Solar-driven Desalination by Humidification-dehumidification
(Prototype Fabrication)

By

Hazlami Ahmad Nizam

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Chemical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Chemical Engineering Programme
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(CHEMICAL ENGINEERING)

Approved by,

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May 2013

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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(HAZLAMI AHMAD NIZAM)

ABSTRACT

World-wide water scarcity, especially in the developing world, indicates a pressing need to develop inexpensive, decentralized small-scale desalination technologies which use renewable resources of energy. However, conventional desalination technologies are usually large-scale, technology intensive systems most suitable for the energy rich and economically advanced regions of the world. They also cause environmental hazards because they are fossil-fuel driven and also because of the problem of brine disposal. Solar desalination with a humidification and dehumidification process has proven to be an efficient means of utilizing solar energy for the production of fresh water from saline or sea water. This technique presents several advantages such as flexibility in capacity, moderate installation and operating costs, simplicity, and possibility of using low temperature energy such as geothermal and solar. In this project, the objective is to experimentally fabricate solar desalination prototype applies humidification and humidification principle with minimum low cost of fresh water production and also simplicity in terms of the technology applied. Thus, through this studies and prototype fabrication, the author hope it will be a platform to drive the commercialization of a solar desalination based on humidification and dehumidification principle due to incoming short fresh water supply in future especially for small quantities in remote areas.

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ABBREVIATIONS AND NOMENCLATURES

HDH	Humidification dehumidification
CAOW	Closed Air Open Water
CWOA	Closed Water Open Air

CHAPTER 1

INTRODUCTION

1.1 Project Background

Water is one of the most abundant resources on earth which is essential to life, covering three-fourths of the earth's surfaces. About 97% of the earth's water is salt water in the oceans and 3% is fresh water contained in the poles (in the form of ice), ground water, lakes and rivers, which supply most of human and animal needs. Man has been dependent on rivers, lakes and underground water reservoirs for fresh water requirements in domestic life, agriculture and industry.

However, rapid industrial growth and the worldwide population explosion have resulted in a large escalation of demand for fresh water. On a global scale, man-made pollution of natural sources of water is becoming one of the largest causes for fresh water shortage. Then, provision of fresh water is becoming an increasingly important issue in many areas of the world.

In order to counter this, many countries have turned to desalination to derive usable water from the seawater because the only nearly inexhaustible sources of water are the oceans. Their main drawback, however, is their high salinity. Therefore, it would be attractive to tackle the water-shortage problem with desalination of this water. Desalinize in general means to remove salt from seawater or generally saline water.

1.1.1 Desalination Process

According to World Health Organization (WHO), the permissible limit of salinity in water is 500 parts per million (ppm) and for special cases up to 1000 ppm, while most of the water available on earth has salinity up to 10,000 ppm, and seawater normally has salinity in the range of 35,000–45,000 ppm in the form of total dissolved salts (Kalogirou, 2004). Excess brackishness causes the problem of taste, stomach problems and laxative effects.

The purpose of a desalination system is to clean or purify brackish water or seawater and supply water with total dissolved solids within the permissible limit of 500 ppm or less. Desalination can be achieved by using a number of techniques. Industrial desalination technologies use either phase change or involve semi-permeable membranes to separate the solvent or some solutes. Desalination of seawater can be accomplished by several desalination methods as shown in Table 1.

Desalination Process	
Phase-change Processes	**Membrane Processes**
Multi-stage Flash (MSF) Multi Effect Boiling (MEB) Vapour-compression (VC) Freezing Humidification/Dehumidification Solar Stills	Reverse Osmosis (RO) Electrodialysis

Table1.1: Desalination Process

The conventional desalination techniques like (MSF), (ME), (VC) and (RO) are only reliable for large capacity ranges of 100–50,000 m3/day of fresh water production (Shaobo Houa, 2005). Desalination processes require significant quantities of energy to achieve separation of salts from seawater. These technologies are also expensive for small amounts of fresh water, and they cannot be used in locations where there are limited maintenance facilities and energy supply.

In addition, the uses of conventional energy from hydrocarbon fuels sources to drive these technologies have negative impacts on the environment. Thus, apart from satisfying the additional energy demand, environmental pollution would be a major concern (Shaobo Houa, 2005). Table 1.2 summarizes the comparative analysis of different methods of solar desalination and other methods of conventional desalination in terms of their advantages and disadvantages.

Method	Advantages	Disadvantages
Multi-stage Flash	• Relatively low investment costs.	• High maintenance cost, since it requires extensive training
Reverse-Osmosis	• One of the simplest forms of desalination in theory. • Simply pushes the water through a filter.	• Requires a skilled laborer to operate. • The membranes are also complex polymers that require precise manufacturing
Electrodialysis	• Does not require any of the solution to change its state of matter. • Simply separates the solute from the solvent, in this case salt and water respectively	• Requires massive amounts of electricity to produce the desired effect. • May not be financially feasible for many countries suffering from water shortages
Solar Desalination	• No energy costs due to the use of solar panels. • Costs of solar panels are decreasing. • Very low maintenance	• Requires a lot of space. • Initial investment cost due to the price of land. • Current costs of panels are expensive. • No economy of scale.

Table1. 2: Comparative Analysis of Desalination Methods (Zachary Taillefer)

1.1.2 Solar Desalination

Fortunately, there are many parts of the world that are short of water but have exploitable renewable sources of energy that could be used to drive desalination processes. Thus, desalination processes by using solar radiation or solar desalination processes are future promising alternative that can partially support human needs for fresh water with free environmentally friendly energy source and also suitable for few families or small groups in remote areas (Hassan E.S. Fath, 2001).

Solar desalination may be divided into direct and indirect methods. In the direct methods, the solar energy collector and desalination unit is an integral unit, for example is solar stills. In the indirect method, the solar energy is first converted to usable heat or electricity which is then used as an energy source for desalination units (Hassan E.S. Fath, 2001).

Literally, solar desalination requires an efficient method of evaporation and condensation at relatively low temperatures. Therefore, the most promising development in solar desalination to enhance productivity efficiency was the use of the humidification and dehumidification principle. Thus combining the principle of humidification-dehumidification with solar desalination appears to be the best method of water desalination with solar energy (Said A1-Hallaj, 1998).

Potentially, solar desalination offers an ecologically advantageous means of renewable energy utilization at a minimum cost and modest level of technology employed. Although solar desalination is not viable option at the present, further research in the efficiency of solar energy utilization will make solar desalination the most economically advantageous of methods.

1.2 Problem Statement

The supply of fresh water is becoming an increasingly crucial issue in many areas of the world. *Potable water shortage is expected to be one of the major worldwide challenges of the near future*. A considerable increase in fresh water demand, coupled with a lack of fossil energy sources is expected, especially for developing countries experiencing significant population growth.

These conventional processes are well established and well documented, but they are costly and inefficient from the viewpoint of energy consumption. Moreover, these units require high maintenance and skilled operation due to the practical difficulties associated with the high operating temperature, such as corrosion and scale formation.

The sequence of scenarios of having mass demand of fresh water supply in future *necessitates designing desalination processes that use renewable energy* such as solar energy in the least capital-intensive manner.

1.3 Objective

The objective of this project is to experimentally fabricate solar desalination prototype applies humidification and humidification principle and to study the effect of water flowrate and air flowrate towards overall collection efficiency.

Thus, through this studies and prototype fabrication, the author hope it will be a platform to drive the commercialization of a solar desalination based on humidification and dehumidification principle due to incoming short fresh water supply in future especially for small quantities in remote areas, with minimum low cost of fresh water production and also simplicity in terms of the technology applied.

1.4 Scope of Study (Feasibility of the Project)

The completion of this project is divided into two stages where the first stage is majorly involves a lot of research study to understand the concept of humidification and dehumidification processes in solar desalination. Thus, previous research papers about solar desalination are reviewed to give better understanding of this project and also to find any gaps of improvements from the previous pilot plants and the prototype built. While, fabrication of prototype is done in the second stage which involves experimental studies to further improve the prototype designed.

