STUDY OF THE COMBINED EFFECT OF THERMAL STORAGE AND SUNLIGHT CONCENTRATION FOR A SOLAR DISTILLER

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A project report submitted in partial fulfilment of the requirements for the award of Bachelor of Mechanical Engineering with Honours

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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.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"STUDY OF THE COMBINED EFFECT OF THERMAL STORAGE AND SUNLIGHT CONCENTRATION FOR A SOLAR DISTILLER"** was prepared by **LEE SHAU MENG** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Mechanical Engineering with Honours at Universiti Tunku Abdul Rahman.

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ABSTRACT

Solar distillation is one of the methods used for water desalination. It involves only evaporation and condensation process to remove impurities from the saline water and produces clean water. The only source of energy required by solar distiller is solar thermal energy, which makes it an ideal choice for rural areas that is lack of advanced technologies. The performance of the solar distiller can be improved by implementing thermal storage and sunlight concentration devices. Thermal storages made from phase change materials are commonly used. However, the low thermal conductivity of phase change materials reduces the efficiency in storing and releasing heat energy. Therefore, conductive particles such as aluminium is added into the phase change materials to increase the thermal conductivity. Besides, the Fresnel lens with higher concentration ratio is able to concentrate more solar irradiance towards the solar distiller. Experiments were conducted to find out the optimal ratio of paraffin wax to aluminium scraps as a thermal storage and the optimal Fresnel lens concentration ratio. Saline water of 35000 ppm was used in this research to imitate the salinity of seawater. The optimal ratio was found to be 8:2. It increased the productivity and efficiency of the basic solar distiller by 93.06% and 10.74% respectively. The Fresnel lens with concentration ratio of 25.00 was implemented onto the solar distiller with thermal storage had further improved the productivity and efficiency of the basic solar distiller by 506.39% and 25.89% respectively. The clean water was produced with a total dissolved solids value ranges from 69 ppm to 92 ppm which complied to the safe water drinking standard by World Health Organisation (WHO) which stated that the total dissolved solids value should be lower than 500 ppm for safe drinking water.

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LIST OF SYMBOLS / ABBREVIATIONS

TES		Thermal Energy Storage
PCM		Phase Change Material
TDS		Total Dissolved Solids
PW		Paraffin Wax
Al		Aluminium
CR		Concentration Ratio
$h_{fg,w}$		Specific heat capacity of water, kJ/kg·°C
$h_{fg,sw}$		Specific heat capacity of saline water, kJ/kg·°C
T		Temperature, °C
S		Salinity of water, g/kg
E		Energy, kJ
$I(t)$		Solar Irradiance, W/m^2
A_{SW}		Area of saline water basin, m^2
Δt		Time, hr
m_{yield}		Mass of water yield, g
A_{ap}		Area of aperture
A_{rec}		Area of receiver
U_T	=	Total combined uncertainty
U_R	=	Uncertainty due to repeatability
U_A	=	Uncertainty due to accuracy.

CHAPTER 1

INTRODUCTION

1.1 General Introduction

Human beings have 4 basic needs in life in order to survive which are food, water, air and shelter. The lack of any of these will results in non-survival. Human can only survive few days without drinking any water. Adequate hydration by drinking water is vital for human to maintain their body's fluid balance in order to ensure proper body functions such as circulation, temperature regulation and digestion. In addition, the consumption of contaminated and unclean water will cause diseases such as typhoid, hepatitis A, diarrhoea and many more. Lack of proper treatment to these diseases can lead to death. On the other side, the importance of clean water does not only limit to hydration purpose, but clean water is also important in human's daily life for hygiene and sanitation purpose. For example, clean water is used to clean cooking utensil and cutlery that is used to prepare and serve the food that human consumes into their body. On top of that, clean water is also important when it comes to healthcare industry as the environment and facilities must be cleaned and sterilized to provide a suitable environment for patients with low immunity.

Despites the importance of water for a human being, there are billions of humans worldwide do not have access to clean and drinkable water. According to the data from United Nations World Water Development Report 2023, there is approximately 2 billion people all over the world has been facing scarcity in clean and safe drinking water. While at the same time, around 46% of the world's population, which is around 3.6 billion people, do not have access to proper sanitation services. Sub-Saharan Africa, certain region of Middle East, South Asia and Central America are some of the countries and regions that are most severely affected by clean water scarcity. According to the same report from United Nations, there are 771 million people facing severe water scarcity to an extend that even the basic drinking water service is unavailable, and half of the 771 million people lives in Sub-Saharan Africa. Water scarcity and contaminated water has endangered millions of humans.

The innovation and advancement of technologies in water desalination have become so vital to overcome the issue of water scarcity. Desalination is a process of removing the impurities, mineral components and salts from saline water in order to make it safe and clean for drinking purpose. The most common and widely used technologies for desalination is distillation, which is a process that separates the mineral components and salts from the saline water through evaporation and condensation process. This process usually conducted in a solar still, where saline water is evaporated and condensed on a specially designed inclined surface which will allows the condensed vapor to be collected into a specific storage that will contain fresh water. There are multiple innovative distillation technologies available such as solar distillation, vacuum distillation, vapor-compression distillation and membrane distillation. However, the lack of facilities and technologies available in the rural areas making advanced distillation technologies to be challenging to be implemented. Therefore, traditional solar distillation method that does not require high operating cost and advance equipment has become an ideal solution to freshwater scarcity as it only requires heat energy and sun irradiation in the process.

The efficiency and performance of a conventional solar distiller can be poor as they only rely on the heat and mass transfer of natural convection, and this is insufficient for produce sufficient fresh water. The innovation of technologies on solar distiller has contributed to a higher performance and efficiency solar distiller by implementing solar concentration device (Fresnel lens) and thermal storage using phase change material. Solar concentration device has the function of reflecting and focusing the sunlight onto a specific spot, which will provide a high concentration of sunlight and thermal energy onto the saline water to enhance the evaporation process. The most common solar concentration device is a Fresnel lens due to its advantages such as small in size, light weight, low cost and small focal length. Other than that, thermal storage has a function of storing heat energy and will be extracted for usage when necessary. Phase change material is used in thermal storage because the phase change of material is capable to store and release a large amount of thermal energy. However, most phase change material has a poor thermal conductivity which reduces the effectiveness of storing and releasing thermal energy. Therefore, a high thermal conductivity material such as aluminium is introduced into the phase change material thermal storage to improve its performance.

This study focuses on experimenting the optimal combination of thermal storage and solar concentrator on a solar distiller for outdoor environment usage. The optimal specification of Fresnel lens to achieve the optimum solar concentration will be analysed. Besides that, the optimal ratio of high thermal conductivity material implemented into the phase change material will be analysed. The result of the enhanced combination of solar concentration and thermal storage will be analysed, and the optimal combination will be proposed.

1.2 Importance of the Study

The importance of this study is to investigate and produce an optimal combination of solar concentrator and thermal storage in solar distiller to improve the efficiency of the solar distiller. The currently available combination of solar concentrator and thermal storage is able to increase the water yield from solar distiller, but it can be enhanced with further studies. A better performance solar distiller can further reduce water scarcity faced globally.

The goal of this study is to increase the efficiency and advance the performance of the solar distiller with the optimal Fresnel lens specification and ratio between the high conductivity material and phase change material in the thermal storage.

1.3 Problem Statement

The requirement of freshwater in the world has increasing significantly while the freshwater scarcity issue has not been able to solve thoroughly. The conventional water distiller has poor performance due to its high dependency on solar irradiation and the lack of efficiency in receiving thermal energy. The solar distiller will not be able to operate during nighttime as there is minimal thermal energy that is insufficient to evaporate the saline water.

Various research has been done to increase the efficiency and water yield of conventional solar distiller by implementing solar concentrator and thermal storage. However, the unoptimized solar concentrator and thermal storage has further reduced the potential of the solar distiller to produce freshwater. Therefore, the efficiency and performance of the enhanced solar distiller must be further optimized to satisfy the freshwater needs of human being especially in the rural area and countries that faces severe freshwater scarcity.

Conductive particles are added into the thermal storage made from phase change material like paraffin wax to increase the thermal conductivity. However, the conductive particles such as aluminium scrap has low capacity in storing heat. Therefore, the optimal ratio of paraffin wax and aluminium scraps should be studied.

1.4 Aim and Objectives

The aim of this study is to conduct experiments combining thermal storage made of paraffin wax mixed with conductive particles (aluminium scraps) and sunlight concentrator which is a Fresnel lens to find out the best possible combination and further increase the efficiency and water yield of a solar distiller. Hence, the objectives of this study are as stated below:

1. To analyse the optimal ratio of paraffin wax and aluminium scrap as a thermal storage on a solar distiller in outdoor environments.
2. To analyse the optimal concentration ratio of Fresnel lens on a solar distiller with thermal storage in outdoor environments.
3. To evaluate the enhancement achieved by the combined methods as compared to basic solar distiller and propose the optimal combination of Fresnel lens and thermal storage.

1.5 Scope and Limitation of the Study

The scope of this study is to focus on optimizing the performance and efficiency of the solar distiller with the enhancement combination of thermal storage and solar concentrator. The experiment will be conducted at outdoor environment to collect data on the performance of the solar distiller. The optimal quantity of aluminium scraps added into the paraffin wax as thermal storage are to be studied.

The solar distiller is mainly targeted to be used in rural areas that faces water scarcity and does not have advance technologies to produce clean water. Therefore, the design should be low maintenance, simple and cost-efficient.

Therefore, this set limitations on the design of the solar distiller to enhance the performance. Some of the technologies like pumps, heat exchangers or solar tracking system are not considered in this study.

There are some other limitations in this study. First of all, the experiment will be conducted at outdoor environment and the limitation of this factor will be the weather condition during the experiment. There are multiple factors that will affect the result of the experiment such as temperature, solar irradiation, rain and wind speed. Besides that, the use of Fresnel lens as a solar concentrator in this experiment will require position adjustment of the Fresnel lens in order to focus the thermal energy towards the saline water to evaporate it. The sun position will be moving from time to time which will cause the thermal energy not focused onto the saline water properly. Therefore, the adjustment of Fresnel lens from time to time is required and will be depending on the availability of the experimenter and skill to adjust the Fresnel lens properly.

1.6 Contribution of the Study

This study contributes towards the enhancement of a solar distiller to improve the performance and efficiency of it. The specification of optimal thermal storage and optimal Fresnel lens will be studied, and the optimal combination will be proposed. The potential to improve the performance of the solar distiller will be revealed and the outcome of this research will contribute towards a higher efficiency and performance solar distiller to be used in the rural area to reduce water scarcity issue. This also contributes towards the SDG goal of providing clean water and sanitisation.

1.7 Outline of the Report

This report consists of 5 chapters which includes introduction, literature review, methodology, result and discussion, and conclusion and recommendations. The introduction chapter provides an insight and overview of the concept of solar distillation, the field of study, objectives and scope and limitation. The next chapter literature review provides a in-depth study on the components in a solar distiller such as the solar still, thermal storage, and sunlight concentration devices. Chapter 3 outlines the research methodology of this study. The next chapter will present the results of this research and discuss on the results obtained. Chapter 5 will conclude this research and provide recommendations for future works.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter will be focusing on the research and studies done on the solar distiller, solar still, solar concentrator and thermal storage. In depth study will be conducted on Fresnel lens and thermal storage using phase change material combined with aluminum scrap to study on the parameters that affects the performance and efficiency in order to enhance the combination of Fresnel lens and phase change material thermal storage in the solar distiller.

2.2 Solar Distiller

Solar distiller is one of the technologies invented in order to purify the uncleaned water into clean and drinkable water. The only dependencies of solar distiller on sun making it sustainable and has become a widely used technology globally especially in rural areas that are lack of electricity. The cost of making a solar distiller is cheap and requires minimum skills to fabricate. Therefore, these characteristics has contributed to the remarkable usage of solar distiller all around the world.

A simple solar distiller will consist of components such as a basin to contain the contaminated water. The inner of basin is usually painted in black colour to improve the solar irradiation absorption while insulation is done on all side including bottom of the basin to prevent heat losses (Jamil and Akhtar, 2014). Besides that, a glass cover that is secured at an angle inclined on top of the basin and sealed the basin completely to isolate the vapor from exiting the basin. The vapor will be condensed on the glass cover and form droplets that will drop into a channel or collector to collect the purified water. Other than that, there will be a water inlet to refill the contaminated water and a drainage to drain the water out whenever necessary.

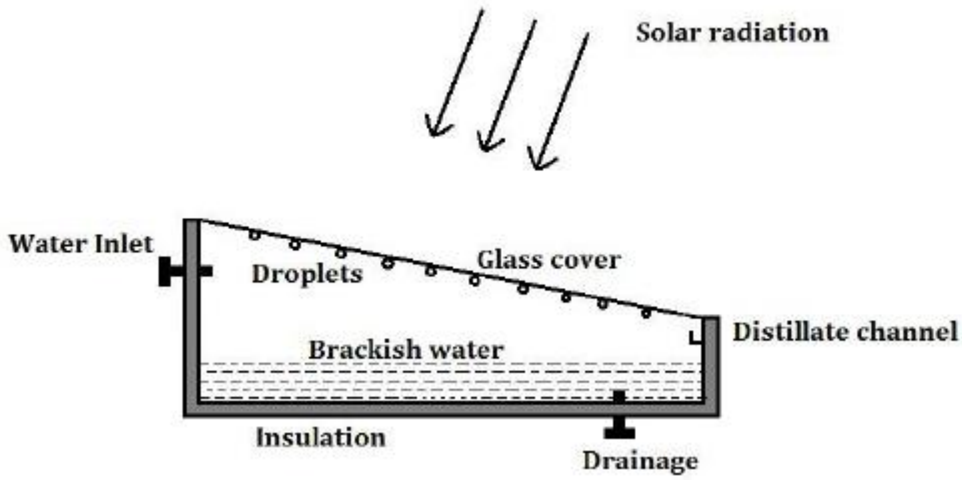

Figure 2.1: Components of a Simple Solar Distiller (Jamil and Akhtar, 2014)

2.2.1 Working Principle of Solar Distiller

The working principle of a solar distiller is considerably simple. The overall process involves 2 phase changing process which are the heated water in the basin evaporates into vapor and condenses on the inside of the glass cover (Mehta et al., 2011).

