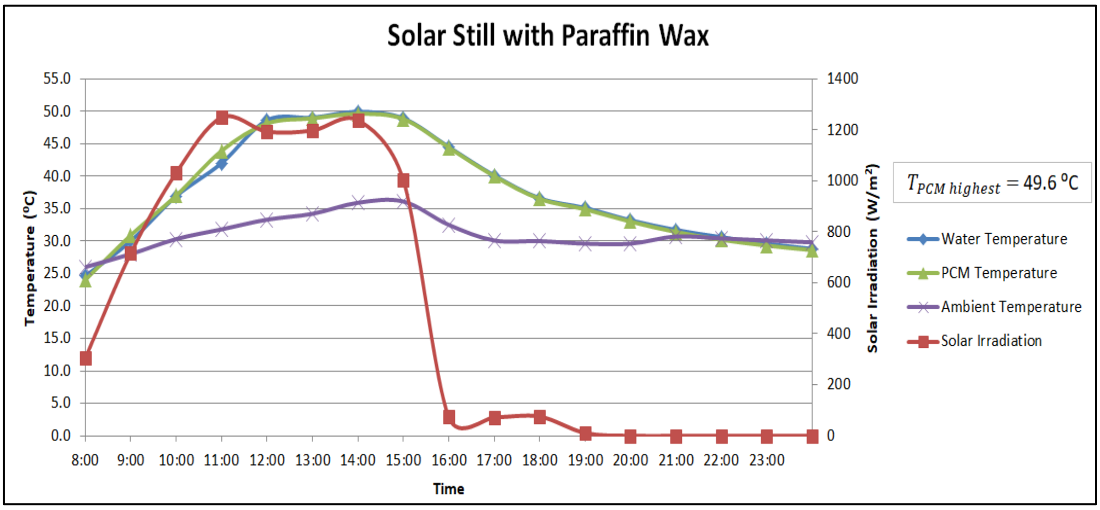


Figure 4.5: Temperature Graph of Solar Still with Paraffin Wax

According to figure 4.5, the temperature of paraffin wax rises to the maximum of 49.6 ºC in the experiment. However, the melting point of paraffin wax used in this study is around 58 ºC which means that the paraffin wax did not undergoes phase transition process as the temperature is lower than the melting point. According to chapter 2.3, PCM needs to undergo phase transition process so that it is able to store energy in sensible heat form and latent heat form. But, the paraffin wax in this study only store heat energy in sensible heat form as the temperature did not rises to the melting point and therefore it did not contribute much to increase the water productivity of solar still.

Comparing figure 4.4 and figure 4.5, it can be seen that the temperature of saline water in solar still without PCM drops sharply while the temperature of saline water in solar still with PCM drops in a much smoother trend and the dropping trend of the temperature is flatter than the solar still without PCM. This is due to PCM in the solar still is releasing the heat energy stored during the period when the solar irradiation is low and therefore it is able to maintain the saline water at a higher temperature compared to solar still without PCM.

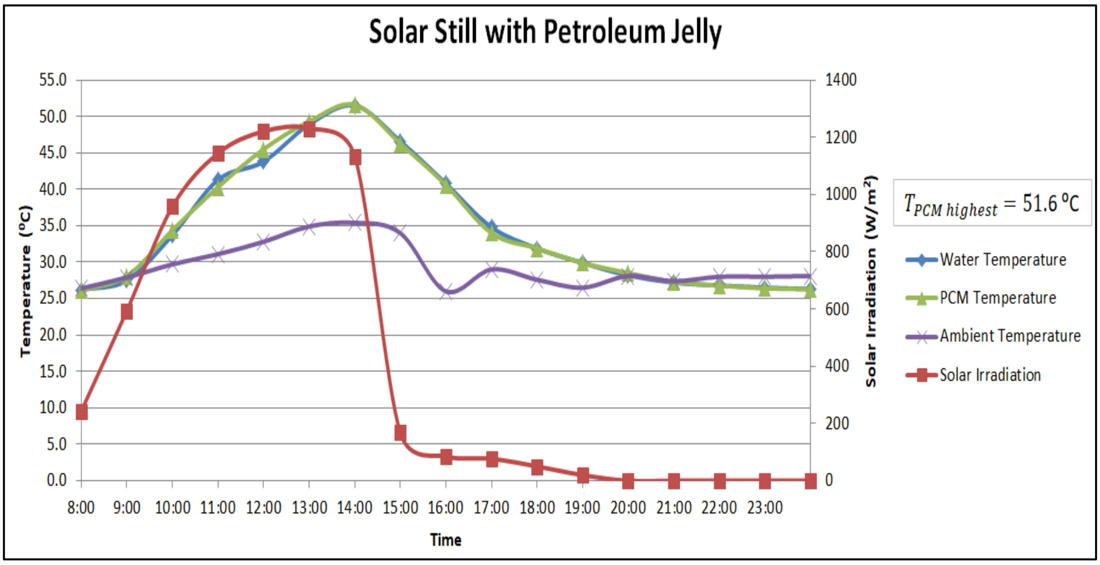


Figure 4.6: Temperature Graph of Solar Still with Petroleum Jelly

The melting point of petroleum jelly used in this study is around 37 ºC. Based on figure 4.6, it can be seen that the temperature of petroleum jelly rises progressively with time up to 14:00 reaching 51.6 ºC which is higher than the melting point of petroleum jelly. Thus, it can be confirmed that the petroleum jelly has undergone phase transition process and therefore the solar heat energy input is stored in the PCM as sensible heat form and latent heat form.

