Efficient Water Recycling Through Solar Distillation

by

Haziq Asiad Mazhanash

15015

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CERTIFICATION OF APPROVAL

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Approved by,

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(Ir. Kamarudin Shehabuddeen)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
January 2015

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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HAZIQ ASIAD MAZHANASH

ABSTRACT

The supply of clean water that can be used to meet human demands is very limited, where only less than one percent is available. Water scarcity faced by several countries in the world such as in Saudi Arabia, African countries and India has become worse each year due to the impacts of global warming thus limiting the clean water supply for their domestic use. The use of oil/diesel generators to purify and recycle used water or brackish water is very expensive and non-environment friendly; hence a need of developing a renewable energy water recycling method is to be addressed, as such provided by this project.

A pyramid shape cascade solar still model is chosen from the several conceptual designs proposed. This model is the result of improvement of the previous designs to create a better efficiency model. In this project, experiments and CFD simulations are conducted to determine the highest rate of fresh water production yielded by the solar still. The experiment is conducted by using pre-heated tap water via solar heaters to increase the inlet water temperature that promotes efficiency of fresh water production from the solar still.

From the experiment, a maximum rate of fresh water production of 0.47 $kg/m^2.hr$ is yielded which results a significant 57% increase in productivity when compared to a single slope cascade solar still model and 27% increase compared with an inclined solar still model. From the CFD simulation, the maximum rate of fresh water production predicted is 0.51 $kg/m^2.hr$. The CFD simulation predictions and the experimental results are agreeable with a percentage deviation ranging from 7.8% – 15.7% by comparing the rate of fresh water production from both types of analysis.

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"In the name of Allah, The Most Gracious and The Most Merciful"

All praise and thanks are to Almighty Allah, the creator of all worlds for providing me the courage and perseverance to complete this work successfully. May there be every peace and blessings upon the holy prophet Muhammad (PBUH), his family and his companions.

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ABBREVIATIONS AND NOMENCLATURE

$\dot{m}$	mass flow rate (kg/s)
q_{ew}	rate of evaporation (W/m^2)
A_b	area of base plate (m^2)
L	latent heat (J/kg)
h_{ew}	evaporative heat transfer coefficient (W/m^2.$^\circ$C)
T_w	temperature of water ($^\circ$C)
Tg	temperature of glass cover ($^\circ$C)
h_{cw}	convective heat transfer coefficient (W/m^2.$^\circ$C)
P_w	partial pressure of water (N/m^2)
P_g	partial pressure of glass cover (N/m^2)
CFD	computational fluid dynamic

CHAPTER 1 : INTRODUCTION

1.1 Background of Project

Solar distillation technology has been changed and improved by the engineers since the first solar distillation was developed in 1872 by Carlos Wilson, the creator of the first modern sun-powered desalination plant. Solar distillation simply means using solar distillation to purify the salt water or the brackish water. The system works by heating the water till the evaporation point where water vapor will be formed and condensed on the surface of the glass and collected to the distillate tank. The fact that driven the inventors to the development of the solar distillation on the first place is due to the small amount of clean, pure water on the earth's surface. As we know, 70% on the earth's surface is covered with water which only less than 1% of water is considered clean and safe to be used by mankind. Taking account about 97% percent of the remaining is salt water; the desalination technology has been considered to be the most effective way to tackle the problem as the desalination process uses renewable solar energy that comes from the sun. Since the solar technology has been improved and varied for decades by several researchers, this project aims to evaluate all of the designs proposed by the researchers to result in with one ideal design composed of all the good aspects in each design.

1.2 Problem Statement

People nowadays face the problem in finding clean water supply, where more than 3.4 million people die each year from water, sanitation and hygiene-related causes [1]. From the Human Development Report, stated that [the water and sanitation] crisis claims more lives through disease than any war claims through guns where over 99 percent of the death cases occur in the developing world [2]. Taking an example of an incident in Malaysia where several states; mainly Selangor faced critical water crisis due to the excessive and wasteful use of water by the people in that area. According to reports by The Star, the water supply in peninsular Malaysia in 2050 will decrease approximately by 3000 m^3 per year [3]. This assumption is based on the study that showed Malaysians use 226 liters of water per person in daily basis which make it among the highest among countries in the Southeast Asia. The recommended daily limit for Malaysians is 165 liters of water per person daily. From the findings, 70% of Malaysians used more water than what they should have every day and 70% from that figure do not intend to change the current water usage habit [4]. As reduction of clean water sources is mainly becoming an issue, techniques on producing own supplies are researched. Solar water distillation is claimed to be an efficient method for obtaining a clean water source, however there are issues regarding the process and model efficiency. With this increasing need of clean water, the productivity of the distillate yielded becomes the major factor in determining the efficiency of a solar distillation system. Problems arise as the existing ideas of a solar water distillation models are of low clean water yielding efficiencies hence deemed not cost effective. Hence, a need for a better design is required to meet the upcoming water demands, which shall be assessed.

1.3 Objectives and Scope of Study

This project aims to develop an ecofriendly solar distillation system that is capable to yield higher mass flow rate of distillate compared to single slope cascade solar stills and double basin slopes. In completing this project research, the scope has been identified as follows:

- The effects of temperature difference of the glass cover and water on the rate of evaporation of the water inside the solar still.
- The comparisons of results in terms of the rate of fresh water production by the solar still between the CFD simulation and the experiment.

CHAPTER 2 : LITERATURE REVIEW

2.1 Existing Design Review

Solar water distillation concept is actually a natural phenomenon which happened from the beginning of time. The solar radiation from the sun evaporates water from the sea and lakes, condense it as a clouds and return to the earth as rainwater. Basin-type solar still replicate these concepts in a small scale and are the most common type of still system used for water distillation. The water in the basin will evaporates when the absorber plate absorbs adequate amount of solar radiation that can initiate the evaporation process to occur. When the water turns into water vapor, it will condense on the inner surface of the tilted cover glass and straight into the distillate tank. The waste water or what they usually called as brine will be drained out through the drain point. The advantage of this design is the fabricating and manufacturing cost is low when compared to other methods. When considering the cost and amount of productivity by the basin-type solar still, this type is not cost-effective due to the lower distillate being produce for each interval. Comparing basin-type solar still with basin-type solar wick still, the present of wick on the surface of the plate clearly affects the amount of distillate water being produced at the end of the day. Plus with the ability of the wick to be tilted according to the position of the sun also the strong point on why a basin-type wick still is much preferable rather than the basin-type solar still.

With that, Hikmet S. Aybar has conducted an experiment to determine the amount of the distillate water being produced by varying the type of plate being used where the evaporation of water takes place [5]. The experiment was conducted under actual environment conditions of northern Cyprus and contrasting with the usual solar still design, the water will flow down the absorber plate and undergo evaporation at the same time instead of being left inside the basin and evaporate. It is assumed that the longer the water flow on the surface of the plate, the higher the productivity of the distillate water. Other than producing distillate water, the waste water or the brine will be use as a hot water if it is not too briny. All of the equipment that came in contact with water will be made from stainless steel in order to avoid corrosion to occur. The experiment used three different types of plate which is the first one is a bare plate which made of from galvanized steel and painted to form a matt black surface. The matt black surface is to ensure a maximum absorption of solar radiation by the plate (absorptivity of 0.96 and emissivity of 0.08) thus increasing the rate of evaporation by the water. The second type is by using black-cloth wick layered on top of the absorber plate. As what the author proposed, the black-cloth will act as a porous medium which is layered on top of the bare plate to ensure an even distribution of water on top of the absorber plate which in turn will increase the rate of production of the distillate when more surface area of the plate is covered with water. The amount of water on the surface of the plate can be easily control when using the black-cloth wick other than reducing the amount of solar radiation being reflected away rather than being absorb. The third type is by using a black fleece as the wick with approximately 2 cm long fur. The function of the black fleece is quite the same with the black cloth which only to increase the flowing-down time of the water from the top to the bottom of the plate and a larger heat transfer area.The plate was tilted for about 30^o to allow the condensed distillate water and feed water to run down the glass cover and the plate straight into the collecting tanks. This method also to ensure the solar radiation can reach the surface of the water more frequently during the day. The experiment was repeated for four times and each time is from 9:00 am to 4:00 pm (7 hours) through 17^{th} to 30^{th} of May 2004. From the results, it is clearly stated that by using the wick, the productivity of the distillate increase for about two to three times when compared with bare plate. This is due to the low flowing-down time by the bare plate that reduced the rate of evaporation of the water and also the distribution of the water on top of the bare plate is not even because of the plate deformation because of its increasing temperature. Based on the theoretical and experimental result, wick type is the leading and most prefer economic option for the distillation process [6].

On the other study done by A. S. Nafey, the presence of surfactants additives can possibly enhance the boiling heat transfer of the water [7]. The surfactants usually used to change the surface properties of the water such as reducing the surface tension of the water, the skin friction in the tubes and the boiling heat transfer of the water. An experiment has been conducted to test the effects of surfactants towards the productivity of the distillate where different concentration of surfactant was used. An A.C. electric heater was used as the replacement for the solar flux used in the actual solar collector and the input power for the A.C. electric heater is controlled by the variac transformer in the range of 0 – 2000W. The power input will be set to one value once the actual condition of the surrounding being determined. It has been found that the productivity of the system during summer is around 4.18 – 7.00 kg/day/m^2 while during winter is from the range of 1.04 – 1.46 kg/day/m^2. It showed that during summer, the productivity of the system is 80% more than during winter. Hence, the experiment will be set based on the summer operating system together with the environmental data (solar radiation) by setting the variac transformer to quantify higher system daily productivity. The productivity of the system increase with respect to the concentration but started to decrease when the concentration reached 500ppm. The maximum concentration that can be used to increase the productivity up to 7% from the original value is only until the range of 300 – 400 ppm only. The productivity drastically decreased for about 6% when it reached 500 ppm. This is due to the formation of foam when the concentration reached 500 ppm.

Other than the additional of additives, Tiwari and Yadav had conducted a study on a multi-wick with the objectives to increase the rate of evaporation of the brine [8]. The production of multi-wick is always higher than the basin type due to the negligible heat capacity of the water mass. This type of still is only applicable in a medium scale application due to its complexity in design and maintenance. Experiment conducted by Minasian and al-Karaghouli showed that a combination of wick and basin still increase the productivity for about 85% more than basin still alone and 43% more than wick still alone [9]. The hot brine from the wick still will flow inside the basin still which is covered by a jute wick which is soaked inside a cooling water so that the temperature difference between the wick and the basin is high thus promote further evaporation process to occur.

Another study that have being conducted by Fatemeh Bakhtiari Ziabiri, the use of stairs-like or cascade design for the still is used as the basic design which is further improve during this study [10]. There was significant increase of about 26% of the fresh water production when compared to the initial site’s unit. The conductivity of the produced distilled water reduced to 10–20 μS/cm which is a satisfactory range in the solar still science. Also, it is found that, the residence time of the water flow can be upsurge by using weir on each step of stills and a small down comer at the end of them which also cause the water to forced flow. Besides, the weirs are to keep the water film as shallow as possible and cause to improve the water distribution upon the evaporation surface while evading dry spots. By including an additional cotton black absorber on top of each step for the cascade still also can increase the productivity up to 53% when compared to the conventional solar still [11].

One of the things that become the major concern is the temperature difference inside the cavity. The higher the temperature difference, the higher the rate of evaporation by the water. So, Moustafa M. Elsayed has proposed a design together with a cover cooling [12]. The design will keep the glass cover cool to make sure there is huge temperature difference between the glass cover and the absorber plate. In this method, the evaporation rate increase and so as the productivity. Zeinab S. Abdel Rahim has proposed a design by using a packed layer of glass ball that will act as the thermal storage for the still [13]. The glass ball with a diameter of 13.5 mm each were packed in one layer and being placed at the bottom of the still to absorb heat which will be used after the sunset. The heat stored will help in the evaporation of water during the night as there is no solar radiation during that time. This method will increase the productivity as the evaporation of the water also take place during the night.