The process starts with solar irradiation absorption. The sunlight will be able to penetrate through the glass or plastic cover and the heat will be absorbed by the black inner wall of the basin (Lal et al., 2015). When the basin heats up, the contaminated water in the basin will be heated up until it undergoes evaporation, which is a phase change process from water to vapor. During the evaporation process, the water molecules will gain kinetic energy as it absorbs heat energy and break free from liquid phase and turns into vapor.

Next, the vapor that carries latent heat of evaporation, leaves the water surface and rise up towards the inside of the glass cover. The vapor will rise due to the natural convection mechanism. Natural convection can be explained as a heat transportation where fluid motion is caused by buoyancy, the difference in temperature causes the fluid density to be different (Zheng and Zhang, 2017). The vapor which is higher in temperature causes the molecules to be very far apart and have lower molecules per unit volume, therefore it will have lower density and rise up towards the glass cover.

The vapor that rises towards the glass cover will get in contact with the glass cover that has relatively lower temperature compared to the vapor. The conduction heat transfer between the vapor and the glass cover will cause the vapor to release heat energy towards the glass cover. The vapor condenses and there will be heat transfer the condensation surface while the condensation surface will conduct the heat to the outside environment via external convection (Bhardwaj et al., 2013). The releasing of latent heat of vaporization from the vapor causes the temperature to decrease and undergoes phase change process into liquid, which is a condensation process.

The condensation process of vapor causes the molecules to get closer to each other and will form water droplets. These water droplets are purified water droplets that has been desalinated and is safe to consume. The gravity will cause the water droplets to drop while the inclined glass cover will guide the water droplets to fall into the water collection trough which will transfer the water droplets into a clean water container (Abutayeh et al., 2015).

As summary, the solar distiller works by involving evaporation and condensation of water and vapor to purify the saline water and collect the clean water using gravity and inclined glass cover design while leaving the impurities such as salt in the basin.

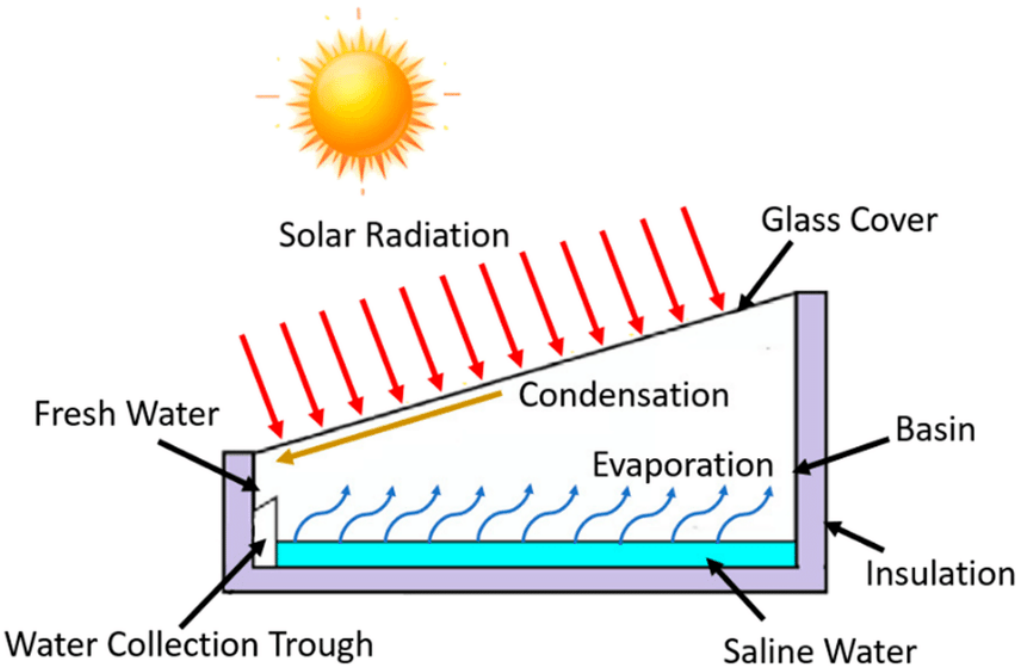

Figure 2.2: The working principle of solar still (Johnson et al., 2019)

2.2.2 Passive Solar Distiller

A passive solar distiller is a device that does not uses any electrical or mechanical components to complete the distillation process. The passive solar distiller works purely on solar and heat energy. The operation involves natural evaporation a condensation only which makes it a sustainable and cheap distillation device. The dependency on purely solar energy makes passive solar distiller a preferable choice in off-grid area where technologies and facilities are not fully fitted.

Passive solar distiller has multiple advantages such as simple to build, low cost and maintenance, environmental-friendly and sustainable. However, due to the dependence on solar irradiation, passive solar distiller has some disadvantages such as slow water production and weather dependant. The performance of passive solar distiller can be further improved by combining it with solar concentrator and thermal storage.

2.2.3 Active Solar Distiller

An active solar distiller is a device that incorporates mechanical or electrical components in the water purification process. This advance solar distiller technology works the same as the passive solar distiller, which is by using evaporation and condensation processes to purify the saline water. However, the incorporation of mechanical or electrical components such as pumps, heat exchangers and condenser will further enhance the evaporation and condensation process. Accelerated evaporation which uses pumps or fans to increase the air or water flow will accelerates the evaporation process while the vapor produced will go through condensation process in a condenser which has lower temperature than the glass cover in the passive solar distiller which will cause the condensation rate of to be higher.

Active solar distiller has multiple advantages such as high efficiency, high performance and less dependent on weather conditions which makes the consistency of producing clean water high. However, some of the disadvantages of active solar distiller are complex design, higher cost and maintenance, and the usage of mechanical and electrical components demands for high power consumption which makes it non-environmental-friendly. This advance device has higher performance and efficiency but has requirements on technologies and facilities which makes it not convenient to be implemented in off-gride and rural areas.

2.2.4 Factors Affecting Performance of Solar Distiller

A solar distiller works by evaporation and condensation depending on solar energy. There are many factors that will have impacts on performance of the solar distiller which is the freshwater production rate. These factors can be categorized into climatic, design and operational factors.

2.2.4.1 Climatic Factor

The solar distiller will be placed at outdoor environment and operates by capturing energy from the sun to purify water. Therefore, the weather condition which is a climatic factor will have impacts on the performance of the solar distiller. These climatic factors such as solar irradiation, wind speed and ambient temperature which are meteorological factors are impossible to be controlled. The evaporative and convection heat transfer coefficient and water glass temperature will vary due to these factors (Singh et al., 2021).

Solar irradiation is the intensity of sunlight. It is one of the main factors determining the efficiency and water yield of the solar distiller because it is the main energy input of the distillation process. The productivity of freshwater using solar distillation method depends significantly on the intensity of the solar irradiation (Omar and Mazen, 2006). The stronger the solar irradiation, the higher efficiency the solar distiller.

A strong wind will reduce the glass cover temperature by convective heat transfer, increase the difference in temperature between glass cover and vapor formed hence increasing the efficiency of the condensation process. (El-Sebaii, 2000). However, the fractional energy of evaporative heat transfer will reduce as the wind speed increases (Nafey et al., 2000). Therefore, the solar distiller must be completely insulated from the surrounding to reduce the effect of wind on the evaporation process. If the solar distiller is not well insulated, wind will reduce the temperature inside the basin and the saline water which will slow down the evaporation process hence decreasing the efficiency and water yield of the solar distiller.

Another climatic factor that will have impacts on the performance of solar distiller is the ambient temperature. The increase in ambient temperature will increase the yield of a solar distiller (Al-Hinai et al., 2002). The solar distiller is exposed to the ambient and convection heat transfer occurs. When the ambient temperature is high, the temperature inside the basin will be high, hence increasing the rate of evaporation. However, the high ambient temperature will increase the temperature of the glass cover thus reducing the efficiency of the condensation process.

2.2.4.2 Design Factor

The design of the solar distiller such as the physical design and materials selection has certain impacts on the efficiency of the solar distiller. The design of the solar distiller should be focusing on improving the rate of evaporation and condensation. The inclination of the glass cover, the materials used to fabricate, the depth of the basin and the insulation.

The inclination of the glass cover directly to the path of sunlight will increase the solar energy captured which will increase the efficiency of the evaporation process. Besides that, the inclination of the glass cover will allow the water droplets form during the condensation process to fall into a water collection trough effectively and prevent the water droplets formed to evaporate again.

The characteristic of the materials used to fabricate the solar distiller is also important in ensuring high efficiency. The basin cover in solar distiller is significantly important as it allows solar irradiation to enter the solar distiller while at the same time vapor goes through condensation processes on the glass cover. Therefore, it is important to select the correct material and thickness for the basin cover. Glass is a better choice compared to plastic as the basin cover because of its durability, heat resistance, longevity, and resistance to chemicals. The thickness of the glass cover has highest efficiency at 3mm as compared to 5mm and 6mm (Ghoneyem and Ileri, 1997). Another important part of the solar distiller is the basin. The material used for the basin must be efficient in absorbing solar irradiation, well insulated to prevent water leakage and able to resist high temperatures. Some of the materials that are suitable for basin are polyurethane, gypsum and Styrofoam.

The depth of the basin will affect the rate of evaporation of the saline water. As the depth of the basin increases, the output of the solar distiller decreases (Phadatare and Verma, 2007). The depth of the basin increases the volume of the saline water, thus more heat energy is needed to increase the temperature of saline water at higher volume. Therefore, the depth of the basin should be kept at minimum to achieve optimal efficiency.

Insulation traps heat energy inside the basin to heat up the saline water while at the same time prevent heat loss to the surrounding that has an ambient temperature lower than the temperature in the basin. The insulation thickness is directly proportional to the water yield performance of the solar distiller (Al-Hinai et al., 2002).

2.2.4.3 Operational Factor

The operation of solar distiller involves some factors such as color of water and salt concentration. These factors will affect the rate of production of the freshwater thus affecting the efficiency of the solar distiller. Some of these factors are uncontrollable when it comes to real life applications. For example, the salt concentration of the saline water depends on the water source of the local area. However, the salt concentration should be controlled during the experiment in order to ensure the consistency of the experiment.

The saline water in the basin will be absorbing from the sun as well instead of just the basin. Therefore, the color of the water will have impacts on the efficiency to produce freshwater for solar distiller. When the solar energy penetrates through the glass cover, it heats up both the saline water and basin as well. The usage of dye in saline water will improve the absorption of solar irradiation thus increasing the evaporation rate. Black dye has increased productivity of solar distiller by 29% (Rajvanshi, 1981).

The concentration of salt in saline water must be taken into consideration as well. The concentration of salt in saline water is inversely proportional to the water yield of the solar distiller due to the increase in partial pressure of salt in the saline water (Kalbasi and Esfahani, 2010). However, it is noticed that as the salt concentration increases, the rate of decrease in productivity decreases (Akash et al., 1999).

2.3 Solar Concentrator

The evaporation process of the solar distiller requires high temperature applications to provide sufficient heat to the saline water and break the water molecules free to change its phase into vapor. However, a conventional solar distiller receives unfocused solar energy which reduces the efficiency of it and takes longer to reach the evaporation process. Therefore, solar concentrator is needed to focus the solar energy towards the solar distiller especially towards the basin. The concentrated solar energy carries high amounts of heat and heats up the saline water quickly hence increasing the efficiency of the solar distiller (Ouederni et al., 2009).

This study focuses on the implementation of one of the most commonly used solar concentrator for solar distillers which is Fresnel lens. Solar distillers implemented with Fresnel lens is able focus and concentrates the solar energy toward the saline water and basin thus increase the rate of evaporation as compared to conventional solar distiller without any solar concentrator.

2.3.1 Fresnel Lens

Fresnel lens was invented by Augustin-Jean Fresnel, a French physicist in the early 19th century. It was initially used in the light house to focus the light from a light source and project it towards the sea. The use of Fresnel lens allows the light to be focused and projected to a long distance. Fresnel lens which has a flat surface is invented to replace the bulky material of the conventional lens. The extra materials are removed from the conventional lens and only remain the contour profile. This allows the reduction of material while at the same time reduce the absorption loses (Kumar et al., 2015). Fresnel lens is a preferably choice as compared to other solar concentrators because of its high optical efficiency, less bulky in terms of size and weight and the low-cost requirements (Leutz et al., 2000). The surface of Fresnel lens is made up of multiple small concentric grooves where each groove will act like a prism to refract light as light passes through. Refraction of light occurs as light enters to a medium from another medium with different density. When it enters to the medium that are denser, it will bend away from normal and vice versa. The difference between conventional lens and Fresnel lens are shown as in figure below.