The time frame given is approximately 5 months to complete the project. This project is feasible to be carried out within the time frame. The equipment and tools needed to conduct the experiment are all available and provided, furthermore the dateline in the gantt chart guide the project progress accordingly.

CHAPTER 2

LITERATURE REVIEW/THEORY

2.1 Literature Review/Theory

This chapter will discuss on the previous work done by the researcher and critical analysis towards the results and methodologies used.

2.1.1 Overview of Humidification-dehumidification (HDH) Desalination

Solar desalination is gradually emerging as a successful renewable energy source of producing fresh water and potentially, solar desalination with a HDH process has been proven experimentally to be an efficient means of utilizing solar energy for the production of fresh water from saline or sea water. The technology of humidification and dehumidification satisfies these fresh water demands with flexibility in capacity, moderate installation and operating cost (IS. Bourounia)

Nawayseh et al. have shown that humidification and dehumidification process is an efficient methods solar desalination and Figure 2.1 show the sketch of such desalination.

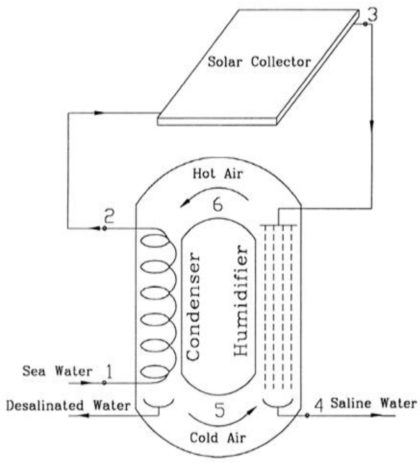

Figure 2.1: Sketch of Solar Desalination Process (Nawayseh NK)

The units, based on such a process, usually consist of two vertical ducts connected from the top and the bottom ends to form a closed loop for air circulation. The units may be operated in a forced or natural draft mode. A large surface condenser is usually fixed in one of the ducts, while wooden packing is used in the other duct for efficient humidification of the air (Nawayseh NK).

Based on Figure 2.1, the saline water is fed to the condenser to condense partially the water vapor from the air. The latent heat of condensation is used to preheat the feed water, which is further heated in a flat solar collector before it is sprayed over the wooden the wooden packing in the humidifier. The air is continuously heated and humidified, then partially dehumidified in the condenser. The desalinated water is collected from the bottom of the condenser, while the warm brine is rejected from the bottom of the humidifier (Nawayseh NK).

The successful feature of the process lies in its ability to utilize the latent heat of condensation by preheating the feed saline water (Hamad, 1993). Al-Hallaj et al. also investigated a solar desalination unit functioning by humidification and dehumidification and found out that the key to success is by utilizing the latent heat of condensation to preheat the feed saline water. In their unit, the circulated air by natural or forced convection was heated and humidified by the hot water obtained either from a flat-plate solar collector or from an electrical heater. The latent heat of condensation was recovered in the condenser to preheat the saline feed water (S. Al-Hallaj, 1998) .

2.1.2 Parameter Affecting Performance of Desalination Unit

Water desalination by humidification and dehumidification has been the subject of many investigations (Nebbia, 1968). Different experimental data are available for using humidification and dehumidification at the pilot or industrial scale. An inspection of these data allows establishing many perspectives for this process. Performance of the desalination unit may be affected by different parameters on the system productivity such as water flow rate, air flow rate, solar intensity and the design of the unit itself. Since then, continuous investigation on these influences were made to optimize the performance of solar desalination based on humidification and dehumidification principle.

K.Bourouni et al. highlighted a strong effect of water flow rate on a unit production. In fact, the unit production first increases upon increasing the flow rate to an optimum value. Beyond that value the unit production decreases with increasing water flow rate. This is because increased water flow rate increases heat and mass transfer coefficient as well as the solar collector efficiency. At the same time, it lowers the operating water temperature in the unit, hence lowers the evaporation and condensation efficiency (IS. Bourounia).

The simulation done by Nawayseh et al. concluded that the effect of air flow rate on the desalination production was found small. In their further research, the effect of air flow was very small, indicating that natural draft is more favorable than the forced draft operation (NaserKh. Nawayseha, 1998). K.Bourouni et al. also showed that no significant improvement in the performance of the desalination unit was achieved using forced air circulation at high temperature. While at lower temperature, a larger effect was noticed. K.Bourouni et al. related this to low mass transfer coefficients at low temperatures and to the non-linear in the water vapour pressure with temperature (IS. Bourounia).

The effect of solar intensity on the productivity was studied by Nafey et al. (A.S. Nafey a, 2003). In their study, the increasing solar intensity increases the total energy gained by the system that increases the temperature both the water and air inlet to the humidifier. This leads to increasing that rate of water vaporization and the unit productivity. Within the range studied, the ambient temperature however an insignificant effect on the productivity.

According to their investigation (IS. Bourounia) it was shown that mass of the unit is another factor that negatively affects the unit performance. A delay of 3 hour was noticed between sunrise and the start of production of fresh water. It was noticed that most of the energy received in these early hours is used as sensible heat to warm up the large mass of the unit, which was about 300 kg. This lag time could be avoided by using a lighter material than galvanized steel for construction.

Most of the previous investigators (Mahmoud Ben-Amara, 2004) on the humidification and dehumidification solar desalination reported that the large variation in the productivity of the different desalination units in the literature suggests that the design of some of these units was far from optimum. The effects of some parameters such as water flow rate, air flow rate and solar intensity on the production rate was complicated by its combined effects on the performance of the condenser, humidifier and solar collector.

2.1.3 Review of Components Design

Solar water-heating systems have been studied and used widely for many decades and hence extensive knowledge exists on the design of these systems. Solar air heating, in contrast, has not been studied extensively (HP, 1975).

The collectors are typically flat plate with large airflow channels. Air flows over or under the absorber plate, and double-pass strategies are sometimes employed. Figure 2.2 taken from shows the layout of a typical air-heating collector.

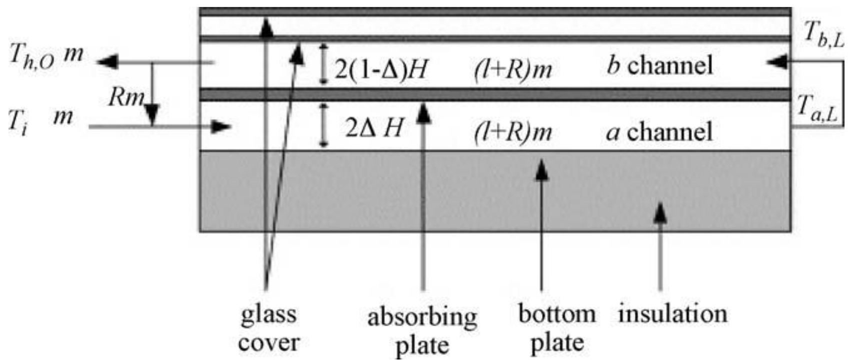

Figure 2.2: Layout of a Typical Air-heating Collector (Ho CD, 2005)

Solar air-heating systems have been used since the World War II for home heating and low temperature applications. The Colorado solar house, built in 1959, utilized a heater that had stacked absorber plates in a panel with a single glazing to achieve a moderate temperature rise for home heating and cooling with 30% collection efficiency (Lof GOG, 1963). To date there are no commercial systems that utilize solar air heaters for solar desalination, only for home heating and crop drying. Most products have moderate temperature rise, and are very expensive.

Many devices are used for air humidification including spray towers, bubble columns, wetted-wall towers and packed bed towers (RE, 1980). The principle of operation for all of these devices is same. When water is brought into contact with air that is not saturated with water vapor, water diffuses into air and raises the humidity of the air. The driving force for this diffusion process is the concentration difference between the water–air interface and the water vapor in air. This concentration difference depends on the vapor pressure at the gas–liquid interface and the partial pressure of water vapor in the air.