Another type of thermal storage is by using the charcoal particle. Mona M. Naim proposed that, by using charcoal, the productivity can be increase up to 15% when compared with the wick-type [14]. This is due to the nature of the charcoal that can functions as the heat absorber and at the same time as the wick for the stills. The charcoal will absorbs the required heat for the evaporation to occur after sunset and also acts as the wick where the coarse charcoal yield a high productivity when high flow rate was applied. The finest charcoal will yield high productivity also but with a moderate flow rate due to its fine grains which enable the water to diffuse between the tiny particles of large surface area and resulted with a low rate of heat transfer. The low rate of heat transfer is due to the consequent temperature drop between the inside and outside of the particle.

Al-Karaghouli has proposed another method in his other study which is using a floated jute wick [15]. The jute wick will floated with the help of polystyrene sheet and it has been found that this method produce more distillate than tilted wick design and basin type design. By using the floating wick, the dry spot on the wick can be avoided with the presence of goof capillarity of the floating wick fibers. The floating wick type is capable of increasing the productivity up to the range of 72% when compared to the simple basin type. Table 2.1 and 2.2 show the summarization of the design being studied and considered during the research studies of this project.

Table 2.1: Overview of the existing designs

Type of Design	**Year**	**Location**	**Name**	**Background**	**Result**
Stepped Solar Still with cotton black absorber	2014	Tanta, Egypt	S.A. El-Agouz	Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt	The productivity of distillate increase 47% for salt water and 53% for sea water with the presence of cotton black absorber.
Cascade Stills with weir	2013	Iran	Fatemeh Bakhtiari Ziabari, Ashkan Zolfaghari Sharak, Hamid Moghadam, Farshad Farshchi Tabrizi	Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran. Department of Chemical Engineering, University of Sistan and Baluchestan, Zahedan, Iran.	The average fresh water production for the modified cascade solar still is around 6.7 lit/day m2, which shows 26% increase in compare to the initial site's units.
Various Wick-type	2013	India	V. Manikandan, K. Shanmugasundaram, S. Shanmugan,	Department of Physics, Karpagam University, Eachanari Post, Coimbatore, Tamilnadu, India	The floating-type wick by Minasian are consider to be the most effective type of solar still.

			B. Janarthanan, J. Chandrasekaran	Department of Physics, SRMV College of Arts and Science, Coimbatore 641020, Tamilnadu, India	
Surfactant Additives	2008	Enclosed area with no sun flux effect	A.S. Nafey, M.A. Mohamad, M.A. Sharaf	Faculty of Petroleum and Mining Engineering, Department of Engineering Science, Suez Canal University	The maximum increment of productivity only up till 7% with a 300 ppm surfactant added. 7% from original productivity of 4.18 – 7.00 kg/day/m^2.
Glass Ball Layer Packed	2005	Cairo, Egypt	Zeinab S. Abdel-Rehim, Ashraf Lasheen	Mechanical Engineering Department, National Research Center, Dokki, Cairo, Egypt. Mechanical Engineering Department, College of Eng., Zgazeg University, Egypt	The efficiency of the solar still increase in the range of 5 – 7.5%.

Black-cloth Wick	2005	Northern Cyprus	Hikmet S. Aybar, Fuat Egeliofglu, U. Atikol	Department of Mechanical Engineering, Eastern Mediterranean University	Increase the productivity by 24% compared to bare plate.
Black-fleece Wick	2005	Northern Cyprus	Hikmet S. Aybar, Fuat Egeliofglu, U. Atikol	Department of Mechanical Engineering, Eastern Mediterranean University	Increase the productivity by 109% compared to black-cloth wick.
Charcoal Particle	2002	Alexandria, Egypt	Mona M. Naim, Mervat A. Abd El Kawi	Chemical Engineering Department, Faculty of Engineering, Alexandria University, Alexandria, Egypt. lnstitute of Graduate Studies and Research, Alexandria University, Alexandria, Egypt	Increase the productivity by 15% more than the wick-type.
Floating-Wick type	1995	Baghdad, Iraq	A. N. Minasian, A. A. Al Karaghouli	Solar Energy Research Center, Jaderiyah, Baghdad, Iraq	Increase productivity up to 72% when compared to basin still.
Combined Wick-Basin	1995	Experimental field of the Solar Energy	A. N. Minasian, A. A. Al Karaghouli	Solar Energy Research Center, Jaderiyah, Baghdad, Iraq	Increase the productivity by 85% more than basin type and 43& more than the wick type.

		Research Center in Baghdad			
Cover Cooling	1994	Jeddah, Saudi Arabia	Moustafa M Elsayed, Ibrahim S Taha, Jaffar A Sabbagh	King Abdulaziz University	Cover cooling produces more distillate than the original design which is without the cover cooling.
Multi-wick	1984	New Delhi, India	Tiwari, G.N., Sharma, S.B., Sodha, M.S.	Centre of Energy Studies, Indian Institute of Technology	Increase the productivity by 20% over the single wick.

Table 2.2: Advantage(s) and disadvantage(s) of the design

Design	**Advantage(s)**	**Disadvantage(s)**
Basin Still (single slope)	- has less convection and radiation loss. - gives better performance in cold climate.	- low absorption of radiation. - need repositioning when the position of the sun changing.
Basin Still (double slope)	- able to absorb maximum amount of radiation. - better performance in summer climatic condition. - no need repositioning of the still.	- more convection and radiation loss.
Black-cloth Wick	- increase radiation absorption. - lengthen the water flowing down time. - no dry spot on the absorber plate.	- can be easily contaminate and difficult to service.
Black-fleece Wick	- increase radiation absorption. - lengthen the water flowing down time. - no dry spot on the absorber plate. - better performance than black cloth.	- can be easily contaminate and difficult to service.
Cover Cooling	- increase the temperature difference between the glass cover and absorber plate, thus increase rate of evaporation.	- need to regularly clean the inner cover from the contaminants from cooling water. - more reflection loss takes place.

Surfactant Additives	- enhance the boiling heat transfer of the water.	- only limited till 300ppm, beyond that the productivity will drastically drop.
Multi-wick	- excess vapor can be condensed on the additional glass cover and reduce the heat load on the glass cover, hence increase temperature difference. - better performance than single wick. - less maintenance	- large heat flux and large heat loss from the absorber plate to ambient.
Floating-Wick	- there will be no dry spots on the wick surface, thus increase the amount of distillate being produce.	- difficulty to control salt accumulation on the wick surface.
Charcoal Particle	- good absorbent of heat. - porous medium which can enhance evaporation of water due to even distribution of water.	- charcoal cannot be reuse once contaminate with salts or impurity.
Packed Layer	- good absorbent of thermal energy which can be reuse for evaporation process in the absence of the sun.	- glass ball need to be regularly cleaned to ensure maximum absorption of thermal energy.

Combined Wick-Basin	- brine undergoes evaporation twice, starts from the wick and lastly basin. - better efficiency than basin and wick type.	
Cascade Still with weir	- increase the residence time of the water. - encourage force flow of water, thus avoid dry spot.	
Stepped Still with Cotton Black Absorber	- even distribution of water on top of the step.	- difficulty in doing maintenance for the cotton black absorber.

CHAPTER 3 : METHODOLOGY

Methodology becomes the main part in every project and research in determining the progress and results of the project or research. For a project of designing with the objectives to enhance or improve certain project, many steps should be considered closely in order to yield a good results and explanations.

3.1 Project Activities

The first step is by doing and excellent literature review on the past works by other people. Literature review needs to cover up all aspects in term of the type of stills that have been used by these people, the surrounding condition with respects to the productivity yield by the design, the type of additives to encourage the rate evaporation of the water and the hybrid between all the good aspects of any available designs. A tabulation of the criteria and advantages/disadvantage offered by all of the design is done to ease the selection of the design. From this table, all of the good aspects can be simply determine and combined to come out with several conceptual designs that will be evaluate later. These conceptual designs need to have the advantage and other good aspects from various type of design by the past works and at the same time minimizing the disadvantage of the previous design. A simple improvement on the previous work also can be considered as a new conceptual design. All of these conceptual designs need to be drawn and the functionality have to go through for of each design and the advantage offered.

Later after the, all of these designs will be tabulated and evaluated according to the attributes such as the cost, the productivity, the availability, the serviceability and the life expectancy. Cost is mainly about the cost of fabricating the product, the productivity is the rate of the distillate being produce with respect to time, the serviceability is the complexity of the equipment when the service and maintenance work need to be done and the life expectancy is the life span of the design before it fail to produce and working smoothly. From all of this attributes, each design will be rated from the lowest, 1 to the highest which is 10. The total scores of the conceptual design will determine which conceptual design that will be used as the ideal design to create an efficient solar water distillation system. The evaluation of the design need to be tally with what have been done inside the literature review and need to prove with scientific theory and governing equation.

Designs that possess the highest score among the conceptual design will be choose as the final selected design and simulated inside specific software. The final governing equation need to be determined before proceeding with the experiment to make sure all the calculation is correct. An experimentation result will be obtained by conducting an experiment in order to validate the simulation result that previously been done. The simulation and experimentation result will be compare once both are done and some recommendation for the future improvements for the design will be suggested at the end of the report. A more detail and sequential view of the whole activities can be referred in the Gantt chart (Appendix 1). The process flow of the whole project can be refer to the flow of activities in Figure 3.1.

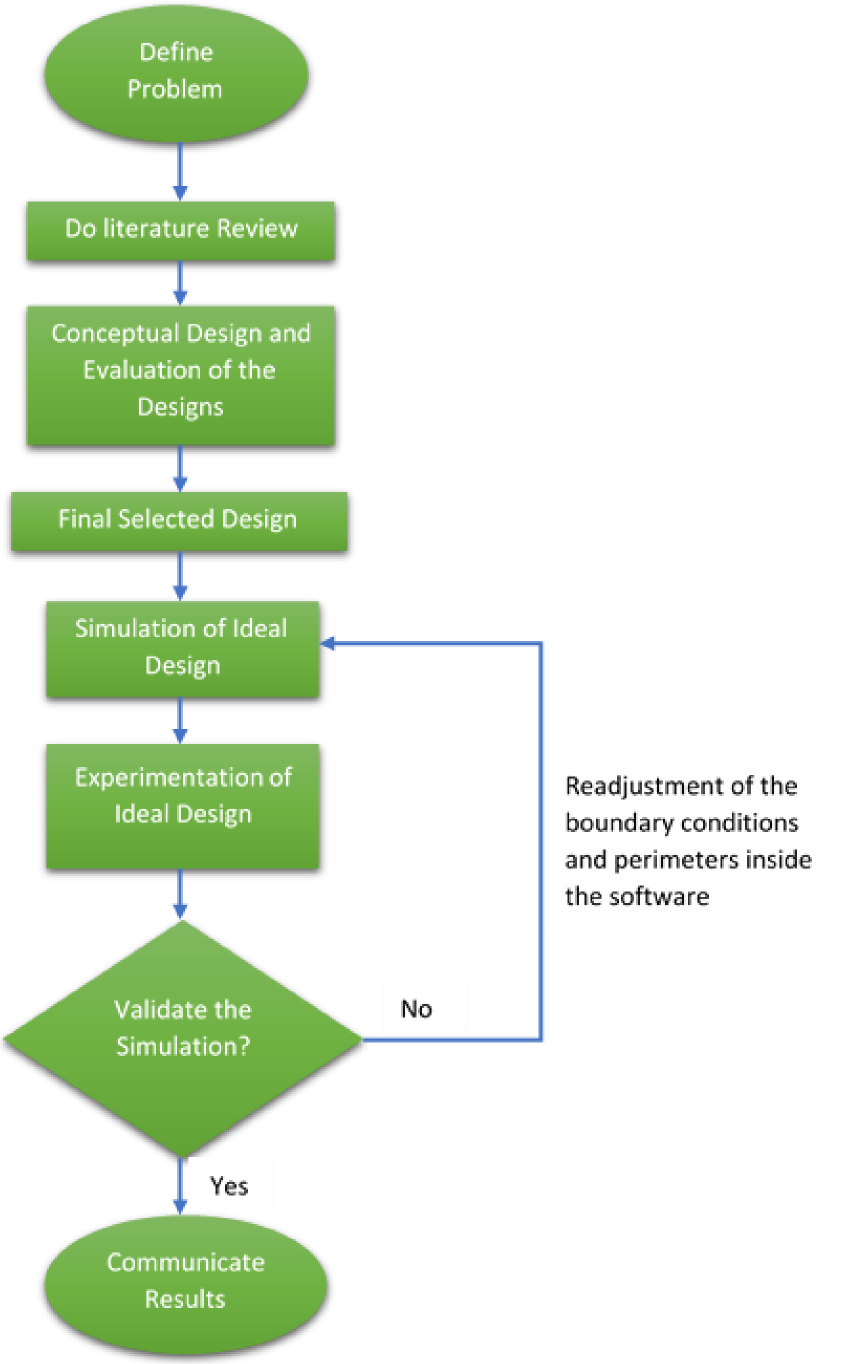

Figure 3.1: Flowchart of activities

3.2 Key Milestones

3.2.1 Final Selected Design

Final selected design came right after the evaluation of all the conceptual designs. The evaluation of the designs will be based on certain criteria or attributes that can contribute on increasing the efficiency of the solar still. By completing this final selected design only the project can be continue for the simulation or experimentation process later after that.