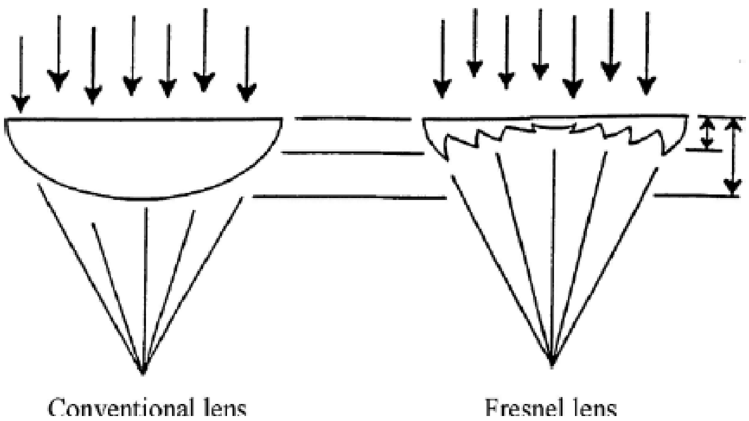

Figure 2.3: Fresnel lens as compared to conventional lens. (Khamooshi et al., 2014)

Fresnel lens can be categorized into two type, imaging and non-imaging. Imaging Fresnel lens is used in product a sharp image. Due to this requirement, the production of imaging Fresnel lens requires high accuracy and quality control which causes the cost to increase while making the design to be complex (Kumar et al, 2015). However, the concentration of imaging Fresnel lens is lower than the non-imaging Fresnel lens. Non-imaging Fresnel lens is more widely used as solar concentrators in solar distiller due to its high concentration ratio (Xie et al., 2010). The advantage of imaging Fresnel lens in producing sharp images are not important while the advantage of non-imaging Fresnel lens to have high concentrations ratio can significantly increase the efficiency of the solar distiller. The difference of imaging and non-imaging Fresnel lens is shown in the figure below.

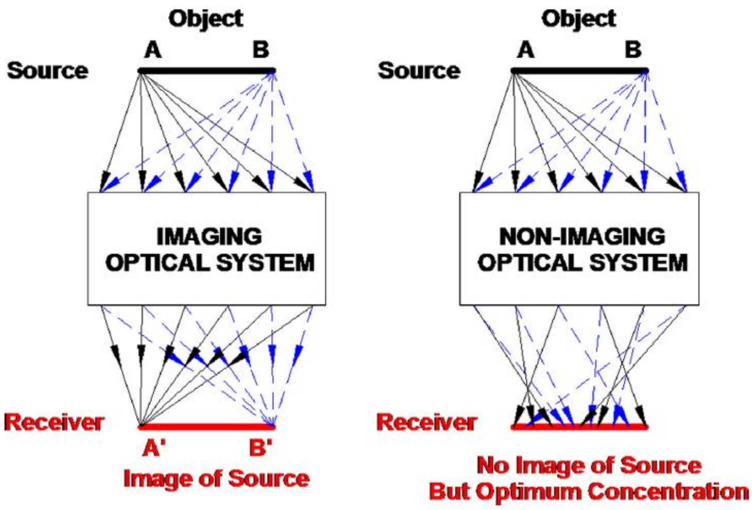

Figure 2.4: Difference between imaging and non-imaging optical system (Kumar et al., 2015)

2.3.2 Selection of Fresnel Lens

Concentration ratio is the ratio of solar radiation that enters to the collector to the solar radiation arrived at the receiver. Concentration ratio can also be simplified by the concept of geometric which can be defined by the ratio of light aperture area to the receiver area. (Zheng, 2017). The concentration ratio of Fresnel lens must be taken into consideration when implementing it into solar distiller. The Fresnel lens with right specification will be able to improve the efficiency of the solar distiller. From the formula of concentration ratio below, it is noticed that the higher the area of aperture and smaller the area of receiver, the higher the concentration ratio.

The area of receiver can be affected by multiple factors from the design of the Fresnel lens. These factors include the focal length, aperture, curvature and optical quality.

$$CR = A_{ap}/A_{rec} \quad (2.1)$$

where

A_{ap} = Area of aperture

A_{rec} = Area of receiver

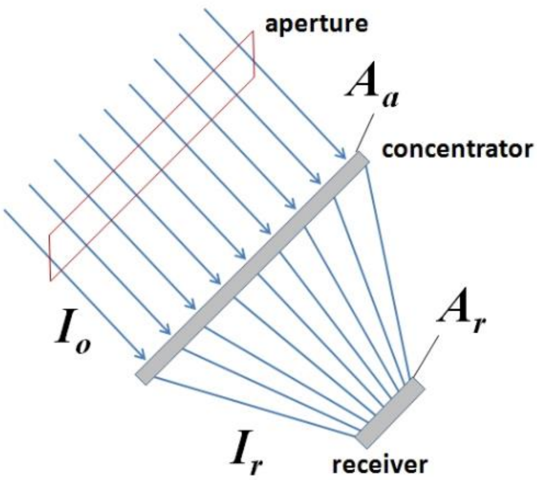

Figure 2.5: Aperture Area and Receiver Area (Zheng, 2017)

2.4 Thermal Energy Storage (TES)

Thermal Energy Storage is a device used to store thermal energy and can be extracted later. The working principle of thermal energy storage involve 3 steps which are charging, storing and discharging (Cabeza, 2012). Thermal energy is stored into a medium which can be solid, liquid or even a phase change material. There are many types of TES available in the market due to its wide application in the industry. Some of the most common types of TES used in solar applications are sensible heat storage and latent heat storage. TES can be implemented into the conventional solar distiller to improve its efficiency. The TES will absorb heat energy simultaneously with the saline water when the temperature of both is low. When the solar radiation or heat energy supplied to the solar distiller is absent or low, the thermal energy stored in the TES will be extracted to provide heat towards the saline water. This additional heat energy provided to the solar distillation process will be able to increase the efficiency of the solar distiller.

2.4.1 Sensible Heat Storage

Sensible heat storage utilizes sensible heat to store the thermal energy in a medium such as water, rock beds, bricks, concrete and sand. The process of charging, storing and discharging of thermal energy from the medium does not involve any phase change. The material used for sensible heat storage is usually depends on the heat capacity of the material and the space available for the heat storage (Dincer and Rosen, 2021).

2.4.2 Latent Heat Storage

Latent heat storage utilizes latent heat to store the thermal energy in a medium that will undergo phase change process when absorb or release heat. This material is commonly known as phase change materials (PCM). One of the most commonly used PCM in solar distillation process is paraffin wax. Latent heat storage is more preferably in solar distillation process because its is able to store and release heat energy at a constant temperature which is the phase transition temperature of the material and it has high energy storage density (Sharma et al., 2009).

2.4.3 Phase Change Materials (PCM)

Phase change materials are materials that will undergo phase transition process from solid to liquid and vice versa when heat is absorbed or released. When heat energy is supplied to PCM, the molecule energy of the PCM increases until the melting point and the heat energy supplied will be accommodated to break the intermolecular force of the PCM instead of increasing the kinetic of the molecules. (Cabeza et al., 2020). The ability to absorb and release latent heat allows PCM to have high energy density as compared to the materials such as rocks and concrete that only goes through changes in sensible heat at solar distillation applications. Besides that, PCM is able to maintain at an approximate constant temperature while operates as a TES. This provides a stability in solar distillation process and prevent the need to use material that are capable of withstanding extremely high temperatures for the solar distiller.

There are 3 main categories of PCM available, which are organic, inorganic and eutectics PCM. Organic PCM is a type of PCM that contains organic compounds that usually is carbon-based molecules that will undergo phase transition from solid to liquid and vice versa. Some of the examples of organic PCM are fatty acids, paraffin and vegetable oils. Organic PCM has advantages of high latent heat capacity, non-reactive and will not undergo supercooling and phase segregation. Inorganic PCM are a type of PCM that consist of non-carbon-based compounds. Some of the examples of inorganic PCM are metals and salt. As compared to organic PCM, inorganic PCM has the advantages of high thermal conductivity and extremely high heat capacity. However, inorganic PCM suffers from disadvantages such as potential to cause corrosion and phase separation. Therefore, inorganic PCM is more suitable for high temperature applications instead of solar application. (Shamseldin et al., 2016). Eutectic PCM is a type of PCM that consists of mixture between organic compounds, inorganic compounds or both. Eutectic PCM can be specifically designed to achieve the desired thermophysical properties that is required for its application. (Nazir et al., 2018). This eliminates the disadvantages of both organic and inorganic PCM. However, the cost and complexity are the drawbacks for eutectic PCM.

One of the most widely used PCM in TES for solar distillation application is paraffin wax. Paraffin wax is a by-product from the petrochemical industry which consist of mixture from different hydrocarbons of different melting temperature. Paraffin wax has been favoured as the material for latent heat storage due to its relatively lower cost and high latent heat of fusion (Bugaje, 1997). The usage of paraffin wax in TES for solar distiller is focused in this study.

2.4.3.1 Enhancement on PCM (Paraffin wax) by Adding Conductive Particles

One of the most commonly faced problems of PCM as thermal storage is the low thermal conductivity. (Sopian et al., 2009). This problem has significantly reduced the efficiency of the thermal storage. The heat absorbed and released of low thermal conductivity PCM slows down the process of charging and discharging, hence reducing the amount heat energy available to be transferred to the saline water.

To enhance the efficiency of low thermal conductivity PCM as thermal storage, additives that has high thermal conductivity such as aluminium, copper and graphite can be added into the paraffin wax to increase the overall thermal conductivity (Marin et al., 2005). Research have been done to study on the impact of high thermal conductivity additives in PCM. A study by Mettawee and Assassa (2007) concludes that heat gained has increased in the thermal storage when adding aluminium powder into paraffin wax as compared to pure paraffin wax. Another study by Sopian et al., (2009) has shown that adding 0.5% of aluminium powder particles is able to enhance the heat transfer.

2.5 Summary

The main objective of this study is to study the optimal combination of thermal storage using paraffin wax mixed with conductive particles and solar concentrator (Fresnel lens) to improve the efficiency of the solar distiller. The literature review has been done to suggest suitable modifications and techniques to increase the efficiency of the solar distiller. The conventional solar distiller that has low efficiency in producing freshwater can be enhanced by using PCM thermal storage and Fresnel lens. The ratio of PCM and conductive particles added are to be studied in this research to find out the optimal ratio and the optimal concentration ratio of Fresnel lens are to be studied as well in this research. The combination of both optimal thermal storage and solar concentrator will improve the efficiency of the solar distiller.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter focus on the methodology and work plan for this research. Experiments are conducted in this study to evaluate the performance of the different concentration ratio of Fresnel lens and the different concentration of conductive aluminium scrap in paraffin wax thermal storage. The study and literature review conducted to scope and plan the experiments to be conducted and ways to evaluate the enhancement of the solar distiller. The work plan of this study is as shown in the figure below.

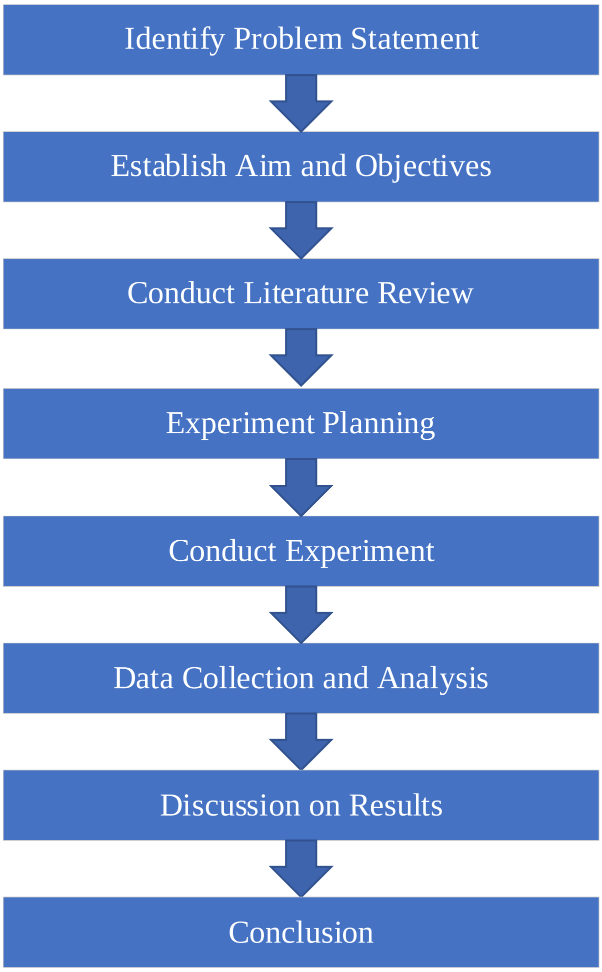

Figure 3.1: Flow chart of work plan.

3.2 Design of Solar Still

Polyfoam was chosen as the outer frame of the solar distiller because it has high heat insulation property. The dimension of the polyfoam outer frame was determined to be 19.6cm in length, 16.3cm in width and 8cm for taller side and 5cm for shorter side in height. The internal dimension of the polyfoam dimension was 16cm in length, 13cm in width and 8cm for taller side and 5cm for shorter side in height. The glass cover of 5mm was used to cover the top of the polyfoam box so that solar irradiation can penetrates through it. The glass cover was placed on top of the polyfoam box at an inclination of 15° maximum due to the small size of the polyfoam box. 5mm of glass cover was chosen to accommodate the high temperature application of solar distiller. A thin glass cover will have the risk of cracking thus causing heat energy loss from the solar distiller.

A small diameter hose was attached to the polyfoam box for water input purpose. Another larger diameter orange garden hose was used as the water collection trough. The part of the orange garden hose located inside polyfoam box was cut open in half and was located at the lower side of the inclined glass cover and was placed at an inclined angle of 5 to collect the water droplets formed during the condensation process. Another part of the orange garden hose located outside the polyfoam box was not modified, and the purpose of it was to allow water collected to flow out from the polyfoam box and be collected in a measuring cylinder for data collection.