Younis et al. (Kreith F, 1988) and Ben-Amara et al. (Younis MA, 1993) used a spray tower as the humidifier in their HDH systems. Ben-Amara et al. tested the spray tower humidifier by varying the ratio of water-to dry air mass flow rate and keeping the inlet water temperature and absolute humidity constant. The inlet air temperature (80 8C) was higher than the water spray temperature (60 8C). They found that increasing the amount of water sprayed increased the absolute outlet humidity.

However, further increase in the water quantity resulted in air cooling and this condensed some of the water vapor content in the air. This means a decrease in the absolute humidity, although the outlet air is always saturated. Therefore, for air heated HDH cycles there is an optimum value of the mass flow ratio which gives maximum air humidity. This fact promotes the use of multi-stage air heater and humidifier combinations to increase the fresh water production.

Wetted-wall towers have been used as humidifier in HDH systems by Mu¨ ller-Holst et al. (E, 2004) and Orfi et al. (Orfi J, 2004). In a wetted wall tower, a thin film of water is formed running downward inside a vertical pipe, with air flowing either co-currently or counter currently. Water is loaded into the top of the tower and a weir distributes the flow of water around the inner perimeter of the tube that wets the inner surface of the tube down its length. To improve the heat and mass exchange process, they covered the wooden vertical wetted-walls with a cotton wick to reduce the water flowing velocity and use the capillary effect to keep the vertical walls always wetted. Their design shows higher performance with about 100% humidification efficiency.

The types of heat exchangers used as dehumidifiers for HDH applications vary. For example, flat-plate heat exchangers were used by Mu¨ ller-Holst et al. (E, 2004). A flat-plate heat exchanger made of double webbed slabs of propylene was used by Mu¨ ller-Holst et al. in his HDH system. The distillate runs down the plates trickling into the collecting basin. Heat recovery is achieved by transferring heat to the cold seawater flowing inside the flat-plate heat exchanger. The temperature of seawater in the condenser increases from 40 to 75 8C.

Bourouni et al. (IS. Bourounia) used a condenser made of polypropylene which was designed to work at low temperatures (70–90 8C) for a HDH system. It is similar to a horizontal falling film-type condenser. At the top of the dehumidifier, the hot humid air is forced down where the distilled water is recovered. It is important to note that heat recovery in an HDH system requires a larger heat transfer area for improving the overall system performance.

CHAPTER 3

RESEARCH METHODOLOGY

This chapter will discuss the detail explanation of methodology that is used upon completing the project. This project is divided into a few stages to ensure a smooth flow.

3.1 Work Process Flow

Figure 3.1: Work Process Flow

3.2 Project Activities

Methodologies in this experiment is developed to comply with objectives that been stated in previous chapter.

3.2.1 To Study the Concept of Humidification-dehumidification Desalination

In order to achieve the first objective, the background study on the concept of humidification and dehumidification in solar desalination are necessary to be done. Background study helps to have better understanding of the project. By doing research study, overview of the project become clearer and helps to justify the direction and purpose of this project.

During preliminary research, work of study and read journals of previous work related to solar desalination with humidification and dehumidification principle. During this phase, outlining the gaps of previous work which will be further closed in this ‘product design’s project. Using all the references, methodologies for this project can be developed and proceed with the next project activities.

3.2.1.1 Findings of the Study

Nature uses solar energy to desalinate ocean water by means of the rain cycle. In the rain cycle, seawater gets heated (by solar irradiation) and humidifies the air which acts as a carrier gas. Then the humidified air rises and forms clouds. Eventually, the clouds ‘dehumidify’ as rain. The man-made version of this cycle is called the humidification–dehumidification desalination (HDH) cycle.

The simplest form of the HDH process is illustrated in Figure 3.2. The process consists of three sub-systems: (a) the air and/or the water heater, which can use various sources of heat like solar, thermal, geothermal or combinations of these; (b) the humidifier or the evaporator; and (c) the dehumidifier or the condenser.HDH systems are classified under three broad categories. One is based on the form of energy used such as solar, thermal, geothermal, or hybrid systems. This classification brings out the most promising merit of the HDH concept, the promise of water production by use of low-grade energy, especially from renewable resources.

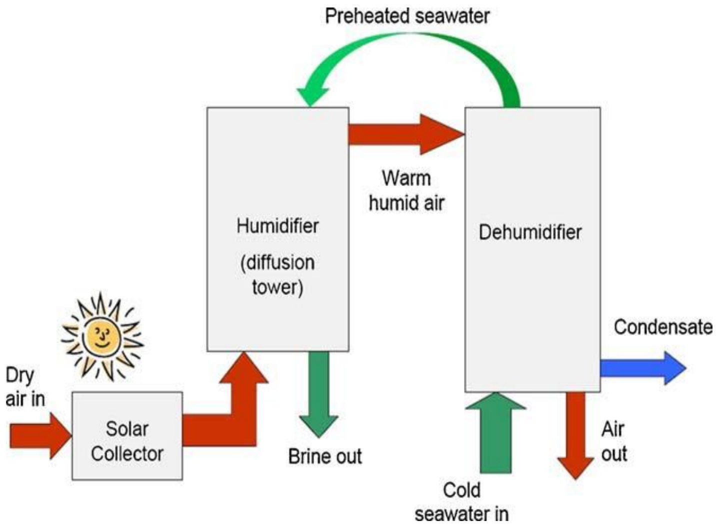

Figure 3.2: A Simple Humidification – Dehumidification (HDH) Process

The second classification of HDH processes is based on the cycle configuration as shown in Figure 3.3. As the name suggests, a closed-water open air (CWOA) cycle is one in which the air is heated, humidified and partially dehumidified and let out in an open cycle as opposed to a closed-air cycle wherein the air is circulated in a closed loop between the humidifier and the dehumidifier. The air in these systems can be circulated by either natural convection or mechanical blowers.

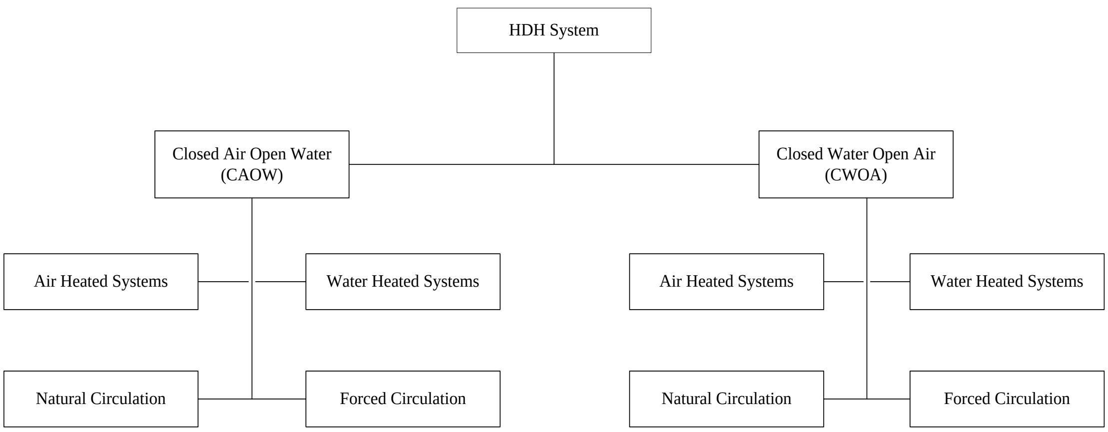

Figure 3.3: Classification of Typical HDH Processes (Based on cycle configuration)

The third classification of the HDH systems is based on the type of heating used: water-heating or air-heating systems. The performance of the system depends greatly on whether the air or water is heated.

