Cape Peninsula
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MULTISTAGE SOLAR STILL DESALINATION SYSTEM

by

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DECLARATION

I, Mfanafuthi Mthandeni Mkhize, declare that the contents of this thesis represent my own unaided work, and that the thesis has not previously been submitted for academic examination towards any qualification. Furthermore, it represents my own opinions and not necessarily those of the Cape Peninsula University of Technology.

Signed **Date**

ABSTRACT

The present study was centred on the design of a thermal multistage solar still desalination system. The design is a multistage with new configurations such as direct vapour input into each stage using vapour make-up tubes and the integration of a multistage with a basin type solar still. The incorporation of float a valve in the secondary seawater tank to regulate the seawater in the assembly eliminated the need of pumps to the system. The circulation of seawater between the evaporator and the evacuated tube solar collector (ETC) was through the pressure difference and the flow back was controlled through the incorporation of one-way flow valve. The ETC was used as a heat source to supply the thermal energy into the multistage system. The system had no electrical connections and therefore, no forced circulation as no pumps or any electrical components were used. The system consisted of six stages in total, the evaporator supplied the vapour to five of the six stages of the system.

The system was tested on the roof of Mechanical Engineering Department and this location was chosen because of less sun's intensity obstructions. The system was tested for nine (9) days but the distillate collection was not performed for the whole each day. This was due to the controlled access to the roof and the minor repairs that had to occur before the tests were conducted. The duration on which the tests were conducted varied in each day. The data was supposed to be logged from 08h00 am to 18h00 pm but this was not so due to the controlled access to where the tests were conducted. This data logging period was chosen based on the assumptions that the sun's intensity would be at maximum within this period.

The longest period of test was approximately 7 hours and the system managed to produce about 1500 ml and the maximum temperature for the day was 28^{o}C. The system produced a minimum of 225 ml in the space of 3 hours and the temperature of the day was 26^{o}C. The total amount of distillate produced was about 7600 ml and this amount was produced within the period of 49 hours. The 49 hours is equivalent to two days and 1 hour. It is anticipated that the system would have produced more should there be no repairs involved during the tests. The system produced a maximum of 48 ml at night and a minimum of 8ml in some nights. The night tests were not controlled and monitored due to limited access. It was noticed that the system was empty in each morning of the first few days of the tests. This emptiness contributed to the leakage occurred to the evaporator. The leakage of the evaporator was caused by unmonitored heat supplied by the ETC. The evaporator was constructed using unsuitable material and this was another factor which contributed towards the failure of the evaporator.

ACKNOWLEDGEMENTS

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GLOSSARY

Terms/Acronyms	Explanation
Secondary seawater tank	Pre-heated seawater storage tank
Primary seawater tank	Cold seawater storage tank
Direct vapour input	Vapour is supplied directly into each stage from the evaporator
Vapour make-up	Vapour supplementing the vapour in the stages
Zig-zagged tube	Tube making multiple passes
Vapour transfer	The vapour transferred from one stage to the next
Brine tank	Brine storage tank
Brine	Saltier seawater rejected after heating and evaporation
CPUT	Cape Peninsula University of Technology
MED	Multi-effect distillation
ETC	Evacuated Tube Collector
FTO	Fluorine Doped Tin oxide
DoE	Department of Energy
PV	Photovoltaic
DC	Direct current
SA	South Africa

CHAPTER ONE

INTRODUCTION

1.1 PROBLEM STATEMENT

Solar stills have become progressively popular in recent years and more so in the 21st century. This is partly, if not entirely due to the need to invent new alternative means to produce fresh drinking water. The solar stills have evolved from simple solar stills which were mainly passive and to more complex active solar stills. In achieving the active and sophisticated solar still, solar panels have played a great role in facilitating their advancements. Many researchers have explored the active solar still concept, either for a small or large scale water production. However, these explorations have not come without setbacks. This is because, in designing, constructing and commissioning of a solar still there are some costs attached to that. Due to these costs, one has to minimize the cost of building such an equipment to avoid making the design incredibly unattractive.