Two basins made from aluminium were used inside the polyfoam box for containing saline water and PCM. The basin for saline water was painted with black paint to enhance the heat absorption of the basin. The first basin was larger in size and was used contain the PCM as PCM tend to expand in terms of volume when it is heated. The dimension of the basin for PCM was 160mm x 110mm x 31.5mm. The second basin containing saline water was smaller in size so that it can be placed securely on top of the first basin containing PCM. The dimension of the basin for saline water was 158mm x 102mm x 32mm. The setup of basin was by placing second basin containing saline water on top of the first basin containing PCM as shown in Figure 3.5.

The insulation of solar distiller is an important factor in its performance. Therefore, all the gap between polyfoam box and components such as glass cover, water collection orange garden hose and water input hose were sealed with silicone to ensure the solar distiller has good insulation from the outer environment.

There are four K-Type thermocouples placed in the prototype. The locations were at glass cover, saline water basin, saline water and thermal storage respectively. These thermocouples were used to read the temperature of each location by using the Yowexa YET-640X thermometer. Cloth tapes and silicone were used to secure the thermocouple at the specified locations.

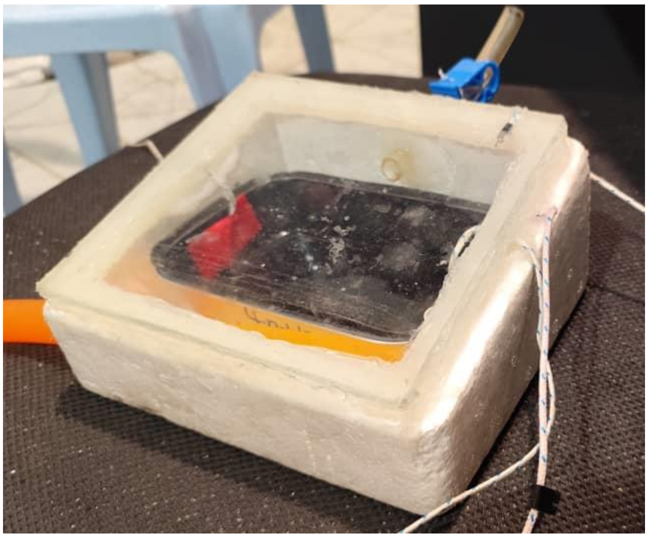

Figure 3.2: Solar still design.

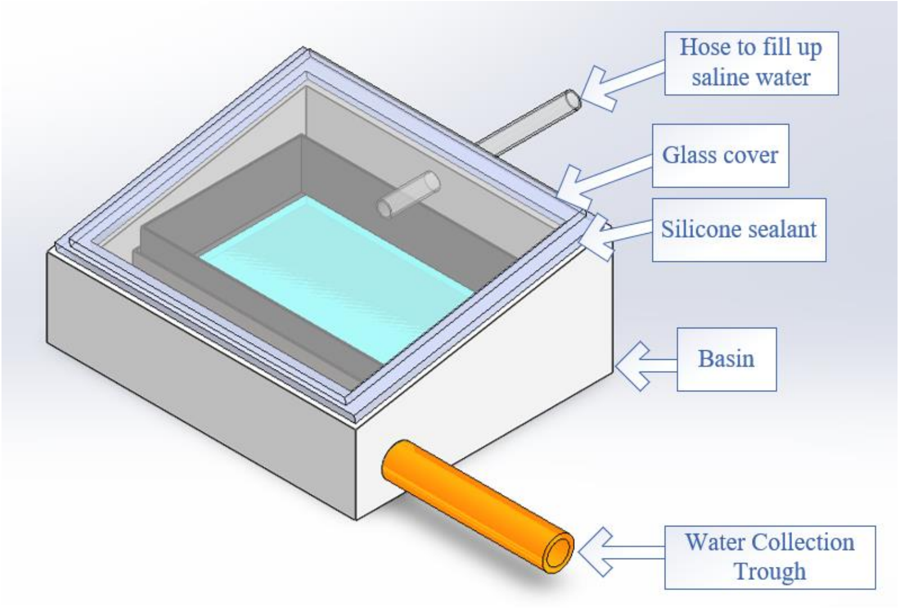

Figure 3.3: CAD drawing of the solar still.

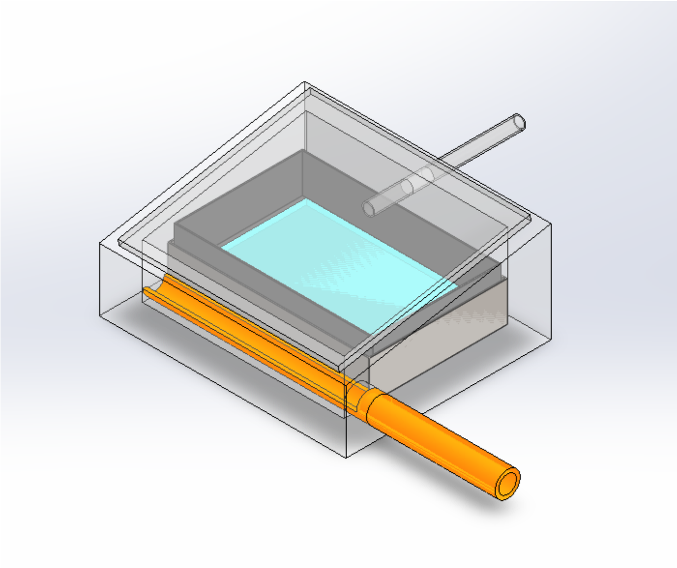

Figure 3.4: CAD drawing of solar still. (Transparent View)

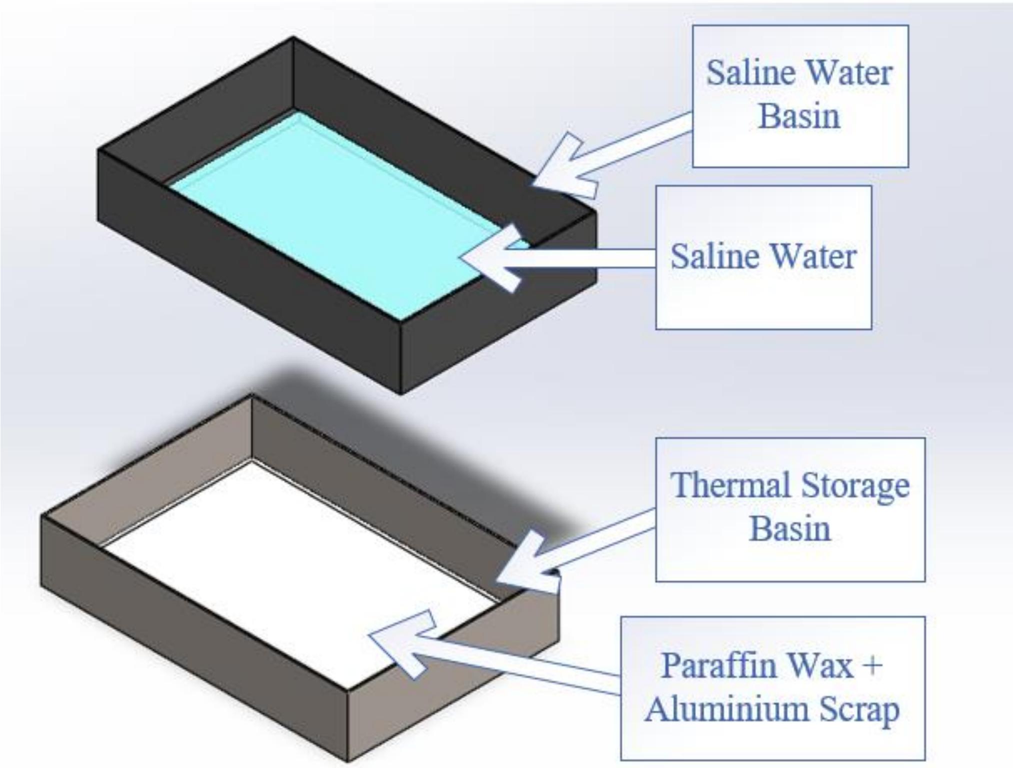

Figure 3.5: Placement of saline water and PCM basins.

3.3 Experiment Sequence

The solar still prototype was fabricated according to the type of experiment to be conducted. First, in order to understand the performance of a basic solar still, a basic solar still without any enhancement was studied to get preliminary results on the performance of it. Then, the next part of the research was to study the optimal ratio of the paraffin wax to aluminium scrap used as thermal storage. Next, the optimal thermal storage was used as thermal storage for the solar distiller during the study of the optimal concentration ratio for the Fresnel Lens. Lastly, the enhancement of optimal combination of optimal Fresnel lens and optimal thermal storage were compared against the basic solar still without any enhancement to understand the improvement achieved.

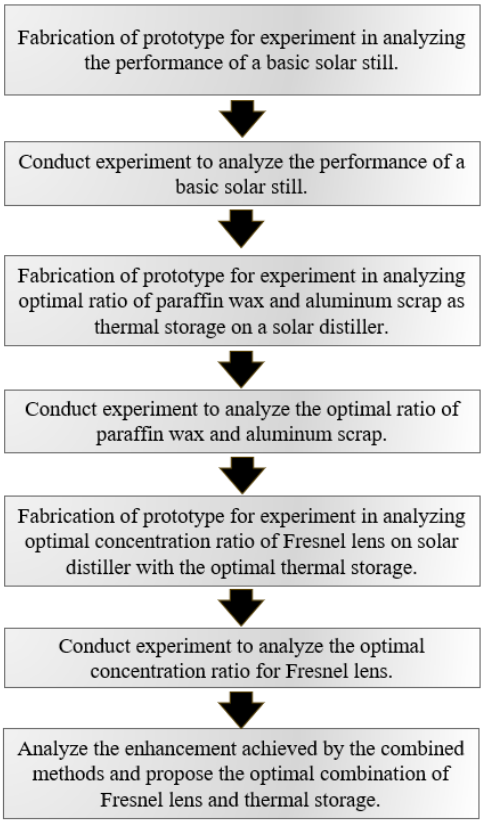

Figure 3.6: Experiment Procedures.

3.4 Optimal Ratio of Paraffin Wax to Aluminium Scrap as Thermal Storage

One of the objectives of this study is to propose the optimal ratio of paraffin wax to aluminium scrap in improving the efficiency of the solar distiller. The optimal ratio was researched through experiment. Excessive aluminium scrap added will reduce the capacity of storing heat while excessive of paraffin wax will reduce the efficiency in storing and releasing heat. Therefore, the optimal ratio was analysed.

3.4.1 Selection of PCM

The preliminary test on the basic solar distiller shows the operating temperature of the solar distiller falls around 47.13°C to 63.64 °C. Therefore, a paraffin wax with the melting point that falls within the operating temperature was chosen. The paraffin wax used in this research has a melting point of about 48°C to 66 °C.

Figure 3.7: Paraffin Wax.

3.4.2 Preparation of thermal storage

The thermal storage consists of paraffin wax and aluminium scraps. The aluminium scraps were obtained from the workshop in UTAR Sungai Long. The aluminium scraps were cut in tiny pieces of different sizes using a metal shear. This size of aluminium scraps can be spread evenly on the paraffin wax in order to have a more evenly distributed enhancement on the thermal conductivity.

Figure 3.8: Cutting the aluminium scrap using metal shear tool.

Figure 3.9: Tiny pieces of aluminium scraps.

The paraffin wax and aluminium scraps were measured using a weighing scale and it was placed into the aluminium basin. The weight and ratio of the paraffin wax to aluminium scraps prepared as thermal storage are as shown in the Table 3.1.

Table 3.1: The specification of the thermal storage.

	Paraffin Wax (g)	Aluminum Scraps (g)	Total Weight (g)	Ratio (PW:Al)
Model A	47.5	2.5	50	9.5 : 0.5
Model B	45	5	50	9 : 1
Model C	42.5	7.5	50	8.5 : 1.5
Model D	40	10	50	8 : 2

Figure 3.10: Measuring the paraffin wax.

Figure 3.11: Measuring the aluminium scraps.

The basins containing the paraffin wax and aluminium scraps were placed into a hot water bath to melt the paraffin wax. The aluminium scraps were ensured to distributed all over the basin while the paraffin wax is melted completely. The basins were removed from the hot water bath after the paraffin wax was completely melted in order to cool down the paraffin wax until it solidifies.

Figure 3.12: Hot water bath onto the basin to melt the paraffin wax.

3.4.3 Experimental Procedure

Four thermal storages made from paraffin wax and added with conductive particles which were aluminium scraps in this experiment were used to study the optimal concentration of conductive particles in paraffin wax. To ensure the consistency of the experiment, other parameters such as configuration of solar still were remained constant. The experiment was conducted with four identical setup and the only manipulated variable in this experiment was the concentration of aluminium scrap in paraffin wax thermal storage. The experiment was conducted simultaneously to maintain the constant of climatic conditions.

Tap water mixed with salt was used as saline water in this experiment. Every 1000ml of tap water was mixed with 35g of salt to obtain saline water of approximately 35000ppm. This is to simulate the seawater with salinity of approximately 35000ppm.

All the models of prototype were placed in an outdoor environment from 10.00a.m to 4.30p.m. The location of the experiment is at the rooftop of UTAR KB Block. Saline water was added into the saline water basin at 50ml each. The parameters and data that were recorded are saline water temperature, saline water basin temperature, thermal storage temperature, glass cover temperature, ambient temperature, wind speed, solar irradiance and water yield. The data were taken every 2 hours. At 4.30p.m., all the prototypes were moved to indoor environments to study on the effect of the thermal storage while there is no solar irradiance. The data were taken at an interval of 30 minutes until 6.00p.m.. The parameters of saline water temperature, saline water basin temperature, thermal storage temperature and glass cover temperature were measured using Yowexa YET-640X thermometer. The ambient temperature and wind speed were measured using UNI-T UT363 anemometers while the solar irradiance was measured using SM206 Digital Solar Power Meter.

