ENHANCEMENT TECHNIQUES ON A MULTI-STAGE SOLAR DISTILLER

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

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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 **"ENHANCEMENT TECHNIQUES ON A MULTI-STAGE SOLAR DISTILLER"** was prepared by **ANG JIA YI** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Engineering (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

A solar distiller is able to provide clean water to be used in rural areas especially in the poor countries where the people there are hard to access to clean water supply. The water productivity of a solar distiller is strongly reliant on solar radiation, therefore a traditional solar is still unable to deliver sufficient volumes of clean water. Therefore, this research studied an enhanced multi-stage solar distiller designed with corrugated condensation surfaces, and parafin wax as phase change material (PCM) added in each stage. In this research, experiments with different multi-stage solar distiller models have been conducted on four different ways of operation. The first way is a multi-stage solar distiller with flat condendation surface without using PCM. The second way is a multi-stage solar distiller with flat condendation surface with PCM inside every stage. Third is a multi-stage solar distiller with corrugated condendation surface without PCM. Fourth is a multi-stage solar distiller with corrugated condensation surface with PCM. The corresponding fresh water productivity obtained in the result was 0.2031 kg/day, 0.2741 kg/day, 0.3492 kg/day, and 0.4391 kg/day respectively. Whereas, the corresponding cost of clean water per kilogram was RM 1.33/kg, RM 1.03/kg, RM 0.79/kg, and RM 0.66/kg respectively. All experiments were conducted at Cheras, Selangor at the days of 21 March 2022, 22 March 2022, 23 March 2022, and 24 March 2022. The hourly solar irradiance for each experiment and the temperature of condensation surface and water at every stage were measured. The contribution for the study is the ability to provide unlimited supply of clean water in bigger amount in the poor countries by using the designated enhanced multi-stage solar distiller. It was concluded that the fresh water productivity greatly increased in a multi-stage solar distiller integrated with PCM and corrugated condensation surfaces.

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LIST OF SYMBOLS / ABBREVIATIONS

c_p	specific heat capacity, J/(kg·K)
h	height, m
h_{fg}	latent heat of vaporization
M	mass flow rate, kg/s
m	rate of evaporation, kg/s
Q	energy, W
T	temperature, °C
m_o	mass of accumulated fresh water produced, kg
H	Accumulated solar irradiance, MJ/m^2
A	Area, m^2
η	Efficiency, %
n	life-span
S	salvage value
m_a	annual water yield mass, kg
i	interest rate per year

ASI	average solar irradiance, W/m^2. H
PCC	present capital cost, RM
FAC	fixed annual cost, RM
AMC	annual maintainece cost, RM
AC	annual cost, RM

FPC	flat plat collector
ETC	evacuated tube collector
PCM	phase change material
SFF	sink fund factor
CRF	capital recovery factor
ASV	annual salvage value

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CHAPTER 1

INTRODUCTION

1.1 General Introduction

The Earth's surface is occupied by water for about 71%, where the remaining 29% is the continents and islands. Around 96.5% of the total water on the Earth is saline water from the oceans, rivers and lakes. It is not safe to drink nor safe to use because of the amount of salt contains and the harmful microorganisms in it. The majority of the globe today struggles from a severe lack of fresh clean water for drinking. One of the most crucial concerns in recent history has been the production of clean water.

Researchers have been using the available resources to create fresh water. Renewable energy is said to be the gift from the mother's nature, especially the solar energy. Solar energy has been the popular research topic as it is always available to create heat energy. Desalination process is able to produce fresh water by using solar energy, it is a cheap and easy technique and is suitable to place at small areas, especially the rural area where solar energy is widely abundant. A solar desalination system gathers solar energy and directly transforms saline water to distillate. Solar still is a simple device using desalination process. It is claimed to be economic to obtain fresh clean water that are safe in drinking from saline water. Various kind of solar still had been developed and continuously improving to increase its performance. The simplest solar distiller is a single basin solar distiller where it is easy to construct and operate. However, the performance and efficiency of a single basin solar still is low, it produces a very low production of fresh water and the time taken for it to produce is too long. Hence, multistage solar still had been developed to maximize the production. Multistage solar still indicates that a few numbers of trays or basins are stacked up vertically. The benefits of multistage solar still is to reuse the vapor condensation energy released from the first stage to be in the next stage for desalination. This way can also save up a lot of spaces. However, multistage solar still could not produce sufficient amount of fresh water required in a day. Therefore, to further enhance and maximize the productivity of the multistage solar still, various of modifications and enhancing techniques that can be applied on it was studied.

1.2 Importance of the Study

The importance of the study is to help those poor countries that have difficulties in accessing sufficient potable water. About 5 million of South Africans had reported lacking safe drinkable water. People in the rural area can only depend on the ground water or the rainwater which is not 100% clean enough as most of the bacteria is still in the water. Some areas in South Africa also have river but the sewage had contaminated the river. These had caused a severe problem to their public health. The waterborne illness had led half of the people to death. The hygienic and sanitation issue towards the poor country can be improved by building cheap and simple in operation infrastructure such as multi-still solar still devices.

Besides, contamination of rivers had been a major issue to industrial heavy areas. Industrial area often releases unwanted chemical waste to river from their factory and in a result that the resident near by has water shortage problem when related department is still dealing with the water pollution problem. For instance, the water pollution incident in Kim Kim River, Pasir Gudang, Johor which occurred in year 2019, where most of the resident there could not access to water that are safe to use. The incident occurred because of the dumping of chemical toxic to the river by a factory. It is a hard period for them as there were no water supply to each household. The multi-stage solar still can be said to be a backup water supply to resident when incident like this occur. It uses free resources to gain clean water. This solar still can be useful to all the areas in the world that are still dealing with contaminated ground water or river water because of the overdevelopment issue. Contaminated water can cause people there to fall ill and even breathing difficulties. Hence, to ensure the quality of water is safe, more multi-still solar stills which are low in cost can be built in many small places to allow residents to gain potable water.

1.3 Problem Statement

The demand for water is quickly increasing because of the increase of population, developmental of cities, and industrial needs. Unluckily, the growth of development and population had led to the contamination problem in ground water and also in water streams. Until 2014, approximately 40% of the world's population experienced severe water shortage, with the estimation that this figure will rise to 55% by 2025. By the year 2050, over 57% of the world's population would live in areas with serious water shortage (Baniasad Askari and Ameri, 2021). In many regions of the world, the lack of pure water is a severe issue. According to UNICEF, poor countries especially in the Africa, like Ethiopia, Congo, Niger, and Eritrea have facing the problem of lacking clean water (Mekki, 2017). Most people there without the basic access are drinking from contaminated water, such as hand-dug wells, unprotected natural springs, ponds, and other sources. People in these countries suffer from water-related diseases. The weather of these countries has ample of sun and heat to obtain clean water from desalination process. These people can have the chance to get unlimited clean water if solar stills are built in their village. They only need to constantly refill the basin with the water from their ponds or lake, then wait for some time to allow solar energy to work inside the solar still to get fresh water.

The main concern of solar still is it produce very low amount of water and the time taken is very long. To supply to the people according to their population, the solar still must be able to produce high yield of clean water. According to a studies found by Ali Samee *et al.*, (2007), a normal single basin solar still with area of 0.54 m^2 can only obtain 1.7 litters per a day when it was exposed under the sun for eight hours during the month July in PIEAS, Islamabad. To increase the efficiency, the number of basins can be increased to obtain more amount of clean water. This research works to further increase the amount by modifying the design of the solar still.

1.4 Aim and Objectives

The main objective of this project is to study different modifications on a multi-stage solar still that can enhance the performance. A high-performance multi-stage solar still is to create more yielding of fresh water in a day when solar irradiation is high. The multi-stage solar still need to be easy to construct and require lesser maintenance. The specific objectives of this project have been set in order to attain the goal:

I) To investigate different kind of enhancement methods on solar still

II) To design a high productivity multi-stage solar still

III) To build a prototype of an enhanced multi-stage solar still

IV) To evaluate the effectiveness of the enhanced multi-stage solar still

1.5 Scope and Limitation of the Study

This project focused on the improvement method to increase the clean water yield in a multi-stage solar still. Two kinds of condensation surface designs were proposed to compare the effectiveness. The first design is with the inclined flat condensation surface, whereas the second design is a v-corrugated condensation surface. The limitations of this research are:

1. The project depends on the weather condition. The weather condition is not constant most of the time. The wind speed, humidity and sun irradiance are different every day. The amount of clean water is depending on the surrounding temperature too. If the weather rains, the experiment might be affected and the experiment need to be postponed. The weather condition is unpredictable to conduct the experiment for this research.
2. The cost is a major limitation to be considered since the solar still is in few stages and the enhancement technique might need some cost to build it on the solar still. Besides, two multi-stage solar still are required to build to compare with each other..

1.6 Contribution of the Study

This research study encourages the use of multi-stage solar distiller in those poor countries which are lack of clean water supply but also with high solar irradiance for the whole year. Multi-stage solar distiller is able to create clean distilled water by just using solar energy which is a free source of energy and is always widely available.

This study mentioned about the techniques to be applied in a multi-stage solar distiller to improve the performance by maximizing the water yield.

Hence, the new design of a multi-stage solar distiller is discussed and explained in this research project. An enhanced multi-stage solar distiller with high clean water output and low budget cost was built in order to ensure the suitability to use in those poor countries which requires clean water supply.

1.7 Outline of the Report

This study report is divided into five chapters: introduction, literature review, research methodology, results and discussion, and lastly, a conclusion chapter to wrap up the work. The introduction will be written in Chapter 1 which is mainly explaining the importance and the working theory of a solar distiller.

Besides, Chapter 2 is about the literature review of this research project. This chapter will discuss about the different kind of methods to increase the performance of a solar distiller.

Chapter 3 is the methodology for this research project. The design of the multi-stage solar distiller prototype and the number of stages will be discussed in this chapter. The methods to enhanced the multi-stage distiller will be decided and further discussed in Chapter 3.

Moreover, Chapter 4 is the results and discussion part where the graphs of tempearature of the multi-stage solar distiller for different design of prototypes will be included. The fresh water yield by the multi-stage solar distillers built, efficiency of multi-stage solar distillers, and the economic analysis are also discussed in this chapter.

Lastly, Chapter 5 is the final chapter for this research study, in which all of the information taken from the experiment done will be summarised, and the recommendation for improving the project will be listed.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter is mostly focusing on the general principle of the desalination process using solar distillers to get clean fresh water. This section explains the working principle of multi-stage solar distiller and the modifications on it to increase the amount of clean water produced on a daily basis. The various design alterations each have their own set of benefits and drawbacks. It is critical to make effective changes in the design of solar distiller, especially the multi-stage distiller in order to provide enough clean water to a society with a limited supply of high-quality water.

2.2 Principle of Operation of Solar Distillers

A solar distiller is a simple and cheap device that turns saline water into pure water that is safe to drink through solar desalination process. Solar desalination is a method of purifying water involving solar heat from an unclean source such as brackish water, saline water or sea water by evaporation and condensation process (Khechekhouche et al., 2019). A simple single solar distiller uses greenhouse effect technique which consist of a basin, transparent cover, and a collection trough. The saline water filled up inside a basin where the whole body is black in colour to create a blackbody to maximise the absorption of heat by radiation. It helps to increase the water temperature in the basin. The transparent cover on top of the basin which places in incline position. The transparent cover can be a glass cover or a plastic cling. This allows the sunlight to penetrate into the cover and direct it to the saline water to heat it up. Here is where evaporation happens when water turns from liquid states to vapor state. The vapor rises to the sloped transparent cover’s inner surface and turns into water droplets by condensation (Khechekhouche et al., 2020). The salts and impurities in the saline water do not evaporate with it, leaving impurities in the basin. The amount of condensed water droplet increases with time and all the droplets are collected using the help of gravity into a collection trough which is positioned near the cover’s lower edges

(Abutayeh et al., 2015). The drawback of single stage solar distiller is the slow and low productivity. This is because of the condensing vapour's latent heat being badly dissipated. Hence, many researchers did investigations to increase the number of stages of the solar distiller to improve the efficiency.

According to the research paper from El-sebaii and El-bialy (2015), a double stage solar still can produce 36% higher on average compared to a single stage solar distiller. The higher productivity of multi-stages still is due to the former latent heat of condensation is being used more than once to heat the saline water for evaporation (Feilizadeh et al., 2015). A number of investigators had studied on the methods and techniques to enhance the efficiency of multi-stage system to obtain higher productivity of fresh water.

2.3 Modified Solar Distillers with Concentrator

A number of enhancement techniques as well as some modifications were developed on the solar distillers to produce a higher efficiency. The modifications made were inexpensive and easy to build. One of the techniques is to add a concentrator to gain more solar energy to increase the temperature of water.

2.3.1 Sub-subsection Title

The research work that was investigated by Gorjian *et al.*, (2014) which used a point focus parabolic solar distiller to desalinate brackish water into pure clean water. The parabolic concentrator with a diameter 2 m and had a 0.693 m focal length produced up to 3.142 m^2 of reflecting area. The solar still consisted of a PLC based sun tracking system too. The focal point is where all the sunlight were concentrated and reflected at an absorber. The evaporation process took place inside the absorber where the brackish water pumped into it. Since the sunlight was all concentrated and reflected to the position of absorber, more water was heated and vaporized into steam. The steam flows out from absorber and condensed at the heat exchanger where it was connected to the absorber as seen in Figure 2.1. Based on the findings of the experiment, the solar distiller’s highest output for a day was 5.12 kg/m^2 after operating for 7 hours. The drawback of the design is it requires desirable tracking system to get a better efficiency.

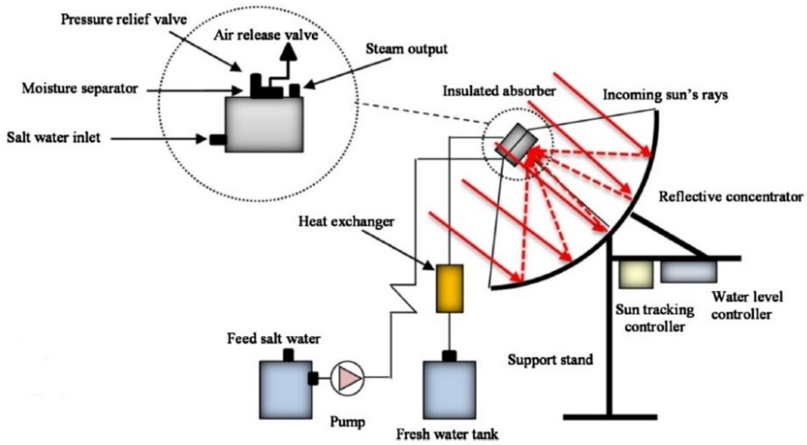

Figure 2.1: Parabolic concentrator solar distiller design (Gorjian et al.,2014)

Another design of solar distiller that involved the parabolic concentrator was studied by Arunkumar et al., (2016). The whole design of it was called as a compound parabolic concentrator concentric tubular solar distiller. A tubular solar still is different in the still design where the shape is cylindrical which carries more saline water (Kabeel et al., 2020). This increases the surface area of the basin and increases the evaporation rate and also the amount of steams. The experiment by Arunkumar *et al.*, (2016) used a 2 m^2 parabolic concentrator concentric and a 0.25 m^2 single stage distiller. A total of five tubular concentric tubes were design and each tube was positioned at the line focus parabolic concentrator which shown in Figure 2.2. This helped to preheat the water before entering the 0.25 m^2 distiller. The method speeded up the evaporation process in the distiller (Arunkumar et al., 2019). The result of the experiment obtained a 6.41 kg/m^2 of clean water for a day. The study increased the productivity as the water undergo two times heating processes but the whole set up occupied more spaces.