In the present day, fresh drinking water has become a scarce commodity and governments in many countries are out-stretched on resources to continue supplying fresh drinking water to their respective communities. Cape Town government (2017) has implemented level 4 on water restriction which has prohibited all use of municipal water for outside and non-essential use and this will further restrict residents to 100 litres per person per day. Pugsley et al. (2015) reported that population growth and depleting fossil fuel reserves are the most contributing factors towards water scarcity. This is due to the fact that more energy is required to produce fresh water to meet the needs of the growing population. The solar systems has made a change since it only requires a sun’s energy to function and produce fresh water.

Bundschuh and Hoinkis (2012), reported that economically exploited conventional energy resources have become increasingly limited because of natural limitations. Their use is also questioned by large population groups, especially in industrialized countries, because of their adverse impact and because of their contribution to global climate change. Furthermore, the explanation of the different approaches in an attempt to improve the productivity of solar stills is provided as, many modifications to improve the performance of solar still have been made. These include linking the desalination process with the solar energy collectors, incorporating a number of effect to recover the latent heat of condensation, improving the configurations and flow patterns to increase the heat transfer rate and using low-cost material in construction to reduce the costs. In an attempt to maximize fresh water production, Shafii et al., (2016) designed a new desalination system. The evacuated tubes were used for both the thermal collection as well as a basin to heat and evaporate water. This configuration proved that solar desalination stills has a real potential in the production of water in small and large scale. Another configuration studied was the integration of the basin type solar still with an evacuated tube solar collector under a forced mode.

This set-up was discussed in a study conducted by Kumar et al., (2014). The study reported that the use of the evacuated tube collector in a forced mode system enhanced the fresh water productivity as well as the temperature of the saline water. It is therefore, very prudent to apply the same approach to achieve high portable water productivity. In the present day, the widely used system for the purification of water is done through expensive fossil fuel. This method requires substantial amounts of budget for its continuous operations, some costs are coupled with indirect costs such a maintenance and manpower. Duffie and Beckman (2013) reported that the solar energy is a formidable competitor to fossil fuels and that the solar energy could replace the fossil fuel processes entirely. The current study is attempting to design a thermal desalination system that is self-sufficient and have all its important components interacting with each other to achieve one common goal. Most heat is captured within the system and reused to contribute towards making the system more efficient and productive. Solar energy proves to be a suitable alternative and a viable supplement to a conventional desalination method and might even replace the fossil fuel entirely in a near future.

Solar energy in solar water heating has a real potential in small and large scale applications. This is mostly true when the adverse effect of the fossil fuel is taken into account. The solar energy will therefore, play a huge role in curbing the pollution accompanying all fossil fuel processes. The usage of the fossil fuels in South Africa is briefly explained by Joubert et al., (2016), coal usage is at 57% mainly for industrial applications. Oil and other related products such as diesel, paraffin, petrol etc. for heating purposes contributes only about 3%. In residential heating however, wood is at 46%. Furthermore, the study goes on to reiterate that South Africa is suffering from rapidly increasing fuel prices. It is therefore, for this reason, very clear that either in the industrial or domestic water heating, steam generation etc. solar energy will play a huge role and thus continuous research will contribute positively in designing new and improving on existing designs.

Soni et al., (2017) conducted a study on an adaptable wind/solar powered hybrid system. The study was aimed at developing an adaptable, affordable and sustainable household waste water treatment system. The design produces 17.4 kilograms per square meter per day and the study acknowledges the need to find alternative means to produce fresh drinking water as most regions are water scarce. This is true as in most Southern African regions, especially those areas that are considered off grid and under developed, the provision of clean water is insufficient or non-existent at all.

The renewable energy systems may prove to be more economical and sustainable means for water provision. Keeping that in mind, there are other challenges such as that South Africa (SA) as a developing country faces a huge challenge of storing rain water which will later be purified to fresh drinking water, most of this rain water end up in the sea. Anderson et al., (2013) conducted a study on improving crop yield and water productivity by ecological sanitation and water harvesting in South Africa. The study discovered that 95% of the pond water could not be stored which results in this water flowing downstream and most probably ends in the sea. Due to the lack of water storage and deepening water crisis many researchers has considered the methods of extracting fresh water from the sea and this study focuses on a thermal desalination system to achieve the extraction of freshwater from seawater. The system heats up raw water (seawater) and separates the almost pure-water vapour mixture which becomes fresh water subsequent condensation.