Figure 3.13: Measuring temperature using Yowexa YET-640X Thermometer.

Figure 3.14: Measuring ambient temperature and wind speed using UNI-T UT363 Anemometers.

Figure 3.15: Measuring Solar Irradiance using SM206 Digital Solar Power Meter

The volume of the clean water yield from the solar distiller were measured using measuring cylinder. The total dissolve solids (TDS) of the clean water yield were also measured using the HANNA HI98301 TDS tester.

Figure 3.16: Measuring TDS using HANNA HI98301 TDS tester.

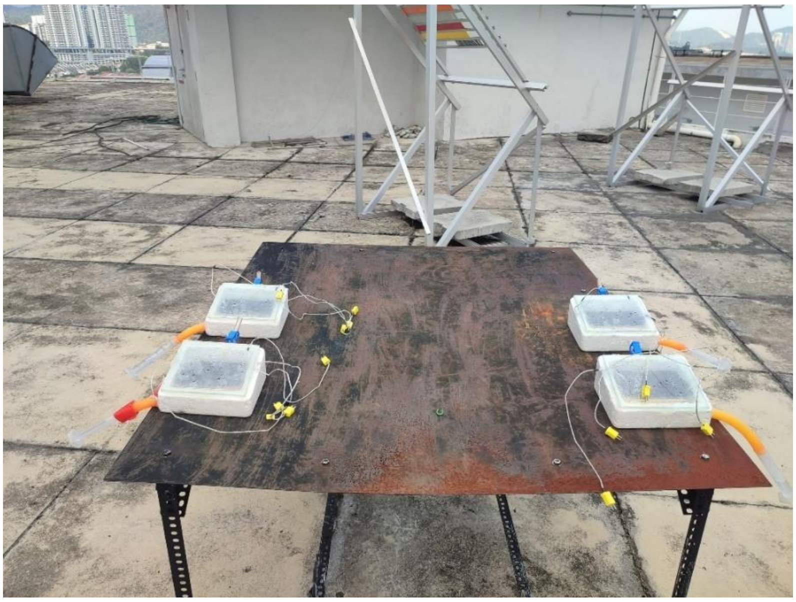

Figure 3.17: The experiment conducted on UTAR KB Block Rooftop.

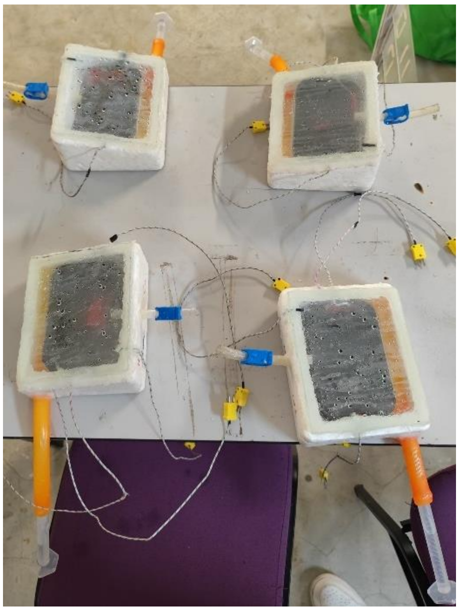

Figure 3.18: Moving prototypes to indoors at 4.30p.m..

3.5 Optimal Concentration Ratio for Fresnel Lens

Another objective of this study is to propose optimal Fresnel lens concentration in improving efficiency of the solar distiller. The optimal concentration ratio was researched through experiment.

3.5.1 Specifications of the Fresnel Lens

The specification of the Fresnel Lens used in this part of the research are attached into the appendix A. The concentration ratio of four Fresnel lens used were 10.08, 10.90, 11.47 and 25.00 respectively as shown in the table below.

Table 3.2: Specification of Fresnel Lens in each prototype

	Fresnel Lens Concentration Ratio
Model A	10.08
Model B	10.90
Model C	11.47
Model D	25.00

3.5.2 Experiment Procedure

The experiment procedure in this part is similar to the experiment procedure in the previous part. The differences were the usage of Fresnel lens and the specification of thermal storage. The thermal storages in all four prototypes were the optimal thermal storage studied in the previous part. From the previous part, it was found that the optimal ratio of paraffin wax to aluminium scrap is 8:2. Therefore, all the thermal storages used for solar distiller in this part were the one with 8:2 ratio, which consist of 40g of paraffin wax and 10g of aluminium scraps.

Four Fresnel lens with different concentration ratio were used to study on the optimal concentration ratio. In order to ensure the consistency of the experiment, all the other parameters such as configuration of solar still and thermal storage were maintained constant. The experiment was conducted with four identical setup and the only manipulated variable was the concentration ratio of the Fresnel lens used. The experiment was conducted simultaneously at the same time under the same weather conditions to ensure the climatic factors that will have impacts on the water yield of the solar distiller were constant for all four setups.

The saline water used in this part of experiment were similar as the previous part where 35000ppm of saline water was used. 50ml of saline water was added at the start of the experiment and it is refilled constantly whenever the saline water is low. This part requires more refills as the Fresnel lens will focus the solar irradiation and able to evaporates the saline water quickly as compared to previous part.

The experiment setup was similar as of previous part but there is an addition of two retort stand and Fresnel lens on each prototype. The retort stand was used to hold the Fresnel lens on top of the prototype. The flexibility and adjustability of the retort stand makes it suitable for holding the Fresnel lens so that the solar irradiance can be focused properly onto the saline water. The Fresnel lens was adjusted at intervals of 1 hour to ensure the focal point was located onto the saline water.

Figure 3.19: Prototype setup with Fresnel lens.

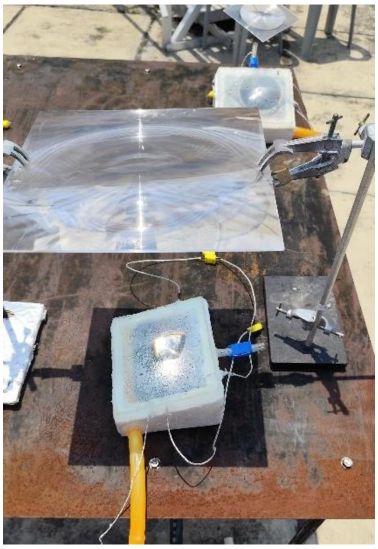

Figure 3.20: Prototype setup with Fresnel lens.

The parameters and data recorded were the same as previous part and the equipment used were the same as well.

3.6 Analysis On the Enhancement achieved by Combined Methods

The enhancement achieved by using the combination of optimal combination of Fresnel lens and thermal storage was evaluated. The purpose was to review on the improvement in efficiency and performance of the solar distiller using the optimal combination. The Fresnel lens with optimal concentration ratio and the optimal thermal storage which produced the highest water production was compared with the performance of the basic solar distiller.

However, there are slight differences in terms of solar irradiance when different experiments were conducted on different days. Therefore, the evaluation on the performance of the enhanced solar distiller cannot be compared directly using the water yield. Productivity and efficiency of solar distillers were used in this section to evaluate the improvement. The productivity and efficiency of the solar distillers can be calculated using the formulas as shown below.

$$h_{fg,w} = 2500 - 2.386T \quad (3.1)$$

$$h_{fg,sw} = h_{fg,w}\ x\ (1 - \frac{S}{1000}) \quad (3.2)$$

$$E = I(t)A_{SW}\Delta t \quad (3.3)$$

$$Productivity = \frac{\sum m_{yield}}{\sum E} \quad (3.4)$$

$$Efficiency = \frac{\sum m_{yield} h_{fg,sw}}{\sum E} \quad (3.5)$$

where

$h_{fg,w}$	=	Specific heat capacity of water, kJ/kg·°C
$h_{fg,sw}$	=	Specific heat capacity of saline water, kJ/kg·°C
T	=	Temperature, °C
S	=	Salinity of water, g/kg
E	=	Energy, kJ
$I(t)$	=	Solar Irradiance, W/m^2
A_{SW}	=	Area of saline water basin, m^2
Δt	=	Time, hr
m_{yield}	=	Mass of water yield, g

3.7 Specification of the Measuring Instruments & Equipment

The measuring instruments used in this research includes the Yowexa YET-640X thermometer, UNI-T UT363 Anemometer, SM206 Digital Solar Power Meter, HANNA HI98301 TDS Tester and a digital weighing scale. The specification of these measuring instruments and equipment are as shown in the table 3.3.

Table 3.3 Specification of Measuring Instruments & Equipment.

Equipment	Measuring Range	Resolution	Accuracy	Parameters
Yowexa YET-640X Thermometer	-200℃ ~ +1370℃	0.01℃	±0.1℃	• Saline Water Temperature • Saline Water Basin Temperature • Thermal Storage Temperature • Glass Cover Temperature
UNI-T UT363 Anemometer	0 ~ 30m/s -10 ~ 50℃	0.1m/s 0.1℃	±(5%rdg+0.5) ±2℃	• Wind Speed • Ambient Temperature
SM206 Digital Solar Power Meter	0.1 ~ 3999W/m²	0.1W/m²	±10W/m²	• Solar Irradiance
HANNA HI98301 TDS tester	0 ~ 2000 ppm	1 ppm	±2%	• Total Dissolved Solids (TDS)
Digital Weighing Scale	0.1g ~ 3000g	0.1g	±0.1g	• Mass of Paraffin Wax and Aluminium Scraps

The repeatability of the measuring instruments and equipment is observed by taking the measurements multiple times continuously within a short period of time. The repeatability aspect can be defined as the how close the successive measurements of the same object carried out in the same measurement condition (Reinstein et al., 2006). In order to study on the repeatability of the measuring instruments and equipment, the measuring process was repeated by using the same equipment, operated by the same operator, and was conducted continuously to ensure the measuring conditions are the same. The results obtained were used to calculate the standard deviation which relates to the repeatability. The lower the standard deviation, the higher the repeatability of the measuring instruments, which indicates high reliability as well (Deziel, 2020). The standard deviations obtained from the repeated measurement using the measuring instruments above are around 0.05033 to 0.07351 for Yowexa YET-640X thermometer, 5.8506 for SM206 Digital Solar Power Meter, 3.5118 for HANNA HI98301 TDS tester and 0.05773 for Digital Weighing Scale. The repeatability test was not conducted on the UNI-T UT363 Anemometer as the parameters recorded are for observation only and not relatively significant to the analysis in this research.

3.8 Uncertainty in Temperature Measurement

The measurement error occurs due to multiple reason such as the accuracy of the measuring instrument and human error. Therefore, the error in measuring temperature can be analysed through uncertainty.

The contributors of uncertainty in this research are identified to be the repeatability and accuracy of the measuring instruments. To calculate the combined uncertainty, the Root Sum Square method is used where the squared component of each uncertainty is added together, and the square root of the result is the total combined standard uncertainty (Brown, 2013).

The uncertainty test is conducted on the temperature measurement for saline water temperature, saline water basin temperature, thermal storage temperature and glass cover temperature which were measured using the Yowexa YET-640X thermometer. The repeatability or standard deviation for this measuring instrument ranges from 0.05033 to 0.07351, the highest value is used for the uncertainty test. In addition, this thermometer has an accuracy of ±0.1°C. The total combined uncertainty is calculated using formula below. The total combined uncertainty calculated is ±0.1241°C. The uncertainty is relatively small, and it is negligible.

$$U_T = \sqrt{{U_R}^2 + {U_A}^2}$$

where,

U_T = Total combined uncertainty

U_R = Uncertainty due to repeatability

U_A = Uncertainty due to accuracy.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter discuss the results obtained from the experiment for the basic solar distiller, solar distiller with thermal storage, and solar distiller with both thermal storage and Fresnel lens. The data were analysed to determine the optimal combination of Fresnel lens and thermal storage by using the optimal concentration ratio of Fresnel lens and optimal ratio of paraffin wax to aluminium scrap as thermal storage.

The enhancement was studied by analysing the increase in the productivity and efficiency of the improved solar distiller as compared to the basic solar distiller.

4.2 Basic Solar Distiller

The basic solar distiller that does not have any enhancement was studied and tested to understand the performance of it. This setup does not consist of any solar concentration device or thermal storage.

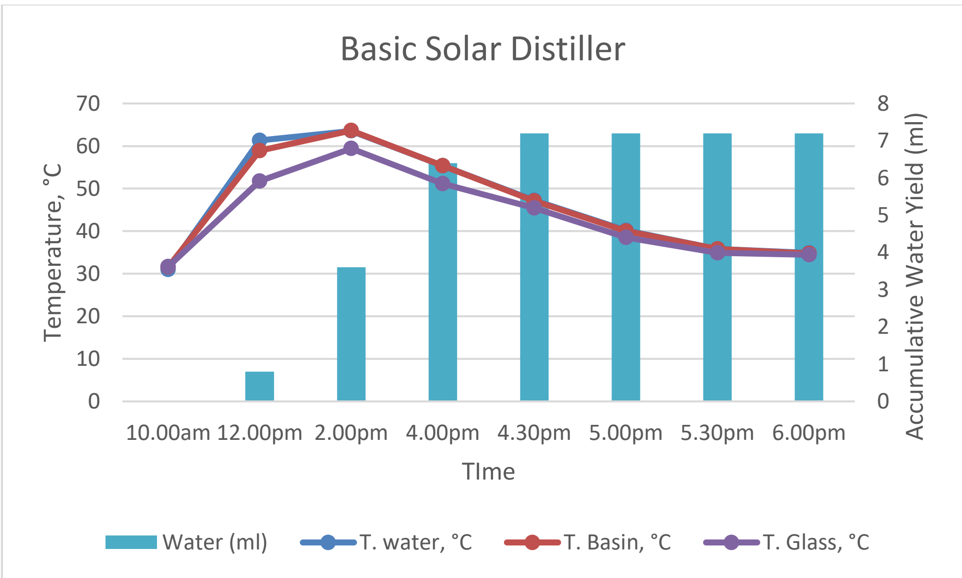

Figure 4.1: Graph of data for basic solar distiller.