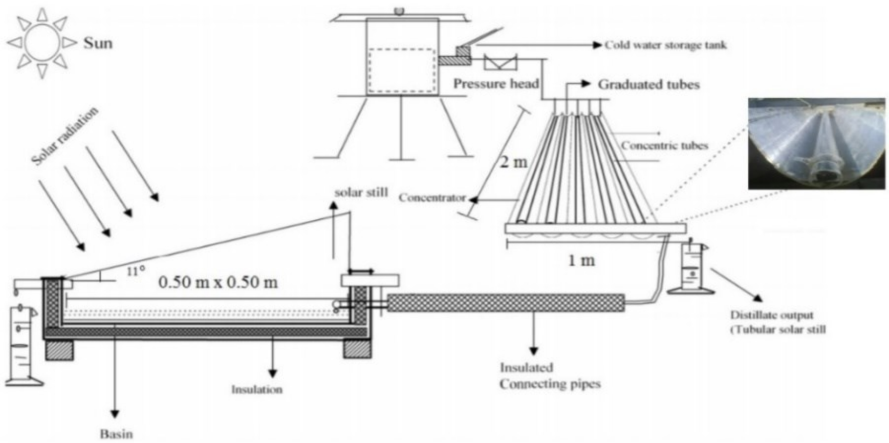

Figure 2.2: Parabolic concentrator in single slope solar still
(Arunkumar et al., 2016)

The research by Hassan, (2020) was regarding the double slope solar still incorporated with a parabolic trough collector. The distiller was 1.4 m^2 big and the cylindrical shape parabolic trough collector with a size of 3 m^2 which was made from stainless steel material. The parabolic trough reflected the sunlight to a pipe with oil passing in it. The heated oil of 75°C was then flowed to the distiller basin location. The oil flowed to the built-in heat exchanger under the basin of saline water. The water heated up by absorbing the heat from the oil from the heat exchanger. The result of the experiment showed that the maximum pure water obtained is 8.53 kg/m^2.

2.3.2 Solar Distiller with Fresnel Lens

Fresnel lens is more preferrable compared to a conventional lens. One of the characteristics of Fresnel lens is flat on one side and rigid on the other making the lens very thin. It is able to refract parallel light beams and gather into a point which known as focal point. The drawback of using conventional lens is because it produces a lesser sharp focus as it scatters light across a medium, as shown in Figure 2.3. Many little concentric grooves go over the surface of the Fresnel lens. As a result, each groove acts as its own prism (Binu et al., 2017). Thanks to this construction. a high concentration of solar energy is able to achieve.

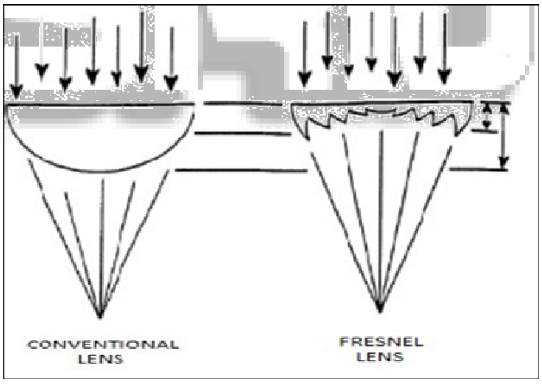

Figure 2.3: Conventional lens (Left) compared to Fresnel lens (Right) (Binu et al., 2017)

An investigation regarding a three-stage solar still with Fresnel lens had studied by Younas et al., (2016). The investigation used an acrylic plastic Fresnel lens with the area of 1.37 m^2 and focal length of 1.2 m. A mechanical tracking system was used to track the sun and also it had the function of holding the weight of the still and the Fresnel lens. A lens frame was connected to this system so that it can be rotated about the point of focal. As the sun moved from east direction in the morning to west direction at the afternoon. The lens frame can be rotated to track the sunlight manually. The sunlight beams concentrated on the focal point and the saline water in the lower basin was located at that point to gain the maximum heat from solar energy. The high temperature in the first still increase the rate of evaporation. The second still used the latent heat of condensation from the lower still to produce clean water. The maximum yielding from the three-stage still with Fresnel lens was 5 kg/m^2. A study regarding the number of stages and the productivity of the still was also conducted. By referring to Figure 2.4, nine stages of still were taken into account but it showed that the output did not increase after five number of stages. The productivity of five stages of still was found to be 8.3 kg.

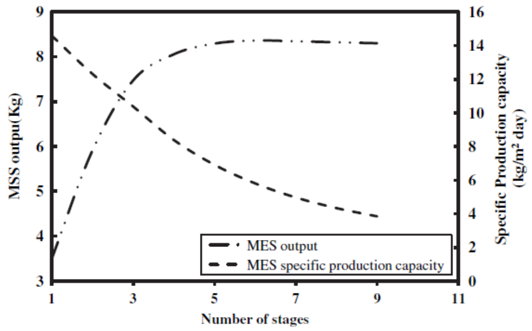

Figure 2.4: Result of output (kg) and the number of stages (Younas et al., 2016)

2.3.3 Comparison of Parabolic Concentrator and Fresnel Lens

Table 2.1 summarized the pros and cons of parabolic concentrator and Fresnel lens. Each of the design has their own unique characteristics. Both are equally effective in maximizing the temperature of saline water by focusing the solar energy into a point.

Table 2.1: Parabolic concentrator compared to Fresnel lens

Parabolic Concentrator	Fresnel Lens
Occupied more spaces when installing it	It requires lesser ground to be installed on
Has higher optical efficiency due to the lower loss in sunlight	Lower efficiency due to some sunlight is absorbed in the glass
It requires heavy maintenance	It requires less heavy maintenance
It is easier to clean the parabolic concentrator.	It is easier to get dirty due to the groove on the lens and take more efforts to clean it.

2.4 Heating Mechanism in Solar Distiller System

Al-Garni, (2012) did an experiment by applying two heaters of 500 W each to heat up the water in the basin. The basin's dimension is 1 m^2 with water depth of 0.06 m. The experiment was taken at Saudi Arabia during the winter period by using a double slope solar distiller with an external cooling fan blowed the glass cover to reduce its temperature to enhance the condensation process. The usage of heater in the still helped the water raise the temperature quickly and the evaporation process was increased to produce more steam in a short time. A comparison of a solar distiller system with no heater was also done to compare the productivity of clean water. Without the water heater, the water in basin's maximum temperature was 46.9°C and glass temperature was 43.2°C. While with the heater, the water in basin raise to the maximum temperature of 62.3°C and glass temperature of 53.2°C. The result of the experiment showed the productivity of 11.8 kg/m^2 with heater and 2.51 kg/m^2 with no heater. This had proven that this technique had enhanced effectively the solar still system.

Ahmed et al., (2009) researched about a three-stage evacuated solar still with a heat exchanger. In the studies, a solar collector was connected to the heat exchanger to provide heat to the saline water at the lower stage of the still. After most of the heat was transferred to the saline water, it circulated back to solar collector to gain heat again as shown in Figure 2.5. The design provided the advantage of reusing the heat released by the latent of condensation to the upper stage solar still. The solar still included a technique of evacuating non-condensable gases from each stage by using a solar functioned vacuum pump. The evaporation rate increased as the internal pressure decreased (Mackay and Van Wesenbeeck, 2014). The efficiency of the design gave a 14.2 kg/m^2 maximum yielding with the vacuum pressure operating at 0.5 bar.

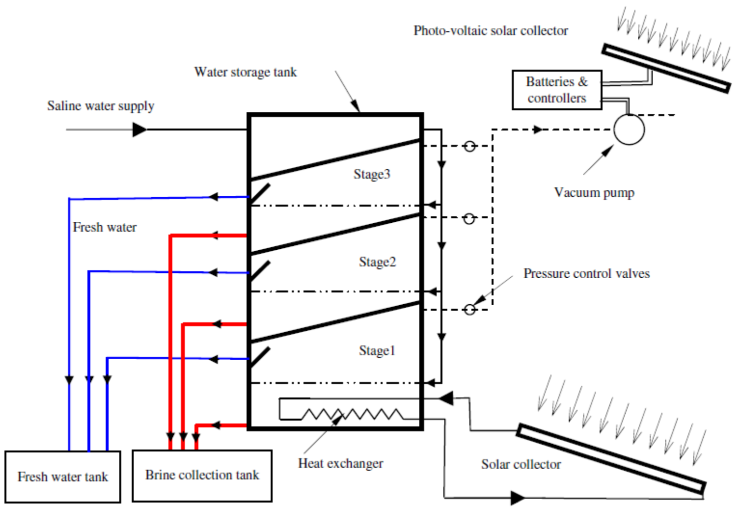

Figure 2.5: Three-stage evacuated solar still with heat exchanger (Ahmed et al., 2009)

2.5 Solar Distiller with Collector

The function of solar collector is to preheat the saline water before sending it to the basin in the solar distiller. There are different kind of solar collector available which different design and price. Solar distiller with collector can increase the water temperature much more compared to the solar distiller with no solar collector.

2.5.1 Evacuated Tube Collector

An evacuated tube collector is made from a number of evacuated glass pipes arranged in parallel order. It acted as a solar panel and was cylindrical in shape which is always receiving sunlight as it is perpendicular to it. Each glass pipe consists of two tubes, an inner tube and an outer tube. The outer tube is usually a transparent glass that allow sunlight to pass to the inner tube, whereas the inner tube absorb the heat. The inner tube is coated with a coating to prevent heat lost from it, and also increases the heat absorptivity. The term evacuated is because a vacuum is formed between the two tubes to ensure no heat is transferred out from the inner tube (Sabiha et al., 2015).

An evacuated tube collector (ETC) solar water heater was used in a study by Sampathkumar and Senthilkumar, (2012) using a single stage still of 1 m^2 and containing a 50 kg amount of water with the experiement setup showed in Figure 2.6. The ETC solar used had 15 evacuated tubes with total capacity of 100 L. Each tube is made with an outer thicker tube and inner thin tube. The space between these tubes was vacuumed. The experiment did were comparing two cases where the first case is the ETC was used for the whole day and another case of ETC was used for the period of 12p.m. to 5p.m. only. For the first case, the saline water was heated to maximum temperature of 86°C when ETC is used, the one without ETC had a maximum temperature of 66°C. For the second case, the ETC solar still's maximum temperature obtained was 75°C and 66°C maximum temperature without ETC. For the case that ETC operated for the whole day, the maximum yielding per hour was 1.2kg/m^2 and 0.56 kg/m^2 for ETC still and none ETC still respectively. The maximum yielding obtained after operating for the second case, operated during the afternoon period only was 4.82 kg/m^2 and 2.748 kg/m^2 with ETC and without

ETC respectively. The experiment showed that the extra thermal energy that gained from the ETC before sending to the basin was 96% effective.

Figure 2.6: Evacuated tube collector solar distiller (Sampathkumar and Senthilkumar, 2012)

2.5.2 Flat Plate Collector

A flat plate collector work by using the greenhouse effect. A flat plate collector is made up of a big size heat-absorbing plate, which is usually made of copper or aluminium because of their high thermal conductivity. The heat-absorbing plate is painted in black colour to absorb more sun radiation. There are multiple tubes locate across the surface of the plate where water flows in it and absorbs the heat from the plate. The pipes and plates are enclosed with a glass sheet to trap the heat in it, acting like an “oven”. The glass traps the heat inside the “oven” and the heat is unable to transfer back to the atmosphere. Hence, the plate is able to absorb heat then transfer to the water in the pipes.

The experiment did by Rajaseenivasan et al., (2014) used a flat plate collector (FPC) with a size of 0.35 m^2 in a solar still system, the FPC was able to preheat the saline water before sending it to the basin. The fins were added to the basin to absorb more heat from the sunlight. The basin had six compartments with gaps in between, fins of size 0.07 m^2 each was inserted to the gaps. Another conventional solar still without the FPC and fins was also studied in the experiment to do a comparison in the performance between them. The experiment was left from 9 am to 6 pm when the sun intensity is the highest.

It was found that the conventional still and FPC solar still had maximum distillate yields of 3.62 kg/day and 5.82 kg/day. For the same basin condition, the effect of the preheated water supply by the flat plate collector enhances the distillate of the FPC solar still by roughly 60% compared to the conventional still.

Another experiment was conducted by Morad et al., (2015) to study the performance of a flat plate collector in a double slope still. The flat plate collector is 1.35 m^2 big with the galvanized iron as the absorber plate. A traditional passive solar still was also used in the experiment to do a comparison. The experiment was conducted from 9 am to 5 pm. The result showed that the maximum water temperatures in the basin achieved 54.5°C for the passive still and 75°C for the flat plate collector still. The maximum productivity of clean water for the passive still and flat plate collector still was 7.8 kg/m^2 and 10.06 kg/m^2 respectively.

Rajaseenivasan *et al.*, (2013) studied the performance of a two-stage solar still with a flat plate solar collector to send heated water to the bottom still. The experiment found that the flat plate collectors gave a 50% higher productivity compared to the common two-stage still. The thermal analysis was studied in this case and found that the evaporation rate increased when the heat of the water in the lower basin increased.

2.5.3 Comparison of Evacuated Tube Collector and Flat Plate Collector

Figure 2.7 showed an evacuated tube collector which is in the right side, and a flat plate collector showed in the right side. In short, both of the evacuated collectors and flat plate collectors were highly effective in increasing the productivity of fresh water in solar still.

Figure 2.7: Evacuated tube collector (left) and flat plate collector (right)

The comparison of the advantages and disadvantages of both collectors was summarized as shown in Table 2.2. Table 2.2 concludes that evacuated tube collector has more advantages and also have higher efficiency compared to flat plat collector but the cost of it is higher.

Table 2.2: Comparison of evacuated tube collector and flat plate collector

Evacuated Tube Collector	**Flat Plate Collector**
It has faster heat generation	It has slower heat generation
Heat loss in the evacuated tubes is minimal during daytime	Heat loss in the collector is high during the daytime due to convection
It has low maintenance	It requires high maintenance
It is higher in cost	It is lower in cost
It is able to perform in colder weather due to the vacuum in tubing	Its performance is lower in colder weather

2.6 Fins in Solar Distillers

One of the enhancement techniques in solar distiller is by adding fins in the basin. In order to increase distillate output, fins are utilised in the solar still to shorten water preheating time. The efficiency of the solar still grew dramatically after fins were added, but it was also revealed that the material of the fins did not affect the efficiency (El-Sebaii and El-Naggar, 2017). Fins is to increase the surface area of water which leads to an increase of water exposure to the sun. This improves the heat transfer and the evaporation rate. The sub-chapters below described various kinds of fins used in the solar distiller.

2.6.1 Pin Fins Solar Distiller

Pin fins are high in the surface area which can provide the heat transfer from the pin fin to the brackish water. Pin fins are something that looks like spikes which are very thin but high in total surface area.

A study conducted by Rabhi *et al.*, (2017) was to investigate the use of pin fins with a height of 5 cm and the productivity in a single slope single basin still as shown in Figure 2.9. The experiment was conducted by comparing the conventional still, pin fins still, and pin fins still with condenser. The conventional still achieved the maximum temperature inside the still was 63.9°C and for pin fins still is 77.7°C. The maximum temperature inside the still for pin fins still with condenser was 76.1°C. It was obvious that the pin fins absorbed the heat from the solar energy and transfer it to the brackish water to increase its temperature. The condenser did not seem to help to increase the temperature of the water, but the aim of adding condenser was to increase clean water productivity by increase the condensation process. The condenser was connected to the solar still to act as an addition condenser which shown as Figure 2.9, although the glass surface covering the basin was acted as a condenser already. The maximum distillate clean water outputs for the conventional still, pin fin still, and pin fins still with condenser were 2.471 kg/m^2, 2.83 kg/m^2 and 3.492 kg/m^2 respectively. In short, the hourly efficiency of the conventional still, pin fin still, and pin fins still with condenser were 3.1%, 9.7% and 12.9% respectively.