3.2.2 Complete Experimentation Using Prototype

The experimentation process will be done after the simulation is complete or may also can be done during the simulation process take place. The experimentation will only be conducted on the completed prototype of the design in order to determine the actual result from the actual condition of the environment. The experimentation need to be complete in order to validate the simulation result later.

3.2.3 Complete Comparison of Simulation Result and Experiment Result

The completion of the comparison of the simulation result and the experimentation result will validate the simulation result. The experimentation result will be used to check the accuracy of the simulation result being conducted earlier. A good simulation will enable the project to be upscale in the future.

3.3 Conceptual Designs

Conceptual design is the first step in determining what type of concepts or designs that shall be used upon conducting further experiment and simulation on the final selected design. The conceptual designs will comprise of all the plusses from the literature survey that have been conducted, combined together to form a new design that can possible yield a higher efficiency from the previous design. The following are the list of conceptual designs for the project before the final selected design being chosen.

Design 1 – Single Slope Cascade Still with Charcoal

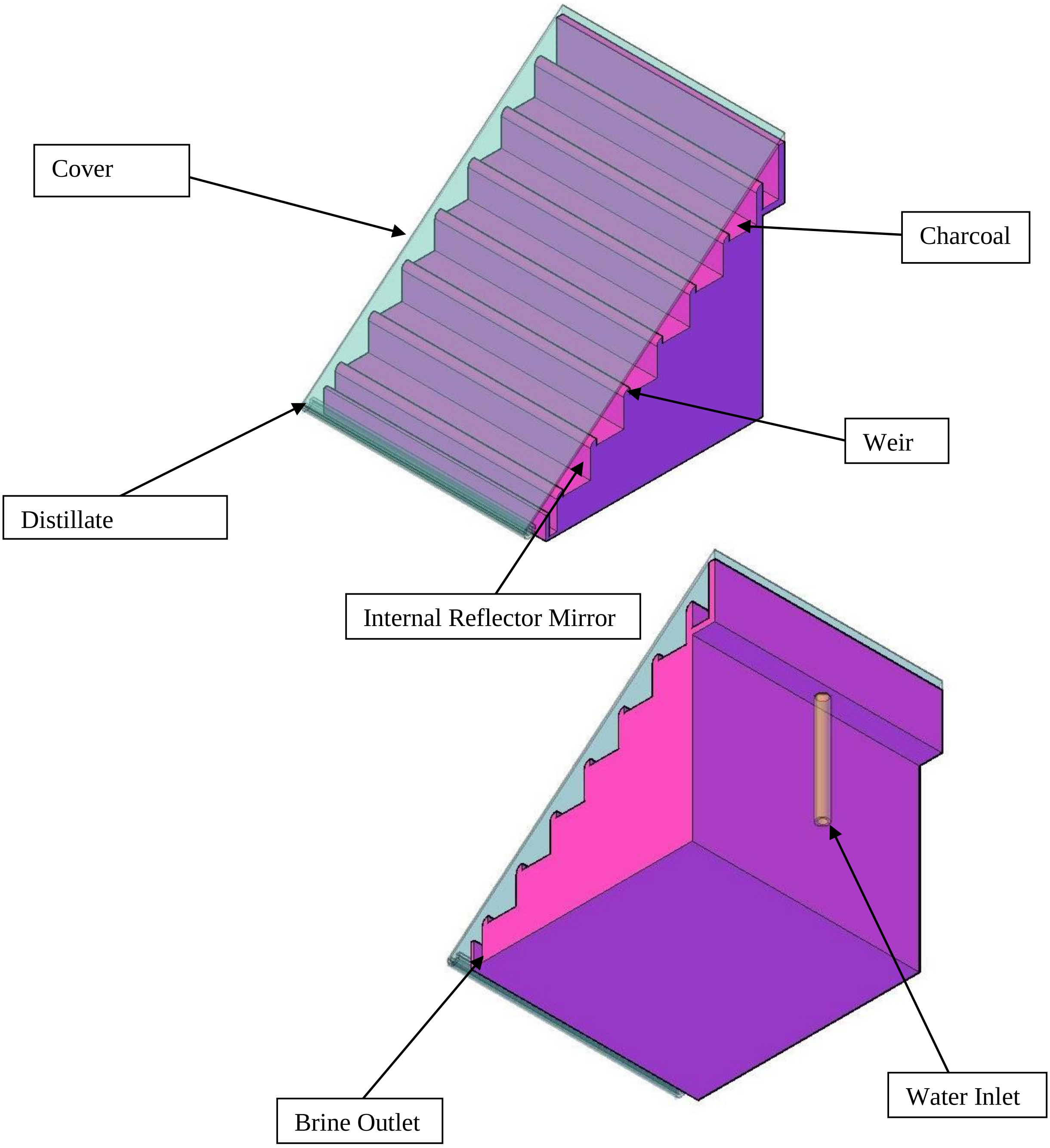

Figure 3.2: Single Slope Cascade Solar Still

- The use of charcoal at every step will improve the absorptivity of the solar radiation to enhance the rate of evaporation inside the still. The presence of the weir is to ensure the flowing of the water from top to below be equally distribute along the step while the internal reflector mirror is to guarantee the water get the maximum amount of solar radiation during the day.

Design 2 – Cone Shape Cascade Still with Packed Layer Glass Ball

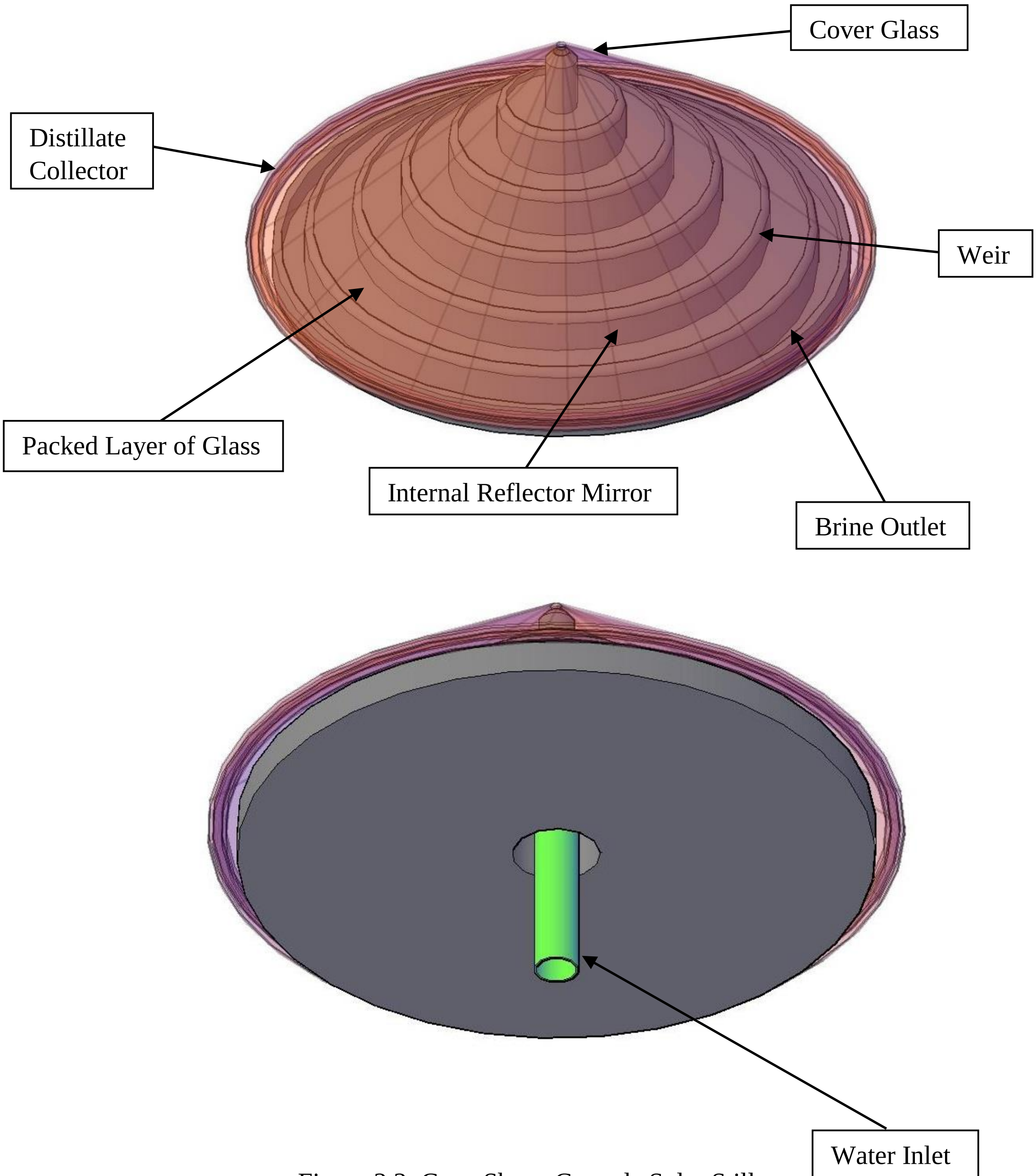

Figure 3.3: Cone Shape Cascade Solar Still

- The cone shape still will increase the total area exposed to solar radiation and the still does not need to be reposition according to the direction of the sun. The use of packed layer of glass ball as the thermal storage will enable the still to undergo evaporation even after sunset. The advantage of using weir and internal reflector mirror is the same as design 1.