I. Closed-air open-water (CAOW) water-heated systems

A typical CAOW system is shown in Figure 3.4. The humidifier is irrigated with hot water and the air stream is heated and humidified using the energy from the hot water stream. The humidified air is then fed to the dehumidifier and is cooled in a compact heat exchanger using seawater as the coolant. The seawater gets pre-heated in the process and is further heated in a solar collector before it irrigates the humidifier.

The dehumidified air stream from the dehumidifier is then circulated back to the humidifier.

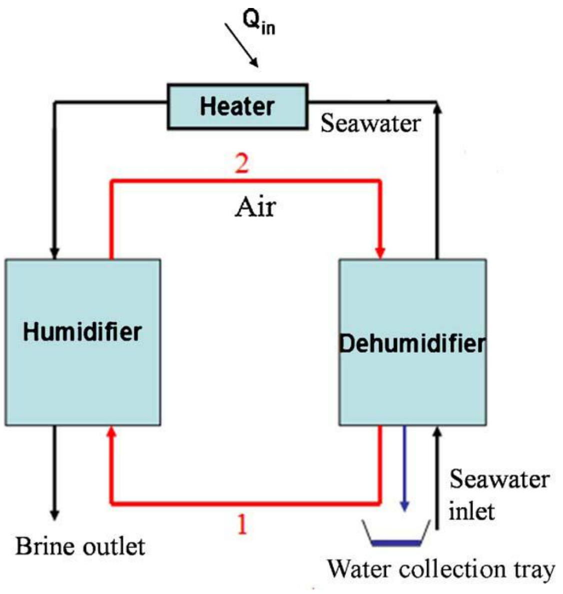

Figure 3.4: A Typical Water Heated CAOW HDH Process

There are several works in the literature on this type of cycle. The important features of the system studied and the main observations from these studies are tabulated in Appendix A (Table A.1). Some common conclusions can be drawn from this table. Almost all the investigators have observed that the performance is maximized at a particular value of the water flow rate.

There is also an almost unanimous consensus that natural circulation of air yields better efficiency than forced circulation of air for the closed-air water heated cycle. However, it is not possible to ascertain the exact advantage in performance (for natural circulation) from the data available in literature.

II. Closed-water-open-Air (CWOA) water-heated systems

A typical CWOA system is shown in Figure 3.5 In this system the air is heated and humidified in the humidifier using the hot water from the solar collector and then is dehumidified using outlet water from the humidifier. The water, after being pre-heated in the dehumidifier, enters the solar collector, thus working in a closed loop. The dehumidified air is released to ambient.

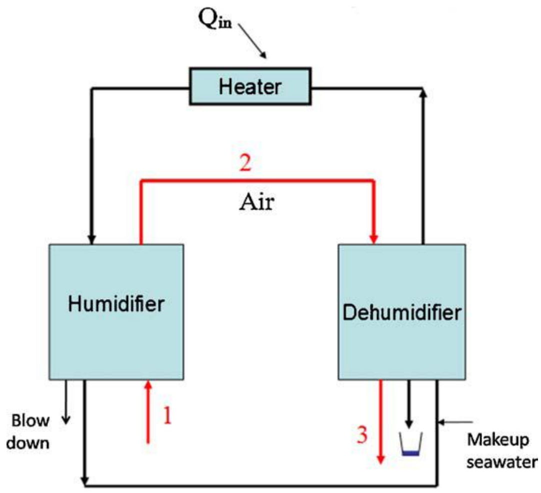

Figure 3.5: A Typical Water-heated CWOA HDH Process

Previous works on water-heated (CWOA) is shown in Appendix B (Table B.1). One disadvantage of the CWOA is that when the humidification process does not cool the water sufficiently the coolant water temperature to the inlet of the dehumidifier goes up. This limits the dehumidification of the humid air resulting in a reduced water production compared to the open-water cycle.

However, when efficient humidifiers at optimal operating conditions are used, the water may be potentially cooled to temperature below the ambient temperature (up to the limit of the ambient wet-bulb temperature). Under those conditions, the closed-water system is more productive than the open-water system.

III. Closed-air open-water (CAOW) air-heated systems

Another class of HDH systems which has attracted much interest is the air-heated system summarized in Appendix C (Table C.1). These systems are of two types– single and multi-stage systems. Figure 3.6 is a schematic diagram of a single stage system. The air is heated in a solar collector to a temperature of 80–90ºC and sent to a humidifier. A major disadvantage of this cycle is that the absolute humidity of air that can be achieved at these temperatures is very low (<6% by weight). This impedes the water productivity of the cycle (G. Prakash Narayan a, 2010).

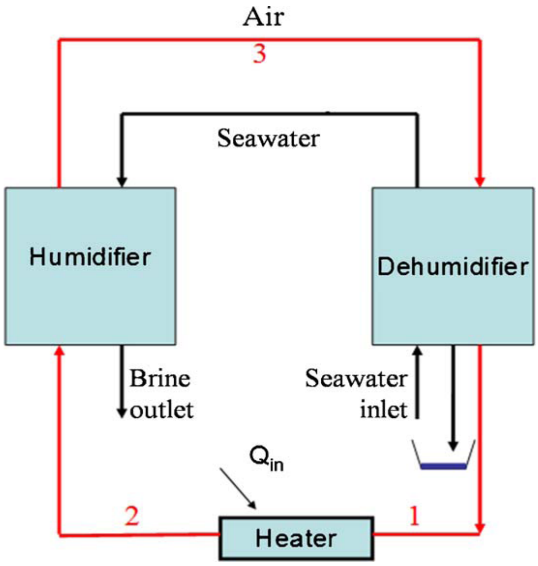

Figure 3.6: A Typical Air-heated CAOW HDH Process

3.2.2 Prototype Fabrication

At this stage, the author has come out with several design of prototype. Selection of the most viable design will be done based on the available materials needed; simplicity of fabrication, minimum cost and the most important is the feasibility to fabricate the prototype. There are three main components involved in fabrication which are water-heating solar collector, humidifier and dehumidifier. (Fabrication of Prototype shown in **Appendix F**)

I. Water-heating Solar Collector (Kit, January 2009)

Solar collector (or Solar Heat Collector) capture the sunlight and transform radiant energy into heat energy. The system consists of wooden casing body with good insulation using Rockwool. The transparent medium is double glass cover to allow the solar radiation penetrate to the collector plate. The plate is designed as heat exchanger which is copper plate with extended surface (fins) in the wax medium.

Water is flowing through the system by two main headers as feeding and discharging header with eight copper pipes connecting them to allow water flow.

The 14 mm internal diameter header and 10 mm diameter internal diameter copper tubes are immersed in the storage unit and the tubes are in perfect touch with the extended surface of the heat exchanger unit to achieve heat transfer to the flowing water. Figure 3.7 shows the sketch of the designed water-heating solar collector.

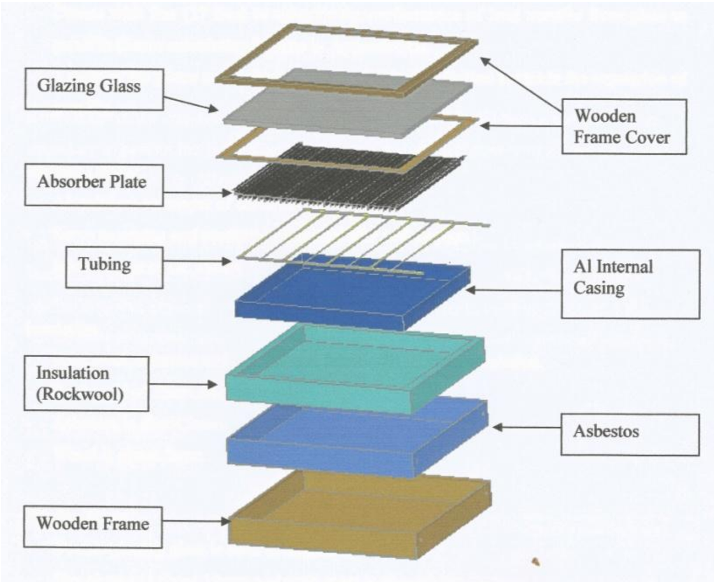

Figure 3.7: Exploded View of Solar Collector (Kit, January 2009)

The solar collector is made of four main components, absorber plate, internal casing, insulation and glazing glass. Table 3.1 shows the features of the solar collector.