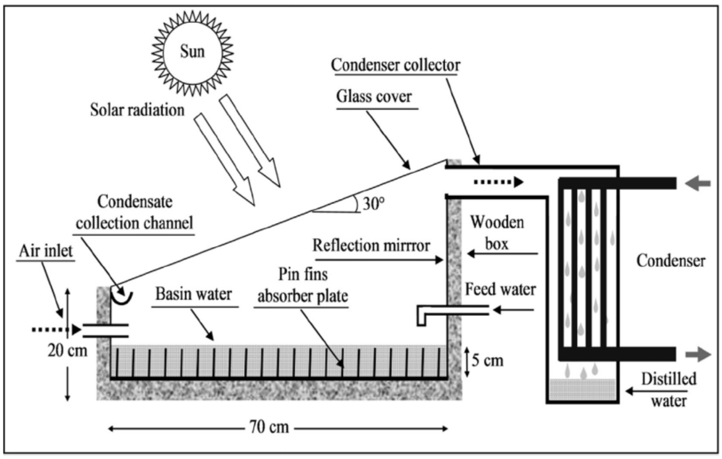

Figure 2.8: Pin fin still with condenser (Rabhi et al., 2017)

Furthermore, Kateshia and Lakhera, (2021) conducted an investigation study regarding pin fins still with phase change material (PCM). PCM are substances that absorb or release huge latent heat energy when their state turns from solid to liquid or vice versa. As a result, PCM is regarded as very efficient in heating or cooling (Pause, 2018). The PCM used in this experiment is palmitic acid which is located below the brackish water to act as a heater to it. Two cases were studied in the experiment, Case 1 was with PCM reservoir solar still and Case 2 was a PCM reservoir with pin fins solar still. For Case 2, the 81 pin fins' material used is aluminium with a diameter of 5 mm and 5 cm in height. The highest temperature in Case 1 was 61.5°C without the pin fins. For Case 2, the highest temperature of the brackish water was found to be 65.9°C with pin fins. The greatest productivity of both cases was 4.9 kg/m^2 and 5.4 kg/m^2. The efficiency of Case 1 is 52% and Case 2 is 57%. In short, the productivity of the solar still increased by adding highly conductive pin fins to the PCM reservoir due to greater heat transfer within the PCM.

2.6.2 Porous Fins in Solar Stills

Porous fins are one of the enhancement methods to increase the heat transfer from the surface of the fins to the ambient fluid. Porous fins perform better in terms of thermal performance than conventional fins of identical weight because of their increased in effective surface area (Kiwan and Al-Nimr, 2001). Srivastava and Agrawal, (2013) had carried out an experiment related to a modified solar still with porous fins compared to conventional solar still from 6 a.m. to 7 p.m. in central Indian city. It was found that the highest temperature of the basin water was 65°C in the porous fins solar still. Whereas the highest temperature of basin water in conventional still is 70°C. according to the results of the experiment, since the vertical extended fins began to receive solar radiation in the morning, the porous fin solar still produced a larger distillate production in the morning.

Panchal and Sathyamurthy, (2020) also conducted an experiment to compare conventional still and porous fins still. The total number of porous fins was 20 in a 1 m^2 solar still, each was made by aluminium with a height of 11 cm, and diameter of 3 cm but with a 1 cm diameter hole in it to make it porous. The water temperature was at maximum of 72°C and 80°C for conventional still and porous fins still respectively. The highest distillate output was 2.67 L for the conventional still and 3.8 L for the porous fins still. The porous fins still reached the percentage increment of 42.3%.

2.6.3 V-corrugated Basin

V-corrugated absorbers were used in the experiment done by El-Sebaii and Shalaby, (2015), the purpose of using it was to increase the temperature of the water in the basin. V-corrugated absorbers were located below the brackish water and it acted as a heat source to absorb the heat and released it to the water by convection, its ability to absorb heat was high as its total surface area was greatly increased. The solar radiation was absorbed by passing through the glass cover and brackish water to the absorbers. This experiment studied about the parameters of the v-corrugated absorbers such as the height of the V, the numbers of “vees” and the angles. The v-corrugated absorbers were made out of galvanized iron sheet painted in black. A conventional still with a flat plate galvanized iron was used to represent the absorber to do a comparison. It was found that daily production raised linearly as the number of "vees" and height of V were raised. However, it increased exponentially when the V angle was raised. The result showed that the water temperature in v-corrugated still was greater than the conventional still one due to the increased amount of absorbed solar energy by the v-corrugated absorber, leading to a rise in the water temperature. The maximum productivity of conventional still for a day was only 4.027kg/m^2 v-corrugated still is 8.679 kg/m^2 with 31 numbers of “vees”. As a suggestion in enhancing the solar still’s performance, the depths of basin water should be shallower to lower the thermal inertia. This can be done by increasing the surface area of the basin.

2.7 Phase Change Material (PCM)

The biggest issue faced in a solar still is the solar energy lost as heat to the surrounding which caused the saline water inside the still to not heat up to the desired temperature. Only 38.4% of the solar energy is used to evaporate the brackish water, despite the fact that the remaining 61.6% of the energy is wasted as heat (Ranjan et al., 2016). The Phase Change Material (PCM) takes place in solar still to act as an insulation to reduce the energy lost. A PCM is a kind of material which absorbs or discharges latent heat when there is a change in the physical state, such as solid state turn to a liquid state (Pause, 2010). The PCM is able to store energy when the solar radiation is at the strongest, it then released the energy when the solar energy is at the weak period. The energy released is acted as the source for the brackish water to heat up and evaporate to a vapour state.

Abdullah et al., (2020) carried out an experiment to improve the performance a solar still with PCM and nanoparticle mixture. A conventional solar still without the use of PCM was constructed to compare the performance with the one with PCM solar still. Paraffin wax was used in the solar still by placing it below the basin water. Moreover, the basin was painted with black paint mixing with copper oxide nanoparticles. The copper oxide nanoparticle is to increase the thermal conductivity so that the heat transfer is enhanced. The saline water used in both of the solar still is 6.8 kg. The temperature of the saline water was found to be 62.5°C for the conventional solar still and 65°C for the solar still with PCM and copper oxide. The result stated that the yield of clean water for the solar still with paraffin wax and paint mixed with copper oxide nanoparticles was about 14.0% higher than the conventional still.

2.8 Condensation Surfaces

Some enhancement techniques were made on the condensation surface to increase the productivity of clean water from a solar still. According to the experiment studied by Xiong et al., (2013), the solar still with 3 stages used two corrugated shape stacked trays to enhance the condensation surfaces. The advantage in this design is that the water droplets produced on the surface can drop quicker compared to the traditional one as the condensed water droplets traveled in shorter distances and the slope of the surface was increased. Besides, since the total surface area of the condensation surface was enlarged, it improved the vapor's heat transmission efficiency. The maximum freshwater yield was 43 kg per day by using 140 kg of seawater on the bottom stage, and 30 kg on the second stage and third stage respectively.

The research done by Zeroual et al., (2011) was about the effect of the clean water yield based on the cooling of the condenser of a double slope solar still. The first case studied is the cooling of condenser by running water on the glass cover. The second case is decreasing the glass cover's temperature by using a rectangular screen above the north glass cover to create a shading for two hours only in the afternoon. The intermittent sun-shading on the glass cover of the solar still gave the result 2.94% increment of daily performance. Whereas the productivity was increased by 11.82% when the glass cover condenser was cooled by water.

2.9 Summary

In summary, the literature review had summarized the suitable techniques to increase the efficiency of a multistage solar distiller. A concentrator can be designed in a multistage solar distiller. This is to increase the temperature of brackish water in the basin from the solar irradiance. Besides, collectors in solar distiller are used to trap heat from the sunlight to use it in heating the brackish water. Whereas the purpose of fins is to absorb heat energy and transfer it to the water in the basin. A higher temperature can increase the rate of evaporation and speed up the process. The evacuated multistage solar still is also a good idea in increasing the evaporation rate as it decreases the pressure of each stage. Pins were used to increase the efficiency of the heat transfer. Phase change material (PCM) functioned as the heat source whenever the sun is set. The productivity can be increased by improving on the condensation surface.

CHAPTER 3

METHODOLOGY AND WORK PLAN

3.1 Introduction

This chapter is about the methodology and the work plan to carry out the project based on the knowledge by the literature review in the previous chapter. The work plan for this project is shown as Figure 3.1.

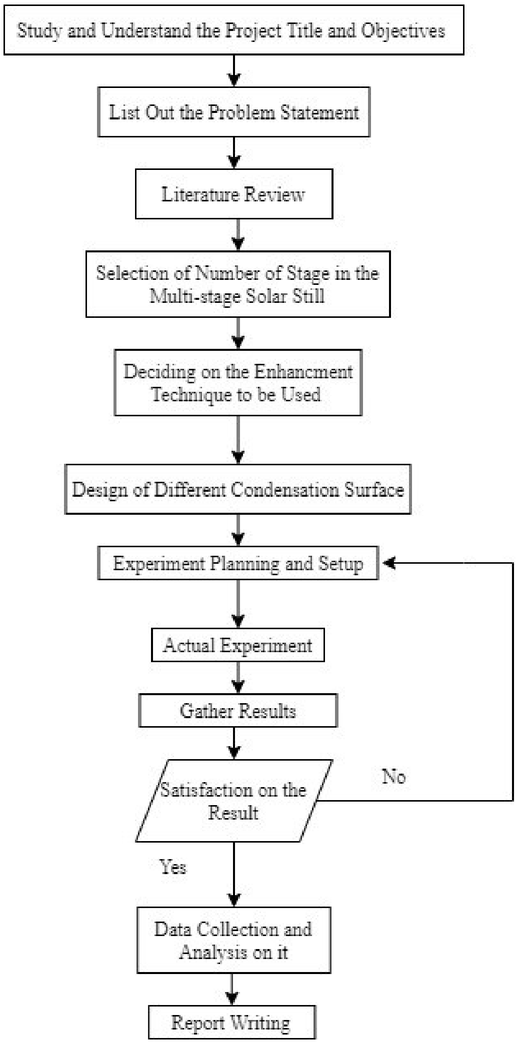

Figure 3.1: Flow chart for the work plan

3.2 Number of Stages

The number of stages in a multi-stage solar still is crucial in getting the optimum amount of freshwater. The production of freshwater for the next stage can be enhanced by three to four factors (Schwarzer et al., 2009). Since each tray will be stacking on each other in the multi-stage solar still device, the space will not be limited. The decision for the number of stages is important by considering the production cost and the maintenance cost. The purpose of this design is for the use in rural areas of some poorer countries. The cost of the whole model must be considered and should keep low. Hence, each stage in a multi-stage solar still must be effective in producing a good amount of freshwater. The amount of latent heat of vaporization given out by each stage will be decreased as it goes up until the last stage, which means the last and the top stage will receive the least amount of latent heat. According to the research of Schwarzer et al., (2009), the optimum stages in the research are three to four stages because the weight of the water production in the fifth stage is almost the same as the fourth stage. The water production in a solar still device with four stages increased linearly (Karimi Estahbanati et al., 2015). Since the maintenance cost and production cost must be minimized, the final decision will be three stages in the prototype of this project.

3.3 Mathematical Modelling of Multi-stage Solar Still

To understand the heat transfer of a three-stage solar still, the thermal analysis is showed by the heat balance equations below using the energy balance principle. The below assumptions were made for this three-stage solar still:

a) The whole solar still was assumed to be steady state.
b) The energy loss to the surrounding was negligible due to the good insulation.
c) The water flow rate is constant.
d) No vapor leakage from the solar still.

From stage 3:

$$MT_0C_p + m_2{h_{fg2}}^* = (M - m_3)C_pT_3 + m_3{h_{fg3}}^* \tag{3.1}$$

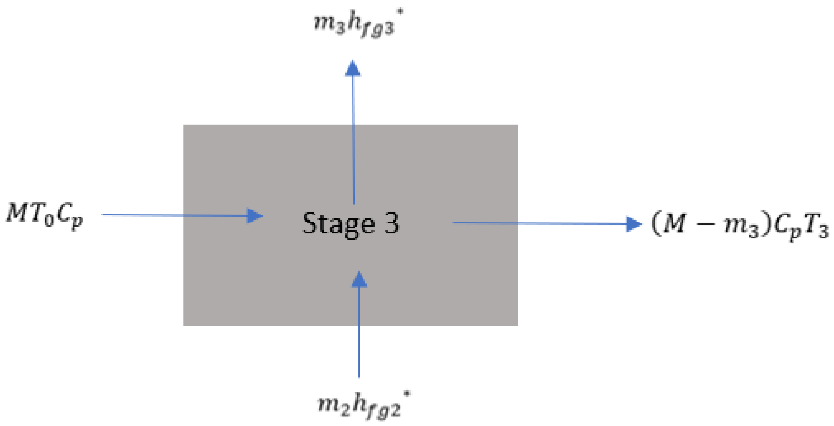

Figure 3.2: Heat balance in stage 3

From stage 2:

$$(M - m_3)C_pT_3 + m_1h_{fg1}{}^* = (M - m_3 - m_2)C_pT_2 + m_2h_{fg2} \tag{3.2}$$

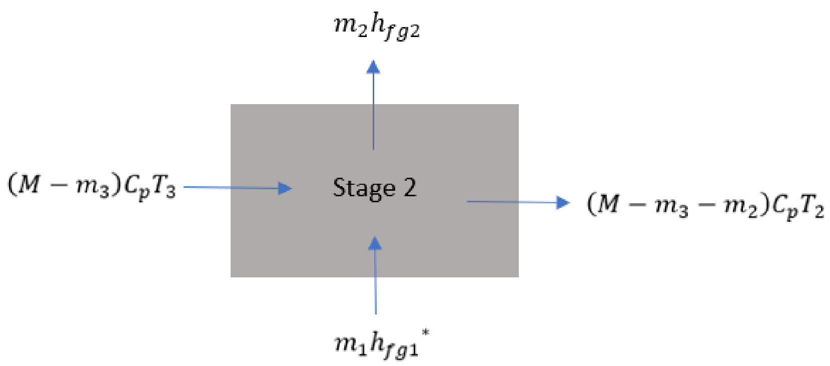

Figure 3.3: Heat balance in stage 2

From stage 1:

$$Q_H + (M - m_3 - m_2)C_pT_2 = m_1h_{fg1} + (M - m_3 - m_2 - m_1)C_pT_1 \tag{3.3}$$

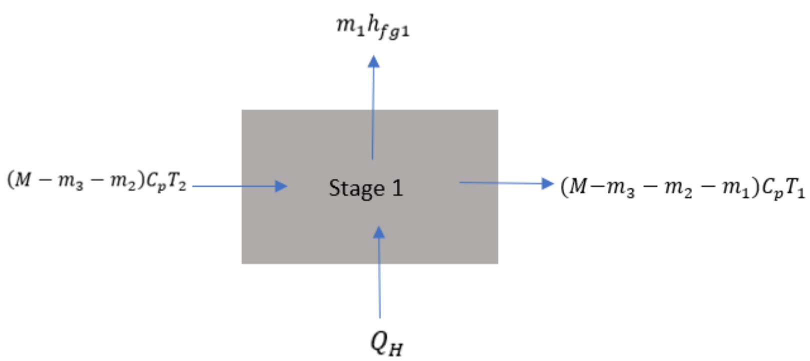

Figure 3.4: Heat balance at stage 1

Overall equation based on Figure 3.5:

$$Q_H + MC_pT_0 = (M - m_3 - m_2 - m_1)C_pT_1 + m_1C_pT_2 + m_2C_pT_3 + m_3h_{fg3}^* \quad (3.4)$$

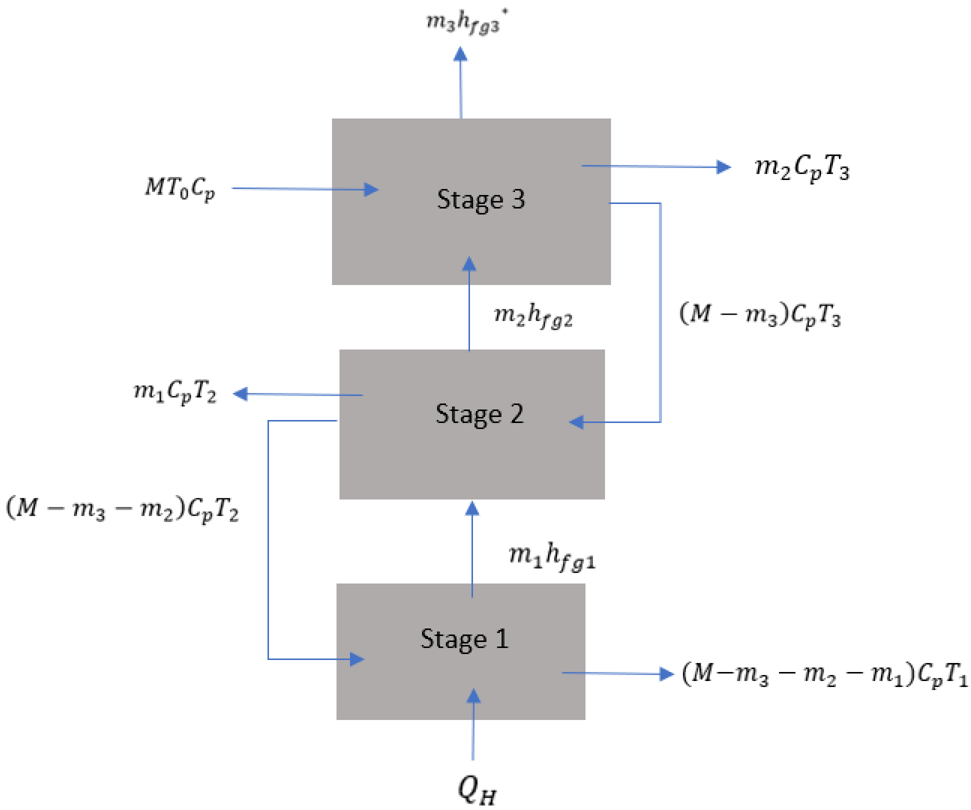

Figure 3.5: Total energy flow through the solar still

The h_{fgi}^* is the corrected latent heat of vaporization of water condensed on the surface which can be found by using the equation 3.5. The heat transferred by evaporation and condensation for each stage is shown in equation 3.6 to equation 3.8.