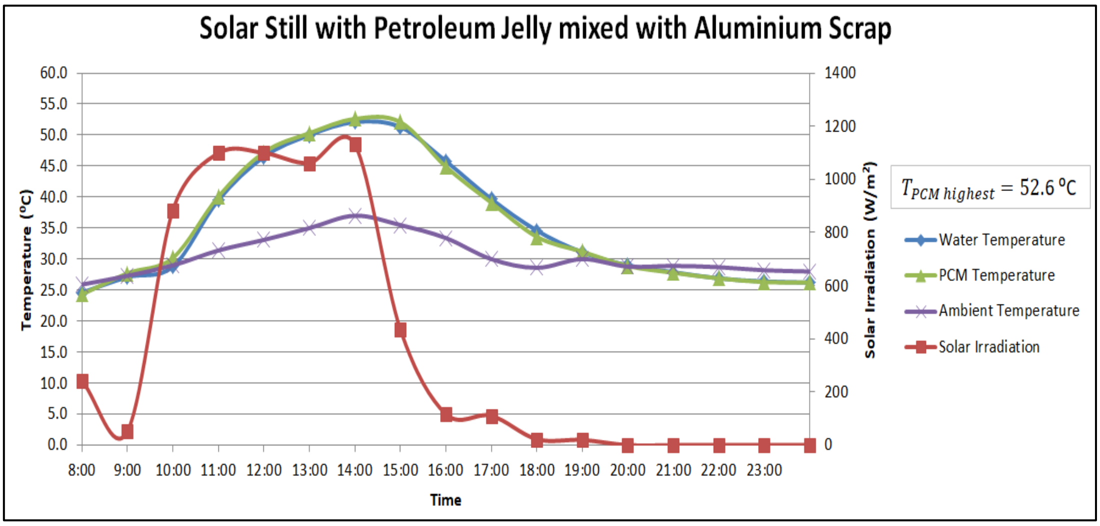


Figure 4.7: Temperature Graph of Solar Still with Petroleum Jelly mixed with Aluminium Scrap

Comparing figure 4.7 to figure 4.6, it is difficult to determine how the thermal conductivity of PCM affects the temperatures because the condition for each experiment is different. Moreover, temperature is a sensitive parameter as it can be easily affected by the solar irradiation, ambient temperature, wind velocity, etc. However, it can be confirmed that the petroleum jelly mixed with aluminium scrap also undergone phase transition process as the temperature of the PCM rises to the maximum of 52.6 ^oC which is higher than the melting point.

By looking into figure 4.5 to figure 4.7, it can be seen that the temperature of PCM is similar with the temperature of saline water for each experiment. The temperature difference between PCM and saline water is very small because PCM and saline water were undergoing heat exchange all the time and therefore the temperatures were rising and dropping together throughout the experiment.

From morning to afternoon when the sun is providing abundant solar irradiation, the temperature of PCM is rising because the solar irradiation is charging the PCM during the period and the temperature of PCM drops after reaching its peak represents that it is undergoing energy discharging process. The temperature of PCM is slightly higher than the temperature of saline water when the solar irradiation is low in each experiment. The energy discharging process occurs when the temperature of saline water is lower than the temperature of PCM. When the PCM discharges the energy stored to the saline water, it allows the solar still to keep running even when the solar irradiation is low.

4.4 Water Productivity

Water productivity of conventional solar still is highly dependent on the solar irradiation. Solar still without thermal energy storage will stop producing water after sunset as there is no solar heat energy supplied to it anymore.

Thermal energy storage using PCM is able to enhance the water productivity of solar still because it can prolong the operation time of solar still. PCM will store the heat energy provided by sun during high solar irradiation period and release the heat energy stored to the saline water during low solar irradiation period. By releasing the heat energy stored to the saline water, PCM allows the solar still to produce water during low solar irradiation period.

The temperature difference between saline water and ambient temperature determines the rate of evaporation and condensation for a solar still. A greater difference will leads to greater water productivity as the rate of evaporation and condensation is increased. Thus, the greatest water yield period is also the greatest temperature difference period.

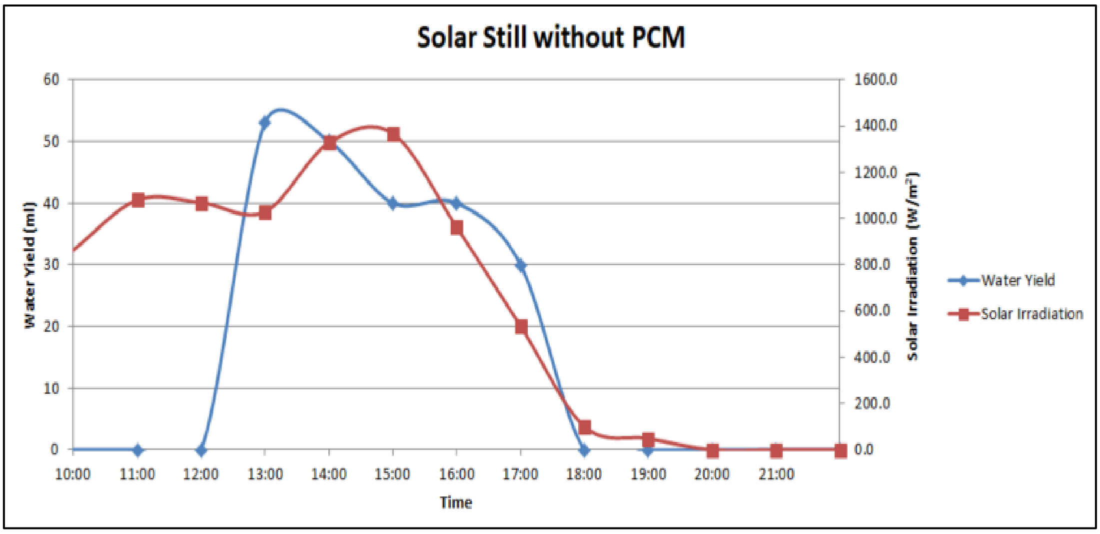


Figure 4.8: Graph of Performance for Solar Still without PCM

Figure 4.8 shows the performance of solar still without PCM which is the conventional solar still. Based on figure 4.8, it can be seen that water yield of solar still without PCM rises slowly to a peak and drop significantly when the solar irradiation decreased and it stop producing water after 1800 which is around the time of sunset. The operation time of solar still without PCM is very short as it only produces water when there is sufficient solar irradiation. The result follows the result predicted as the solar still without PCM will stop producing water after sunset as there is no solar heat energy provided to the solar still anymore.