Table 3.1: Features of the Solar Collector (Kit, January 2009)

Component	Feature
Absorber Plate	• Surface is dark/black in color to ensure maximum heat absorption. • Comes with fins (37 fins) to enhance the performance of heat transfer from plate to paraffin
Internal Casing	• Copper of thickness 1 mm is used • Serve as casing and medium of heat transfer and and storage • Internal area of the casing is $1m^2$

Insulation	• Rockwool, asbestos and the wooden frame will serve as insulation. • Rockwool of 15 cm shall be used • Asbestos is about 3 mm • Wood is about 5 mm
Glazing Glass	• Double glazing glass is used to minimize heat loss • The air gap is about 19 mm and each glass is about 3 mm thickness • Overall thickness is about 25 mm

II. Humidifier

During this stage, the focus is on the preliminary design and concept of humidifier. The basic concept of humidifier is basically a chamber to allow heated water from the solar collector to counter-current with the circulated-air. The purpose of the counter-current process is to let the sprayed heated water to humidify the air. Thus, the role of the circulated air is as the carrier for water vapour to carry water vapour being condensed in the dehumidifier. Figure 3.8 shows the preliminary sketch of the humidifier.

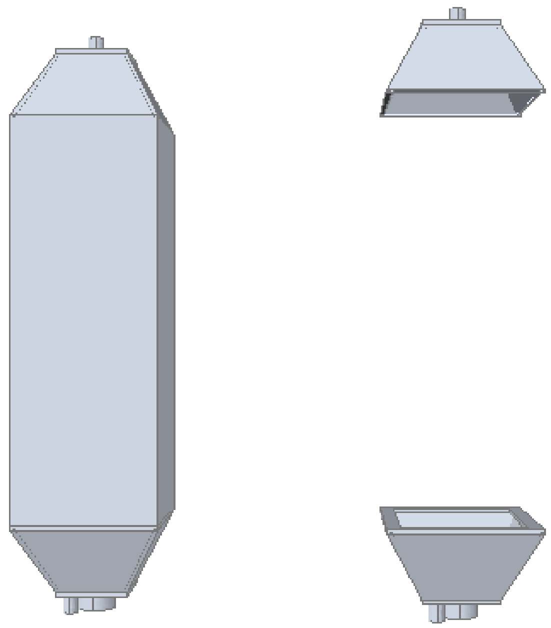

Figure 3.8: Preliminary Sketch of Humidifier

While, packing material will be used and placed inside the humidifier chamber to increase the total surface contact area for the counter-current process take place more effective. Appendix D (Table D.1) shows the previous packing material used in packed bed towers for HDH system. Based on the humidifier preliminary design as shown in Figure 3.8, the dimension for the design can be referred from Appendix E. Table 3.2 shows the preliminary features of the humidifier.

Component	Feature
Humidifier Chamber	• Body of the chamber is made up perspex with 4 mm thick, height of 450 mm and horizontal surface area of 2250 mm^2 (Detail dimension of humidifier chamber is shown in Appendix E) • The edge of chamber is layered with silicone to avoid any leakage or loss of humidified air to the surrounding
Packing Material	• Packing is made of spongy-plastic to increase the contact area of heated water and circulated air during the counter-current process. • The total surface contact area is 35220mm^2

Table 3.2: Feature of the Humidifier and Packing Material

III. Dehumidifier

Figure 3.9 show the preliminary design of dehumidifier chamber.

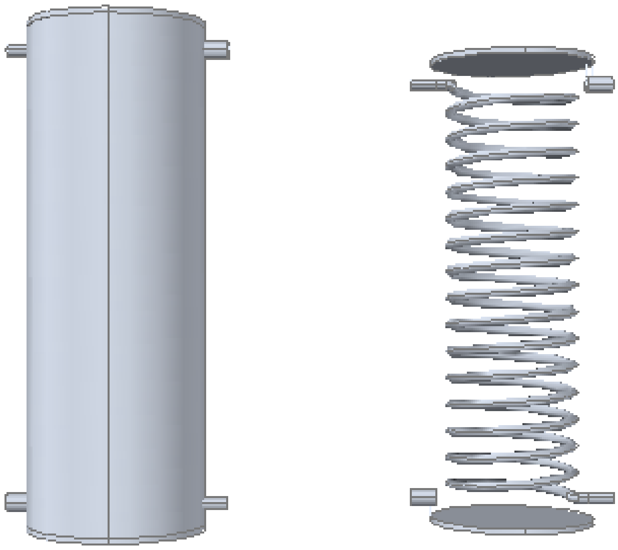

Figure 3.9: Preliminary Design of Dehumidifier

The humidified air from the humidifier chamber will be passed to dehumidifier through a plastic pipe. Basically, the dehumidifier is used to condense the warm humidified air to produce water. The humidifier concept is to exchange the heat like in heat exchanger. The cold seawater will be filled in the dehumidifier chamber while a helical-shaped of copper tube inside the chamber which contained of hot humidified air where the heat exchange will occur.

This so-called heat exchanger will preheat the seawater before being to solar collector for further heating while condensing the hot humidified air to condense desalinated water. Table 3.3 shows the preliminary features of dehumidifier.

Component	**Feature**
Dehumidifier Chamber	• The chamber is made of acrylic tube with 25 mm thick, 450 mm long and 50 mm diameter.
Helical-shaped Tubing	• The coil tubing is made up of copper tube with 0.5 mm thick, 10 mm diameter and 6000 mm long

Table 3.3: Preliminary Feature of Dehumidifier

3.2.3 Test-run Prototype (Setting Boundaries and Parameters)

At this stage, the test run of the prototype will be done at Solar Research Site (SRS), University Technology PETRONAS (UTP). The main objective of this experiment is to test the functionality of the prototype and also the total collection efficiency will be achieved. Procedures to conduct test run will be developed and also setting of parameters are necessary involved constant variable and manipulated variable.

The sun's energy spread out like light from a candle, only small fraction of energy leaving an area of the sun reaches an equal area of the earth which includes Malaysia. The earth rotates about its polar axis, thus any collection device located on the surface of earth can receive the radiant energy for only about one-half of each day.

After taking into consideration, the test run will be conducted under normal sunny day in Malaysia with durations of four hours from 12.00 pm noon until 4.00 pm in the evening for each manipulated variables in order to achieve the objective of this project. Table 3.4 shows the developed variables which will be used for the experiment.

Variable	Description
Constant	• The test run will be conducted for only hours from 12.00 pm at noon until 4.00 pm at the evening. (Normal sunny day)

Table 3.4: Experiment Parameters

3.2.4 Result Analysis

The last stage in completing this project is to analysis the result obtained. From the data obtained at the end of the experiment conducted, the data will be properly tabulated and presented. The basic calculation will be used to calculate the overall calculation efficiency, which amount of desalinated water produced per initial amount of seawater at the end of 4 hours of test run duration allocated for each parameter.

$$\text{Total Collection} = \frac{\text{Amount of Desalinated Water}}{\text{Time Allocated}}$$

From the result obtained, analysis of result will be done in the discussion part and lastly to conclude the overall project. Depending on the result and discussion obtained, there are recommendations can be made for further improvement for this project.

3.3 Key Milestone and Gantt Chart

The figure below shows the timeline of how the project has been conducted during the first semester of FYP.