$$h_{fgi}^* = h_{fgi} + 0.68C_p(T_{sat} - T_s) \quad (3.5)$$

$$Q_{ev1} = m_1 \times h_{fg1} \quad (3.6)$$

$$Q_{ev2} = m_2 \times h_{fg2} \quad (3.7)$$

$$Q_{ev3} = m_3 \times h_{fg3} \quad (3.8)$$

where

C_p = specific heat capacity of water, kJ/kg °C

h_{fgi} = latent heat of vaporization from respective stage, J/kg

h_{fgi}^*= corrected latent heat of vaporization from respective stage, J/kg

M = rate of mass flow of saline water, kg/s

m_i = water evaporation rate from respective stage, kg/s

Q_H = Solar energy transferred to water at first stage, W

Q_{evi} = Solar energy transferred to water at respective stage, W

T_0 =initial temperature of water, °C

T_i = temperature of respective stage, °C

T_{sat} = Saturation temperature, °C

Subscript

1 = stage 1

2 = stage 2

3 = stage 3

3.4 Phase Change Material (PCM) Selection

A phase change material (PCM) is added to the basin in each stage to store the solar energy in it. The criteria for choosing a PCM is definitely looking into its latent heat energy. The high latent heat means the PCM will give a good performance in thermal energy storage. The PCM should allocate below the water basin. This is because the hot water in each stage will heat up the PCM and melts it to increase its temperature. Sensible heat is initially stored in it until the PCM's temperature achieves its melting point. The PCM stores energy in the form of latent heat when it melts. The heat will be again stored as sensible heat when the PCM is totally melted into a liquid state. In this project, the PCM will provide the heat source in the evening where the sun radiation is not strong or when sunsets. This is said so because the solar still components' temperature decreases when solar radiation decreases. The PCM starts to release the heat it stores initially to the saline water in the basin and starts to solidify. Hence, the solar still can continue to produce clean freshwater even the sun is down.

With that said so, another important criterion of choosing PCM is the low melting point. The PCM should melts almost at the temperature of saline water in the still. It should start to melt as soon as the saline water is heated up in the afternoon time so that it can store the solar energy in the early stage before the sun radiation decrease. Most of the saline water in solar still can heat up to the temperature of 55°C due to the strong sun in the area of Selangor, Malaysia. Besides, the PCM must have a high heat capacity, high heat of fusion, and long-term reliability. The most common PCM used in solar distillation devices which has a high latent heat is paraffin wax, petroleum jelly, and hydrated salts. Hydrated salts are corrosive material after using for a long period, therefore it is not suitable to use in this project.

Paraffin wax and petroleum jelly can both provide a high amount of latent heat during solidification. The melting point of petroleum jelly is between 40°C to 60°C depending on the portions. Whereas the melting point of paraffin wax is around 46°C to 68°C (Speight, 2015). Both of the material has similar properties. The availability and price of the material in the market is important since it will be used for four stages. Paraffin wax was found to be highly available in the market in a big batch. Thus, the paraffin wax showed in Figure 3.6 was chosen to be used in this experimental project.

Figure 3.6: Paraffin wax as PCM used in multi-stage solar still

3.5 Enhancement on Condensation Surface

To obtain a higher yield of freshwater, the condensation surface of a multi-stage solar still is designed. The condensation surface area should be increased in order to collect more water droplets. In this project, two kinds of condensation surfaces are used in the three-stage solar still. Therefore, two models were used to test which will give the highest amount of freshwater in the experiment

i) Inclined flat surface

ii) V-corrugated surface

Both will be made out of galvanized iron (GI) metal sheets with a thickness of 15 mm to withstand the water weight on it. The bottom surface of the GI metal sheet will be the condensation surfaces which the water droplets will form on there, and the upper surface will be the basin of saline water for the next stage. Both solar still uses a clear acylic sheet to cover the still at stage three with an inclination of 10° so that water droplets can flow by gravity and drip to the troughs where the freshwater will be collected. This clear acylic sheet cover is to allow sunlight to pass through it to provide heat source at the third stage. Figure 3.7 shows the first design model which is the inclined flat condensation surface. Two heat sources are used which are at the solar collector at the bottom and the transparent cover surface at the third stage.

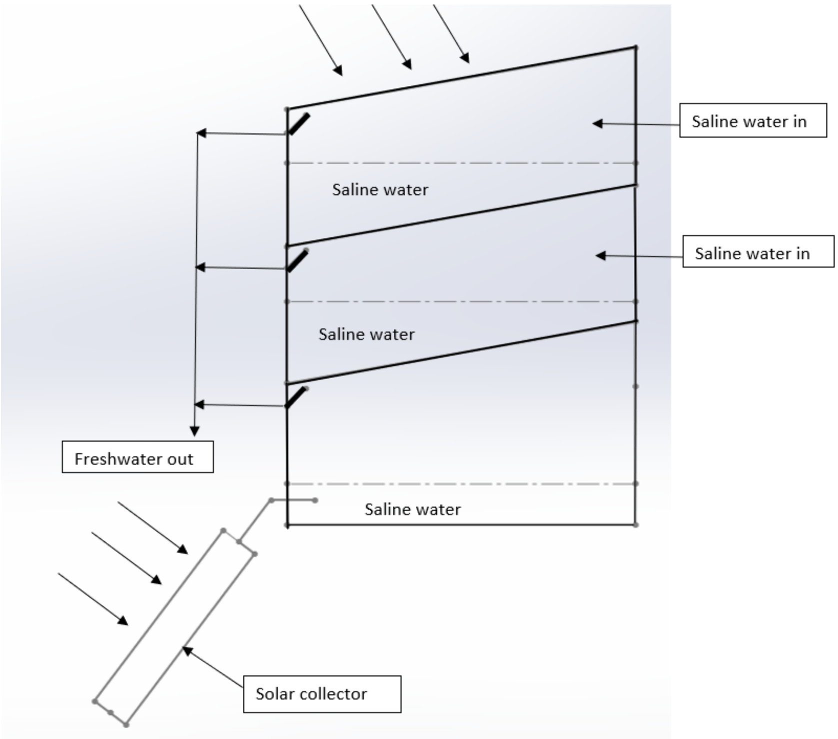

Figure 3.7: Inclined flat condensation surface

Figure 3.8 shows the second design model which is the v-corrugated condensation surface. The number of folds is four and the troughs are placed below the folds to catch the water droplets. The v-corrugated can increase the total surface area so that there is more place for the vapour to condense. Hence, more freshwater can be collected. The solar still is heated up by the same heat source as the first design. The reason for not using the corrugated surface on the third stage is because it will affect the concentration of sunlight as refraction may occur due to the uneven surface.

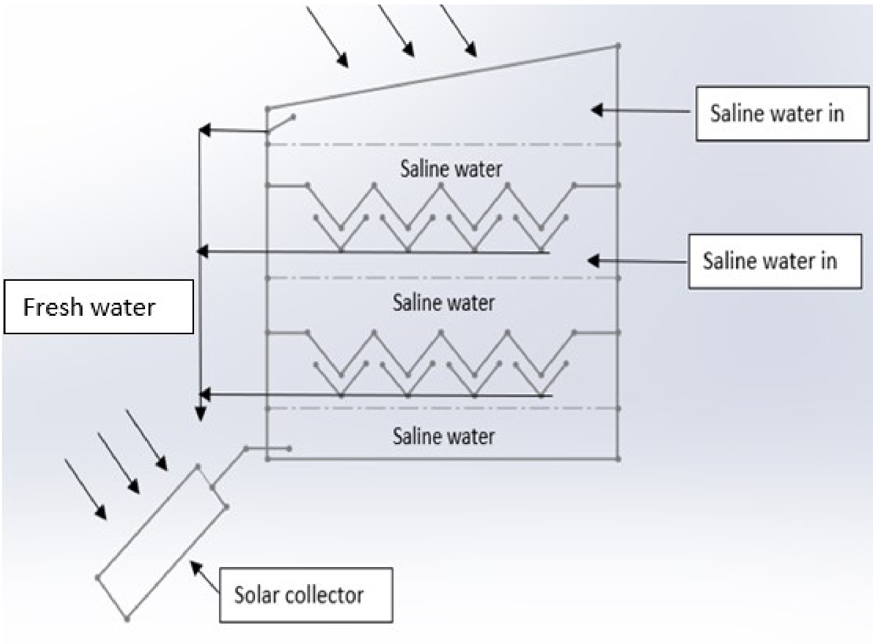

Figure 3.8: V-corrugated condensation surface

3.6 Experiment Setup

3.6.1 PCM Containers

To ensure the PCM is enabled to provide a heat source to the saline water, it must be in contact with it. The PCM is designed to be stored in a few aluminium jars with lid where the jar will submerge in the saline water. The aluminium jars are acting like a container storage for the PCM. The paraffin waxes will be melted and pour into each jars and closed it with the lid tightly. The paraffin waxes shall be waited to solidify again before placing into the basin as showed in Figure 3.9. The total number of aluminium jars will be two in each stage to be equally arranged inside the basin. That will be a total 6 jars to be used in this experiment. Aluminium material of the jar is suitable to use here as the cost of it is cheaper and it has good thermal conduction to transfer the heat to melt the PCM and transfer the heat back to the saline water when it solidifies. The total capacity of the jars is 100 grams. The estimated total volume needed for a three-stage solar still is 600 grams of waxes for this project.

Figure 3.9: PCM in containers

3.6.2 Troughs and Freshwater Tank

The selection of troughs' material must have high corrosive resistance to withstand the moisture inside the solar still. The proposed material for the throughs is PVC pipe (diameter 2.5 cm) which is cut in half horizontally. The PVC pipes are lightweight, non-corrosive, and cheap in cost to be used. To support the PVC pipes inside the solar still, an L-shape stainless steel holder as showed in Figure 3.10 is drilled into the wooden basin. The holder is cheap in cost and does not rust inside the high moisture environment. Another end of the PVC pipe is connected to a rubber pipe to allow freshwater to flow to the freshwater tank below.

Figure 3.10: L-shape stainless steel holder

The container for the freshwater tank is a thick glass bottle with a volume capacity of 2 L. Figure 3.11 is the glass bottle chosen to be used to avoid any contamination happen in the freshwater or any mold grow inside the surface of the container. Therefore, the glass bottle must undergo a sanitization process by using hot boiling water carefully and let it completely dry before using. A stopper is chosen as the cap of it to avoid any air enters the tank. The three pipes are slide through the stopper so that the water can fall into the glass bottle without exposing to any air.

Figure 3.11: Thick glass bottle for the freshwater tank

3.6.3 Solar Collector

The solar collector to be used in this experiment is a flat plate solar collector which is shown in Figure 3.12. It has a lower cost and can give high efficiency in heating the water before sending to the solar still. This flat plate collector is the heat source for the saline water at the first stage. The dimension of flat plate solar collector is 560 mm by 300 mm and the material for it will be plywood. The outer surface of the solar collector is the polyethylene (PE) foam insulation to minimize the heat lost. The absorber is in contact with 4 units of 20 mm diameter galvanized iron pipes. The pipes receive the heat from the absorber and transfer it to the water in it. The wooden box is covered with an acrylic plastic sheet to reduce the cost.

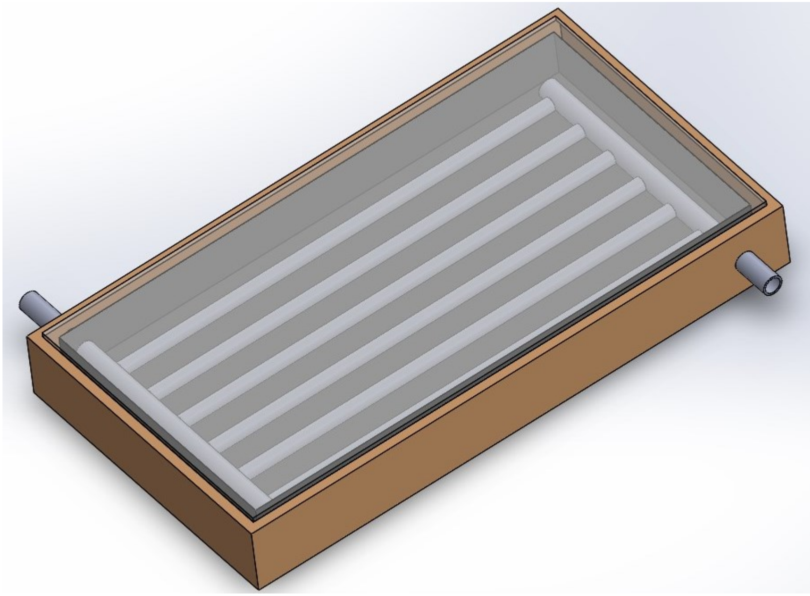

Figure 3.12: Design of flat plate solar collector

The saline water tank is placed at a certain height to ensure a water pressure to flow into the basins as shown in Figure 3.13. The saline water tank at the first stage will be connected to a water pump to allow more pressure to pump the water into the solar collector and flow into the basin at the first stage. The connecting pipe is made of rubber pipe which connects the outlet of the flat plate collector to the inlet of solar still. The connecting pipe is insulated to avoid heat loss.

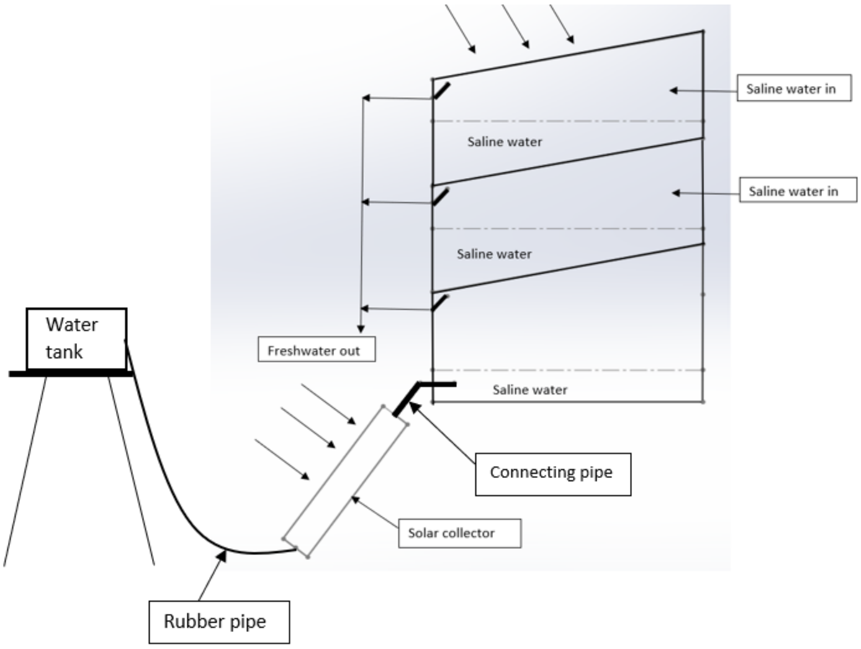

Figure 3.13: The detailed experiment setup

3.7 Design of Multi-stage Solar Still

3.7.1 Inclined Flat Condensation Surface Multi-stage Solar Still Design

Two multi-stage solar still with different condensation surfaces are proposed to be used in this project to carry out the experiment. Figure 3.14 is the drawing of the design of the inclined flat condensation surface. The prototype of the basin is proposed to use woods as the material to ease the fabrication process. To avoid the water soaks the woods, a black silicone sealant is used to paint the inner surfaces so that it acts as a basin, and it will not absorb water. The inner surfaces must be black to increase the absorbent of solar radiation.