Design 3 – Pyramid Shape Cascade Still with Charcoal **(Final Selected Design)**

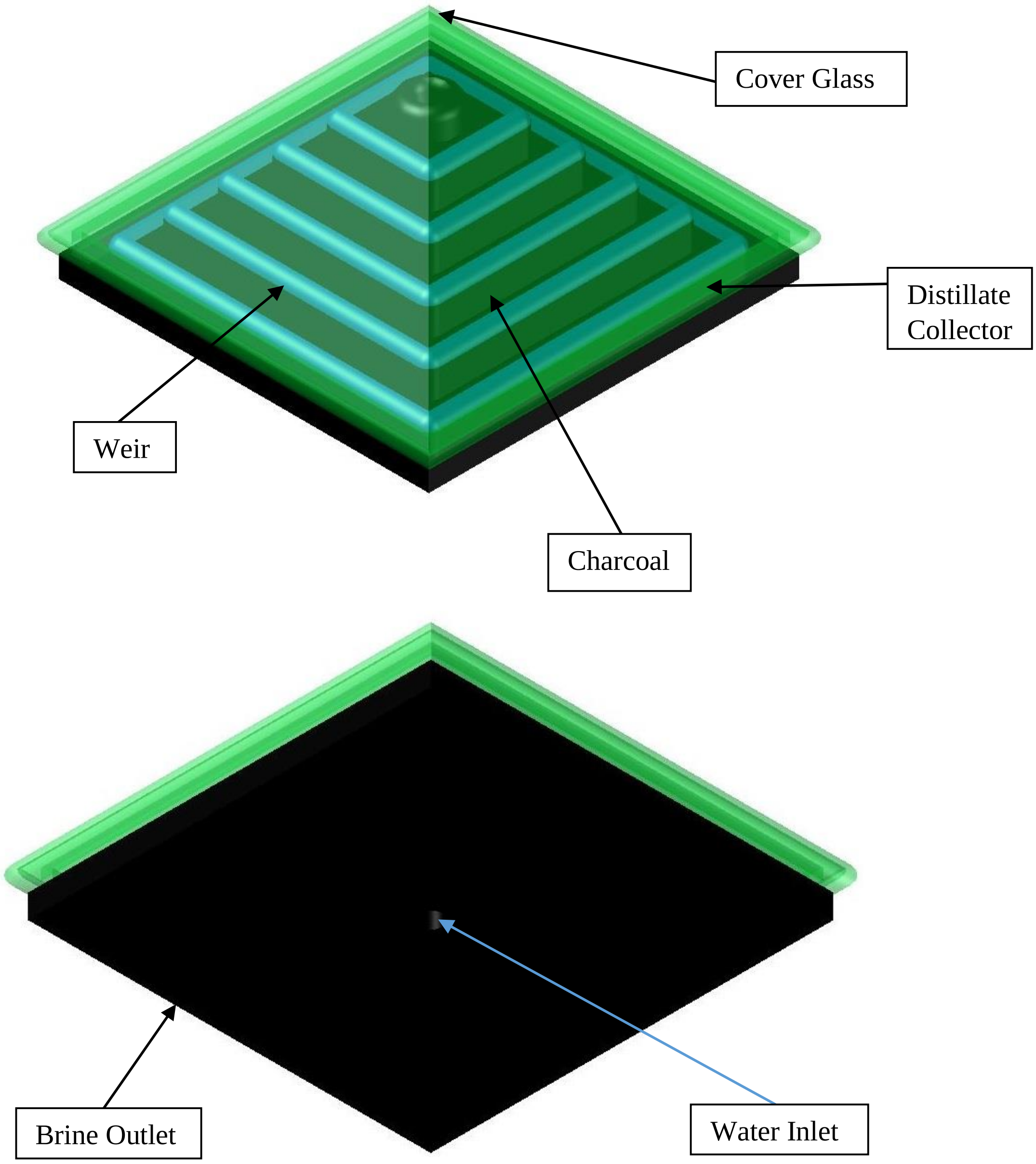

Figure 3.4: Pyramid Shape Cascade Solar Still

- The pyramid shape of the still offered the same function as the cone shape which is to increase the total surface area being exposed to the solar radiation. With the use of charcoal as the absorbent will increase the rate of evaporation inside the still when compared to the cone shape still.

Design 4 – V Shape Still with Floating Wick

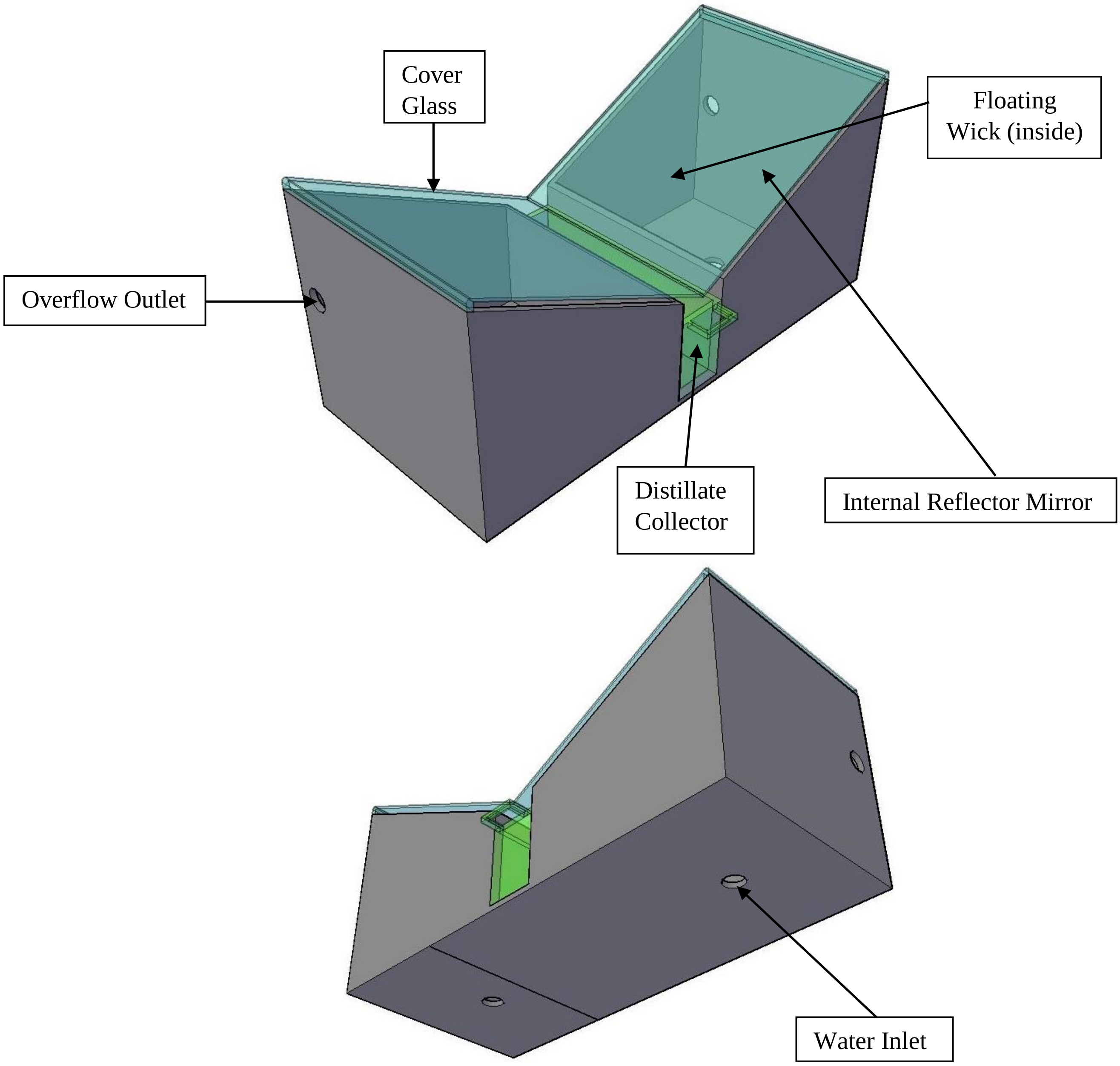

Figure 3.5: V-Shape Solar Still

- The use of floating wick inside the still will encourage a well distributed of water thus will increase the rate of evaporation of the water. Since it is a basin type still, a consistent inlet flow of water is not needed. The presence of internal reflector mirror will not require the still to be repositioned.

3.4 Final Selected Design

The final selected design will be selected from the previous conceptual designs by thoroughly considering all the major factors that contribute in increasing the amount of distillate being produce with respects of time. A decision matrix has been done to compute all of the designs together with the all the factors to assist on deciding and selected the final design to be used.

Design Criterion	Unit	Weight Factor	Single Slope Cascade		Cone Shape Cascade		Pyramid Shape Cascade		V Shape	
			Rank	Score	Rank	Score	Rank	Score	Rank	Score
Total Area Expose	m^2	4	1	4	2	8	3	12	4	16
Fabrication Complexity	n/a	2	4	8	2	4	2	4	4	8
Fabrication Cost	RM (MYR)	3	4	12	3	9	4	12	4	12
Operating Cost	RM (MYR)	3	3	9	3	9	2	6	2	6
Maintenance	n/a	2	2	4	3	6	4	8	4	8
Volume Flow Rate	l/s	3	3	9	3	9	3	9	3	9
Absorptivity	W/m^2	4	4	16	3	12	4	16	3	12
Residence Time	s	4	4	16	4	16	4	16	2	8
		Raw Score	78		73		83		79	
		Relative Weight	24.92		23.32		26.52		25.24	
		Rank Order	3		4		1		2	

Figure 3.6: Decision Matrix

From the decision matrix in Figure 3.6, **pyramid shape cascade still** has been selected as the final selected design as it has found to accumulate the highest score than other type of still. The isometric diagram for the final selected design is as follow.

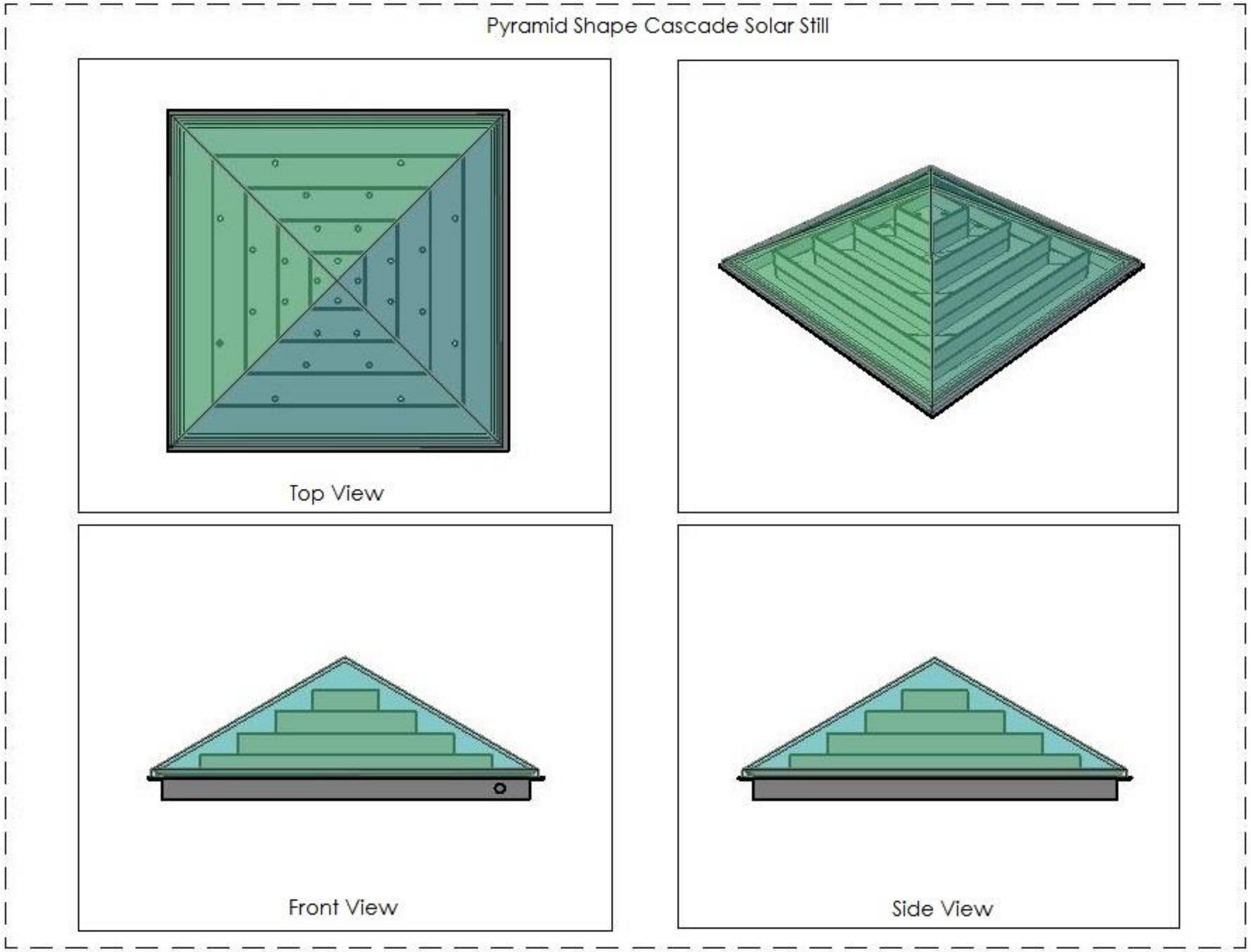

Figure 3.7: Isometric Drawing of Pyramid Shape Cascade Solar Still

3.5 Design Description

The experimental setup for the experiment will be based on the pyramid shape still as in Figure 3.7. The bottom plate has an area of 504 x 504 mm^2 and followed by the first step with a height of 30 mm but with a much smaller area of 400 x 400 mm^2. Each step will have a width of 50 mm with a 4 mm weir to ensure an evenly water distribution from each tray to the subsequent tray below. The holes on the horizontal plate at each tray indicates the nuts and bolts holes for the assembly purposes but can be neglected during the fabrication process if other attachment method is used instead of nuts and bolts. From the Front View section based on Figure 3.7, the hole on the vertical plate on the bottom part of the solar still is the overflow drain point for the brackish water. This overflow drain point functioning to avoid the contamination of the distillate being collected with the overflow of brackish water from the solar still base plate. Four distillate collecting tank will be placed at every edge of the solar still to collect the distillate produce. Each tray plate will be painted matt black to enhance the absorptivity of solar radiation and also be filled with a charcoal granules which functioning as absorber medium and thermal storage in order to increase the rate of evaporation of the water inside the solar still. Each tray will be made from Perspex sheet due to low cost and ease of fabrication works. 4mm thickness of Perspex is used for the model to increase the rigidity of the model in retaining the flowing of water inside the solar still during the experiment. For the glass cover, 4 triangular Perspex of 4 mm thickness is being glued together with an epoxy and silicon glue and fitted on the top of the still which will acts as a radiation receiver and the inner glass is where the distillate will be condensed. The application of silicone sealant at every edge of the model is to prevent water leaking between the Perspex joint.