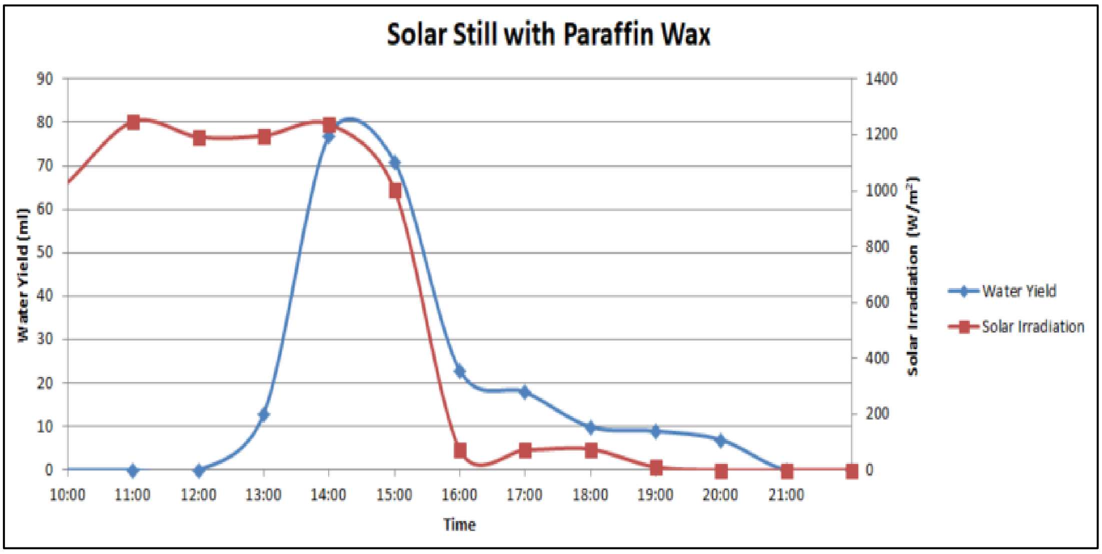


Figure 4.9: Graph of Performance for Solar Still with Paraffin Wax

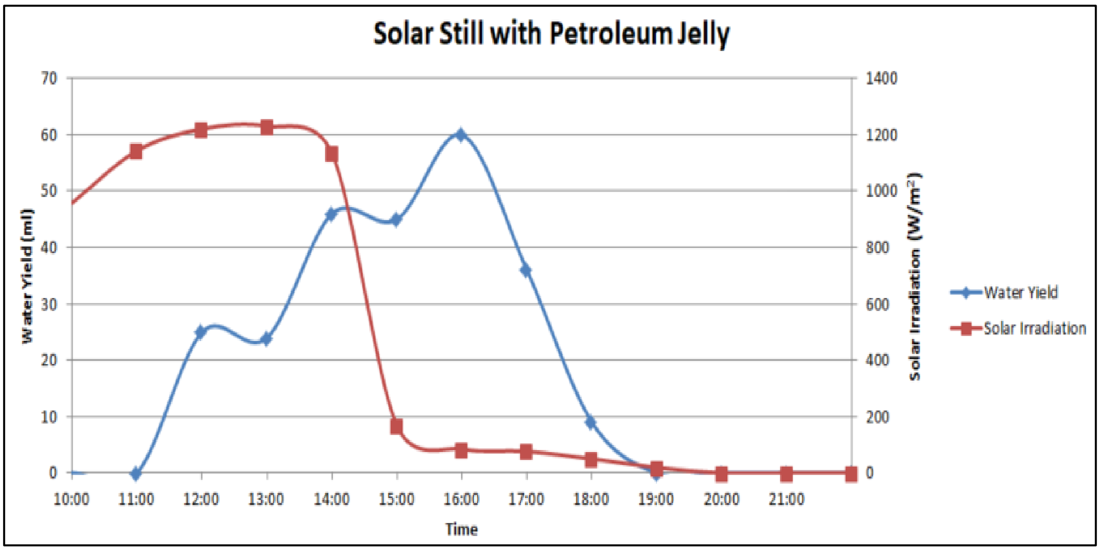


Figure 4.10: Graph of Performance for Solar Still with Petroleum Jelly

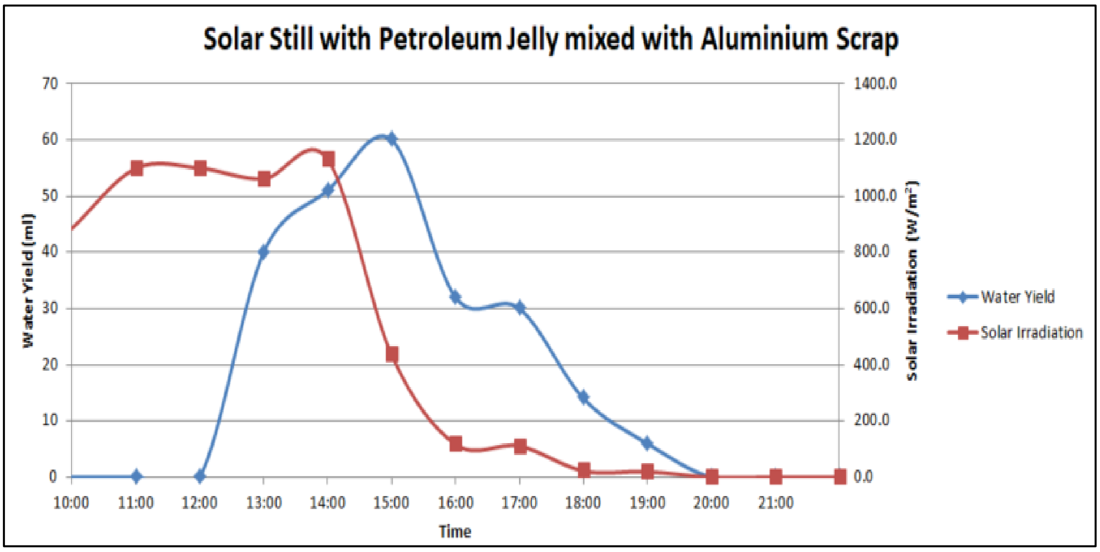


Figure 4.11: Graph of Performance for Solar Still with Petroleum Jelly mixed with Aluminium Scrap