The dimension of the basin is having a length of 400 mm, width 400 mm, length 100 mm. The cover of the first and second stages are using a galvanized iron sheet with a thickness of 1.5 mm, the third stage is using a acylic sheet cover with a dimension of 420 mm x 420 mm x 2 mm. The acylic sheet cover is sealed on top of the wooden basin by using silicone sealant. Three stages are having an inclination of 10°, three trays are being stacked up. The second and third tray is having the dimension of 420 mm x 420 mm x 100 mm. Three holes of a diameter of 15 mm are being drilled to connect the troughs to a pipe so that freshwater can flow down to the freshwater tank. Another two holes with a diameter of 15 mm are drilled on the sides to act as the saline water inlet for second and third stages. The surrounding of solar still is being insulated by polyethylene (PE) foam to reduce the heat lost to the surrounding.

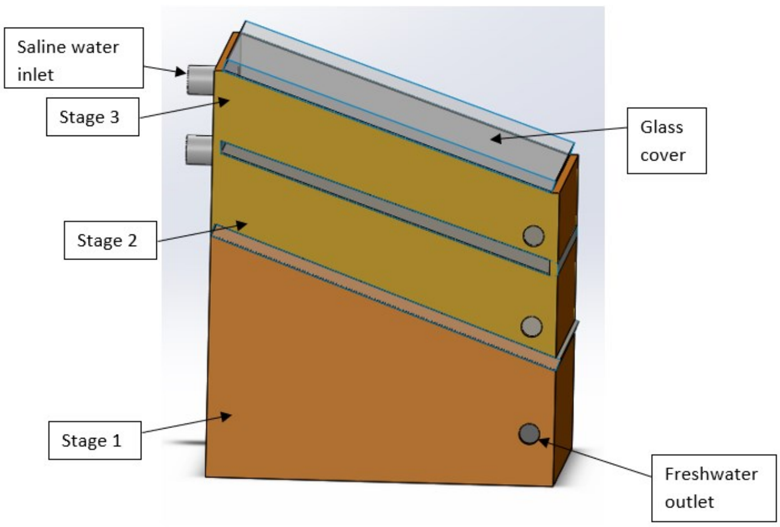

Figure 3.14: The inclined surface of three-stage solar still design

3.7.2 V-corrugated Condensation Surface Multi-stage Solar Still Design

The corrugated condensation surface is made by galvanized iron sheet painted with black paint with four identical folds with triangular dimension of 100 mm length, 100 mm height, and metal sheet of thickness 8 mm. A few holes are drilled at each stage to connect the troughs which is shown in Figure 3.15. Three stages are being stacked up and the acylic sheet cover at third stage is 420 mm length, 420 mm height and 4 mm thickness to allow sunlight to pass through.

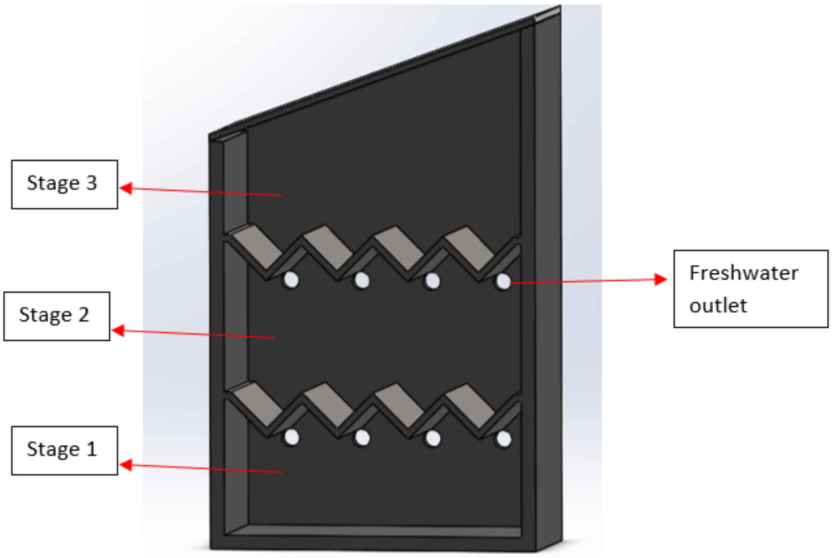

Figure 3.15: Section view of the v-corrugated multi-stage solar still

There is another two holes connected to a PVC pipe (diameter 15 mm) to act as the saline water inlet which is shown in Figure 3.16. Inside of the basin also is layered by a black silicone sealant to avoid water soaking into the wood. The surrounding of solar still is being insulated by polyethylene (PE) foam to reduce the heat lost to the surrounding.

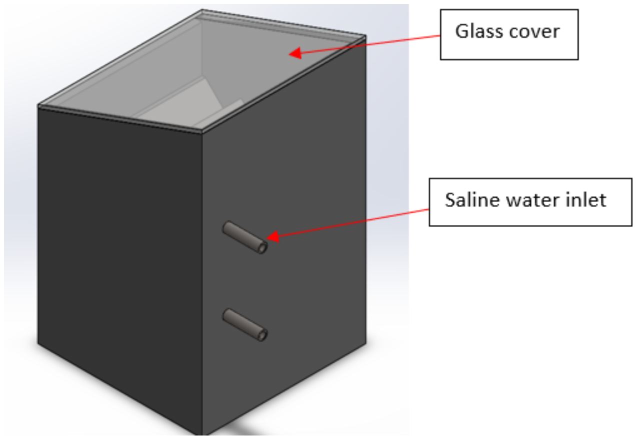

Figure 3.16: Isometric view of v-corrugated multi-stage solar still

3.8 Experiment Procedure

The prototypes proposed are used to conduct the experiment to determine the productivity of freshwater for both still. The procedure of the experiment is listed as below:

I. Set up all the apparatus as shown in Figure 3.13 with the inclined condensation surface solar still and the v-corrugated condensation surface solar still. Seal all the edges with silicone to avoid leakage.

II. Setup the type-k thermocouples by placing them at the inner surfaces of every condensation surface and at the water basin with tape to measure the temperature.

III. Melt the paraffin wax and fill it into the PCM containers, close the containers with the caps tightly. Arrange the PCM containers in the basin at every stage.

IV. Fill the basin at stage 1, stage 2 and stage 3 with 2 kg of saline water each.

V. Turn on the pump to allow water to flow into the flat plate solar collector.

VI. Allow the multi-stage solar still to be exposed under the sun from 8 am to 7 pm at the location in Selangor.

VII. Pour out the freshwater from the glass bottle into a measuring cup and measure and weight the amount of freshwater produced.

VIII. Take the readings of solar irradiance of the solar meter and the temperature of the thermocouples at the condensation surface and saline water in the basin every hour.

IX. Repeat the experiment by following step IV to VIII without placing the PCM in the basin.

3.9 Experiment Prototype

Two different prototypes were built to carry out the experiment in this project. A solar collector prototype was also built to increase the thermal efficiency of the multistage solar distiller. Both prototypes are made from woods and the inner surfaces were spread with a thin layer of black silicone to ensure the waterproof of the model. Both prototypes used baking trays made from aluminium to act as a basin to fill the saline water in the solar still. The black baking trays were used to maximize the absorption of solar radiance inside the solar still which eventually increased the thermal efficiency. The saline water depth was ensured to be less than 3.0 cm to increase the rate of evaporation of saline water. Hence, the dimension of baking trays used in the three-stage solar still was 33.5 cm by 22 cm by 5.5 cm for every stage. Therefore, the 2 kg of amount of water was poured into the basin through the inlet for every stage and the depth of saline water was 2.71 cm. In this project, four experiments were being conducted to compare the water productivity. The first experiment was the flat surface condensation three-stage solar still (normal solar still) without PCM. The second experiment was using the same prototype solar still but with PCM. The third experiment was enhanced three-stage solar still which is using the corrugated surface condensation without PCM. While the fourth experiment was the enhanced three-stage solar still with PCM.

Figure 3.17 and Figure 3.18 showed the two three-stage solar stills built for this project. Stage 1, stage 2, and stage 3 were being stacked up and was detachable for cleaning or for maintenance purposes. Saline water in stage 2 was heated up by latent heat of condensation released by stage 1. While saline water in stage 3 was heated up by latent heat of condensation released by stage 2, and by the sun light which was passed through the transparent acrylic plate.

Figure 3.17: Multi-stage solar still with flat plate condensation surface (Normal multi-stage solar still)

Figure 3.18: Multi-stage solar still with corrugated plate condensation surface (Enahnced multi-stage solar still)

The measuring equipment used in the project were electronic balance, thermocouple, and solar power meter. The amount of fresh water yield by the multi-stage solar still was measured hourly by the electronic balance with a measurement error of ± 5%. The solar irradiance was measured hourly by a SM206 digital solar power meter with a ±10% measurement error. The condensation surfaces of the solar still and the water temperature inside the basin was recorded down by using Type K thermocouples connected to a thermometer recorder with multi-channel to ease the measuring process and the measuring error of the thermocouple is ± 0.5%. Figure 3.19 showed the solar power meter used in the experiment, which was placed on the left side and a Type K thermocouple with thermometer recorder, which was placed on the right side.

Figure 3.19: Solar meter (left) and type K thermocouple (right)

3.10 Summary

To sum up this chapter, three-stages solar still prototypes with flat and corrugated condensation surface will be built to investigate the affect on the water productivity of the solar still. To increase the efficiency of the prototype, parrafin wax as the phase change material (PCM) will be used in the solar still to provide a heat source during low solar irradiation in the evening. A flat plate solar collector will be designed to provide the heat to the multi-stage solar stills. Each stage of the solar still will produced clean water and will be collected in glass bottles. The final result that are interested in the experiment is the total amount of clean water produced by the solar stills in a day.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

This chapter presents the result and discussion of the experiment conducted by the multi-stage solar still prototypes. Firstly, the discussion commenced with the concentration of the saline water and the solar irradiance during the experiment day. Next, the results of the hourly temperature of condensation surfaces and saline water, hourly solar irradiance for each experiment, followed with the water yield are shown.

4.2 Temperature under Different Weather Condition

The performance of the solar still can be influenced by the humidity of the environment, the heat lost by the solar still to the surrounding, the wind speed of the surrounding and more. Therefore, these factors were ignored in this project as it was grouped as uncontrollable factor. One of the major factors that affect the performance of the multi-stage solar still is the solar irradiance as it affected the temperature inside the solar still. Since the experiment was conducted in Cheras, Selangor, the solar irradiance was very high. The experiments were conducted under genuine weather conditions for four days from 21th to 24th March 2022 to compare the performance the two type of multi-stage solar still with and without phase change material (PCM). Before starting the experiment, saline water was prepared and made by mixing 35 grams of fine salt, which is known as sodium chloride with 1000 grams of tap water as the average concentration of seawater is about 35 parts per thousand. Therefore, 2 kg of the saline water were filled into the basin for each stage. Table 4.1 showed the solar irradiance measured every hour during the experiment of the normal and enhanced multi-stage solar still with and without PCM.

Table 4.1: Hourly Solar Irradiance of Normal and Enhanced Multi-stage Solar Still with and without PCM

Time	**Solar irradiance (W/m^2)**			
	Normal Multi-stage Solar Still		**Enhanced Multi-stage Solar Still**	
	Without PCM	With PCM	Without PCM	With PCM
8:00	218.4	205.1	351.2	228.2
9:00	672.2	914.5	874.6	907.8
10:00	954.8	1121.2	976.4	984.6
11:00	1122.5	1167.8	997.1	1165.1
12:00	1213.8	1321.6	1241	1259.4
13:00	1321.2	1311.2	1288.1	1357.1
14:00	1251.5	1338	1324.8	1388.2
15:00	953.6	1251.3	1203.4	1126.0
16:00	587.1	648.1	602.3	956.8
17:00	257.0	153.0	227.1	264.5
18:00	155.6	217.8	164.6	148.6
19:00	87.2	62.1	78.6	74.8

The first experiment conducted was the normal multi-stage solar still without the PCM submerged in the saline water. By looking at Table 4.1, the solar irradiance was at the peak at the time of 13:00 which was 1321.2 W/m^2 and was gradually dropped at 16:00 which was 587.1 W/m^2 as the sunlight was not strong during the evening time.

Figure 4.1 showed the temperatures of water three stages for the experiment of normal multi-stage solar still without PCM. It was clearly showed that the temperatures of water gradually increased as the solar irradiance increased. The temperature rises to a peak at 13:00 and then begins to fall at 14:00 when the solar irradiation started to decrease. This outcome was consistent with the theory since the heat energy produced by solar irradiation was to heat up the saline water to evaporate and produced steams that condensed and then distilled water was collected. The maximum water temperature of the multi-stage solar still was 58.1°C at the time of 13:00 which was at the first stage. The highest water temperature of second and third stage was also at 13:00 which were 54.8°C and 51.5°C respectively.

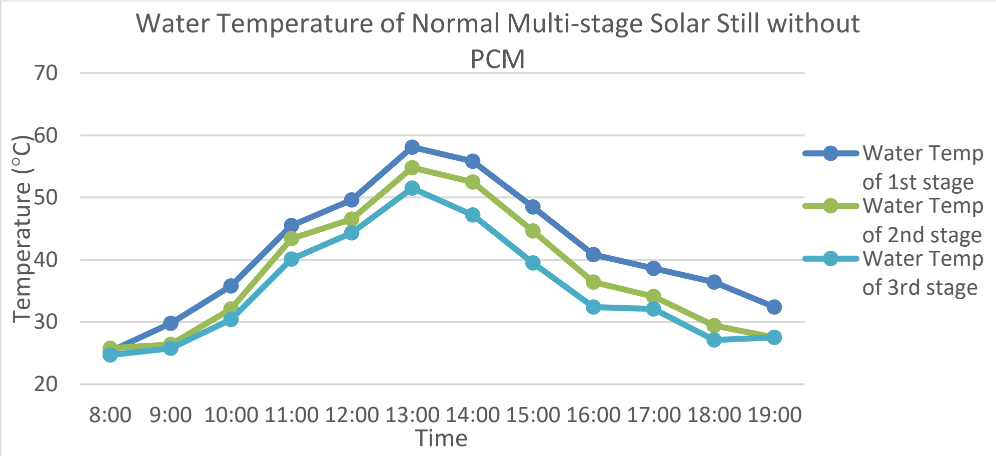

Figure 4.1: Graph of water temperature of normal multi-stage solar still without PCM

Figure 4.2 showed the condensation surface temperature of the normal multi-stage solar still without PCM. The water and condensation surface temperature decreased from the first stage to the third stage which was expected as the latent heat of condensation produced from the lower stage was used to heat up the upper stage. Therefore, the latent heat was reduced from one stage to the another as parts of the heat were lost to the surrounding. The maximum temperature of condensation surface of first stage, second stage and third stage are 55.2°C, 52.2°C and 49.5°C.

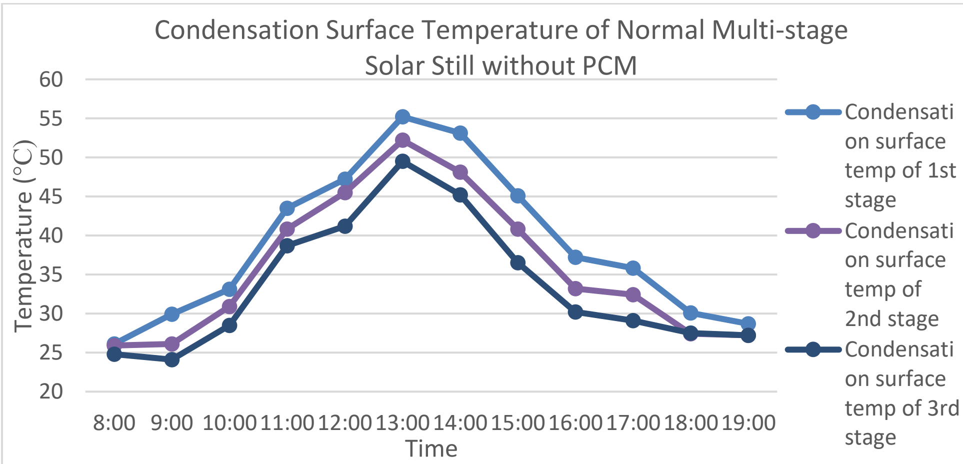

Figure 4.2: Graph of condensation surface temperature of normal multi-stage solar still without PCM

The second experiment was conducted by using the same prototype, normal multi-stage solar still but adding PCM into the basin and submerged into the saline water. By refering back to Table 4.1, the highest solar irradiance for this experiment was 1338.0 W/m^2 happened at 14:00 afternoon. The solar irradiance was decreased tremendously to 153.0 W/m^2 at 17:00 and rise to 217.8 W/m^2 after an hour as the weather at 17:00 was very cloudy.