As for reading measurement purposes, two type K thermocouples connected to data logging thermometer are placed at certain area on the solar still to measure the change in temperature for the numerical analysis to be conducted later. One thermocouple is placed at the base plate of the solar still to monitor the change in temperature of the water on the solar still, and another thermocouple is placed on the surface of the glass cover to monitor the change in temperature on the glass cover. These two temperatures will determine the rate of evaporation that occur inside the solar still, and the rate of fresh water production from the solar still.

3.6 Working Mechanism of the Solar Still

The supply of water will come from the supply tank via the Siphon method. A tap water will be directly used as the source for the feed water that will firstly pass through the copper tube of the solar water heater before being feed into the solar still. The water will come from the inlet situated at the top of the solar still, control by the ball valve attached to the hose. The water will then moisture up the charcoal at each tray. The water will overflow to the next subsequent tray one after another until the water being collected at the bottom of the still by the conventional basin through the overflow drain point. The water inside the solar still will undergoes evaporation while overflowing from one tray to another due to the temperature difference inside the still between the water and the glass cover on top of the still. The distillate will condensed on the inner surface of the glass cover and flowing down straight into the glass gutter which will channel the collected distillate into the distillate tank collector.

3.7 Experimental Procedure

1. The setup for the experiment like in Appendix 2 can be refer from the design description and working mechanism section.
2. The recording of data for the experiment is conducted by using HH309A 4 input Data Logging Thermometer as what can be refer in Appendix 4.
3. The data logger is calibrated first according to the standards or by getting assistant from the accredited calibration provider.
4. Two type K thermocouples with a ranges of -270 to 1370^{o}C and accuracy of ± 2.2^{o}C are used for this set of experiment.
5. The recording of data is conducted by placing the thermocouples on the location where the change in temperature need to be measured.
6. The first thermocouple is placed at the inlet feed water to measure the fed water temperature.
7. The second thermocouple is taped at outer surface of the glass cover to measure the glass cover temperature and the third thermocouple is taped at the base of the plate to measure the temperature of the water on the plate.

8. The inlet water into the still is controlled by the ball valve located right after the copper tube. The ball valve is fully open to ensure a constant flow rate of water into the still during the experiment.
9. There are several conditions being measured constantly throughout the experiment which are:
    (a) The temperature of the water on the base plate.
    (b) The temperature of the glass cover.
    (c) The amount of distillate being produced.
7. The experiment is conducted with a continuous supply of water into the solar still through the solar concentrator starting at 0900 hours till 1600 hours every day for a duration of 1 weeks.
8. A tabulation of data is done based on the data fetch by data logger and one types of curve can be obtained from the data that is graph of time (in hour) against productivity (amount of distillate).

CHAPTER 4 : RESULTS AND DISCUSSION

This chapter presents and compare the results obtained from the experiments and CFD simulation. The productivity in term of fresh water production by the solar still during the experiments is tabulated and plotted into graph. The results from the CFD simulation that is the glass cover and water temperature is further calculated to get the rate of fresh water production which then will be compared with the experiments results in order to obtain the percentage deviation between the two results.

4.1 Numerical Analysis

The mass flow rate of the distillate being produce is given by [16],

$$\dot{m} = \frac{q_{ew} A_b}{L} \quad (1)$$

The rate of evaporation of water is given by,

$$q_{ew} = h_{ew}(T_w - T_g) \quad (2)$$

The evaporative heat transfer coefficient is given by,

$$h_{ew} = (16.273 \times 10^{-3}).\, h_{cw}.\, \frac{P_w - P_g}{T_w - T_g} \quad (3)$$

Since temperature range is from 25°C to 60°C, Dunkle's relation can be use where [17],

$$h_{cw} = 0.884 \sqrt[3]{\left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{(268.9 \times 10^3) - P_w}\right]} \quad (4)$$

With partial vapor pressure of water, P_w and glass cover P_g is found by relation,

$$P_w = \exp\left(25.317 - \frac{5144}{T_w + 273}\right) \quad (5)$$

$$P_g = \exp\left(25.317 - \frac{5144}{T_g + 273}\right) \quad (6)$$

4.2 Analysis and Discussion

4.2.1 CFD Results Analysis

The CFD simulation is conducted via ANSYS Fluent 14.5. DO Radiation model is used for the simulation model. For the solar load models, solar ray tracing is used and the global position (latitude: 4.359039, longitude: 100.9849, time zone: +8.00 GMT) of the actual location of where the experiment is conducted is used in order to specify the sun direction vector. During the simulation, a few assumptions have been made in order to yield the expected results approximately tally with the experimental that is conducted. The assumptions include the inlet temperature of the water which is assume to be 30 ºC from the solar water heaters, the thermal properties of the glass cover is affected by the radiation, base plate as a heat flux and all the basic chemical properties of the water including the density, thermal conductivity and specific heat capacity. From the CFD simulation, the highest temperature ever recorded for a 324 iteration with a time step of 100 s for the water is 51.0 ºC and the lowest for the glass cover is 30.2 ºC. The glass cover and the water temperature at nine (9) different point on the solar still will be tabulated to get the rate of evaporation of water inside the solar still by proceeding with the numerical analysis which then will determine the productivity of the solar still. A huge different in the temperature between the two structures indicates a high rate of evaporation inside the still which results with high rate of fresh water production by the solar still. Below is the graph of distribution of temperature on the glass cover and the water in nine (9) different positions on the solar still.

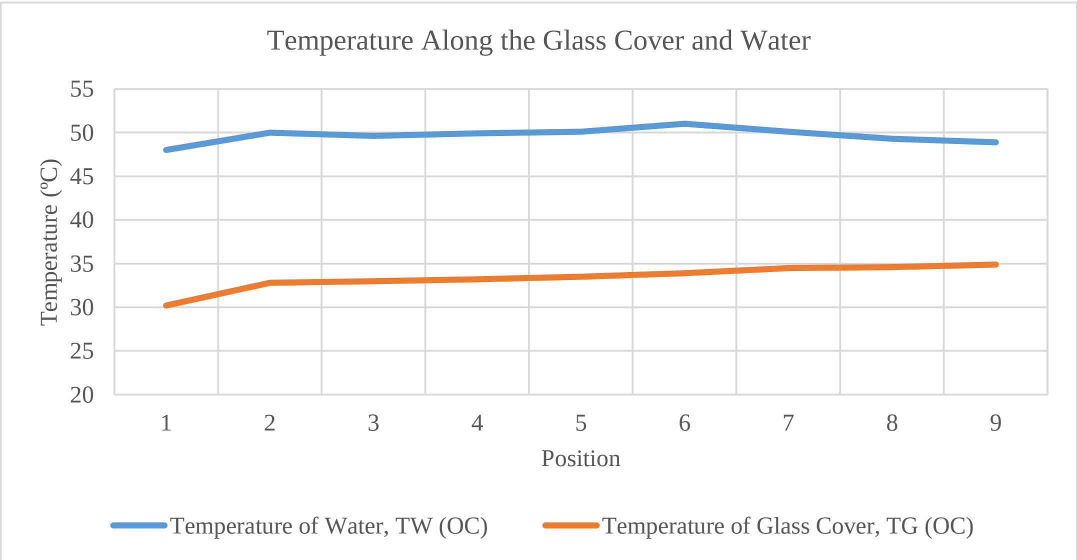

Figure 4.1: Temperature along glass cover and water

The maximum temperature experience by the water is taken as T_w while the minimum temperature experience by the glass cover is taken as T_g. The calculation of the partial pressure, evaporative and convective heat transfer coefficient, the rate of evaporation and the flow rate is calculate based on the value of T_w and T_g get from the graph in Figure 4.1 below is the computed data in the form of a table.

Table 4.1: Predicted results from CFD Simulation

Position	Temperature of Water, T_W (°C)	Temperature of Glass Cover, T_G (°C)	Fresh Water Production Rate (kg/m^2.hr)
1	48.00	30.20	0.45
2	50.00	32.80	0.48
3	49.63	33.00	0.46
4	49.90	33.20	0.47
5	50.10	33.50	0.47
6	51.00	33.90	0.51
7	50.10	34.50	0.44
8	49.30	34.60	0.40
9	48.90	34.90	0.37

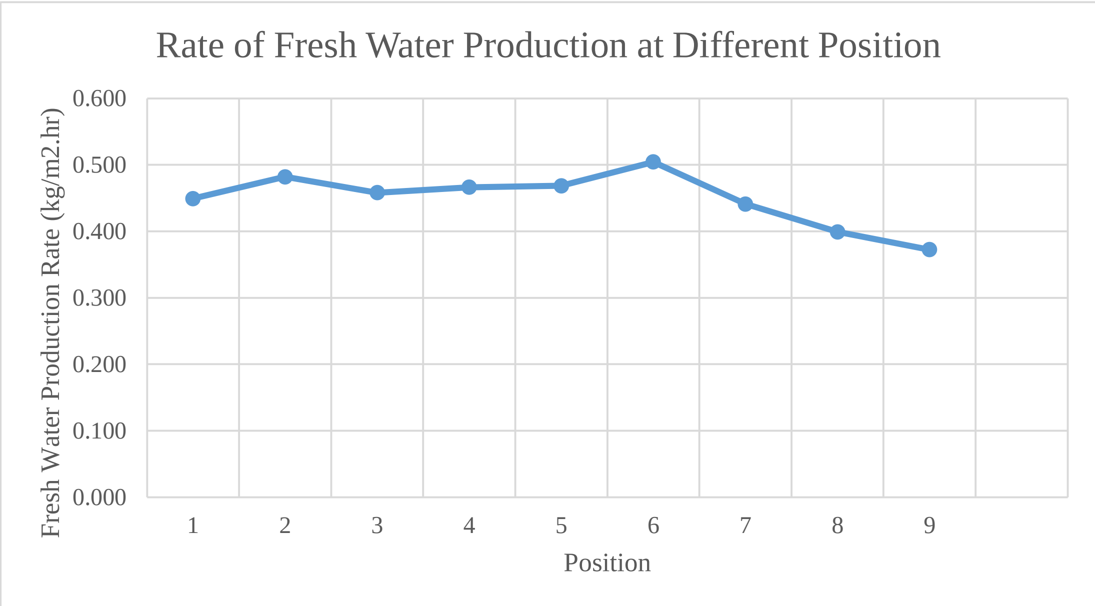

Figure 4.2: Rate of fresh water production at different position

According to Figure 4.2, the highest rate of fresh water production ever recorded is 0.51 kg/m^2.hr. The results obtained from the experimental analysis is used to compare with this simulation results to validate the simulation whether it is acceptable or not. The acceptable simulation can be used for future works if the solar still considered to be built in a large scale.