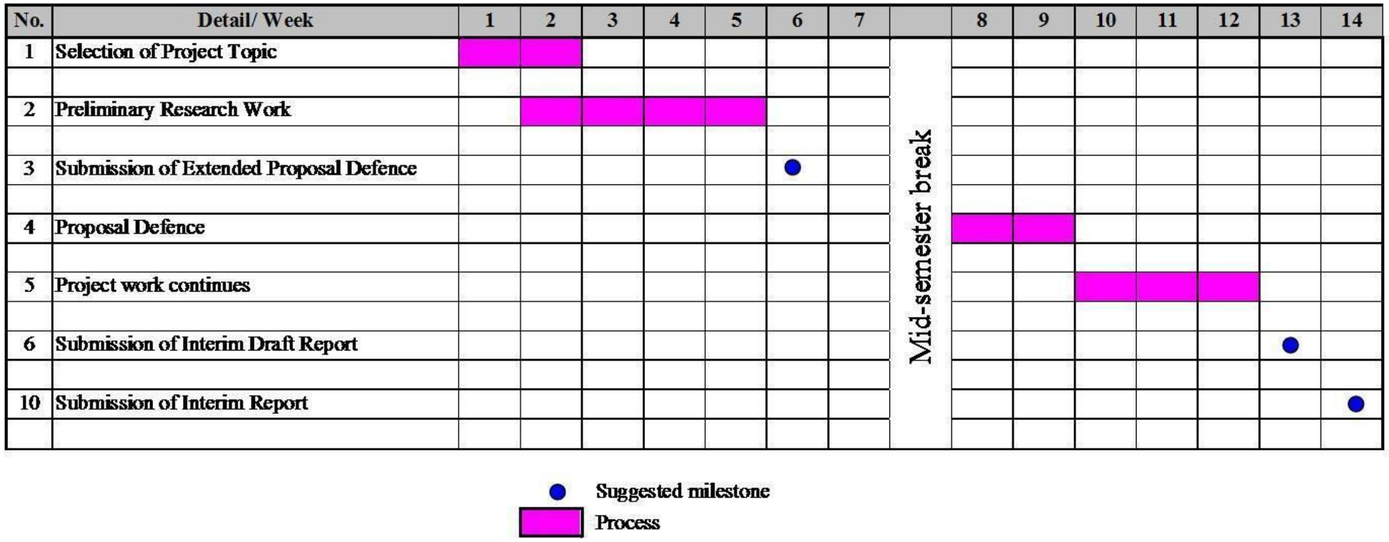

Figure 3.10: FYP I Gantt Chart

The tree main tasks to be completed for FYP I are:

i. Extended Proposal
ii. Proposal Defence
iii. Interim Report

On the other hand, for the second semester (FYP II), the project flow is to be carried out as in the Gantt chart below.

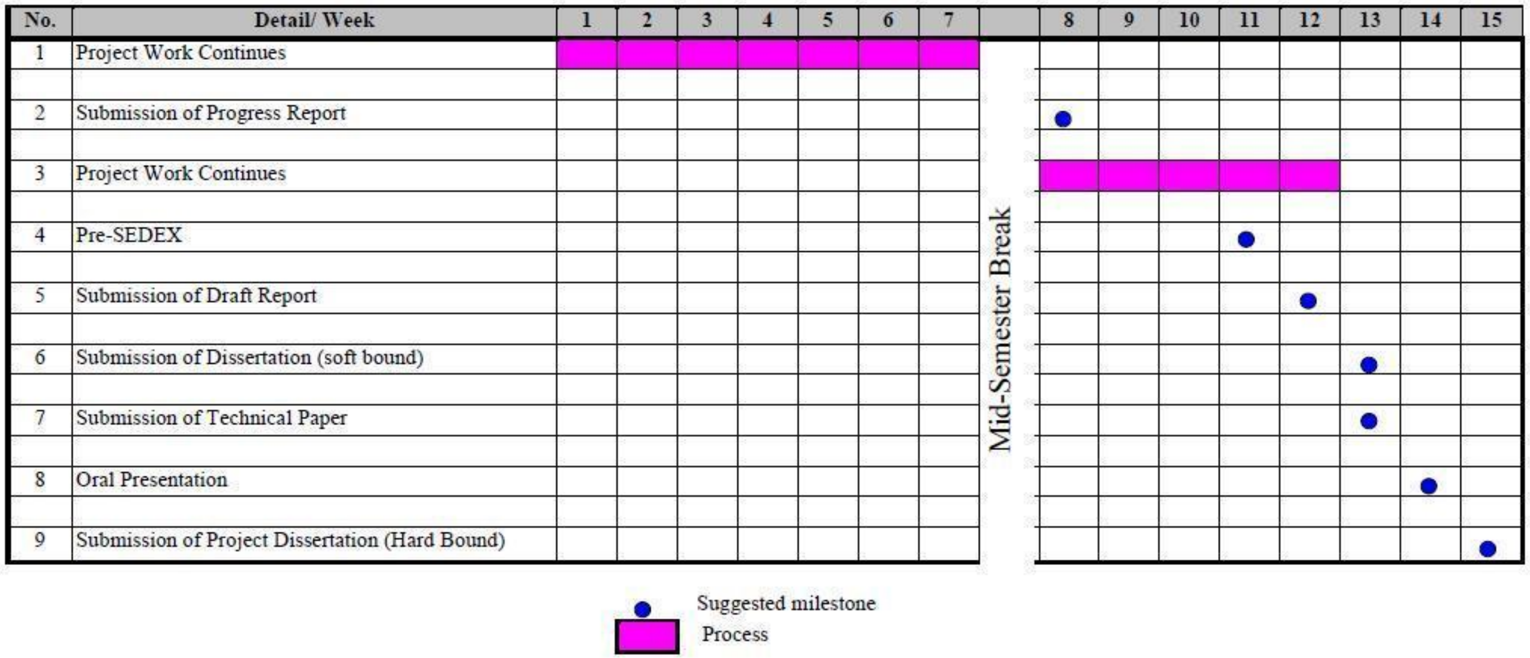

Figure 3.11: FYP II Gantt Chart

The main tasks for FYP II are:

i. Progress Report

ii. Pre-SEDEX

iii. Technical Paper

iv. Oral Presentation

v. Dissertation

CHAPTER 4

RESULT AND DISCUSSION

4.1 Result (Prototype and Presentation of Data)

4.1.1 Prototype (Test-run)

Data (parameters during test run):

Inlet Seawater Temperature	35ºC
Outlet Seawater Temperature	65ºC

Table 4.1: Data for Water-heating Solar Collector

Test run of the prototype was conducted at Solar Research Site (SRS), Universiti Teknologi PETRONAS (UTP). Initially, the test run will be conducted from 12.00 pm to 4.00 pm during normal sunny day. But, due to delay in preparation, the test run started at 3.00 pm. Figures below shows the setup during test run.

Figure 4.1: Setup of the Test-run (Side view)

Figure 4.2: Humidification Process (Left: Initial test-run and Right: During test-run)

4.1.2 Total Collection

$$\text{Total Collection} = \frac{\text{Amount of Desalinated Seawater}}{\text{Time Allocated}}$$

$$\text{Total Collection} = \frac{3\ \text{ml}}{15\ \text{minutes}} = 0.2\ \text{ml/min}$$

Figure 4.4 shows the collection of desalinated seawater.