Figure 4.9 to figure 4.11 show the performance of solar still integrated with thermal energy storage using different PCM. By looking at the figures, it can be seen that water yield of solar still integrated with PCM rises gradually to a peak and drops significantly when the solar irradiation decreased just like the conventional solar still. However, solar still integrated with PCM is able to maintain a low water yield during low solar irradiation period and after sunset when there is low or no solar heat energy provided to the solar still. Unlike conventional solar still, solar still integrated with PCM has longer operation time and therefore it can be concluded that solar still integrated with PCM is able to perform better and produces more water because PCM prolongs the operation time of solar still.

By looking into the figure 4.8 to figure 4.11 is not enough to explain the impact of thermal energy storage using different PCM on water productivity of solar still because the experiments were conducted in different day and therefore the condition for each experiment is different. According to chapter 2.4.2, performance of solar still varies with meteorological parameters which cannot be controlled during the experiment such as weather condition, wind speed, solar irradiation, etc. Thus, the figures are unable to provide detailed insights on how different PCM affects water productivity of solar still.

Since the water productivity of solar still is mainly dependents on the solar irradiation and therefore other factors is ignored when comparing the results between different solar still. The solar irradiation is different for each experiment and the solar irradiation also changes periodically with time from sunrise to sunset. Thus, average solar irradiation was calculated for each experiment in order to calculate a measurement called water yield per average solar irradiation for each experiment to determine the impact of different PCM on water productivity of solar still.

$$Water\ yield\ per\ Average\ solar\ irradiation = \frac{V_{water\ produced}}{I_{average}} \tag{4.1}$$

where,

$V_{water\ produced}$ = Amount of water produced in millilitre, ml

$I_{average}$ = Average solar irradiation, W/m^2·h

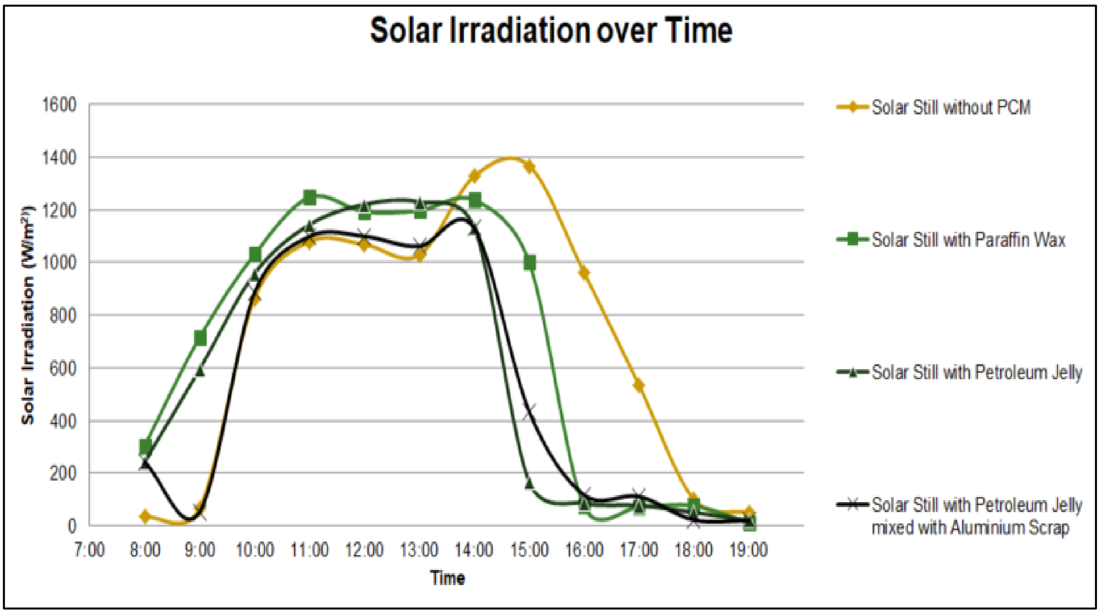


Figure 4.12: Graph of Solar Irradiation over Time

Table 4.1: Average Solar Irradiation for Each Experiment

Average Solar Irradiation (W/m^2·h)	
Solar Still without PCM	706.842
Solar Still with Paraffin Wax	680.042
Solar Still with Petroleum Jelly	577.025
Solar Still with Petroleum Jelly mixed with Aluminium Scrap	522.901