4.2.2 Experimental Analysis

The experimental process is conducted with constant variable in term of material use and the place on where the experiment is conducted. The experiment is conducted for seven (7) days in the month of April at Universiti Teknologi PETRONAS, Perak, Malaysia. Since Malaysia climate have the characteristics of a uniform temperature, high humidity and copious rainfall with the location in the equatorial doldrum area, it is particularly intermittent to have one full day with a completely clear sky even during drought seasons [18]. Due to this condition, the results obtained from the experiment are not consistent when compared day by day. With the presence of charcoal as a thermal absorbent in the solar still, the degree of variation of the results have been minimize. The presence of charcoal ensure the water can be continuously evaporate and turn into distillate whenever the sky turns cloudy for a while [14]. But under certain circumstances, the experimental procedure are unable to be fully conducted due to rainfalls that happen late in the evening.

The experiment mainly aim on constantly monitoring the temperature of water, T_w and temperature of the glass cover, T_g of the solar still. From this two value, the rate of fresh water production can be estimated in the end thus reflect the efficiency of the solar still. The recorded temperature for T_w and T_g for each day is tabulated as follow together with the rate of fresh water production in hourly basis followed by the graph on the rate of fresh water production on hourly basis for each day.

Table 4.2: Experimental observation for day 1 of experiment

Time (hour)	**Temperature of Water, T_w (^OC)**	**Temperature of Glass Cover, T_g (^OC)**	**Fresh Water Production ($kg/m^2.hr$)**
0900	28.60	28.50	0.00
1000	34.50	29.60	0.04
1100	37.60	32.30	0.08
1200	40.60	34.80	0.08
1300	43.20	37.50	0.12
1400	44.80	37.70	0.16
1500	48.50	38.30	0.28
1600	45.80	36.50	0.20

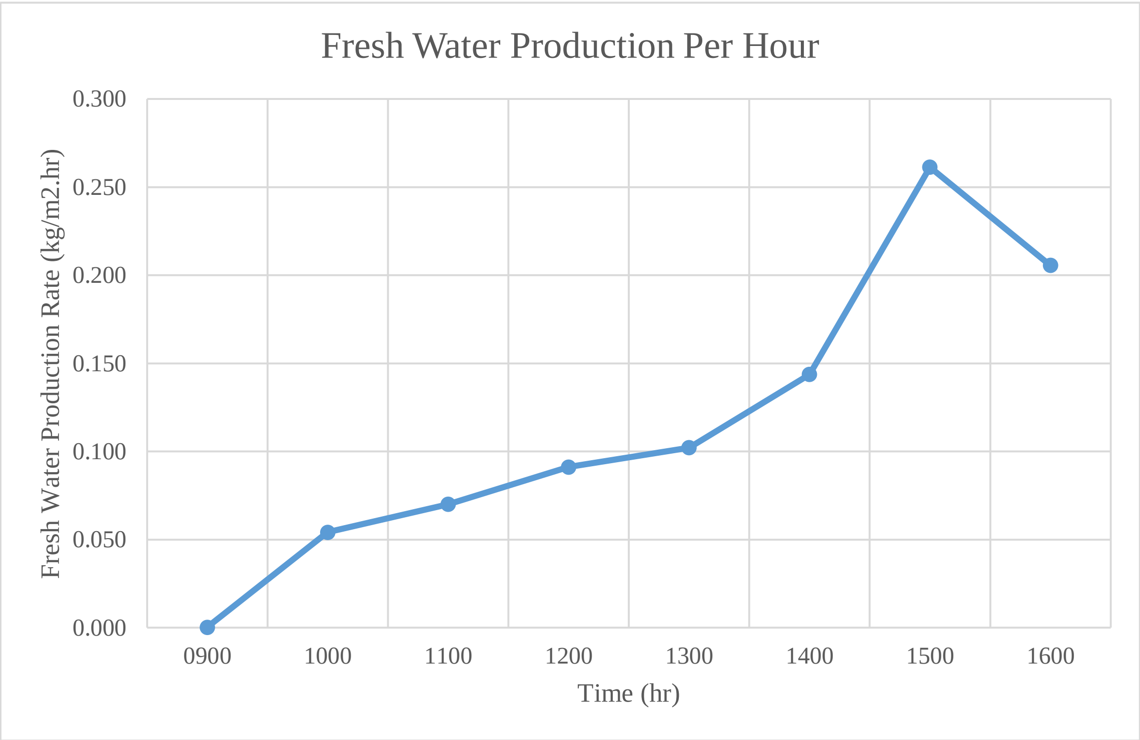

Figure 4.3: Hourly fresh water production for day 1 of experiment

Table 4.3: Experimental observation for day 2 of experiment

Time (hour)	**Temperature of Water, T_w (^OC)**	**Temperature of Glass Cover, T_g (^OC)**	**Fresh Water Production ($kg/m^2.hr$)**
0900	29.30	28.40	0.00
1000	33.20	29.10	0.04
1100	37.50	31.50	0.08
1200	39.80	33.60	0.08
1300	43.60	36.80	0.12
1400	44.90	36.90	0.16
1500	47.50	37.20	0.24
1600	45.60	36.80	0.20

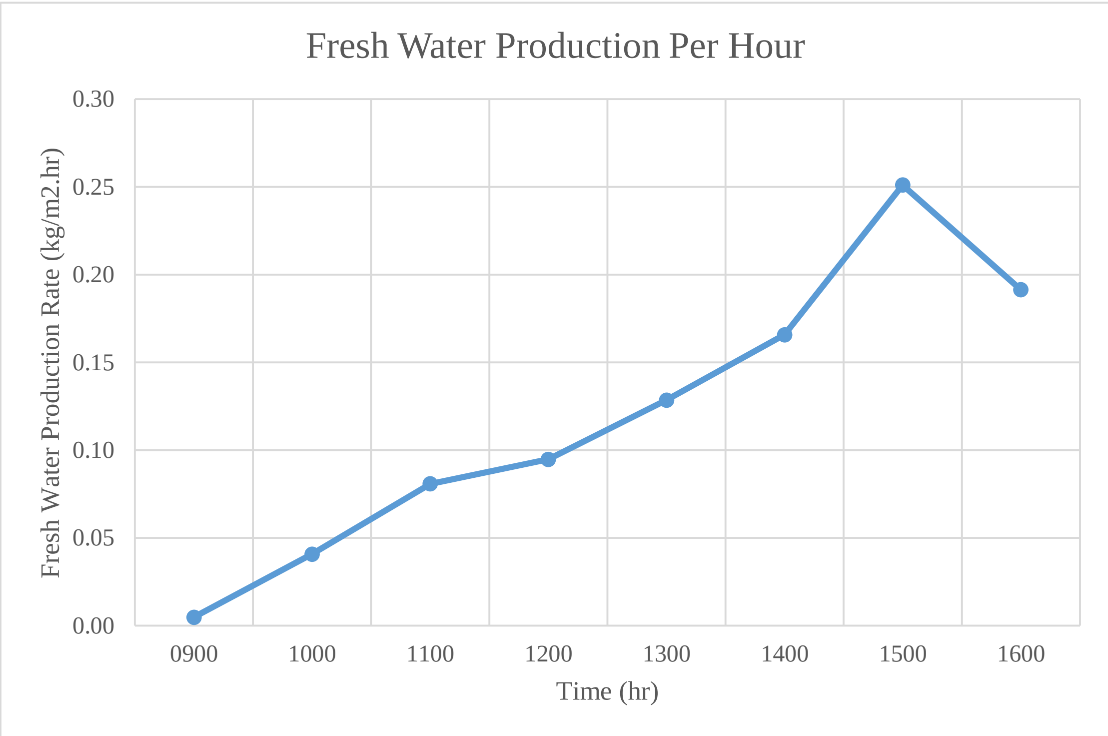

Figure 4.4: Hourly fresh water production for day 2 of experiment

Table 4.4: Experimental observation for day 3 of experiment

Time (hour)	**Temperature of Water, T_w (^OC)**	**Temperature of Glass Cover, T_g (^OC)**	**Fresh Water Production ($kg/m^2.hr$)**
0900	29.20	28.50	0.00
1000	32.70	29.40	0.04
1100	34.30	31.60	0.04
1200	38.10	33.80	0.04
1300	42.50	36.30	0.12
1400	43.80	36.80	0.12
1500	48.40	37.40	0.28
1600	45.40	35.10	0.24

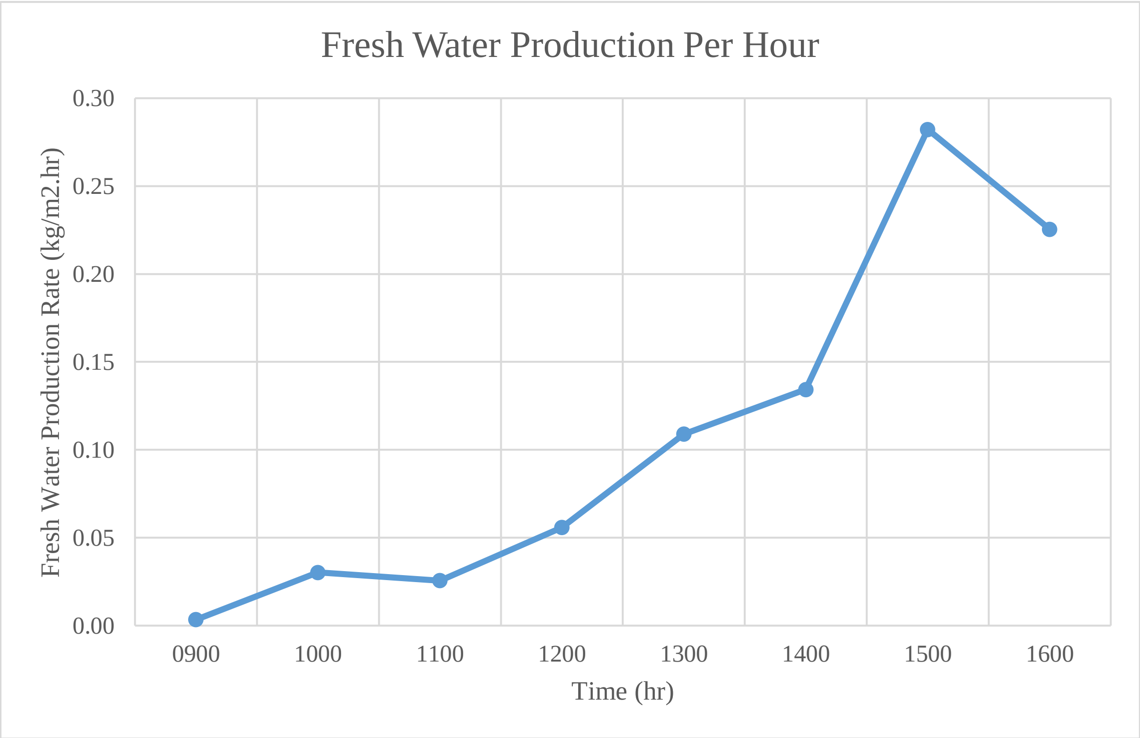

Figure 4.5: Hourly fresh water production for day 3 of experiment

Table 4.5: Experimental observation for day 4 of experiment

Time (hour)	Temperature of Water, T_w (^OC)	Temperature of Glass Cover, T_g (^OC)	Fresh Water Production ($kg/m^2.hr$)
0900	30.40	30.20	0.00
1000	36.20	32.60	0.04
1100	37.50	34.20	0.04
1200	39.60	36.70	0.04
1300	42.30	37.20	0.08
1400	45.70	37.60	0.16
1500	48.70	37.90	0.28
1600	45.20	36.10	0.20