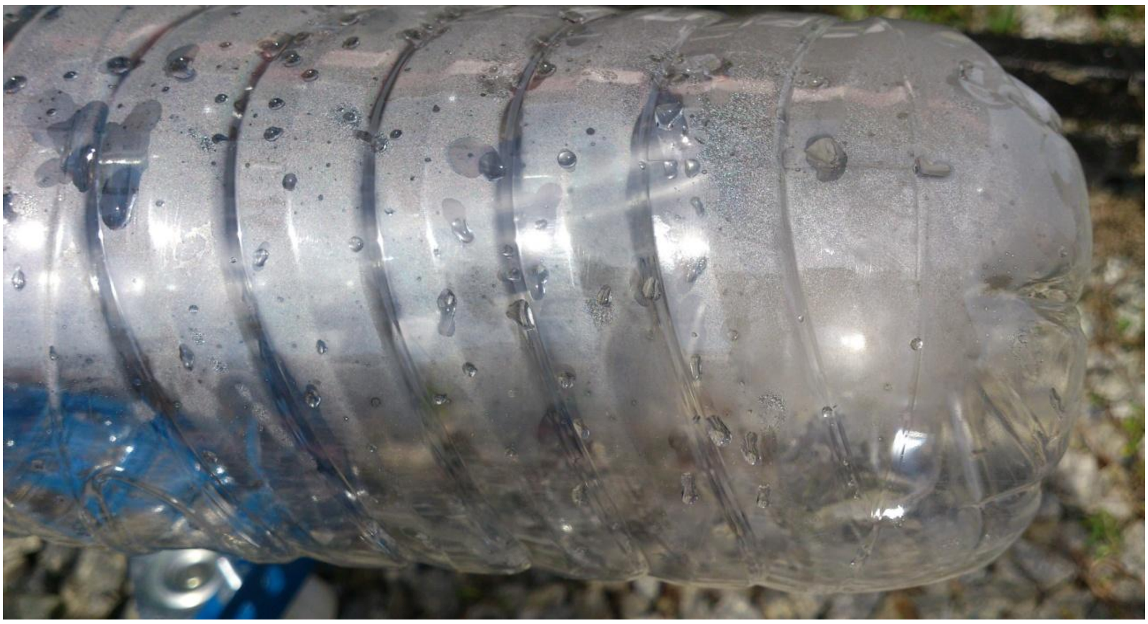

Figure 4.3: Collection of Desalinated Seawater

4.2 Discussion

Based on the result obtained, the solar-driven desalination prototype succeeded in desalinating the seawater. Initially, the test run will be conducted from 12.00 pm to 4.00 pm which is four hours, but the preparation to setup the test run was delayed due to complications occurred. The complications occurred are:

The water tube from the prototype to the solar collector could not be connected properly because both the size of both fittings is different. Thus, the end of water tubes have to be adjusted a bit by thermal expanding in order to be fitted to the connections and tighten by cable tight.

The water pump was not strong enough to pump water up to the condenser in order the water flow into the solar collector and result the flow of water was not continuous. Thus, in order to start up the water flow, the water had to be filled manually into the condenser.

There was leaking at the bottom of the condenser because the flank of the condenser was not glued properly. It was also one of the factors the water being pumped unable to reach at the top of the condenser. Thus, the leakage part was covered manually using cellophane tape.

The test run proceed as soon as the setup done around 3.00 pm. During test run, the humidification and dehumidification process started to be visible, the seawater being sprayed into the humidification chamber started to vaporize and water droplets can be seen on the humidification chamber. While, the water droplets also can be seen inside the tube connected from humidifier chamber to dehumidifier chamber. This observation proved that the humidification and dehumidification took place. Desalinated water was collected in the bottle which connected directly from the outlet tube of condenser. Based on the total collection obtained (0.2 ml/min), the desalinated water collection was taken in 15 minutes due to sudden power shut off and it was out of control. Thus, test run was conducted only in 15 minutes. Based on the collection obtained, the collection is incomparable from the previous research because the most of the previous research, the test run was conducted a whole day, thus the collection is per day. It is because, the thermal energy coming from the sun is inconsistent which affect the final collection of desalinated seawater.

CHAPTER 5

CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The objective of this project is to experimentally fabricate solar-driven desalination prototype. After 4 months of research and prototype fabrication, the test run for the prototype was conducted and succeeded to produce 0.2 ml/min of desalinated seawater. Thus, the objective is achieved. There are many recommendations can be made for further research and improvements. This project also can be a platform for Universiti Teknologi PETRONAS (UTP) to start researching on solar-driven desalination and in future to commercialize this desalination concept in Malaysia.

5.2 Recommendation

In this project, there many recommendations can be made for further research and improvements. Those recommendations include the design of the prototype, materials used in fabrication and setup of the test run. First, design of the prototype focuses on the optimum size of humidification chamber and also the condenser. The type of condenser is also another concern in order to maximize the heat exchange. The design of the prototype should be more flawless for the flow of seawater and vaporized water to flow continuously without any obstacles which result to losses in total collection of desalinated water. A lot of research and study shall be done to find the optimum design of the prototype. Second, materials used in fabrication focus on overall fabrication of prototype. Humidifier chamber should be made up of materials that can reduce heat loss to surrounding and should be designed properly to avoid huge pressure drop that can interrupt flow of circulated air to reach to the top of the humidifier chamber. So do the materials used to fabricate the condenser, tubing, air blower and water pump. While, setup of the test run must be properly studied and prepared in order to avoid any complications occurred which in control.

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APPENDICES

Appendix A

Reference	Unit features	Main observations
Al-Hallaj et al. [80]	• Solar collector (tubeless flat-plate type of 2 m^2 area) has been used to heat the water to 50–70 °C and air is circulated by both natural and forced convection to compare the performance of both of these modes. • Humidifier, a cooling tower with wooden surface, had a surface area 87 m^2/m^3 for the bench unit and 14 m^2/m^3 for the pilot unit. • Condenser area 0.6 m^2 for bench unit and 8 m^2 for the pilot unit.	• The authors noted that results show that the water flow rate has an optimum value at which the performance of the plant peaks. • They found that at low top temperatures forced circulation of air was advantageous and at higher top temperatures natural circulation gives better performance.
Ben-Bacha et al. [21]	• Solar collector used for heating water (6 m^2 area). • There is a water storage tank which runs with a minimum temperature constraint. • Cooling water provided using brackish water from a well. • The packed bed type– used - Thorn trees. • Dehumidifier made of polypropylene plates.	• A daily water production of 19 L was reported. • Without thermal storage 16% more solar collector area was reported to be required to produce the same amount of distillate. • The authors also stated that the water temperature at inlet of humidifier, the air and water flow rate along with the humidifier packing material play a vital role in the performance of the plant.
Farid et al. [67]	• 1.9 m^2 solar collector to heat the water. • Air was in forced circulation. • Wooden shaving packing was used for the humidifier. • Multi-pass shell and tube heat exchanger used for dehumidification.	• 12 L/m^2 production was achieved. • The authors report the effect of air velocity on the production is complicated and cannot be stated simply. • The water flow rate was observed to have an optimum value.
Garg et al. [81]	• System has a thermal storage of 5 L capacity and hence has longer hours of operations. • Solar collector area (used to heat water) is about 2 m^2. • Air moves around due to natural convection only. • The latent is recovered partially.	• The authors conclude that the water temperature at the inlet of the humidifier is very important to the performance of the cycle. • They also observe that the heat loss from the distillation column (containing both the humidifier and the dehumidifier) is important in assessing the performance accurately.
Nafey et al. [82]	• This system is unique in that it uses a dual heating scheme with separate heaters for both air and water. • Humidifier is a packed bed type with canvas as the packing material. • Air cooled dehumidifier is used and hence there is no latent heat recovery in this system.	• The authors reported a maximum production of 1.2 L/h and about 9 L/day. • Higher air mass flow gave less productivity because increasing air flow reduced the inlet temperature to humidifier.
Nawayseh et al. [64]	• Three units constructed in Jordan and Malaysia. Different configurations of condenser and humidifier were studied and mass and heat-transfer coefficients were developed. • Solar collector heats up the water to 70–80 °C. • Air circulated by both natural and forced draft. • Humidifier with vertical/inclined wooden slates packing. • Heat recovered in condenser by pre-heating the feed water.	• The authors observed that the water flow rate has a major effect on the wetting area of the packing. • They also note that natural circulation yields better results than forced circulation. • The heat/mass transfer coefficient calculated were used to simulate performance and the authors report that the water production was up to 5 kg/h.
Müller-Holst et al. [11]	• Closed-air open-water cycle with natural draft circulation for the air. • Thermal storage tank of 2 m^3 size to facilitate 24 h operation. • 38 m^2 collector field size heats water up to 80–90 °C. • Latent heat recovered to heat the water to 75 °C.	• The authors report a GOR of 3–4.5 and daily water production of 500 L for a pilot plant in Tunisia. • There is a 50% reduction in cost of water produced because of the continuous operation provided by the thermal storage device.
Klausner [19,64,65,72]	• A unique HDH cycle with a direct contact packed bed dehumidifier was used in this study. • The system uses waste heat to heat water to 60 °C. • Uses a part of the water produced in the dehumidifier as coolant and recovers the heat from this coolant in a separate heat exchanger.	• The authors demonstrated that this process can yield a fresh water production efficiency of 8% with an energy consumption of 0.56 kWh/kg of fresh water production based on a feed water temperature of only 60° C. • It should be noted that the efficiency is the same as the recovery ratio defined in Section 3.1. • Also the energy consumption does not include the solar energy consumed.
Younis et al. [52]	• 1700 m^2 solar pond (which acts as the heat storage tank) provides heated seawater to be purified. • Forced air circulation. • Latent heat recovered in the condenser to pre-heat seawater going to the humidifier.	• Performance results not reported. • Air flow rate seems to have a major impact on the production of water but surprisingly, water flow rate does not affect the performance.