Figure 4.3 showed is the water temperature in the normal multi-stage solar still with PCM. The maximum water temperatures for the first, second and third stages were 65.1°C, 60.2°C and 57.1°C respectively. The PCM used here was paraffin wax where the melting point for the PCM is 55°C (Speight, 2015). This can explain that the parrafin wax was melted in three of the stages since the volume of paraffin wax is only 100 grams each and the phase transition process occurred where the energy was store as sensible heat in the liquid form of PCM (Reddy, Nallusamy and Reddy, 2014). The graph showed that the water temperature of the three stages slowly decreased after 14:00.

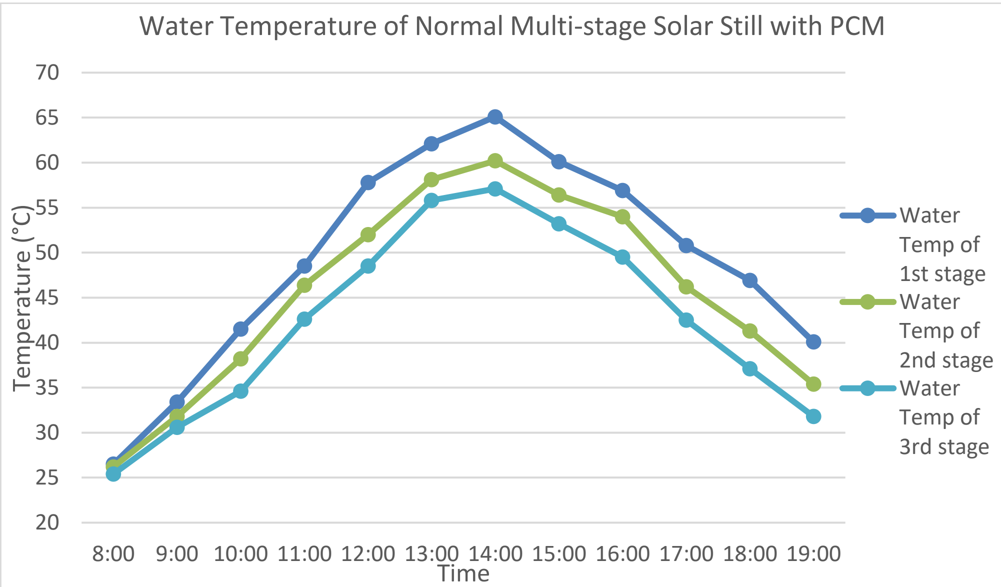

Figure 4.3: Graph of water temperature of normal multi-stage solar still with PCM

Figure 4.4 showed is the temperature of condensation surface in the normal multi-stage solar still with PCM. The maximum temperature of condensation surface on the first and second stage was 62.2°C and 57.9°C. Whereas, by looking back to Figure 4.6, the maximum water temperature of second stage and third stage was 60.2°C and 57.1°C. This showed that the condensation surface temperature n^{th} stage is approximately same to the water temperature of $n^{th} + 1$ stage, where a very small amount of heat was lost.

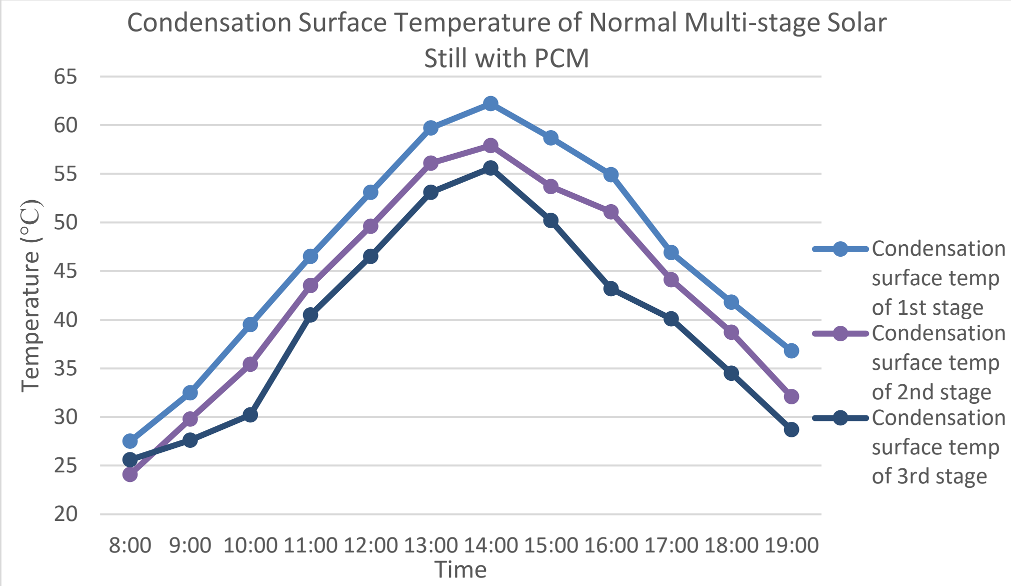

Figure 4.4: Graph of condensation surface temperature of normal multi-stage solar still with PCM

Next, the third experiment was using the enhanced multi-stage solar still without PCM. The maximum solar irradiance is 1324.8 W/m^2 on that experiment day. Figure 4.5 showed the water temperature of enhanced multi-stage solar still without PCM. At the time of 15:00 to 16:00, the water temperature dropped drastically due to the sudden decrease in solar radiation from 1203.4 W/m^2 to 602.3 W/m^2. In addition, the basin do not have any PCM to help provide a latent heat to the water when the solar radiation turned low.

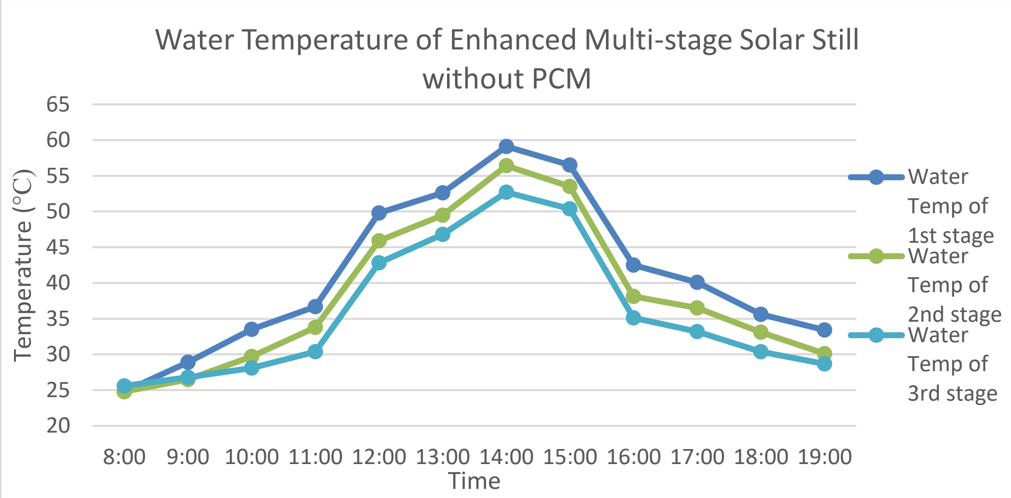

Figure 4.5: Graph of water temperature of enhanced multi-stage solar still without PCM

Figure 4.6 provided the condensation surface trand of the enhanced multi-stage solar still without PCM. It also showed that the temperature trend was not smooth and showed a bell curve. The main reason to it was explained earlier. This showed that the absent of PCM caused a sudden drop in temperature if the solar radiation was decreased.

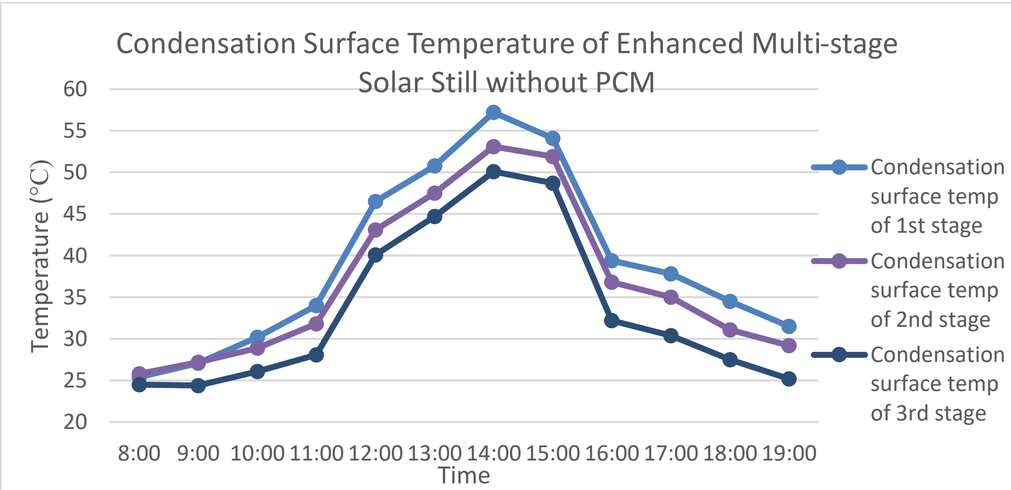

Figure 4.6: Graph of condensation surface temperature of enhanced multi-stage solar still without PCM

The last experiment was using the enhanced multi-stage solar still with PCM. The maximum solar irradiance is 1388.2 W/m^2 at 14:00 on that day. Figure 4.7 presented the water temperature for the enhanced multi-stage solar still with the use of PCM. The highest water temperature achieved was in the first stage which is 66.2°C at 14:00.

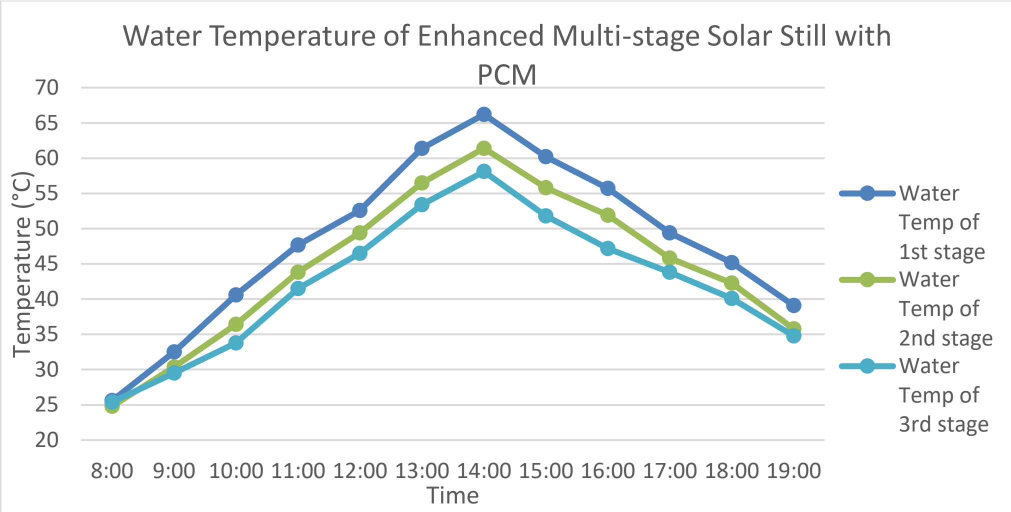

Figure 4.7: Graph of water temperature of enhanced multi-stage solar still with PCM

Whereas, Figure 4.8 is the condensation surface temperature for the enhanced multi-stage solar still with PCM. The highest condensation surface temperature was at the first stage with the value of 62.5°C which is also at 14:00.

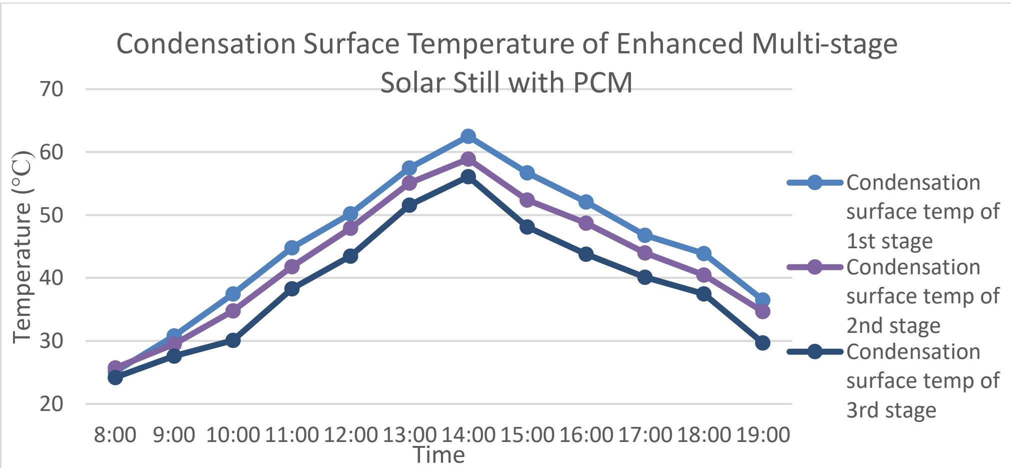

Figure 4.8: Graph of condensation surface temperature of enhanced multi-stage solar still with PCM

For this experiment, the maximum water temperature for each stage was 58.0°C, 60.4°C, and 65.2°C. The PCM which was placed in the basin for each stages were confirmed to be melted. The saline water temperature of enhanced multi-stage solar still with PCM showed a higher result for about 4°C to 6°C values compared to the enhanced multi-stage solar still without using PCM. This is because the PCM serves as a source of heat for the solar stillduring low solar irradiation periods and at night. In addition, for the multi-stage with solar still with PCM, the aluminium container for the PCM acted a good heat conducter which lead to a higher temperature in the saline water.

By comparing the water temperature of enhanced multi-stage solar still with PCM in Figure 4.7 and without PCM, Figure 4.5. The graph with PCM has a smoother trend and the temperature dropped slowly due to the energy released by PCM during low solar radiation. This lead to a same graph trend to the condensation surface temperature of enhanced multi-stage solar still. This is because the amount of latent heat of condensation was affected by the water temperature. Thus, the condensation surface temperature showed a similar trend compared with the water temperature.

The multi-stage solar still with PCM gave a higher saline water temperature which caused to a higher condensation surface temperature compared to solar still without PCM. In short, the solar still can continue to run although the solar irradiation is low due to the PCM discharged the latent heat energy stored in the earlier stage to the saline water. In the another hand, the maximum water and condensation surface temperature of enhanced multi-stage solar still was 1°C higher than the normal multi-stage solar still. Therfore, the temperatures inside of both solar still were almost the same and showed no significant difference in temperature parameter.

4.3 Productivity of Fresh Water

The amount of water produced in a solar still is very heavily reliant on solar irradiation. Solar still that do not have thermal energy storage will stop producing water after sunset since they are no longer receiving solar heat energy.

The paffarin wax as PCM used can improve the performance of a solar still to increase the water production. The PCM acted as a thermal energy storage and extend the duration of water productivity in a solar still. During periods of strong solar irradiation, the PCM are able to retain the heat energy produced by the sun, where the PCM at this stage starts to melt and changed from solid state to liquid state. After that, during periods of low solar irradiation, the PCM starts to turn from liquid state to solid state and release the heat energy stored in the early stage to the saline water. Thus, the solar still can still generate fresh water.

The surface area of condensation in a multi-stage solar still can affect the water productivity. The corrugated sheet condensation surface in the enhanced multi-stage solar still has a higher surface area for condensation compared to the flat plat condensation surface in the normal multi-stage solar still. Therefore, the graphs of the four different experiments were presented to demonstrate the volume of distilled water generated hourly by each stage of the still individually to give a clear picture of how each of the system performed.