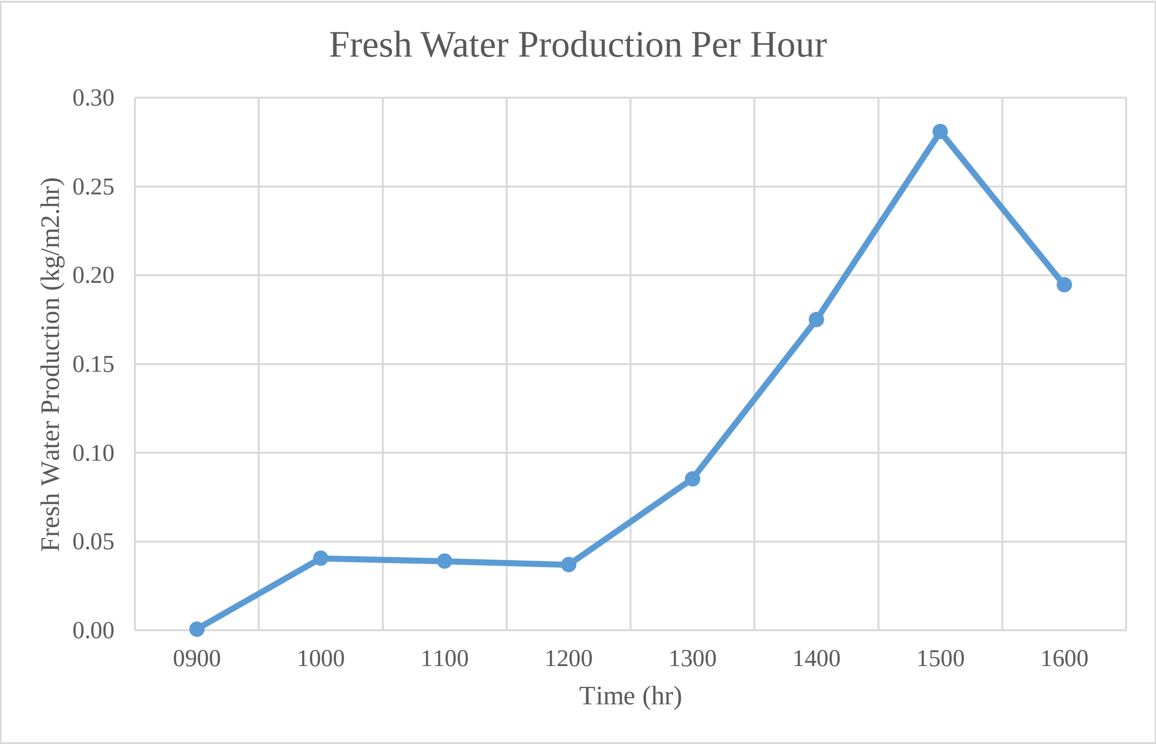

Figure 4.6: Hourly fresh water production for day 4 of experiment

Table 4.6: Experimental observation for day 5 of experiment

Time (hour)	**Temperature of Water, T_w (^{O}C)**	**Temperature of Glass Cover, T_g (^{O}C)**	**Fresh Water Production ($kg/m^2.hr$)**
0900	30.10	28.90	0.00
1000	35.40	32.80	0.04
1100	39.80	34.30	0.08
1200	44.50	36.10	0.16
1300	46.90	36.90	0.24
1400	49.40	37.20	0.32
1500	46.50	34.30	0.28
1600	46.20	34.30	0.28

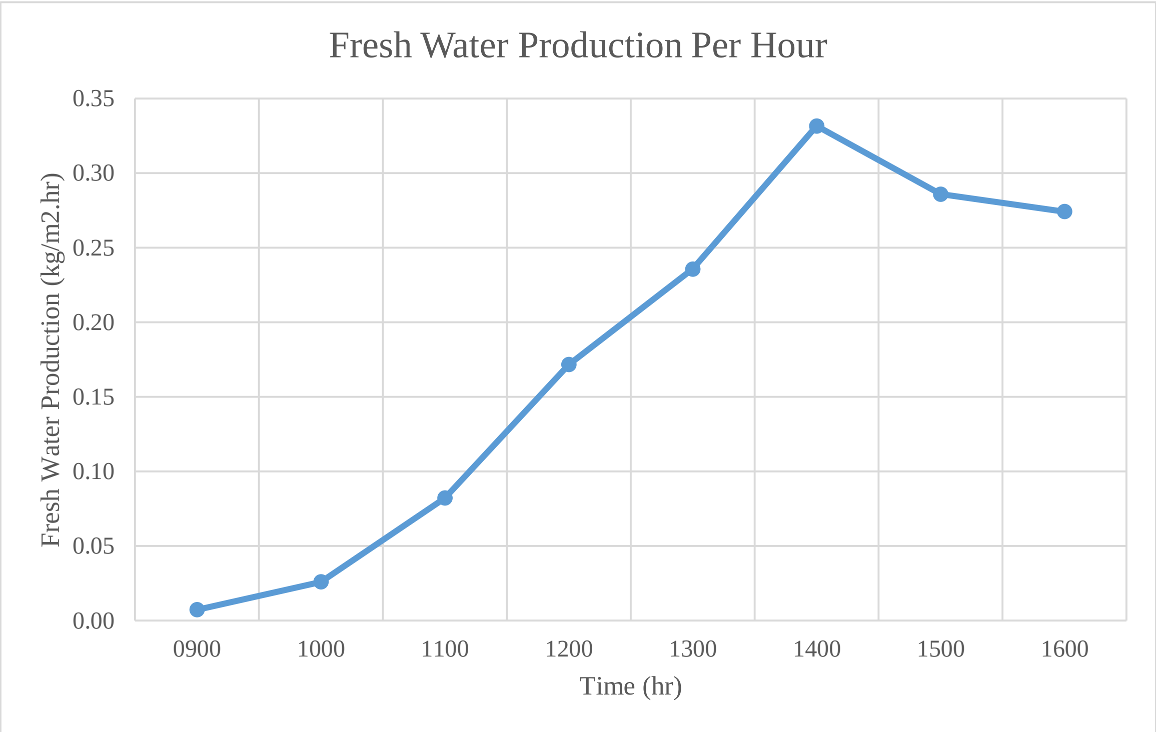

Figure 4.7: Hourly fresh water production for day 5 of experiment

Table 4.7: Experimental observation for day 6 of experiment

Time (hour)	Temperature of Water, T_w (^OC)	Temperature of Glass Cover, T_g (^OC)	Fresh Water Production ($kg/m^2.hr$)
0900	30.40	30.20	0.00
1000	37.30	33.50	0.04
1100	43.10	34.10	0.16
1200	48.90	34.90	0.35
1300	51.40	35.40	0.47
1400	51.00	36.30	0.43
1500	50.50	35.50	0.43
1600	51.50	36.30	0.47

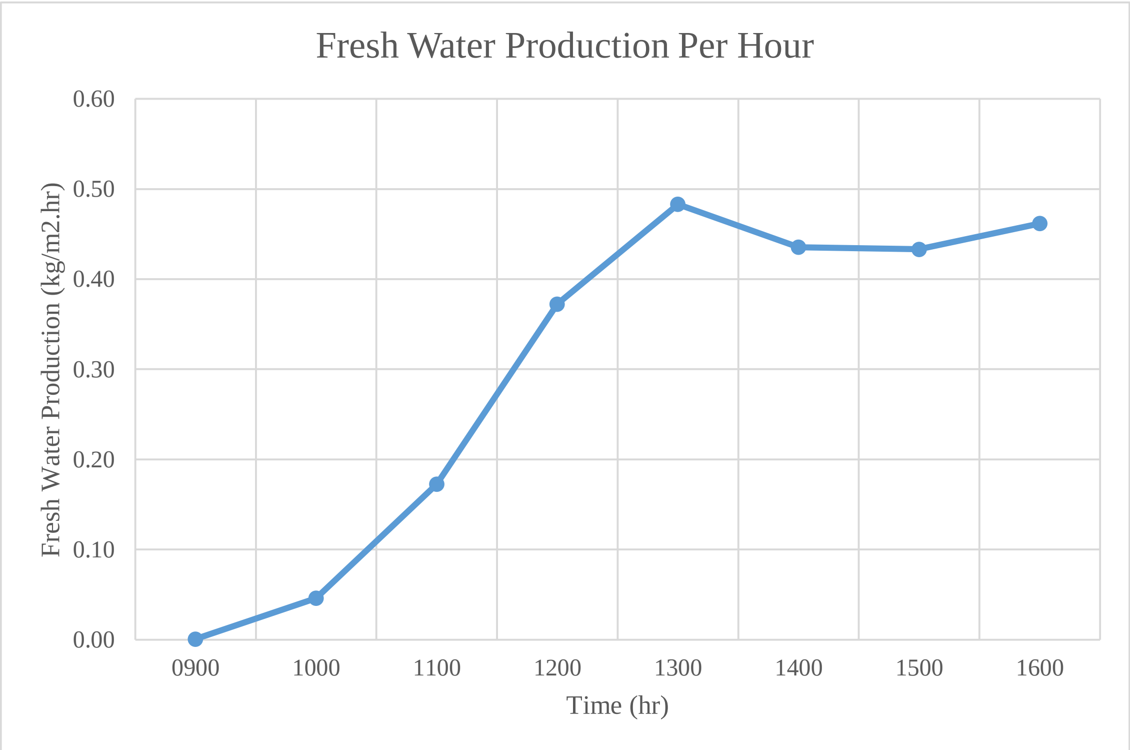

Figure 4.8: Hourly fresh water production for day 6 of experiment

Table 4.8: Experimental observation for day 7 of experiment

Time (hour)	Temperature of Water, T_w (^OC)	Temperature of Glass Cover, T_g (^OC)	Fresh Water Production ($kg/m^2.hr$)
0900	31.70	31.30	0.00
1000	42.80	33.90	0.16
1100	41.70	31.90	0.16
1200	42.50	32.30	0.20
1300	44.80	34.70	0.20
1400	49.80	34.50	0.43
1500	44.30	32.80	0.24
1600	41.50	32.60	0.16

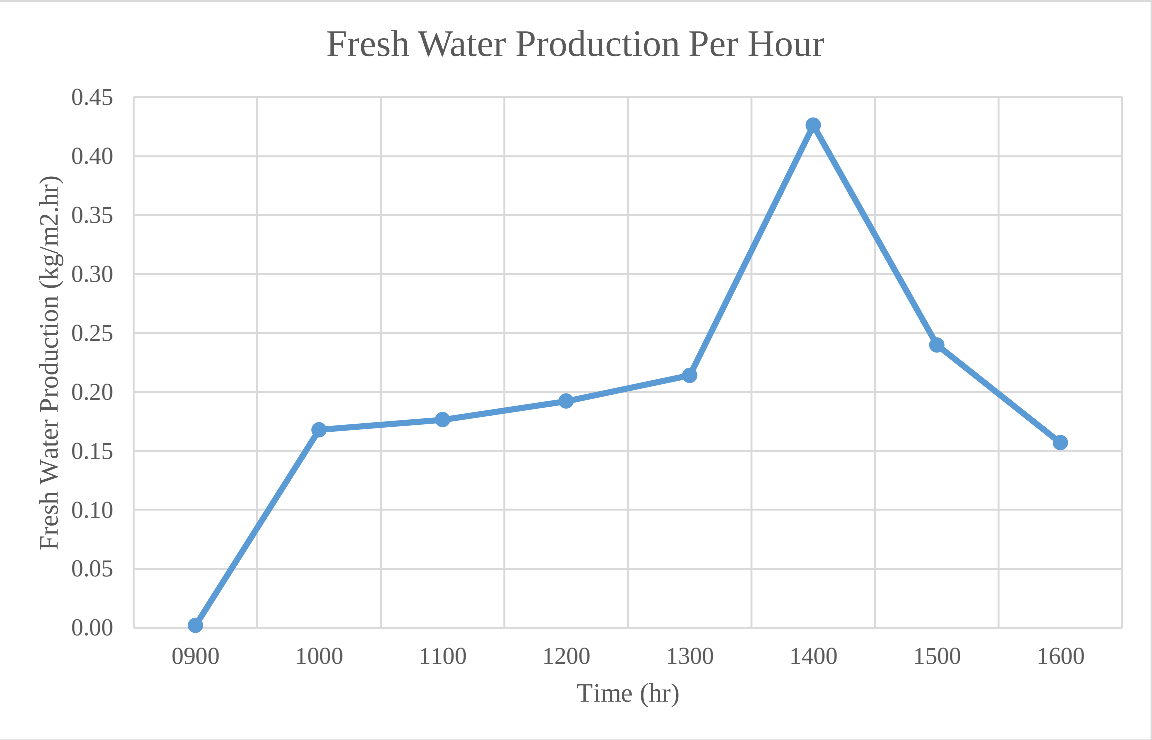

Figure 4.9: Hourly fresh water production for day 7 of experiment

Based on the following results, the pattern of the fresh water production for each day are closely similar. The maximum peak of the rate of fresh water production is between 1300 hours to 1500 hours where during this time the solar still acquire the maximum amount of solar radiation from the sun. Due to inconsistency of the weather during the experiment, the point for the fresh water production rate start to increase differ for each day. From all seven (7) days of the experiment, the maximum rate for fresh water production peaked at 0.47 $kg/m^2.hr$ on the 6^{th} day of the experiment.