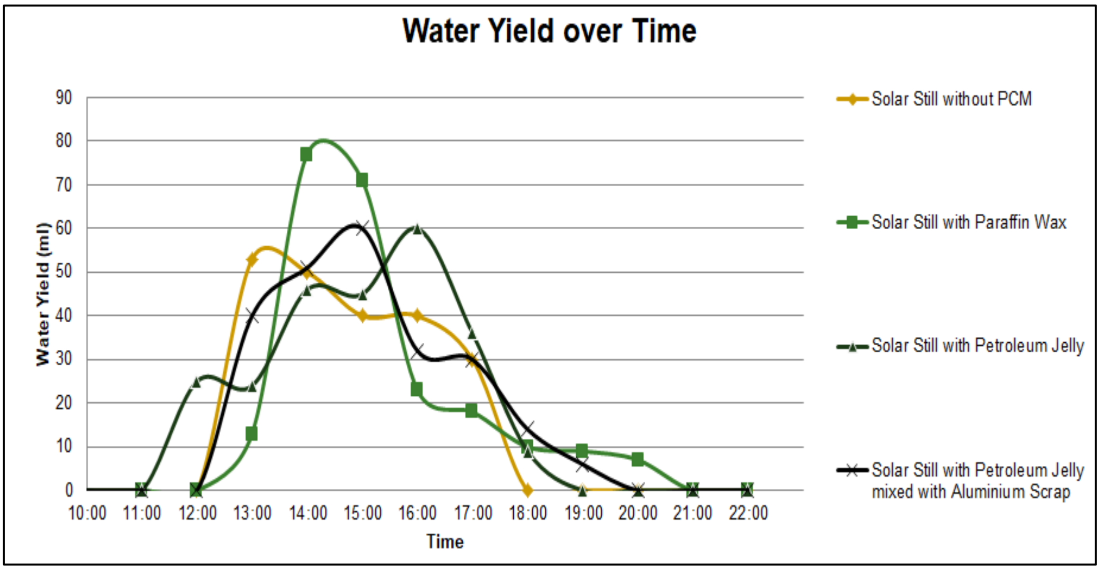


Figure 4.13: Graph of Water Yield of Solar Still Utilizing Different PCM over Time

Table 4.2: Total Water Yield for Each Experiment

Total Water Yield (ml)	
Solar Still without PCM	213
Solar Still with Paraffin Wax	228
Solar Still with Petroleum Jelly	245
Solar Still with Petroleum Jelly mixed with Aluminium Scrap	233

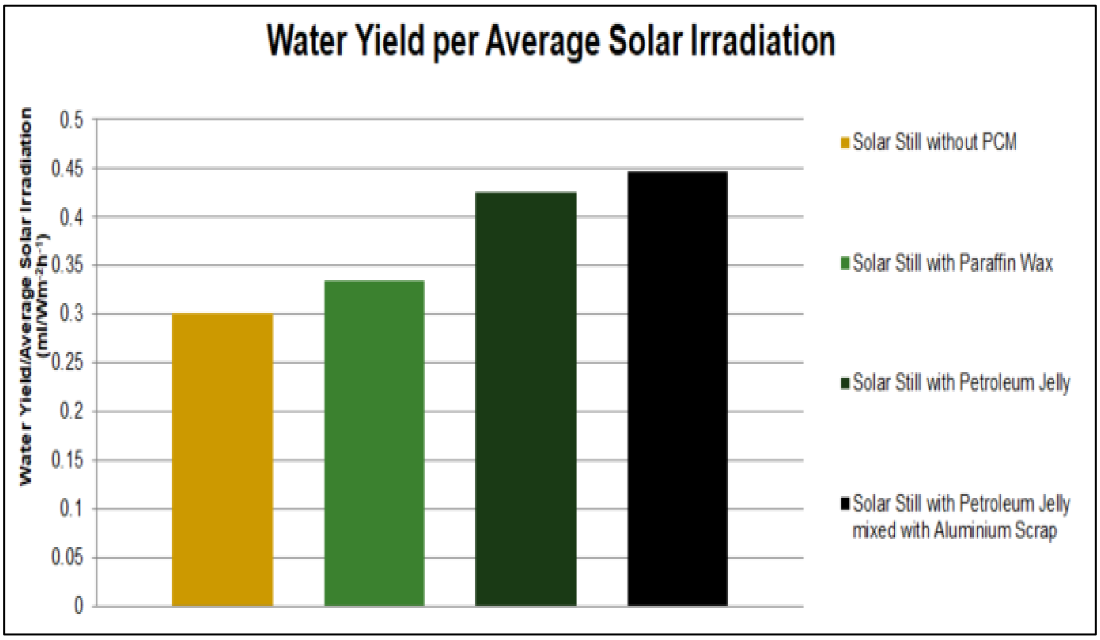


Figure 4.14: Comparison of Water Yield per Average Solar Irradiation

Table 4.3: Water Yield per Average Solar Irradiation for Each Experiment

Water Yield per Average Solar Irradiation ($ml/Wm^{-2}h^{-1}$)		Percentage increment compared to solar still without PCM (%)
Solar Still without PCM	0.3013	-
Solar Still with Paraffin Wax	0.3353	11.3
Solar Still with Petroleum Jelly	0.4246	40.9
Solar Still with Petroleum Jelly mixed with Aluminium Scrap	0.4456	47.9

According to table 4.3, it can be seen that solar still without PCM has the lowest value of water yield per average solar irradiation which is 0.3013 $ml/Wm^{-2}h^{-1}$. Comparing the results of solar still with PCM to solar still without PCM, it can be seen that solar still with paraffin wax shows 11.3 % of increment in water yield per average solar irradiation while solar still with petroleum jelly shows 40.9 % and solar still with petroleum jelly mixed with aluminium scrap shows 47.9 %.

The solar still with paraffin wax shows the lowest increment in water productivity per average solar irradiation even though paraffin wax has higher latent heat of fusion and higher specific heat capacity in solid and liquid state than petroleum jelly. According to the discussion in chapter 4.3, the low increment is due to the paraffin wax used in this study did not undergoes phase transition process and it stores heat energy in sensible heat form only. Therefore, paraffin wax is unable to enhance the performance of solar still significantly. This highlights that the melting point of PCM used must match with the operating temperature of solar still so that it can function at its full potential as latent heat energy storage. Thus, paraffin wax with lower melting point will be more suitable to be used in this solar still design.