Reif and Alhalabi (2015) on the analysis study reported that, a direct solar desalination system by means of a solar thermal collector is the most attractive among the systems analysed. This is not just in a realm of producing the distillate but the cost-effectiveness as well as the efficiency. These systems have a huge potential in being reliable and sustainable in the scope of water production. The need to find alternative means for provision of clean and drinkable water is now undeniable as water is progressively becoming a very scarce commodity. The seawater is available in abundance and one needs to derive a way to purify it for human and other living creature’s consumption. It is scientifically true that heating and vaporizing saltwater and subsequently condensing the water vapour mixture will result in a clean and chemically free water. Hence, this study was focusing on developing a device which evaporates water by introducing thermal energy and exposing hot water vapour mixture to a cool medium. This will induce condensation on contact and produce the distillate.

The design of the present study is a multistage solar still desalination system with the aim of maximizing the production of water through thermal means. It is an active solar device rather than a passive device and its ultimate focus is producing water on a large scale while eliminating any dependencies on electrical supplies. By doing so, the system will be completely off grid in terms of its operations and hence the natural mode of operation is employed rather than a forced mode. The design must be able to operate independent of electricity, pneumatics, hydraulics, etc. and yield the results. The system should start to produce meaningful amount of water in the weather conditions of about 15°C with clear skies.

1.2 BACKGROUND

1.2.1 The Basin type solar still

There are various types of solar stills which includes pit, cone, demo solar stills however, basin type solar still is the most common. The basin type solar stills are known to produce less distillate compared to active solar stills. Phadatare and Verma (2007) conducted a study on a passive basin type solar still covered with a 3 mm thick Plexiglas. The level of seawater was at 2 cm and 2.1 litres of distillate was produced per square meter per day. The authors reported that a maximum efficiency of 34% was achieved. However, the solar stills have evolved from passive conventional solar stills to active solar stills which are coupled with the solar collector to increase the production of the distillate. Among other researchers, the improvement of the still was reported by Sathyamurthy et al. (2016) on a review study. The fresh water yield of a basin type solar still coupled with the collector increased by 36% above that of the passive type.

Phadatare and Verma (2007) in the same study suggested that, painting the inside wall of the still black will increase its absorptivity. The black colour absorbs the solar energy much better compared to other colours. The better absorption increases the productivity of the still. The depth of seawater in the basin type solar still determines its efficiency and productivity. This means that the solar still performs much better when the depth of water in the basin is minimal. Another factor that influences the efficiency and productivity of the basin type solar still is the insulation on the outer body of the still. Elango and Murugavel (2014) reported that the insulated basin type solar still performed much better than the un- insulated one. The insulated one was able to produce the distillate even after sunset but the un-insulated one was mostly productive during the day time.

1.2.2 Multistage solar still desalination system

Present and previous studies have used the latent heat recovered from vapour in the previous stages to heat and evaporate seawater in the following stages. These studies mainly had water bed in the stages and the heat source was placed at the bottom of the assembly. Numerous researchers have conducted such studies (Estahbanati et al., 2014; Adhikari et al., 1995 and Ahmed et al., 2008). The results showed that the heat at the bottom of the assembly provides enough heat to heat and vaporize water in the stage. The latent of heat of condensation was used to heat and vaporize water in the following stages. Mahmoud et al., (2009) conducted a study on a multistage solar desalination system and concluded that, the distillate yield was 5kg/m^2/day. The study incorporated a pump, closed loop siphon circuit and water bed in the stages. The results achieved were much better than that of a conventional basin type solar still. The above system demonstrate that continuous experimentations will improve the solar still desalination system.