Figure 4.9 showed the fresh water yield of each stage of the normal multi-stage solar still without PCM. The number of stages and the solar irradiation have an impact on the amount of fresh water produced. By looking at Figure 4.9, the water started to produce at 12:00 p.m. This is because the saline water in the multi-stage solar still were being heated up by the solar radiation for four hours before it can be evaporated. The amount of water produced was increasing until it reached the peak at 14:00 p.m. although the solar irradiace was at the maximum at 13:00 p.m and started to decrease gradually afterward. This was caused by the temperature disparity between stages due to the high temperature generated by the solar collector. The amount of water yield started to decrease when the solar irradiace decreased and it stop providing fresh water at 18:00 p.m. since the sun was set at that time. Based on Figure 4.9, the highest amount of water produced was at the first stage, then followed by the second stage and third stage. This was due to the latent heat of condensation was decreasing when it went from the bottom stage to the top stage.

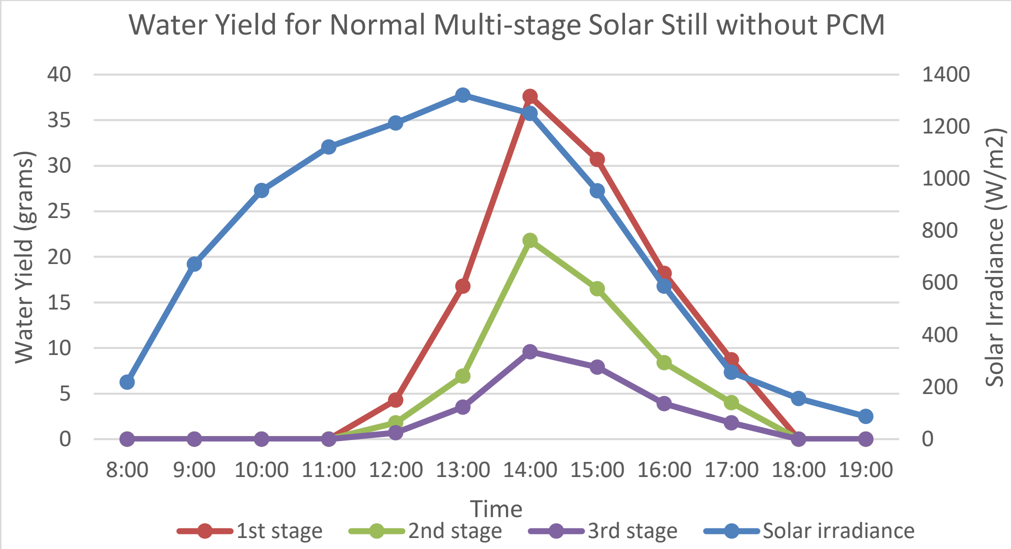

Figure 4.9: Graph of water yield for normal multi-stage solar still without PCM

Figure 4.10 showed the hourly solar radiation and fresh water yield of each stage of the normal multi-stage solar still with PCM. It can be observed that, the productivity of fresh water of a multi-stage solar still with the use of PCM raised steadily to a maximum at 14:00 p.m. and then drops dramatically as solar irradiation decreased after 15:00p p.m. Nevertheless, a solar still with PCM were still able to produce a low water yield during low solar irradiation at 17:00 p.m. to 19:00 p.m. where the solar still did not receive ample of solar energy to heat the saline water.

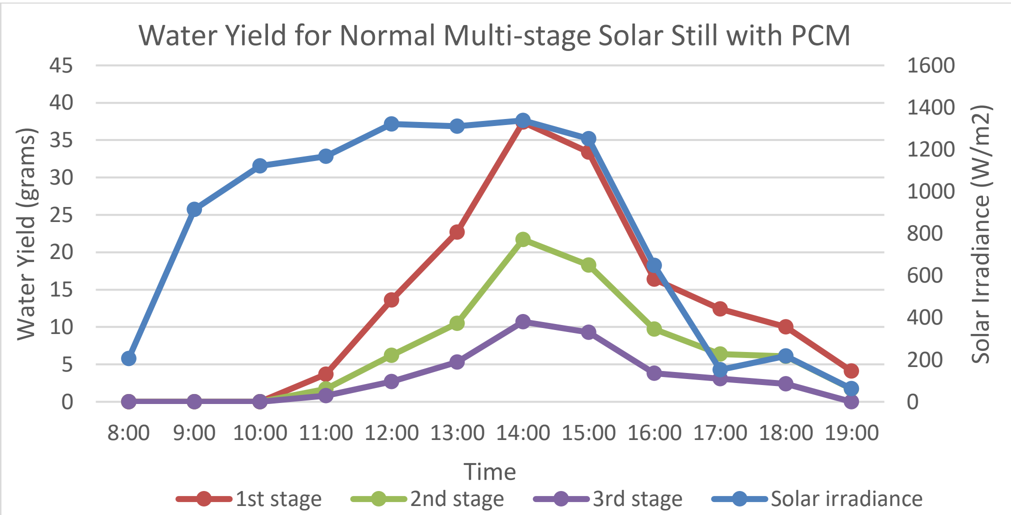

Figure 4.10: Graph of water yield for normal multi-stage solar still with PCM

Figure 4.11 showed the hourly solar radiation and fresh water yield of each stage of the enhanced multi-stage solar still without PCM. By comparing Figure 4.9 and Figure 4.11 where both the multi-stage solar still do not integrate with PCM, the hourly fresh water yield for enhanced multi-stage solar still was higher than the normal multi-stage solar still. This was mainly because of the corrugated condensation surface on the first stage and second stage which increased the total surface area for condensation, which directly increased the amount of fresh water to be collected.

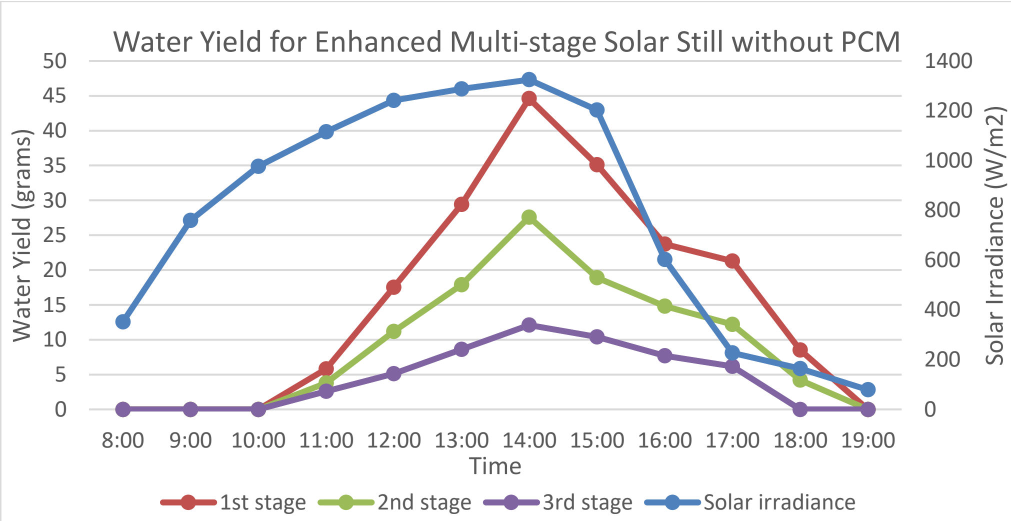

Figure 4.11: Graph of water yield for enhanced multi-stage solar still without PCM

Figure 4.12 showed the hourly solar radiation and fresh water yield of each stage of the enhanced multi-stage solar still with PCM. The solar irradiance slowly increased to the maximum at 14:00 p.m. while the water yield also increased to the peak then it slowly decreased. Although the solar irradiance dropped tremendously at 17:00 p.m., the solar still was able to produce fresh water with almost the same amount at 16:00 p.m. During the sunset at 18:00 p.m., the solar still can continue operate and yield fresh water until 19:00 p.m.

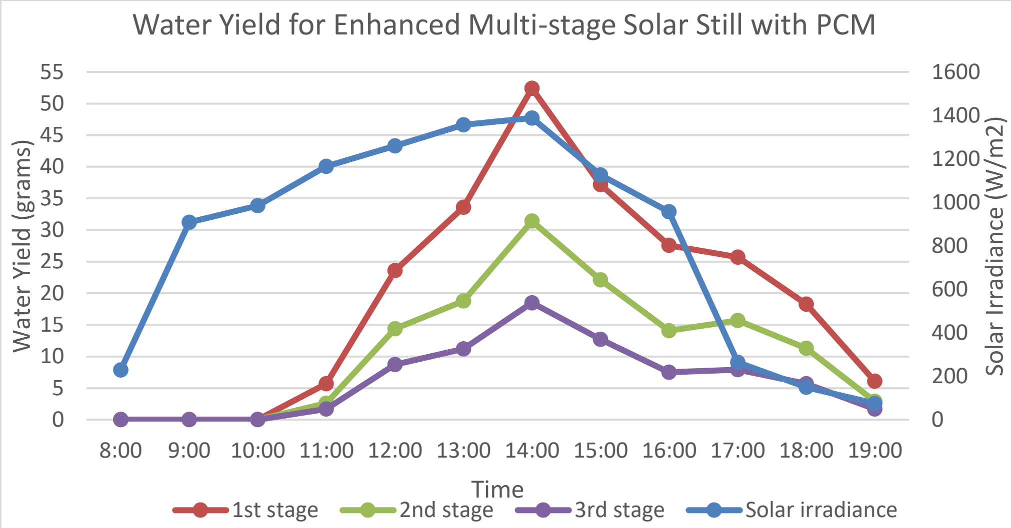

Figure 4.12: Graph of water yield for enhanced multi-stage solar still with PCM

It was noted that the performance of every solar still might have a slight changes due to meteorological factors such as wind speed, humidity of air, ambient temperature which are beyond the control of the experiment. As a result, the results obtained in every experiment were unable to provide accurate and specific information on how different of the designs on the multi-stage solar still influences the amount of water yield.

Table 4.2 concluded the total amount of fresh water produced in every stage and the total water productivity of the multi-stage solar still in a day. Based on table 4.2, the lowest amount of water yield is from the normal multi-stage solar still without PCM with the value of 203.1 grams. By comparing it with the enhanced multi-stage solar still without PCM , the total water yield is 349.2 grams which is 71.9% of increment in water productivity. Whereas, the enhanced multi-stage solar still with PCM has an increment of 60.2% in water yield amount compared to the normal multi-stage solar with PCM. The first and the bottom most stage contributes significantly to the production of the greatest amount of fresh water, whereas the amount of water produced from the second stage is significantly greater than the third stages, which produce the least amount of clean water because of the low temperature in the trays.

Table 4.2: Total water produced at every stage and the total water yield

Multi-stage solar still system	**Total water productivity for every individual stage (grams)**			**Total water yield (grams)**
	Stage 1	**Stage 2**	**Stage 3**	
Normal multi-stage solar still without PCM	116.3	59.4	27.4	203.1
Normal multi-stage solar still with PCM	153.7	82.3	38.1	274.1
Enhanced multi-stage solar still without PCM	185.9	110.6	52.7	349.2
Enhanced multi-stage solar still with PCM	230.2	133.3	75.6	439.1

Figure 4.13 presented the cumulative fresh water yield for the four different multi-stage solar still system. The accumulated fresh water in the normal multi-stage without PCM is 203.1 grams. Whereas, the same solar still with PCM produced a total of 274.1 grams of accumulated fresh water. Besides, the enhanced multi-stage solar still without and with PCM have an accumulated water of 349.2 grams and 437.9 grams respectively. To conclude everything, when comparing multi-stage solar still utilising PCM as a thermal energy storage to multi-stage solar still without PCM, it can be stated that multi-stage solar still with PCM outperforms the multi-stage solar still without PCM. Aside from that, the results showed that the enhanced multi-stage solar still where the condensation surfaces are corrugated obtained higher amount of fresh water due to the bigger surface are. Finally, the best performance showed in the results is the enhanced multi-stage with using PCM compared to the other three types of multi-stage solar still in this study due to its increased thermal conductivity and surface area for condensation.

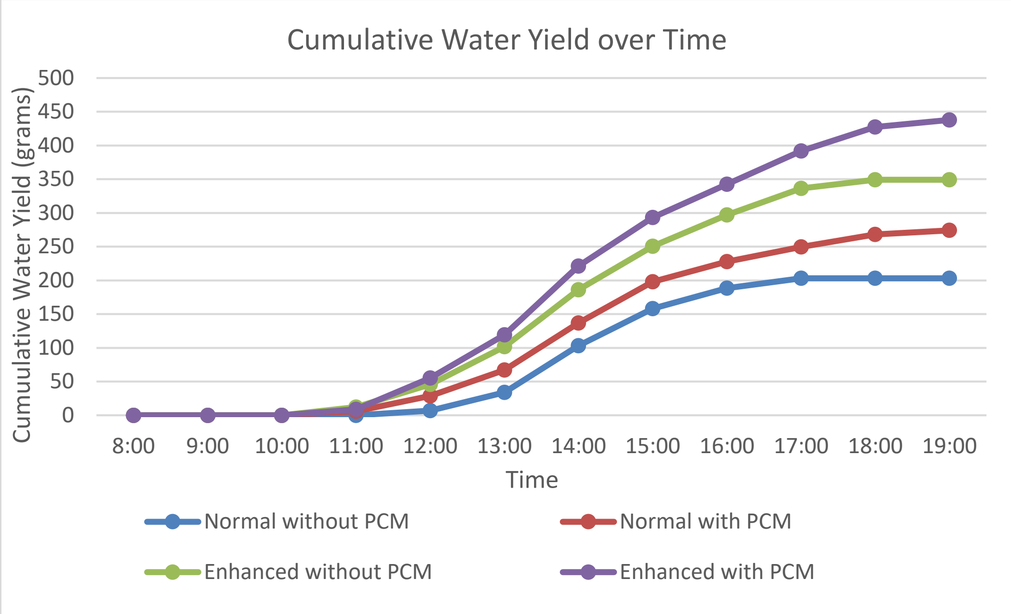

Figure 4.13: Graph of cumulative water yield over time

4.4 Efficiency of Multi-stage Solar Still

The performance of the normal multi-stage solar still with and without PCM, enhanced multi-stage solar still with and without PCM was evaluated by calculating the efficiency of the solar still. The efficiency of the solar still can be found by using the equation 4.1 which was studied in the project of (Xiong, Xie and Zheng, 2013).

$$\eta = \frac{m_o h_{fg}}{H_1 A_1 + H_2 A_2} \times 100\% \qquad (4.1)$$

where,

η = Efficiency of solar still, %

m_o = Accumulated fresh water produced in a day, kg

h_{fg} = Latent heat of vaporization of water, MJ/kg

H_1 = Accumulated solar irradiance of solar collector, MJ/m^2

H_2 = Accumulated solar irradiance of solar still, MJ/m^2

A_1 = Total receiving area of solar collector, m^2

A_2 = Area of acrylic plate of solar still, m^2

The latent heat of vaporization of water, h_{fg} is approximately to be 2.33 MJ/kg for all of the models with and without PCM, and it was based on the average temperature of the first stage solar still. The accumulated solar irradiance of solar collector, H_1 and the accumulated solar irradiance of solar still, H_2 are the same since the solar collector and the acrylic plate of the solar still were being placed at 10°. It was calculated by taking the average solar irradiance, ASI from 8 am to 7 pm, multiplying the time (11 hours) in the unit seconds, which showed in equation 4.2. The total receiving area of solar collector A_1 is 0.145 m^2 and the area of acrylic plate of solar still A_2 is 0.1681 m^2, the value for A_1 and A_2 are all the same for the two models.

$$\mathrm{H} = ASI \times 3600 \times 11 \tag{4.2}$$

where,
H = Accumulated solar irradiance, MJ/m^2
ASI = Average solar irradiance from 8 am to 7 pm, $W/m^2.h$

Therefore, the H_1 and H_2 share the same value. Table 4.3 showed the accumulated solar irradiance and the efficiency for the two models with and without the PCM. It can been seen that the efficiency of the multi-stage solar stills were quite low in the experiments that were carried out. This was mainly because there were factors that affecting the results such as the trough that was unable to catch all the water droplets and the heat lost from the solar still to the surroundings as the wall of solat still is not 100% heat insulated.