By mixing aluminium scrap into petroleum jelly, the thermal conductivity of petroleum jelly is enhanced. The thermal diffusivity is increased as well as thermal diffusivity is the thermal conductivity divided by density and specific heat capacity at constant pressure. Thermal diffusivity determines the rate of heat transfer of a material from the hot end to the cold end. Therefore, petroleum jelly mixed with aluminium scrap has highest water yield per average solar irradiation because it has higher thermal conductivity and higher thermal diffusivity than the pure petroleum jelly which means it can be charged at a faster rate and the heat energy can propagate throughout the entire PCM faster compared to pure petroleum jelly.

In the end, it can be concluded that solar still integrated with thermal energy storage using PCM has better performance compared to solar still without PCM. Besides that, the results obtained have proved that petroleum jelly mixed with aluminium scrap has the best performance among the 3 types of PCM used in this study due to its enhanced thermal conductivity characteristic.

4.5 Water Conductivity

Although the condensate collected from solar still is theoretically safe to drink, but water conductivity test should be conducted to prove that the water produced from this solar still is definitely safe to drink. According to chapter 3.2.7, the fresh water produced should have a PPM value which is well below 500 based on WHO standard. TDS and EC meter was used to measure PPM value of the water produced.

Figure 4.15: Total Dissolved Solids and Electrical Conductivity Meter (TDS and EC)

Table 4.4: PPM Value of Saline Water and Condensate

Solution	Temperature (ºC)	Part per Million (PPM)
Saline Water	33.0	~20000
Condensate	33.6	14

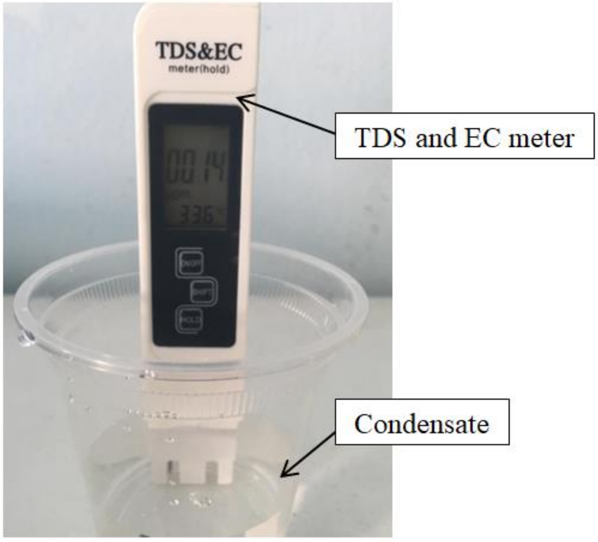


Figure 4.16: Conductivity Test for Condensate

According to table 4.4, it proves that this solar still is able to produce fresh water with PPM value of 14 out from saline water with approximate PPM value of 20000. Thus, the water produced is proved safe to drink.

4.6 Problems Encountered

Throughout the entire study, the biggest problem encountered is the uncontrollable parameters in experiment. Performance of solar still varies with uncontrollable parameters such as atmosphere humidity, weather condition, wind speed and solar irradiation. The weather is mostly cloudy during the experiment period and the cloud is affecting the solar irradiation. Therefore, the inconsistent solar irradiation has caused the performance of solar still in this study not up to expectation.

Besides that, the condensate collection is not efficient as the piping system inside solar still is not well designed. The condensates were stuck in the pipes installed in solar still because the slope of pipes installed is not high enough to let the water fall into collection unit efficiently. Thus, the slope of pipes must be increased so that the condensate collection can be more efficient.

Another critical problem faced that must be highlighted is that the paraffin wax used in this study is not contributing much in enhancing the water productivity of solar still. The melting point of paraffin wax is higher than the operating temperature of solar still in this study and therefore it only performs like a sensible heat storage. To function at its full potential as latent heat energy storage, PCM must undergo phase transition process so that it is able to store heat at sensible heat form and latent heat form. Thus, paraffin wax with lower melting point will be more suitable to be used in this study. However, paraffin wax is not a popular material in Malaysia and therefore searching for suppliers is the most challenging part throughout the study.

Nonetheless, the performance of solar still is affected by the height of solar still in this study. The solar still was designed to be high in order to cope with the focal length of fresnel lens used. However, it was found that the heat will be lost from the solar still system to the surrounding through the side walls and this has significantly affected the performance of solar still. Thus, the height of solar still has to be adjusted and more researches have to be done to solve this problem.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The phase change material storage has been designed and fabricated as shown in figure 3.10 and figure 4.2. The thermal conductivity of phase change material is enhanced by adding additives with high thermal conductivity into it. By enhancing the thermal conductivity of phase change material, its performance as latent heat energy storage is improved because the energy charging and discharging process is enhanced. In this case, aluminium scrap is mixed into petroleum jelly to improve its thermal conductivity. The impact of thermal energy storage using phase change material on water productivity of solar still is studied as well. Pure paraffin wax, pure petroleum jelly and petroleum jelly mixed with aluminium scrap were tested in this study.

In conclusion, solar still integrated with thermal energy storage using phase change material has better performance compared to conventional solar still. Phase change material is able to increase the water productivity of solar still as solar still with paraffin wax shows 11.3 % of increment in water yield per average solar irradiation while solar still with petroleum jelly shows 40.9 % and solar still with petroleum jelly mixed with aluminium scrap shows 47.9 %.

5.2 Recommendations for Future Work

Recommendations for future research and work to resolve the problem encountered mentioned in chapter 4.6 will be discussed here.

To further improve the performance of solar still integrated with thermal energy storage using PCM. The melting point of PCM used must match with the operating temperature of solar still. In future, paraffin wax with lower melting point should be used. Besides that, the height of solar still has to be adjusted so that the heat loss to the surrounding can be minimized. Moreover, modification has to be done on the piping system inside the solar still to ensure that all the condensates can be collected efficiently. Last, modification of PCM containers can be done to study how different geometry affects the performance of PCM in a solar still.