As observed from Figure 4.1, the total water yield for a basic solar distiller from 10.00a.m. to 6.00p.m. is 7.2ml. The saline water temperature reaches peak at 63.54°C at 2.00p.m. and has a significant drop from 4.00p.m. onwards as the solar irradiance is lower at this time and from 4.30p.m. onwards, the prototype is moved into indoor environment where there is solar irradiance is negligible. The absent of thermal storage causes the water temperature to drop significantly as the solar irradiance drops. The water yield performance is optimal from 12.00p.m. to 4.p.m where 77.77% of the total water yield are within this period of time because the solar irradiance is highest.

Besides that, it is also observed that from 4.30p.m. onwards where the prototype is moved to indoor environments, there is no water yield. This can be explained by the absent of thermal storage in the basic solar distiller. Once there is no solar irradiation or heat source to heat up the saline water, there will be no evaporation process thus there is no water yield.

4.3 Solar Distiller with Thermal Storage

The thermal storages that are made of paraffin wax and aluminium scraps are added into the basic solar distiller to enhance the performance. The specification of four different thermal storages used are mentioned in Table 3.1 in Chapter 3.4.2.

4.3.1 Optimal Ratio of Paraffin Wax to Aluminium Scraps

All four prototypes are placed at outdoor environments from 10.00a.m. to 4.30p.m.. Then, they are moved into indoor environments from 4.30p.m. to 6.00p.m. to evaluate the effect of thermal storage when the solar irradiation is completely absent. The graphs below show the temperature of saline water, saline water basin, thermal storage and glass cover. In addition, the result for water yield for each prototype is also shown.

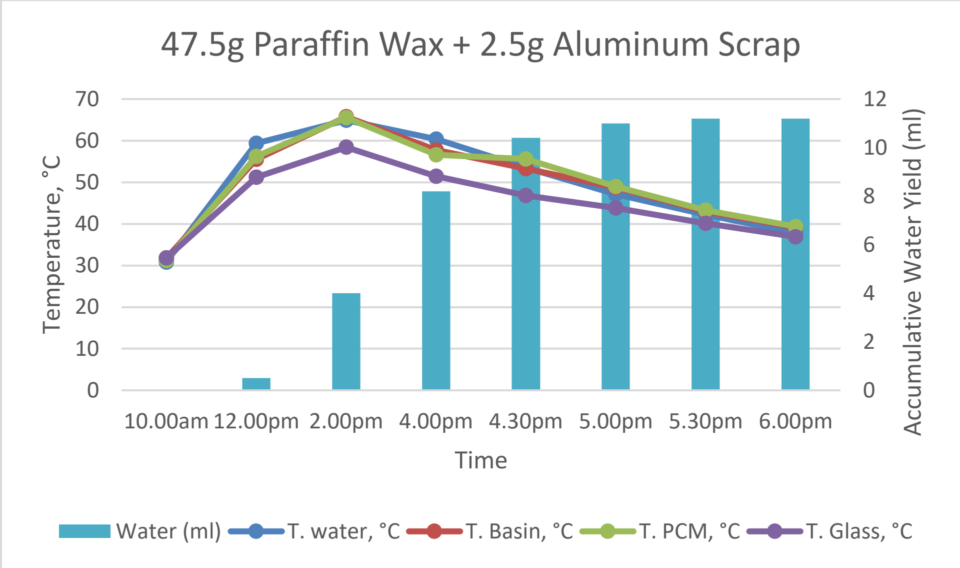

Figure 4.2: Graph of data for Model A (Ratio of 9.5 : 0.5)

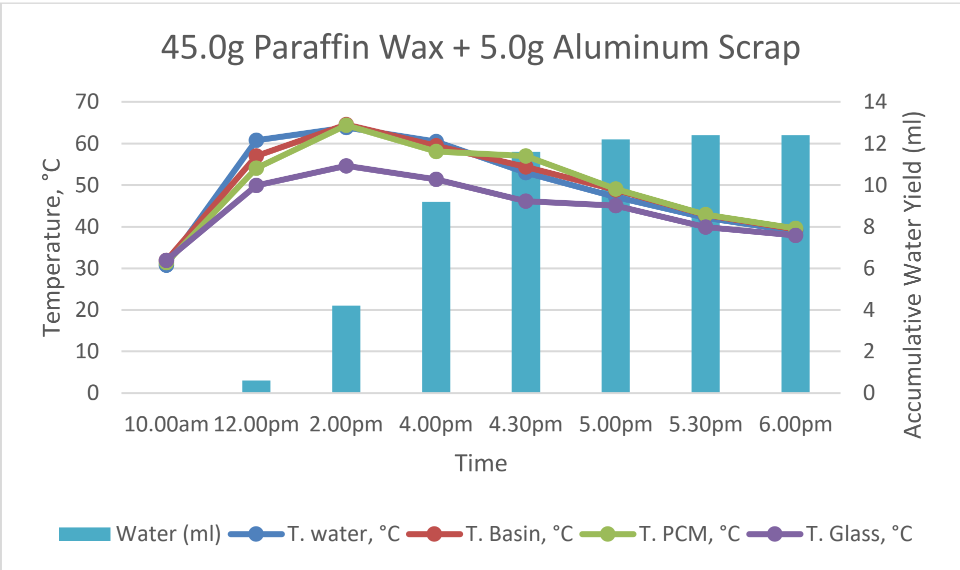

Figure 4.3: Graph of data for Model B (Ratio of 9 : 1)

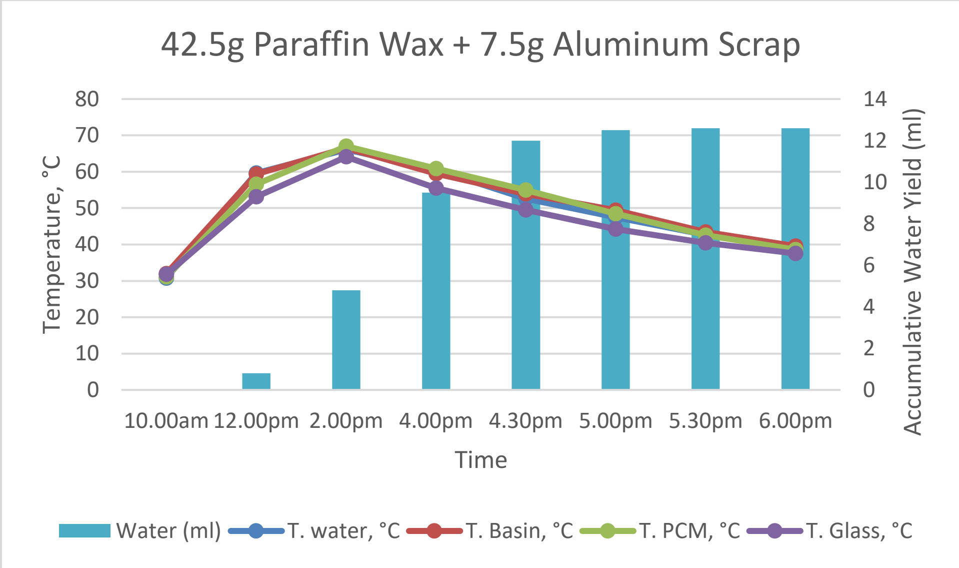

Figure 4.4: Graph of data for Model C (Ratio of 8.5 : 1.5)

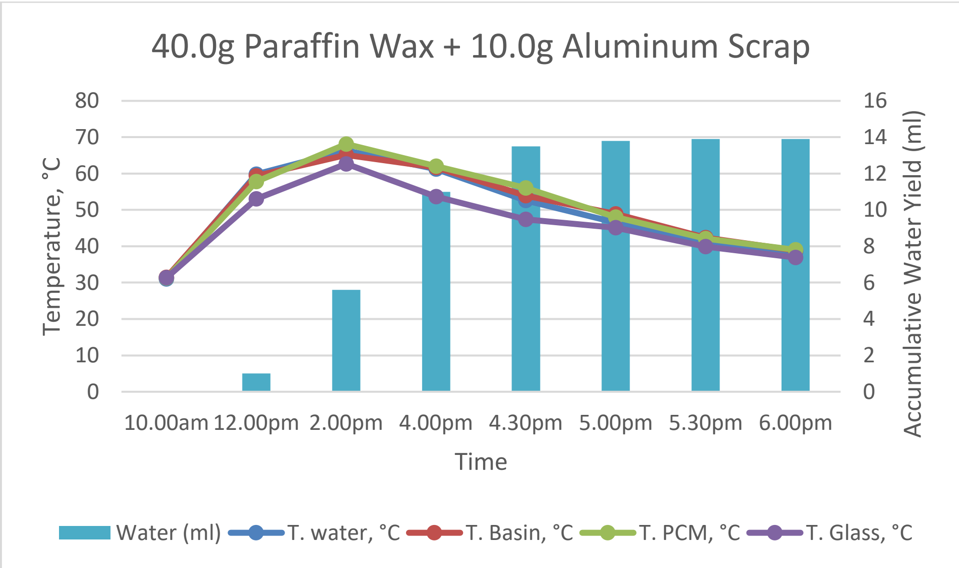

Figure 4.5: Graph of data for Model D (Ratio of 8 : 2)

Based on the graphs in Figure 4.2 to Figure 4.5, it can be observed that the maximum temperature of saline water for Model A, B, C and D are 64.91°C, 63.83°C, 66.12°C and 66.32°C respectively and it occurs at 2.00p.m. where solar irradiance is peaked. Model D has the highest peak saline water temperature. By looking at the trend of the temperature, it is observed that the solar irradiance gradually increases from 10.00a.m. to 2.00p.m. and gradually decrease from 2.00p.m. onwards till the end of the experiment.

Another observation from all the graphs above shows that the temperature of saline water and temperature of thermal storage are close to each other. The paraffin wax has a specific heat capacity of approximately 2.1 kJ/kg °C (Trigui et al, 2013). It is lower than the specific heat capacity of seawater which is about 4.0 kJ/kg °C (Jamieson et al, 1969). However, the saline water basin is placed directly on top of the thermal storage where there is a large surface area of contact between the saline water basin and the thermal storage. Other than that, the saline water is contained in the saline water basin which indicates a large surface area of saline water and saline water basin as well. Due to the large surface area of contact, the temperature of these three parts is almost similar throughout the experiment.

The water yield for Model A, B, C and D are 11.2ml, 12.4ml, 12.6ml and 13.9ml respectively. Model D has the highest water yield. This can be caused by the highest thermal conductivity of the thermal storage for Model D. Due to the intervals of recording data, which is 2 hours, the temperature fluctuation are not significant in the data recorded. However, within the 2 hours timeframe of each data taking, there might be cloudy weather where the sun is blocked by the cloud, thus reducing the solar irradiance on the solar distiller. The purpose of thermal storage is to provide heat energy towards the saline water whenever the solar irradiance is weak. Therefore, the Model D which has the thermal storage with highest thermal conductivity is able to provide highest amount of heat energy towards the saline water within the cloudy weather conditions throughout the experiment.

Another important observation from the graphs above is the glass cover temperature. It is observed that the glass cover temperature is lower than the saline water temperature all the time. This can be caused by the exposure of the glass cover to the surrounding. More than half of the glass cover are exposed to the surrounding where the ambient temperature is significantly lower at around 33.5°C to 42.6°C according to the experimental data while the temperature of the inside of the solar distiller which is insulated from the surrounding is above 50°C throughout the experiment when the prototype is placed at outdoor environment. The exposure of glass cover to the surrounding is subjected to wind as well which will cool down the temperature of the glass cover. It is important for the glass cover temperature to stay as low as possible as condensation process occurs on the glass cover. Therefore, the lower the glass cover temperature, the more efficient the process of condensation occurs.

Based on the water yield performance of each model, the Model D with the paraffin wax to aluminium scraps ratio of 8 : 2 is said to have the best performance as compared to others and the optimal ratio of paraffin wax to aluminium scraps as a thermal storage is 8 : 2.

4.3.2 Effect of Thermal Storage

The main purpose of using a thermal storage is to provide heat energy to heat up the saline water whenever the solar irradiation is weak or absent. The implementation of thermal storage in solar distiller can reduce the drop in temperature on the saline water thus increasing the efficiency and performance of the solar distiller. The effect of the thermal storage in the solar distiller is compared by using the optimal model which is Model D and compare it with the basic solar distiller.