Table 4.3: Accumulated solar irradiance and efficiency of each multi-stage solar still

	Normal Multi-stage Solar Still		Enhanced Multi-stage Solar Still	
	Without PCM	With PCM	Without PCM	With PCM
Accumulated solar irradiance, H (MJ/m^2)	29.02317	32.04861	30.79362	32.54163
Efficiency, η (%)	5.21	6.36	8.44	10.01

4.5 Economic Viability

The analysis of economic for the normal multi-stages solar still with and without the PCM, and the enhanced multi-stages solar still with and without the PCM were performed to compare the most economical and effective multi-stage solar still. The costs of water produced by each of the multi-stage solar still were calculated in the economic analysis by studying the project of (El-sebaii and El-bialy, 2015). The fist step was to find the present capital cost (PCC) which is a fixed cost, and all the cost are one-time expenses. Therefore, the formula for the PCC of each solar still for this project is calculated by the following equation:

$$Present\ Capital\ Cost, PCC = Cost\ of\ materials + Cost\ of\ equipments + Installation\ Fees \tag{4.3}$$

The sink fund factor (SFF) was calculated for the next step. SFF was calculated by using the equation below:

$$Sink\ Fund\ Factor, SFF = \frac{i}{(1+i)^n - 1} \tag{4.4}$$

Where, i is the bank interest rate, for banks in Malaysia the average interest rate is assumed to be 10%. The n is represented the life span of the multi-stage solar still system. The multi-stage solar stills in the project were estimated to have a life-span of seven years. Next, the capital recovery factor, CRF in short was calculated by using the formula of:

$$Capital\ Recovery\ Factor, CRF = SFF\ \times (1+i)^n \tag{4.5}$$

The next step was to calculate the fixed annual cost (FAC). FAC consisted of the utility fees such as electric fees to operate the solar stills, annual rental fees, and the annual salaries for maintenance workers. Therefore, the estimated fixed annual costs for the multi-stage solar still was calculated by using the equation below:

$$Fixed\ Annual\ Cost, FAC = PCC \times (CRF) \tag{4.6}$$

The annual maintenance cost (AMC) for the four different solar stills were also estimated by multiplying FAC with 0.15. The maintenance work for the multi-stage solar still included broken parts replacement, regular cleaning of the basin and condensation surfaces, PCM replacement, daily feeding of saline water, pump protection, piping system protection from corrosion and scaling. Salvage value (S) and annual salvage value (ASV) was also included in the economic analysis of the solar stills. Salvage value is defined by the value of an asset can be sold at the end of its useful life (Depersio, 2021). The formula to calculate salvage value and annual salvage value were shown in equation 4.7 and 4.8 respectively:

$$Salvage\ value, S = 0.2 \times PCC \tag{4.7}$$

$$Annual\ Salavge\ Value, ASV = SFF\ \times S \tag{4.8}$$

Finally, the total annual cost (AC) for each multi-stage solar stills were found by summing up the fixed annual cost (FAC), and annual maintenance cost (AMC), then subtracted with the annual salvage value (ASV). Table 4.4 showed all the costs for the four different multi-stage solar still to compare the economic valuable. The m_a is represented the annual water yield which was calculated by multiplying the daily fresh water production by 365 days in a year by considering the hot weather conditions in Malaysia. The cost of fresh water per kg was calculated by dividing the annual cost (AC) by the annual water yield (m_a).

Table 4.4: Cost analysis for each multi-stage solar still

Parameters	**Unit**	**Normal without PCM**	**Normal with PCM**	**Enhanced without PCM**	**Enhanced with PCM**
Total Material Cost	RM	189.48	210.48	199.48	220.48
Total Equipment Cost	RM	220.04	220.04	220.04	220.04
Installation Fees	RM	50	50	50	50
Present Capital Cost, PCC	RM	459.52	480.52	469.52	490.52
Interest rate per year, i	%	10%	10%	10%	10%
Life span, n	-	7	7	7	7

Sink Fund Factor, SFF	-	0.105406	0.105406	0.105406	0.105406
Capital Recovery Factor, CRF	-	0.205406	0.205406	0.2054055	0.2054055
Fixed Annual Cost, FAC	RM	94.39	98.70	96.44	100.76
Salvage value, S	RM	91.904	96.104	93.904	98.104
Annual Salvage Value, ASV	RM	9.69	10.13	9.90	10.34
Annual Maintenance Cost, AMC	RM	14.16	14.81	14.47	15.11
Annual cost, AC	RM	98.86	103.38	101.01	105.53
Water yield per day	kg	0.2031	0.2741	0.3492	0.4391
Annual water yield, m_a	kg	74.13	100.05	127.46	160.27
Cost of distilled water per kilogram	RM /kg	1.33	1.03	0.79	0.66

Based on Table 4.4, the maximum and the minimum cost of distilled water per kg is the normal multi-stage solar still without the PCM which costed about RM1.33 per kg, and the enhanced multi-stage solar still with the use of PCM which costed RM 0.66 per kg, respectively. To conclude, the use of PCM can give a lower cost of distilled water, and by increasing the condensation surface area, the cost of distilled water can be lowered too. Thus, the enhanced multi-stage with PCM is more worth the price and effort to construct and operate it as it gave the cheapest price for 1 kg of fresh water.

4.6 Summary

As a summary for chapter 4, it was known that the ideal multi-stage solar still was the enhanced with PCM which used the corrugated metal plate as the condensation surface. The highest productivity of fresh water obtained was 0.4391 kg/day from the enhanced multi-stage solar still with PCM. The cost for a kilogram of fresh water calculated was RM 1.33/kg, RM 1.03/kg, RM 0.79/kg and RM 0.66/kg for normal multi-stage solar still without PCM, and with PCM, and enhanced multi-stage solar still without PCM, and with PCM, respectively.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

The enhancement techniques used in this research study to maximize the fresh water productivity is by using corrugated metal plate for condensation area, phase change material (PCM), and solar collector in a stacked tray multi-stage solar distiller as the enhancement methods. The prototypes were built in order to test the performance of different design of multi-stage solar distiller which was shown in Figure 4.1 and Figure 4.2. Flat condensation plate multi-stage solar distiller without PCM, flat condensation plate multi-stage solar distiller with PCM, corrugated condensation plate multi-stage solar distiller without PCM, and corrugated condensation plate multi-stage solar distiller without PCM were tested in this research study to compare the performance for each solar distiller. Therefore, objective one to three in this study were achieved.

In conclusion, the water yield for flat condensation plate (normal) multi-stage solar distiller without PCM is 0.2031 kg/day. Whereas, the flat condensation plate (normal) multi-stage solar distiller integrated with PCM is 0.2741 kg/day. Besides, the corrugated condensation plate (enhanced) multi-stage solar distiller without PCM is 0.3492 kg/day, and the corrugated condensation plate (enhanced) multi-stage solar distiller with PCM is 0.4391 kg/day. Hence, the solar distiller which gave the best performance and the highest effectiveness is the corrugated condensation plate (enhanced) multi-stage solar distiller with PCM. This is because the surface area for condensation increased, and the PCM which stored the latent heat energy during high solar irradiance period and discharged the energy when the solar irradiance was low in the evening, which lead to the increased of water productivity. Thus, objective four was also being achieved through conducting the experiment.

5.2 Recommendations for future work

There are some initiatives to be taken in order to improve the multi-stage solar still's performance in the future. Firstly, the troughs in the multi-stage solar still especially in the enhanced multi-stage solar still can be further improve and design a better trough piping system to maximize the collection of every water droplet that was condensed on the metal plate. Secondly, a heat exchanger linked with a solar collector can be designed at the first or bottom stage to maximize the water temperature in the multi-stage solar still. Thirdly, the size of the basin can be further modified to a bigger area size with a lower height so that the total surface area of saline water in the basin can be increased in order to speed up the heating process and the rate of evaporation can be also increased. Besides, the heat insulator on the multi-stage solar still and solar collector can be further designed to ensure the heat lost to the surrounding is minimized. Lastly, an auto-refill of saline water with a fixed amount for every stage can be implemented in the multi-stage solar still to make it be user-friendly.

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APPENDICES

Appendix A: Tables for temperature result

Table A.1: Temperature of normal multi-stage solar still without PCM

Time	Solar irradiance (W/m^2)	Temperature (°C)					
		Water 1st stage	Condensation surface 1st stage	Water 2nd stage	Condensation surface 2nd stage	Water 3rd stage	Condensation surface 3rd stage
8:00	218.4	25.3	26.1	25.8	25.9	24.7	24.8
9:00	672.2	29.8	29.9	26.4	26.1	25.8	24.1
10:00	954.8	35.8	33.1	32.1	30.9	30.4	28.5
11:00	1122.5	45.5	43.5	43.4	40.8	40.1	38.7
12:00	1213.8	49.6	47.2	46.5	45.5	44.3	41.2
13:00	1321.2	58.1	55.2	54.8	52.2	51.5	49.5
14:00	1251.5	55.8	53.1	52.5	48.1	47.2	45.2
15:00	953.6	48.5	45.1	44.6	40.8	39.5	36.5
16:00	587.1	40.8	37.2	36.4	33.2	32.4	30.2

17:00	257	38.6	35.8	34.1	32.4	32.1	29.1
18:00	155.6	36.4	30.1	29.4	27.4	27.1	27.5
19:00	87.2	32.4	28.7	27.5	27.2	27.5	27.2

Table A.2: Temperature of normal multi-stage solar still with PCM

Time	Solar irradiance (W/m^2)	Temperature (°C)					
		Water 1st stage	Condensation surface 1st stage	Water 2nd stage	Condensation surface 2nd stage	Water 3rd stage	Condensation surface 3rd stage
8:00	205.1	26.5	27.5	26.2	24.1	25.4	25.6
9:00	914.5	33.4	32.5	31.8	29.8	30.6	27.6
10:00	1121.2	41.5	39.5	38.2	35.4	34.6	30.2
11:00	1167.8	48.5	46.5	46.4	43.5	42.6	40.5
12:00	1321.6	57.8	53.1	52	49.6	48.5	46.5
13:00	1311.2	62.1	59.7	58.1	56.1	55.8	53.1
14:00	1338	65.1	62.2	60.2	57.9	57.1	55.6
15:00	1251.3	60.1	58.7	56.4	53.7	53.2	50.2

16:00	648.1	56.9	54.9	54	51.1	49.5	43.2
17:00	153	50.8	46.9	46.2	44.1	42.5	40.1
18:00	217.8	46.9	41.8	41.3	38.7	37.1	34.5
19:00	62.1	40.1	36.8	35.4	32.1	31.8	28.7

Table A.3: Temperature of enhanced multi-stage solar still without PCM

Time	Solar irradiance (W/m^2)	Temperature (°C)					
		Water 1st stage	Condensation surface 1st stage	Water 2nd stage	Condensation surface 2nd stage	Water 3rd stage	Condensation surface 3rd stage
8:00	351.2	24.8	25.4	24.8	25.8	25.6	24.5
9:00	758.8	28.9	27.1	26.5	27.2	26.8	24.4
10:00	976.4	33.5	30.2	29.7	28.9	28.1	26.1
11:00	1115.1	36.7	34	33.8	31.8	30.4	28.1
12:00	1241	49.8	46.5	45.9	43.1	42.8	40.1
13:00	1288.1	52.6	50.8	49.5	47.5	46.8	44.7
14:00	1324.8	59.1	57.2	56.4	53.1	52.7	50.1
15:00	1203.4	56.5	54.1	53.5	51.9	50.4	48.7

16:00	602.3	42.5	39.4	38.1	36.8	35.1	32.2
17:00	227.1	40.1	37.8	36.5	35	33.2	30.4
18:00	164.6	35.6	34.5	33.1	31.1	30.4	27.5
19:00	78.6	33.4	31.5	30.1	29.2	28.7	25.2

Table A.4: Temperature of enhanced multi-stage solar still with PCM

Time	Solar irradiance (W/m^2)	Temperature (°C)					
		Water 1st stage	Condensation surface 1st stage	Water 2nd stage	Condensation surface 2nd stage	Water 3rd stage	Condensation surface 3rd stage
8:00	228.2	25.6	25.1	24.8	25.7	25.4	24.2
9:00	907.8	32.5	30.8	30.4	29.5	29.5	27.6
10:00	984.6	40.6	37.5	36.4	34.8	33.8	30.1
11:00	1165.1	47.7	44.8	43.8	41.8	41.5	38.3
12:00	1259.4	52.6	50.2	49.4	47.9	46.5	43.5
13:00	1357.1	61.4	57.5	56.5	55.1	53.4	51.6
14:00	1388.2	66.2	62.5	61.4	58.9	58.1	56.1
15:00	1126	60.2	56.7	55.8	52.4	51.8	48.1

16:00	956.8	55.7	52.1	51.9	48.7	47.2	43.8
17:00	264.5	49.4	46.8	45.8	44	43.8	40.1
18:00	148.6	45.2	43.9	42.3	40.5	40.1	37.5
19:00	74.8	39.1	36.5	35.8	34.7	34.8	29.7

Appendix B: Tables for water yield result

Table B.1: Water yield for normal multi-stage solar still without PCM

Time	Solar irradiance (W/m^2)	Water yield 1st stage (g)	Water yield 2nd stage (g)	Water yield 3rd stage (g)	Accumulated water yield (g)
8:00	218.4	0	0	0	0
9:00	672.2	0	0	0	0
10:00	954.8	0	0	0	0
11:00	1122.5	0	0	0	0
12:00	1213.8	4.3	1.8	0.7	6.8
13:00	1321.2	16.8	6.9	3.5	27.2
14:00	1251.5	37.6	21.8	9.6	69
15:00	953.6	30.7	16.5	7.9	55.1
16:00	587.1	18.2	8.4	3.9	30.5
17:00	257	8.7	4	1.8	14.5
18:00	155.6	0	0	0	0
19:00	87.2	0	0	0	0

Table B.2: Water yield for normal multi-stage solar still with PCM

Time	Solar irradiance (W/m^2)	Water yield 1st stage (g)	Water yield 2nd stage (g)	Water yield 3rd stage (g)	Accumulated water yield (g)
8:00	205.1	0	0	0	0
9:00	914.5	0	0	0	0
10:00	1121.2	0	0	0	0
11:00	1167.8	3.7	1.7	0.8	6.2
12:00	1321.6	13.6	6.2	2.7	22.5
13:00	1311.2	22.7	10.5	5.3	38.5
14:00	1338	37.4	21.7	10.7	69.8
15:00	1251.3	33.4	18.3	9.3	61
16:00	648.1	16.4	9.7	3.8	29.9
17:00	153	12.4	6.4	3.1	21.9
18:00	217.8	10	6.1	2.4	18.5
19:00	62.1	4.1	1.7	0	5.8

Table B.3: Water yield for enhanced multi-stage solar still without PCM

Time	Solar irradiance (W/m^2)	Water yield 1st stage (g)	Water yield 2nd stage (g)	Water yield 3rd stage (g)	Accumulated water yield (g)
8:00	351.2	0	0	0	0
9:00	758.8	0	0	0	0
10:00	976.4	0	0	0	0
11:00	1115.1	5.8	3.8	2.6	12.2
12:00	1241	17.5	11.2	5.1	33.8
13:00	1288.1	29.4	17.9	8.6	55.9
14:00	1324.8	44.6	27.6	12.1	84.3
15:00	1203.4	35.1	18.9	10.4	64.4
16:00	602.3	23.7	14.8	7.7	46.2
17:00	227.1	21.3	12.2	6.2	39.7
18:00	164.6	8.5	4.2	0	12.7
19:00	78.6	0	0	0	0

Table B.4: Water yield for enhanced multi-stage solar still with PCM

Time	Solar irradiance (W/m^2)	Water yield 1st stage (g)	Water yield 2nd stage (g)	Water yield 3rd stage (g)	Accumulated water yield (g)
8:00	228.2	0	0	0	0
9:00	907.8	0	0	0	0
10:00	984.6	0	0	0	0
11:00	1165.1	5.7	2.6	1.7	10
12:00	1259.4	23.6	14.4	8.7	46.7
13:00	1357.1	33.6	18.8	11.2	63.6
14:00	1388.2	52.4	31.4	18.5	102.3
15:00	1126	37.2	22.1	12.7	72
16:00	956.8	27.6	14.1	7.5	49.2
17:00	264.5	25.7	15.7	7.9	49.3
18:00	148.6	18.3	11.3	5.7	35.3
19:00	74.8	6.1	2.9	1.7	10.7