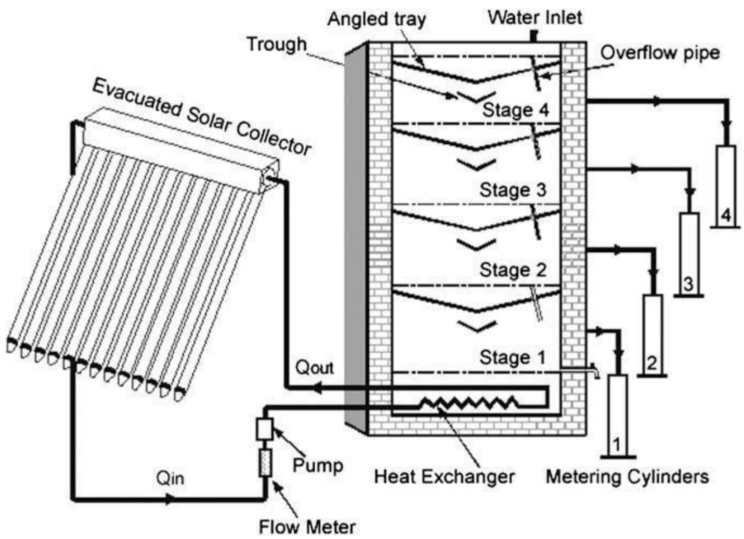

Figure 1.1: Multistage with water bed and heat exchanger

(Mahmoud et al., 2009)

Figure 1.1 illustrates a schematic diagram of a multistage solar desalination system with a closed loop heat transfer set-up and water bed in each stages. The concentration of heat in the system above is in the bottom stage which is stage 1 (basin), then stage 2, 3 and 4 receives the heat from condensing vapour of the preceding stages, respectively. Estahbanati et al., (2014) experimented on a multistage with 4 stages, all stages filled with water and the closed loop forced circulation employed. The electric heater was used in the basin which was the bottom stage of the system. The overall production of the still increased when an additional stage was added in a continuous mode. The prediction made based on the results was that the increase in number of stages in the unit can increase it overall productivity. The stages can be as many as 10 in that particular set-up.

From the study conducted by Mahmoud et al. (2009) on figure 1.1, it is then evident that placing the heat source at the bottom of the stacked trays can make the system productive and achieve a desired yield of the distillate output. Based on the results on figure 1.2, the temperature of water in any of the stages did not reach above 90°C. Also, the temperature in the stages at the top of the assembly was lower than those at the bottom. The heating fluid temperature in a closed loop circuit is evidently higher than that of the water bed in the stages on the figure below. There are number of studies conducted which consisted of a force mode circulation of water. These studies were conducted by (Jubran et al., 1999 and Ahmed et al., 2008) to mention few.

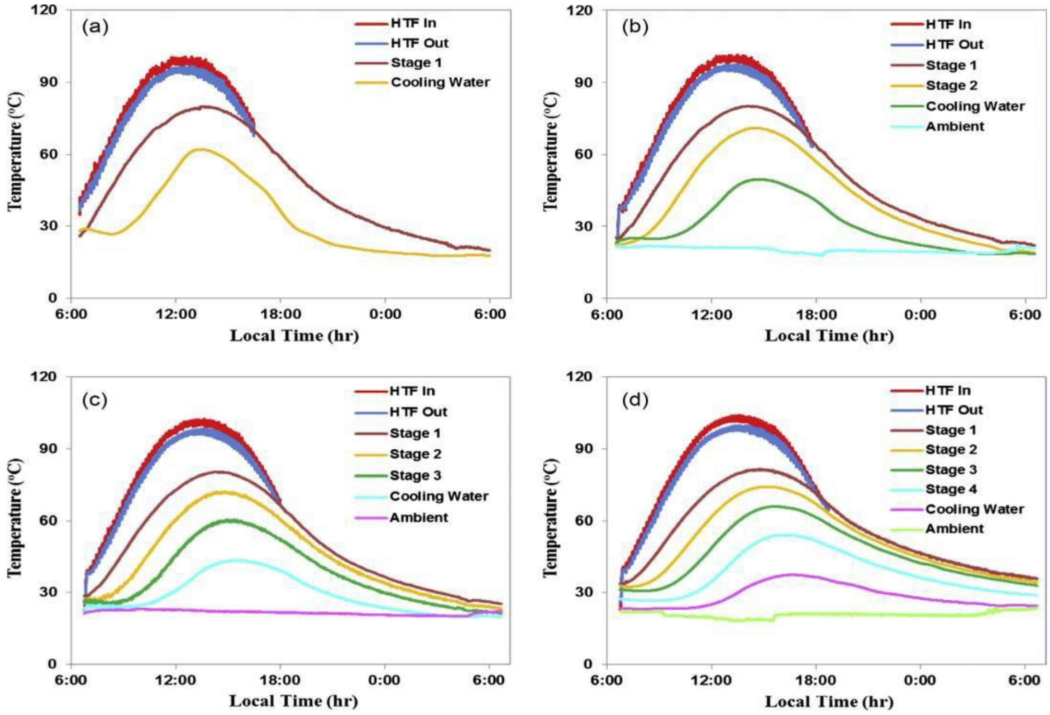

Figure 1.2: Temperature variation on different stages under continuous mode (Estahbanati et al. 2014)

1.3 OBJECTIVES

The objectives of this study are as follows:

- Design and build a low cost multistage solar still desalination system.
- The system should not use any pump in controlling the flow of seawater and fresh water.