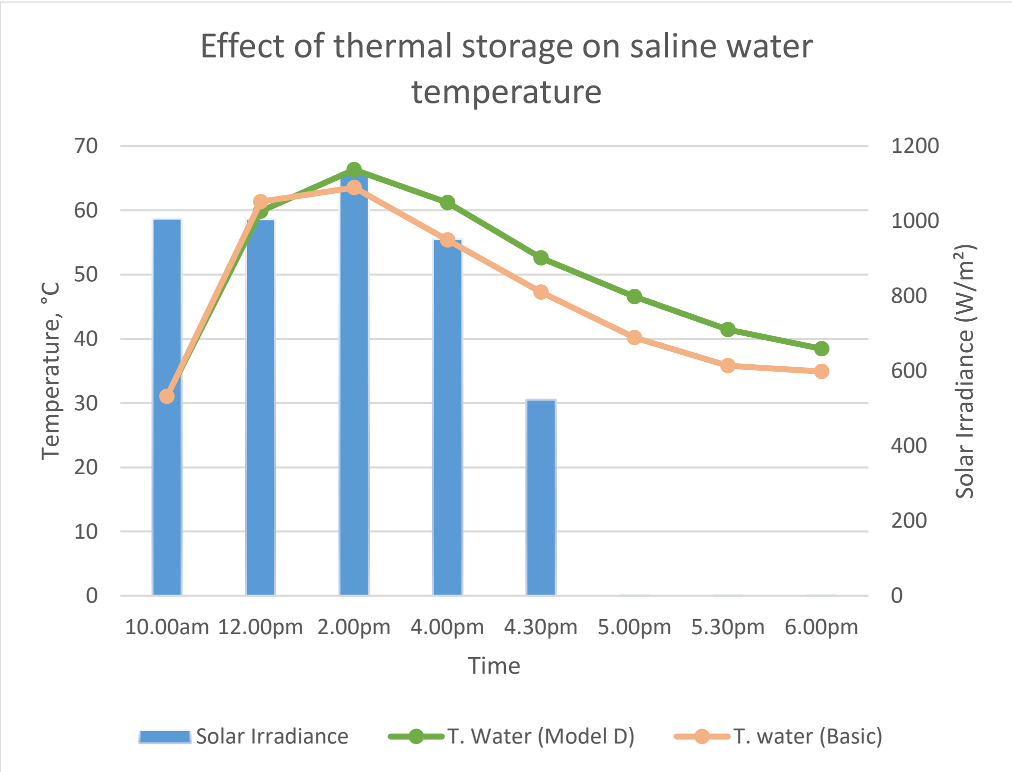

Figure 4.6: Graph of the effect of thermal storage on saline water temperature.

Based on Figure 4.6, it is observed that the temperature of saline water increases at a similar rate from 10.00am to 12.00pm. At this particular time, the solar irradiation is almost constant, and the prototype are starting to heat up. Therefore, the effect of thermal storage is not significant. From 12.00pm to 2.00pm, this is the part where the solar irradiation increases to peak from 1004.9 W/m^2 to 1129.2 W/m^2. The saline water temperature of Model D is slightly higher than the basic solar distiller as there might be some cloudy weather within the timeframe and the thermal storage is able to reduce the drop in temperature. As for the timeframe from 2.00pm to 4.30pm, the basic solar distiller experience significantly drop in saline water temperature as the solar irradiation is getting weaker and also considering the cloudy weather throughout this timeframe. The thermal storage in Model D is able to provide heat energy towards the saline water and reduce the drop saline water temperature. Lastly at 4.30pm to 6.00pm where the prototype is moved into indoor environment and there is no solar irradiation emitted on the prototype, it is observed that the saline water temperature of basic solar distiller is dropped to 34.75 °C which is close to the room temperature of 32.00 °C at 6.00pm while the saline water temperature of Model D drops to 38.44 °C which shows the effect of thermal storage.

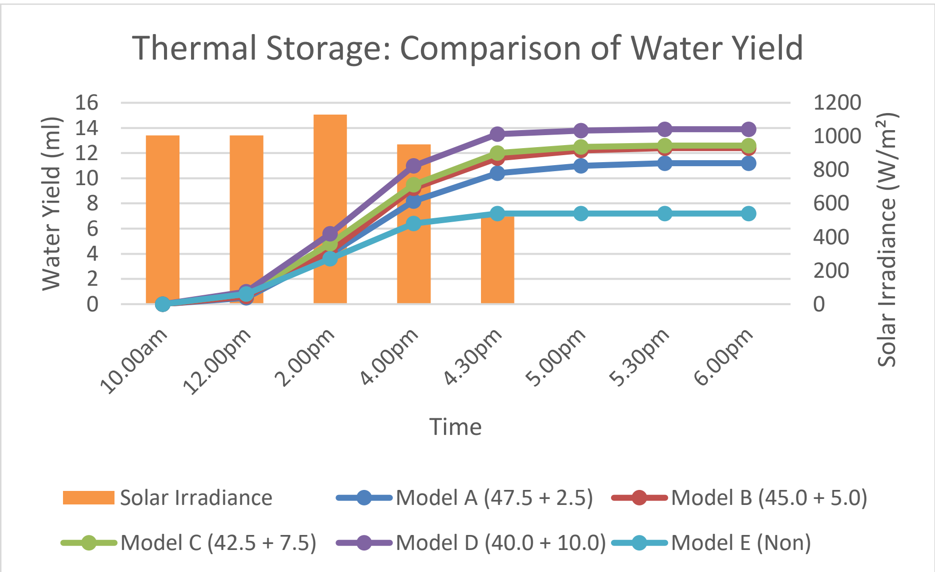

Figure 4.7: Comparison of water yield for models with different thermal storage and basic solar distiller.

From Figure 4.7, it is observed that the usage of thermal storage in solar distiller is able to increase the performance of water yield. The solar distiller with thermal storage has a significant higher water yield as compared to the basic solar distiller. Other than that, it is also observed that the higher the percentage of aluminium scraps in paraffin wax as thermal storage, the higher the water yield. However, the difference in water yield between the models with thermal storage are not significant where the highest water yield from Model D is 13.9ml and the lowest water yield from Model A is 11.2ml which shows a difference of 2.7ml.

4.4 Solar Distiller with Thermal Storage and Fresnel Lens

The thermal storage with the ratio of paraffin wax to aluminium scrap 8 : 2 is used for all four prototypes. Therefore, the only difference between each prototype is the concentration ratio of Fresnel Lens.

4.4.1 Optimal Concentration Ratio of Fresnel Lens

All four prototypes are placed at outdoor environments from 10.00a.m. to 4.30p.m. and they will be moved into indoor environments from 4.30p.m. to 6.00p.m. to evaluate the effect of thermal storage when the solar irradiation is completely absent. The graphs below show the temperature of saline water, saline water basin, thermal storage and glass cover and the water yield for each prototype.

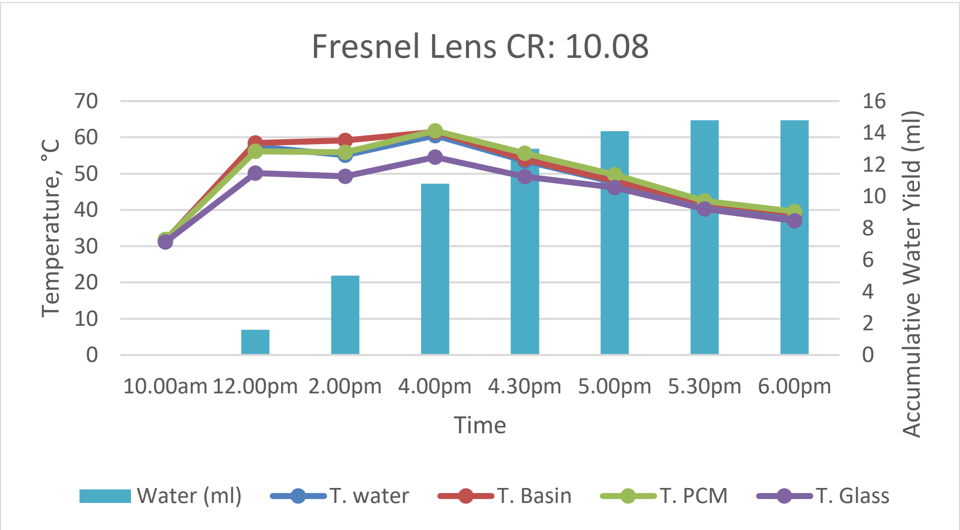

Figure 4.8: Graph of Data for Model A (CR: 10.08)

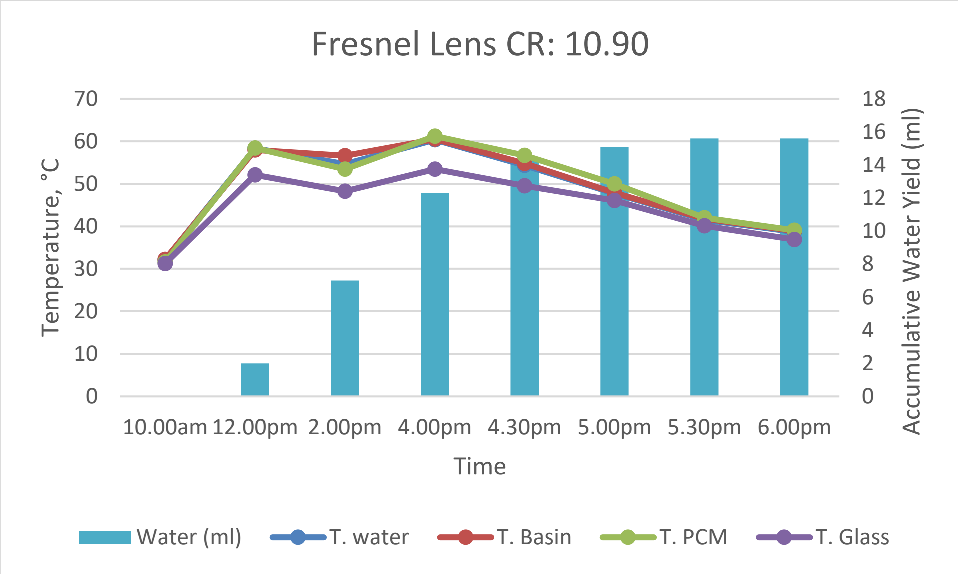

Figure 4.9: Graph of Data for Model B (CR: 10.90)

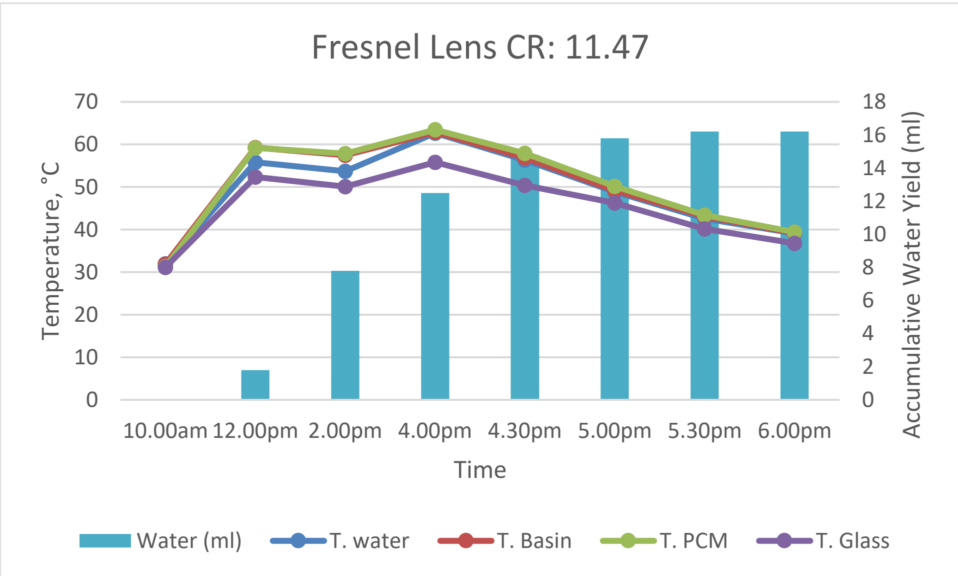

Figure 4.10: Graph of Data for Model C (CR: 11.47)

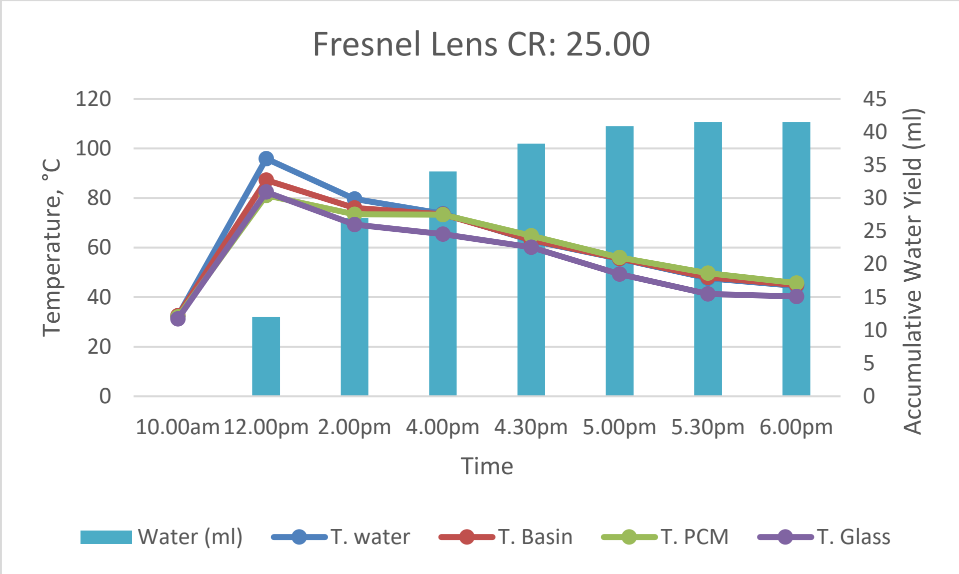

Figure 4.11: Graph of Data for Model D (CR: 25.00)

Based on Figure 4.8 to Figure 4.11, it is observed that for Model A, B and C, the saline water temperature reaches peak at 4.00pm which are 60.51 °C, 60.35 °C and 62.67 °C respectively. However, the peak saline water temperature for Model D is 95.88 °C at 12.pm. The peak solar irradiance is 1159.1 W/m^2 at 12.00pm thus explained the peak saline water temperature achieved by Model D at 12.00pm. The high concentration ratio and large surface area of the Fresnel lens in Model D contributed to the quick rise in saline water temperature. As for Model A, B and C, the peak saline water temperature is at 4.00pm instead of 12.00pm can be explained by the timeline. The experiment is started at 10.00am where the starting temperature of saline water is around 32 °C. The lower concentration ratio and surface area of the Fresnel lens in Model A, B and C has lower performance as compared to Model D thus the saline water temperature did not reach the peak at 12.00pm.