REFERENCES

Abdel-Rehim, Z.S. and Lasheen, A., 2007. Experimental and theoretical study of a solar desalination system located in Cairo, Egypt. *Desalination*.

Abdul-Wahab, S.A. and Al-Hatmi, Y.Y., 2013. Performance evaluation of an inverted absorber solar still integrated with a refrigeration cycle and an inverted absorber solar still. *Energy for Sustainable Development*.

Akash, B.A., Mohsen, M.S. and Nayfeh, W., 2000. Experimental study of the basin type solar still under local climate conditions. *Energy Conversion and Management*.

Akeiber, H., Nejat, P., Majid, M.Z.A., Wahid, M.A., Jomehzadeh, F., Zeynali Famileh, I., Calautit, J.K., Hughes, B.R. and Zaki, S.A., 2016. *A review on phase change material (PCM) for sustainable passive cooling in building envelopes*. *Renewable and Sustainable Energy Reviews*.

Al-harahsheh, M., Abu-Arabi, M., Mousa, H. and Alzghoul, Z., 2018. Solar desalination using solar still enhanced by external solar collector and PCM. *Applied Thermal Engineering*.

Alaudeen, A., Johnson, K., Ganasundar, P., Syed Abuthahir, A. and Srithar, K., 2014. Study on stepped type basin in a solar still. *Journal of King Saud University - Engineering Sciences*.

Anon 2018. *Water Scarcity | Threats | WWF*. [online] Available at: <https://www.worldwildlife.org/threats/water-scarcity> [Accessed 17 Jul. 2018].

Asbik, M., Ansari, O., Bah, A., Zari, N., Mimet, A. and El-Ghetany, H., 2016. Exergy analysis of solar desalination still combined with heat storage system using phase change material (PCM). *Desalination*.

Badran, A.A., Al-Hallaq, A.A., Eyal Salman, I.A. and Odat, M.Z., 2005. A solar still augmented with a flat-plate collector. *Desalination*.

Badran, O.O. and Abu-Khader, M.M., 2007. Evaluating thermal performance of a single slope solar still. *Heat and Mass Transfer/Waerme- und Stoffuebertragung*.

Dashtban, M. and Tabrizi, F.F., 2011. Thermal analysis of a weir-type cascade solar still integrated with PCM storage. *Desalination*.

Fath, H.E.S., El-Samanoudy, M., Fahmy, K. and Hassabou, A., 2003. Thermal-economic analysis and comparison between pyramid-shaped and single-slope solar still configurations. *Desalination*.

Ibrahim, N.I., Al-Sulaiman, F.A., Rahman, S., Yilbas, B.S. and Sahin, A.Z., 2017. *Heat transfer enhancement of phase change materials for thermal energy storage applications: A critical review*. *Renewable and Sustainable Energy Reviews*.

Kabeel, A.E. and Abdelgaied, M., 2016. Improving the performance of solar still by using PCM as a thermal storage medium under Egyptian conditions. *Desalination*.

Kabeel, A.E., El-Samadony, Y.A.F. and El-Maghlany, W.M., 2018. Comparative study on the solar still performance utilizing different PCM. *Desalination*.

Kabeel, A.E., Teamah, M.A., Abdelgaied, M. and Abdel Aziz, G.B., 2017. Modified pyramid solar still with v-corrugated absorber plate and PCM as a thermal storage medium. *Journal of Cleaner Production*.

Kenisarin, M. and Mahkamov, K., 2016. *Passive thermal control in residential buildings using phase change materials*. *Renewable and Sustainable Energy Reviews*.

Khan, M.M.A., Saidur, R. and Al-Sulaiman, F.A., 2017. *A review for phase change materials (PCMs) in solar absorption refrigeration systems*. *Renewable and Sustainable Energy Reviews*.

Kumar, S. and Tiwari, A., 2008. An experimental study of hybrid photovoltaic thermal (PV/T)-active solar still. *International Journal of Energy Research*.

Lin, Y., Jia, Y., Alva, G. and Fang, G., 2018. *Review on thermal conductivity enhancement, thermal properties and applications of phase change materials in thermal energy storage*. *Renewable and Sustainable Energy Reviews*.

Mekonnen, M.M. and Hoekstra, A.Y., 2016. Sustainability: Four billion people facing severe water scarcity. *Science Advances*.

Panchal, H. and Shah, P.K., 2012. Investigation on solar stills having floating plates. *International Journal of Energy and Environmental Engineering*.

Pielichowska, K. and Pielichowski, K., 2014. Phase change materials for thermal energy storage. *Progress in Materials Science*.

Rajamanickam, M.R. and Ragupathy, A., 2012. Influence of Water Depth on Internal Heat and Mass Transfer in a Double Slope Solar Still. *Energy Procedia*.

Reyes, A., Henríquez-Vargas, L., Rivera, J. and Sepúlveda, F., 2017. Theoretical and experimental study of aluminum foils and paraffin wax mixtures as thermal energy storage material. *Renewable Energy*.

Şahan, N., Fois, M. and Paksoy, H., 2015. Improving thermal conductivity phase change materials - A study of paraffin nanomagnetite composites. *Solar Energy Materials and Solar Cells*.

Selvaraj, K. and Natarajan, A., 2018. *Factors influencing the performance and productivity of solar stills - A review*. *Desalination*.

Shalaby, S.M., El-Bialy, E. and El-Sebaii, A.A., 2016. An experimental investigation of a v-corrugated absorber single-basin solar still using PCM. *Desalination*.

Sharma, A., Tyagi, V. V., Chen, C.R. and Buddhi, D., 2009. *Review on thermal energy storage with phase change materials and applications*. *Renewable and Sustainable Energy Reviews*.

Singh, H.N. and Tiwari, G.N., 2004. Monthly performance of passive and active solar stills for different Indian climatic conditions. *Desalination*.