Table A.1: Previous Works On Water-Heated CAOW HDH Cycle

Appendix B

Reference	Unit features	Brief summary of the paper
Al-Enzi et al. [83]	• Solar collector designed to heat air to 90 °C. • Forced circulation of air. • Cooling water circuit for the condenser. • Heater for preheating water to 35–45 °C. • Plastic packing was used in the humidifier.	• The authors have studied the variation of production in kg/day and heat and mass transfer coefficients with respect to variation in cooling water temperature, hot water supply temperature, air flow rate and water flow rate. • They conclude that the highest production rates are obtained at high hot water temperature, low cooling water temperature, high air flow rate and low hot water flow rate. • The variation in parameters the authors have considered is very limited and hence these conclusions are true only in that range.
Dai et al. [84,85]	• Honeycomb paper used as humidifier packing material. • Forced convention for the air circulation. • Condenser is fin tube type which also helps recover the latent heat by pre-heating seawater.	• It was found that the performance of the system was strongly dependent on the temperature of inlet salt water to the humidifier, the mass flow rate of salt water, and the mass flow rate of the process air. • The authors report that there is an optimal air velocity for a given top temperature of water. • The top water temperature has a strong effect on the production of fresh water.
Khedr [77]	• The system has a packed tower (with 50 mm ceramic Raschig rings) dehumidifier. • The first system to use direct contact condenser in a HDH technology. • The performance parameters are calculated numerically.	• The authors report the GOR for their system as 0.8 which shows that heat recovery is limited. • Based on an economic analysis, they conclude that the HDH Process has significant potential for small capacity desalination plants as low as 10 m^3/day.

Table B.1: Previous Works on Water-Heated CWOA HDH Cycle

Appendix C

Reference	Unit features	Brief summary of the paper
Chafik [16,18]	•Solar collectors (four-fold-web-plate, or FFWP, design) of 2.08 m^2 area heat air to 50–80 °C. •Multi-stage system that breaks up the humidification and heating in multiple stages. •Pad humidifier with corrugated cellulose material. •3 separate heat recovery stages. •Forced circulation of air.	•The author reported that the built system is too costly and the solar air heaters constitute 40% of the total cost. •Also he observed that the system can be further improved by minimizing the pressure drop through the evaporator and the dehumidifiers.
Houcine et al. [15]	•5 heating and humidification stages. •First two stages are made of 9 FFWP type collector of each 4.98 m^2 area. The other collectors are all classical commercial ones with a 45 m^2 area for the third and fourth stage and 27 m^2 area for the final stage. Air temperature reaches a maximum of 90 °C. •Air is forced-circulated. •All other equipment is the same as used by Chafik [18].	•Maximum production of water was 516 L/day. •Plant tested for a period of 6 months. •Major dilation is reported to have occurred on the polycarbonate solar collectors. •The water production cost for this system is (for a 450–500 L/day production capacity) 28.65 €/m^3 which is high. • ~37% of the cost is that of the solar collector field.
Ben-Amara et al. [53]	•FFWP collectors (with top air temperature of 90 °C) were studied. •Polycarbonate covers and the blackened aluminum strips make up the solar collector. •Aluminum foil and polyurethane for insulation.	•Variation of performance with respect to variation in wind velocity, inlet air temperature and humidity, solar irradiation and air mass flow rate was studied. •Endurance test of the polycarbonate material showed it could not withstand the peak temperatures of summer and it melted. Hence a blower is necessary. •Minimum wind velocity gave maximum collector efficiency.
Orfi et al. [56]	•The experimental setup used in this work uses a solar heater for both air and water (has 2 m^2 collector surface area). There is a heat recovery unit to pre-heat seawater. •The authors have used an evaporator with the heated water wetting the horizontal surface and the capillaries wetting the vertical plates and air moving in from different directions and spongy material used as the packing.	•The authors report that there is an optimum mass flow rate of air to mass flow rate of water that gives the maximum humidification. This ratio varies for different ambient conditions.
Yamali et al. [86]	•A single stage double-pass flat-plate solar collector heats the water. •A pad humidifier is used and the dehumidifier used is a finned tube heat exchanger. •Also a tubular solar water heater was used for some cases. •The authors also used a 0.5 m^3 water storage tank. •Heat is not recovered.	•The plant produced ~4 kg/day maximum. •Increase in air flow rate had no affect on performance. •An increase in mass flow rate of water increased the productivity. •When the solar water heater was turned on the production went up to ~10 kg/day maximum primarily because of the ability to operate it for more time.

Table C.1: Previous Works on Air-Heated CAOW HDH Cycle

Appendix D

Author	Packing material
Khedr [77]	Ceramic Raschig rings
Farid et al. [67]	Wooden shaving
Al-Hallaj et al. [80]	Wooden surface
Nawayseh et al. [64]	Wooden slates packing
Dai and Zhang [84,85]	Honeycomb paper
Garg et al. [81]	Indigenous structure
Ben-Bacha et al. [21]	Thorn trees
Efat Chafik [18]	Corrugated cellulose material
Nafey et al. [82]	Canvas
Klausner [17]	HD Q-PAC
Al-Enzi et al. [83]	Plastic packing
Houcine et al. [15]	Corrugated cellulose material
Yamali et al. [86]	Plastic packing

Table D.1: Packing Material Used in Packed Bed Towers for HDH Systems

Appendix E

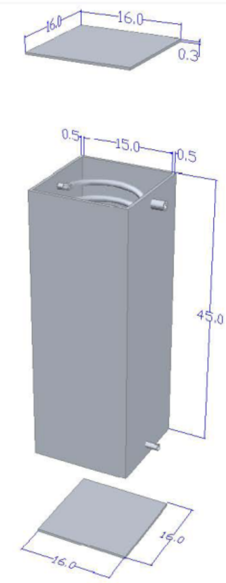

Figure E.1: Dehumidifier

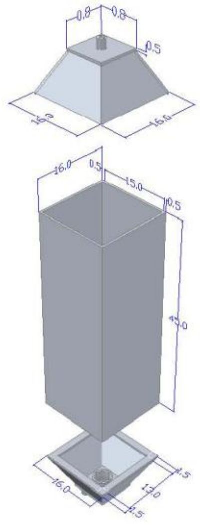

Figure E.2: Humidifier

Appendix F

Picture 1

Picture 2