The water yield for Model A, B, C and D are 14.8ml, 15.6ml, 16.2ml and 41.5ml respectively. It is observed that the higher the concentration of the Fresnel lens, the higher the water yield. The Model D which has the Fresnel lens that is significantly higher in concentration ratio compared to other models has a significant higher water yield, with highest difference of 26.7ml, which calculated into 180% higher as compared to Model A. The high concentration ratio and large surface area of the Fresnel lens in Model D is able to concentrate a large amount of sunlight onto the saline water. The saline water is observed to be boiling as shown in Figure 4.12. The boiling of saline water causes significant higher evaporation rate and thus resulting in higher water yield. Boiling of saline water does not occurs in other models thus the water yield is significantly lower. Therefore, the optimal concentration ratio of Fresnel lens in this study is 25.00.

Figure 4.12: Saline water boiling in Model D.

There is a factor that will affect the performance of Fresnel lens on solar distiller. The Fresnel lens is adjusted at an interval of 1 hour. The focal point of the Fresnel lens where all the solar irradiations are focused onto might not be on the saline water all the time thus affecting the result of water yield. Shorter interval between each adjustment can ensure the focal point is on the saline water at a longer period of time which can further increase the performance of the solar distiller.

From this part of experiment, it can be observed that Fresnel lens plays a major role in improving the performance and efficiency of the solar distiller as the water yield under similar weather conditions are significantly higher than the basic solar distiller and the solar distiller with thermal storage.

4.5 Enhancement Achieved by the Combined Methods

The enhancement achieved by the combined method is evaluated based on the productivity and efficiency of the solar distiller. The solar distiller with the optimal combination of Fresnel lens and thermal storage is compared with the solar distiller with optimal thermal storage and also the basic solar distiller. First, the productivity and efficiency of each model in each part of study are calculated.

Table 4.1: Productivity and efficiency of solar distiller with thermal storage and basic solar distiller.

Solar Distiller with Thermal Storage				
Model	Productivity (g/kJ)	Improvement (%)	Efficiency (%)	Improvement (%)
Model A (9.5 : 0.5)	0.0381	55.56	8.66	3.09
Model B (9 : 1)	0.0421	72.22	9.59	4.02
Model C (8:5 : 1.5)	0.0428	75.00	9.74	4.16
Model D (8 : 2)	0.0472	93.06	10.74	5.16
Model E (Non)	0.0245	0.00	5.57	0.00

From the Table 4.1, it is observed that the Model D has highest productivity and efficiency, which are 0.0472 g/kJ and 10.74% respectively. The basic solar distiller has the lowest productivity and efficiency which are 0.0245 g/kJ and 5.57% respectively. As compared to the basic solar distiller, Model D achieved improvement of 93.06% in productivity and 5.16% in efficiency as compared to the basic solar distiller.

Table 4.2: Productivity and efficiency of solar distiller with thermal storage and Fresnel lens and basic solar distiller.

Solar Distiller with Thermal Storage and Fresnel Lens				
Model	Productivity (g/kJ)	Improvement (%)	Efficiency (%)	Improvement (%)
Model A (CR = 10.08)	0.0529	116.25	11.49	5.91
Model B (CR = 10.90)	0.0558	127.94	12.10	6.53
Model C (CR = 11.47)	0.0579	136.71	12.57	6.99
Model D (CR = 25.00)	0.1484	506.39	31.44	25.87
Model E (Non)	0.0245	0.00	5.57	0.00

From table 4.2, it is observed that the Model D has the highest productivity and efficiency, which are 0.1484 g/kJ and 31.44% respectively. As compared to the basic solar distiller, the Model D has achieved an improvement of 506.39% in productivity and 25.87% in efficiency. Therefore, this shows the importance of Fresnel lens in improving the performance of the solar distiller.

Table 4.3: Comparison of the improvement achieved by the enhancement.

Comparison of Improvement Achieved				
Model	Productivity (g/kJ)	Improvement (%)	Efficiency (%)	Improvement (%)
Basic	0.0245	0.00	5.57	0.00
Optimal Thermal Storage	0.0472	93.06	10.74	5.16
Optimal Thermal Storage and Optimal Fresnel Lens	0.1484	506.39	31.44	25.87

The table 4.3 provides a clear description of the improvements that is achieved by just implementing the optimal thermal storage and also by implementing both the optimal thermal storage and optimal Fresnel lens. It is observed that by just implementing the optimal thermal storage into the basic solar distiller, the productivity and efficiency achieved improvement of 93.06% and 5.16% respectively. In addition, by implementing both the optimal thermal storage and optimal Fresnel lens into the basic solar distiller, the productivity and efficiency achieved improvement of 506.39% and 25.87% respectively. Therefore, the optimal ratio of paraffin wax to aluminium scraps of 8:2 as thermal storage paired with the optimal Fresnel lens with concentration ratio of 25.00 can enhance the performance of the solar distiller significantly.

4.6 Quality of Water Produced

The saline water used in this study imitates the sea water, which has a total dissolved solid (TDS) value of approximately 35,000 ppm. The TDS value indicates the amount of mineral dissolved in the water. The water produced from the solar distiller are supposed to be safe to consume. According to the report "Guideline for Drinking-Water Quality" by World Health Organization (WHO), the total dissolved solids in safe drinking water should not exceed 500ppm.

Water conductivity test has been conducted on each of the prototype in each experiment. The TDS value of the water produced ranges from 69ppm to 92ppm. This is slightly higher than the expected result of around 40ppm. One of the reasons that caused this is the equipment used to contain and measure the water produced might not be clean. Other than that, the orange garden hose which acts as a water trough and the glass cover might not be clean as well. The evaporated vapor which will produce clean water will get in contact with these parts throughout the process. Therefore, it is important to keep all the equipment and the parts of solar distiller clean before conducting experiment to ensure a higher quality of water produced.

4.7 Comparison of Results with Similar Studies

The productivity and efficiency this study was compared with the result of similar studies. The comparison was shown in the table below.

Table 4.4 Comparison of Results with Similar Studies

	Specification			Result	
Author	Solar Still Type	Fresnel Lens	Thermal Storage (PW: Al ratio)	Productivity (g/kJ)	Efficiency (%)
(Yeang et al., 2023)	Double-Slope Single Stage Solar Distiller	4pcs	✗	0.1036	23.5
(Liew, 2022)	Single-Slope Solar Distiller	✗	(98.5 : 1.5)	0.079	17.99
(Ho, 2022)	Double-Slope Solar Distiller	1pcs	✗	0.16	37
(Ho, 2022)	Double-Slope Solar Distiller	1pcs	(100% Petroleum Jelly)	0.14	32
Current Study	Single-Slope Solar Distiller	✗	(8 : 2)	0.0472	10.74
Current Study	Single-Slope Solar Distiller	1pcs	(8 : 2)	0.1484	31.44

From the comparison above, it is seen that double-slope solar distiller with Fresnel lens has achieved higher productivity and efficiency as compared to the model in current study with Fresnel lens and thermal storage. The double-slope solar distiller can significantly increase the amount of solar irradiance received by the saline water thus increasing the productivity and efficiency. Another interesting point to note is that the single-slope solar distiller with 98.5 : 1.5 PW to Al ratio has higher productivity and efficiency than the current study with ratio of 8 : 2.

4.8 Cost of Water Produced

The cost of water produced is one of the factors to determine the usability of the solar distiller. The solar distiller should be able to produce clean water at low cost as it was designed to be used in rural areas that are weak in terms of economic. The cost per litre was calculated in the table below. The solar distiller was determined to have a 2-year working life with a 15% maintenance cost as of the initial cost. The cost per litre annually was calculated to be RM2.63/litre.

Table 4.5 Cost Calculation

	Cost (RM)
Hardware	18.10
Thermal Storage	1.00
Fresnel Lens	56.00
	75.10
First Cost	75.10
Annual Maintenance Cost (0.15*First Cost)	11.27
Total Cost for 2 year	86.37
Water Yield per day(l)	0.05
Water Yield per annual(l)	16.43
Cost per litre annually(RM/l)	**2.63**

4.9 Summary

This chapter shows the results obtained from the experiments. The performance for the thermal storage with different ratio of paraffin wax to aluminium scraps are compared and the ratio of thermal storage with optimal performance is 8:2. Besides that, the performance of the Fresnel lens with different concentrations ratio is also compared. The Fresnel lens with concentration ratio of 25.00 has the best performance. The implementation of optimal thermal storage is able to increase the productivity and efficiency of basic solar distiller by 93.06% and 5.16% respectively while the implementation of both optimal thermal storage and optimal Fresnel lens is able to increase the productivity and efficiency of the basic solar distiller by 506.39% and 25.87% respectively. This improvement indicates the Fresnel lens plays a major role in improving the performance of the solar distiller while thermal storage also provides a small portion of improvement as well. By combining both improvement methods, the performance of the solar distiller can increase significantly.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

As a conclusion, this study concludes that the optimal combination of thermal storage and Fresnel lens is by using a thermal storage with paraffin wax to aluminium scraps ratio of 8:2 and a Fresnel lens with concentration ratio of 25.00.

The optimal thermal storage is able to improve the productivity and efficiency of the solar distiller by 93.06% and 5.16% respectively. The optimal storage is able to absorb and release heat energy more efficiently due to its higher thermal conductivity as compared to other thermal storage. The higher quantity of aluminium scraps in paraffin wax will reduce the capacity of heat able to be stored but the effect of high thermal conductivity shows stronger effect throughout the experiment to reduce the drop in saline water temperature when the solar irradiation is weak.

By using the combined methods which implements both optimal thermal storage and optimal Fresnel lens, the productivity and efficiency of the solar distiller is improved by 506.39% and 25.87% respectively. The Fresnel lens with larger surface area resulting in higher concentration ratio, is able to concentrate higher amount of solar irradiance towards the saline water. The implementation of Fresnel lens with concentration ratio of 25.00 resulting in the boiling of saline water which significantly increase the rate of evaporation of saline water thus increase the water yield. The effect of Fresnel lens and thermal storage is significant based on the results in this study and the combination of the optimal thermal storage and optimal Fresnel lens significantly improved the performance of a solar distiller.

There are some other ways to further improve the efficiency of the passive solar distiller. For example, by using a multistage solar distiller, by using a double-slope solar distiller which increases the absorption of solar irradiance, by increasing the number of Fresnel lens used which will significantly increase the productivity and efficiency of the solar distiller as shown in this study.

5.2 Recommendations for future work

Recommendations for the future work to improve the accuracy, consistency and quality of the result. First of all, the water collection method should be improved. The usage of an orange garden hose located below the end of the slope of glass cover is not an ideal way to collect water. The usage of silicone sealant to fix the garden hose and the gap around it might cause error where the application of silicone is not perfect thus resulting in gap and misplaced of garden hose. A larger collection trough made from a rigid material are suggested so that it can be rigidly fixed on specific position to collect the condensates. Other than that, the measurement of water yield based on the water collected might not be accurate, there are some condensates on the glass cover that falls back into the saline water basin or other location but not on the water collection trough. This can result in misjudge on the performance of the solar distiller. The evaluation of performance of the solar distiller can be done by measuring the reduction in mass of the saline water in the water basin. This can provide a more accurate data on the mass of water evaporated. Lastly, the ratio of aluminium scraps in paraffin wax can be higher to evaluate the performance of thermal storage with amount of aluminium scraps to further determine the optimal ratio.

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APPENDICES

Appendix A: Table

Table A-1: Specification of Fresnel lens.

Model	32-684	32-592	32-682	300mm Large Optical PMMA FL
Specification	5.0" x 5.0", 5" Focal Length, Fresnel Lens	3.0" x 3.0", 3.9" Focal Length, Fresnel Lens	3.0" x 3.0", 7.9" Focal Length, Fresnel Lens	300mm x 300mm , 330mm Focal Length
Center Thickness (inches)	0.06	0.06	0.06	0.0787
Coating	Uncoated	Uncoated	Uncoated	-
Dimensional Tolerance (inches)	±0.05	±0.05	±0.05	-
Dimensions (inches)	5.0 x 5.0	3.0 x 3.0	3.0 x 3.0	11.81 x 11.81
Dimensions (mm)	127 x 127	76.2 x 76.2	76.2 x 76.2	300 x 300
Effective Diameter (inches)	4.0	2.5	2.6	-
Effective Focal Length (inches)	5.00	3.90	7.90	12.99
Effective Focal Length (mm)	127.00	99.06	200.66	330
Groove Density (grooves/inch)	125.00	125.00	25.00	-
Index of Refraction nd	1.49	1.49	1.49	-
Operating Temperature (°C)	80 (Maximum)	80 (Maximum)	80 (Maximum)	-
Substrate	Acrylic	Acrylic	Acrylic	Optical PMMA Plastic
Thickness Tolerance (%)	±40	±40	±40	-
Transmission (%)	92 (from 400-1100nm)	92 (from 400-1100nm)	92 (from 400-1100nm)	92
Type	Fresnel Lens	Fresnel Lens	Fresnel Lens	Fresnel Lens
Wavelength Range (nm)	400 - 1100	400 - 1100	400 - 1100	-
aperture diameter (mm)	101.6	63.5	66.04	300
Aperture area (mm²)	8107.319666	3166.921744	3425.342559	70685.83471
Receiver area (mm²) (estimate)	26350	26350	26350	26350
Concentrated receiver area (mm²) (estimate	706.8583471	314.1592654	314.1592654	2827.433388
radius of concentrated sunlight (mm)	15	10	10	30
Concentration ratio (geometrical)	11.46951111	10.080625	10.903204	25.00000