Velmurugan, V. and Srithar, K., 2011. *Performance analysis of solar stills based on various factors affecting the productivity - A review*. *Renewable and Sustainable Energy Reviews*.

Wang, T., Wang, S., Luo, R., Zhu, C., Akiyama, T. and Zhang, Z., 2016. Microencapsulation of phase change materials with binary cores and calcium carbonate shell for thermal energy storage. *Applied Energy*.

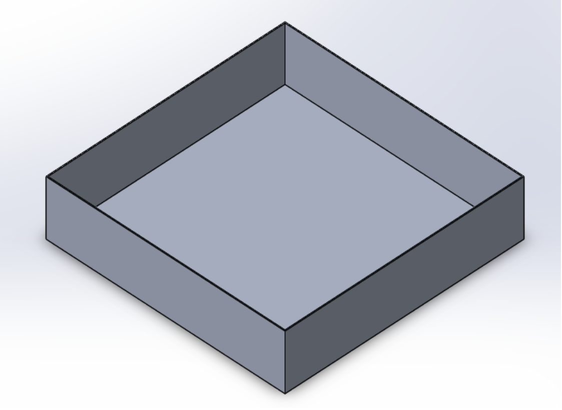
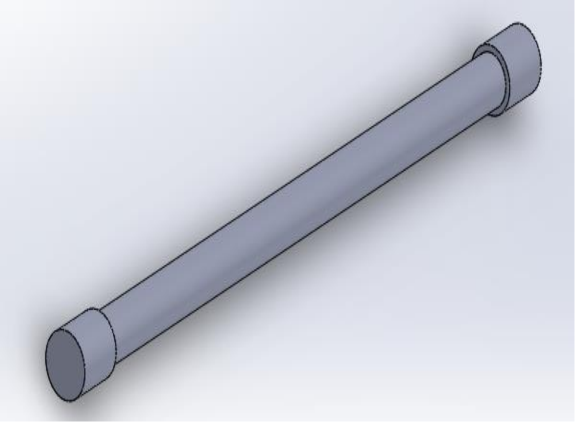
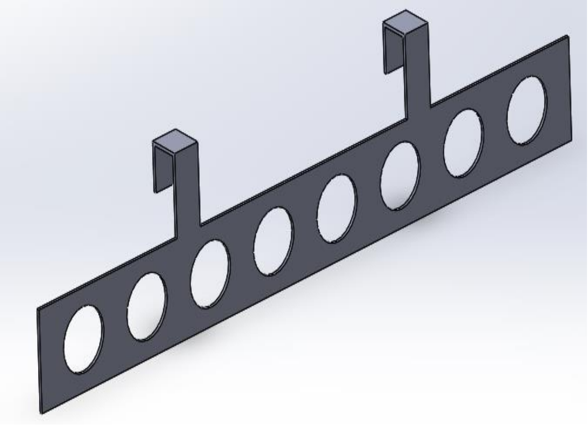
Wang, Z., Qiu, F., Yang, W. and Zhao, X., 2015. *Applications of solar water heating system with phase change material*. *Renewable and Sustainable Energy Reviews*.

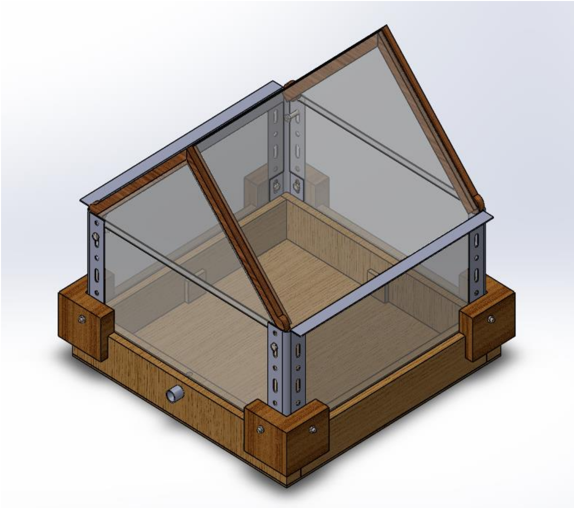
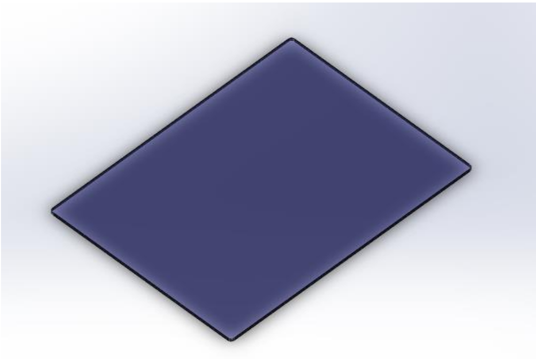
Xu, T., Chen, Q., Huang, G., Zhang, Z., Gao, X. and Lu, S., 2016. Preparation and thermal energy storage properties of d-Mannitol/expanded graphite composite phase change material. *Solar Energy Materials and Solar Cells*.

APPENDICES

APPENDIX A: Tables

Table A-1: Details of Experiment Setup

Item	Description
Basin 	Length: 500 mm Width: 500 mm Depth: 100 mm Thickness: 2 mm Material: Stainless Steel 304
Cylinder 	Outer Diameter: 25.4 mm Length: 480 mm Thickness: 1 mm Material: Aluminium 6063
Holder 	Number of hole: 8 Diameter of hole: 35 mm Material: Stainless Steel 304

<u>Wooden frame</u> 	Length: 600 mm Width: 600 mm Total height: 610 mm Side wall: 470 mm x 240 mm Top cover: 535 mm x 385 mm Angle of inclination: 30^{o} Material: Wood, aluminium and acrylic board
<u>Fresnel lens</u> 	Length: 400 mm Width: 300 mm Focal distance: 600 mm