By comparing the experiment analysis and the simulation analysis results, both results tally with one another. Since the CFD simulation only considered and simulate under the ideal condition of weather, the predicted results from the simulation is quite high when compared to the experimental analysis result where the solar still experience the real condition of environment and weather. From the CFD simulation, the highest rate of production rate recorded is 0.51 $kg/m^2.hr$ while from the experiment results, day 6 shows the closest results with the simulation with a rate of 0.47 $kg/m^2.hr$, 0.47 $kg/m^2.hr$ and 0.43 $kg/m^2.hr$. This is due to that is the only day that the solar still receive a constant amount of solar radiation for the evaporation to occur. The three highest reading from the results for day 6 experiment is taken and compared with the maximum reading from simulation results. The percentage of deviation for the simulation result and the experiment results is calculated to be 7.8%, 7.8% and 15.7%. It is obvious that the CFD predictions and experimental results are agreeable with one another. From both results, it clearly shows that pyramid shape cascade solar still shows a substantial increase in productivity when compared to other existing model even though being conducted in an equatorial climate. The pyramid shape cascade solar still manage to have a 57% increase in productivity when compared to single slope cascade still by Fatemeh Bakhtiari that only have 0.3 $kg/m^2.hr$ of fresh water production rate and an 27% increase in productivity when compared to Hikmet inclined solar water distillation using black fleece as wick that only have a 0.37 $kg/m^2.hr$ rate of fresh water production [5] [10].

CHAPTER 5 : CONCLUSIONS AND RECOMMENDATIONS

As the CFD simulation and experimental analysis completed, it can be observed that the evaporation of water takes place inside the solar still due to the difference in temperature between the glass cover and the water inside the solar still. A higher rate of evaporation of water will significantly affect the rate of fresh water production by the solar still. The highest rate of fresh water production by the pyramid shape cascade solar still recorded during the experiment is 0.47 $kg/m^2.hr$. This figure shows an increase of 57% in productivity when compared to a single slope cascade solar still model by Fatemeh Bakhtiari that only has 0.3 $kg/m^2.hr$ of fresh water production and an 27% increase in productivity when compared to an inclined solar still model using black fleece as wick by Hikmet that capable to yield 0.37 $kg/m^2.hr$ of fresh water production. By comparing the experimental results with the simulation results, both results are agreeable with one another. The results from the CFD simulation and experiment have a percentage deviation ranging from 7.8% - 15.7% in terms of fresh water production. The slight deviation is due to the ideal condition of weather being considered during the simulation where the experiment is conducted under real condition of weather.

Upon the completion of this project, several ideas for improvement are gathered for the future works on this project. The list of the recommendations are as follow:

- The solar still can be incorporated with an internal reflector in each step to increase the efficiency of the solar still.
- The use of glass wool material as insulator for the bottom plate of the solar still is also recommended to reduce the amount of heat loss from the solar still.
- Increasing the number of points where the change in temperature of the water and glass cover monitored during the experiment and cross linking the points to CFD simulation to ensure the consistency of the results for both analyses.
- Putting into account the costing analysis for the project to be implemented in the future by considering the costs of material, construction, total maintenance needed for each year, total revenue generated from the fresh water production and the payback period.

- Specifying on what type of material to be used as the glass cover that can increase the rate of absorption of solar radiation by the solar still by conducting research studies on the conductivity, absorptivity and transmitivity of the glass materials.
- Research studies on the optimization of the distance between the glass cover and the base plate to enhance the rate of evaporation inside the solar still.
- Developing an adjustable angle of inclination for the pyramid shape cascade solar still to optimize the angle of incidence of the solar radiation according to the direction of the sun.
- Enabling the multiphase option inside the modeling of CFD to observe the amount of distillate being produce without having to monitor the temperature of glass cover and water constantly throughout the simulation process.

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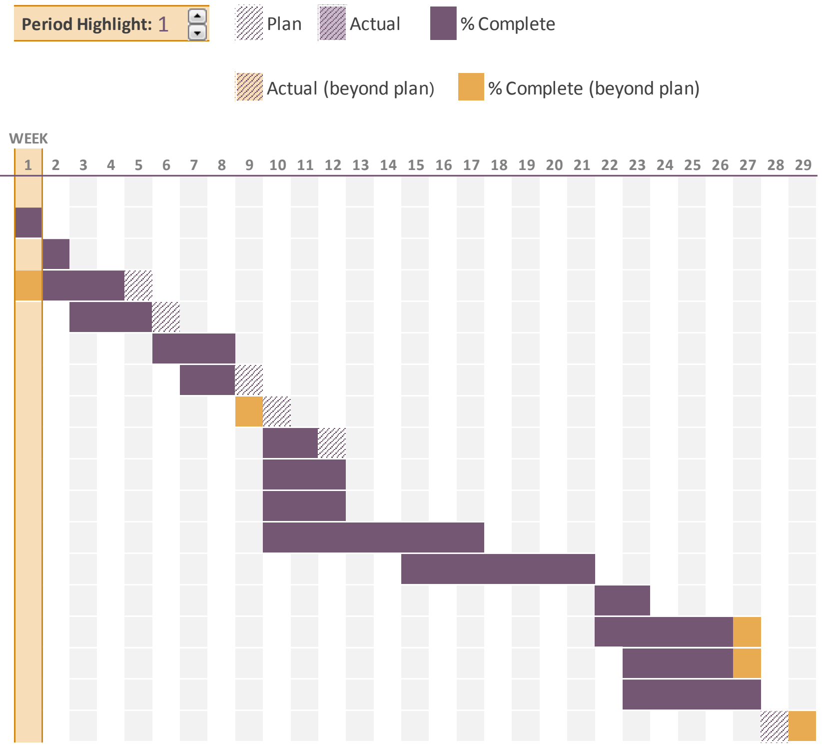
APPENDICES

Appendix 1 – Gantt chart

Efficient Water Recycling Through Solar Distillation

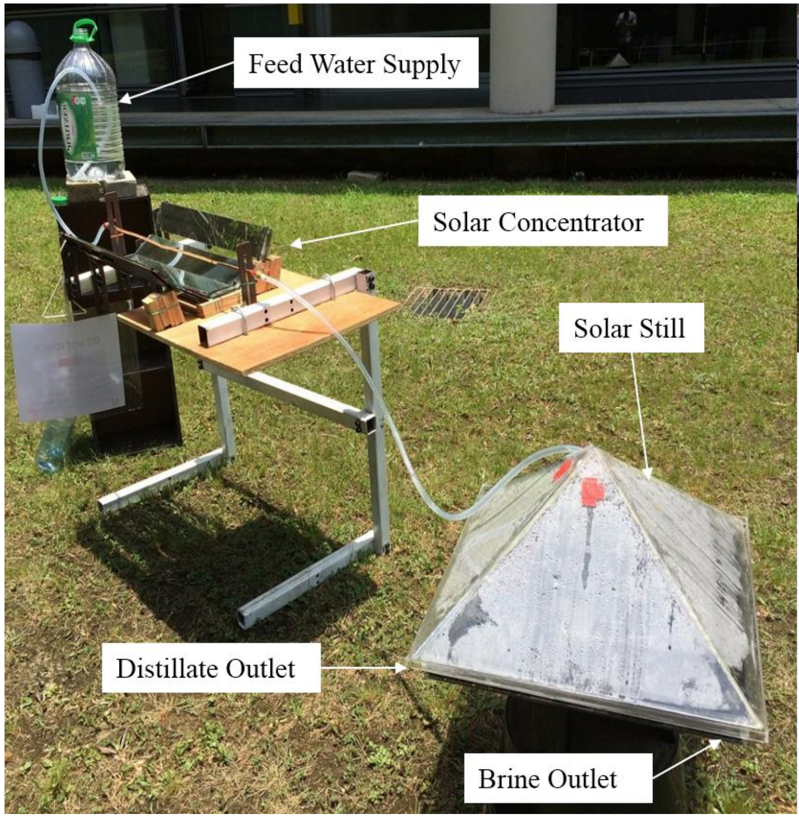
ACTIVITY	PLAN START	PLAN DURATION	ACTUAL START	ACTUAL DURATION	PERCENT COMPLETE
PROJECT PERIOD					
Selection of Project Topic	1	1	1	1	100%
First Meeting with Assigned Supervisor	2	1	2	1	100%
Information Gathering	2	4	1	4	100%
Design Classification and Evaluation	3	4	3	3	100%
Conceptual Designs ₡	6	3	6	3	100%
Evaluation of Conceptual Design ₦	7	3	7	2	100%
Final Selected Design ¶	10	1	9	1	100%
Determination of Project Activities	10	3	10	2	100%
Determination of Tools and Equipments	10	3	10	3	100%
Procurement of Tools and Equipment ₩	10	3	10	3	100%
Project Simulation Using ANSYS ₪	10	8	10	8	100%
Fabrication of Prototype ₱	15	7	15	7	100%
Test Run for the Prototype	22	2	22	2	100%
Project Experimentation Using Prototype ¶	22	5	22	6	100%
Comparison of Results ¶	23	4	23	5	100%
Tabulation of Data and Results ₹ ₺ ₽ ₲	23	5	23	5	100%
Viva ₴	28	1	29	1	100%

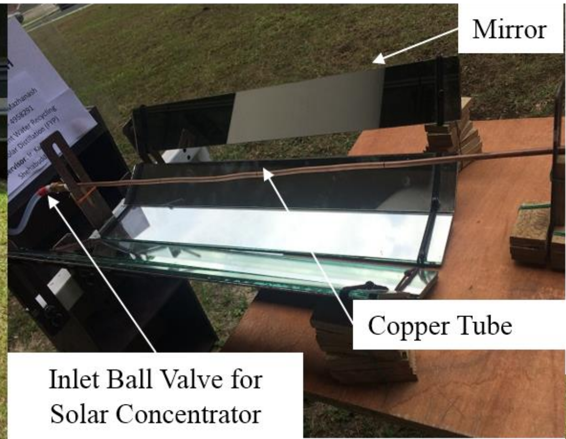


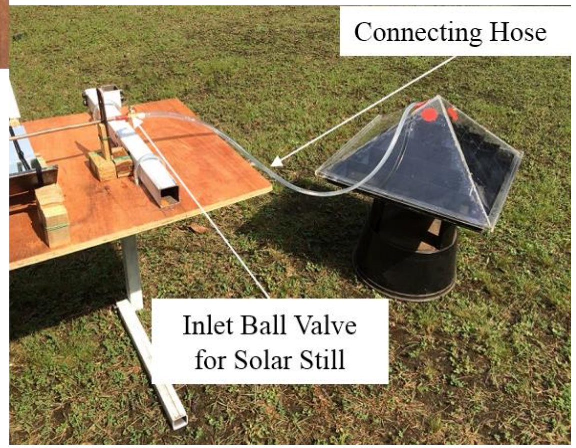
₡ = Submision of Extended Proposal
₦ = Proposal Defence
₩ = Submision of Interim Draft Report
₪ = Submision of Interim Report
₱ = Submision of Progress Report
₹ = Pre-SEDEX

¶ = Key Milestone
₺ = Submision of Draft Final Report
₽ = Submision of Dessertation (Softbound)
₲ = Submision of Technical Report
₴ = Submision of Dessertation (Hardbound)

Appendix 2 – Set up of the Experiment







Appendix 3 – Distillate produce from the solar still

Appendix 4 – Recording of the temperature using data logger thermometer