1.4 DESIGN OVERVIEW

In our study, the design, construction and experimental tests on a multistage solar still desalination system were conducted. The design is a multistage solar still with 6 stages stacked on top of one another. The construction of the design was done in a Mechanical Engineering workshop at Cape Peninsula University of Technology, Bellville campus. Stage 1 located at the bottom and the basin type solar still at the top of stacked stages. The system was mainly made up of galvanised iron sheets and copper tubes of different diameters for a specific purpose. The basin type solar still is located at the extreme top of the stacked stages with its internal walls painted black and made of both the galvanised iron sheet and perspex glass. The basin type solar still produces the distillate independently. The evaporator and the secondary seawater tank is located at the extreme bottom below stage one. The evaporator has multiple tubes connected to it and all these tubes performs different functions as explained below.

Vapour make-up tubes transport the vapour from the evaporator to the respective stages and are connected at the top of the evaporator. Seawater transfer tube transfers seawater from the secondary tank to the evaporator. Brine overflow tube drains the brine into a brine tank. Open loop circuit tubes are connected on the lower side of the evaporator and are used to circulate seawater between the evaporator and the collector. The open loop circuit also has a pressure relief plug on the high pressure side. Both the evaporator and the secondary seawater tanks have sight glasses which are used to observe the level of seawater in them. The secondary seawater tank has a float valve which regulates the amount of seawater flowing in it. It is also connected to the zig-zagged seawater tube which deliver seawater to it. The brine tank is located on the underside of the whole assembly and have a brine discharge tube.

The stage trays are designed in a V-shape and are inclined at an angle. Each stage, except stage five, has vapour transfer tubes which transfers the vapour from one stage to the next. The U-shaped tubes are connected to each stage and to the main distillate tube. The basin type solar still has its own distillate tube which joins the main distillate tube. The evacuated tube solar collector is connected to the open loop circuit tubes and delivers the thermal energy to the whole system. The collector produces the thermal energy by absorbing the solar incidence from the sun's radiation. This energy is then released to the seawater in its manifold and causing the seawater to heat-up and evaporate. A non-return valve was installed in the open loop circuit tube between the evaporator and the collector. As part of the whole assembly a stand was constructed to mount the multistage solar still desalination system, see figure A1 under appendix A.

1.5 THESIS OVERVIEW

Chapter 1 – Introduction

Problem statement, background, objectives, design overview and thesis overview are presented in this chapter according to the sequence listed.

Chapter 2 – Literature Review

This chapter acknowledges all related literature which were consulted and it goes on to lay out the findings on a basin type solar still and the multistage unit. The factors which contributes to the system's efficiency and productivity discussed. Furthermore, the last section of the chapter presents the adverse factors which affects the solar stills.

Chapter 3 – Design and construction

This chapter lays out the description of the major components of the system. It further defines them in terms of their designs, construction and functions. Lastly, it demonstrates how it was arrived at the numerical results obtained through mathematical procedures.

Chapter 4 – Experimental Performances

This chapter explains the instruments used in testing the system during operations. It also details out how the tests were performed under given conditions by means of providing test data related to its performance.

Chapter 5 – Results and discussions

This chapter presents the experimental results and discussion based on the results obtained during the tests.

Chapter 6 – Conclusions and recommendations

This chapter makes the conclusion from the results obtained in the study. It then recommends some improvement and/or approaches to enhance the yield of the distillate

CHAPTER TWO
LITERATURE REVIEW

This chapter presents all the reviewed literature related to this study. It firstly looks at the literature related to basin type and multistage solar stills. It then goes on to describe the factors which influences the efficiency and the productivity of these solar stills. In addition to that, it discusses the short falls and adverse factors which contributes to low distillate outputs. Lastly, a summary of the section is provided.

2.1 BASIN TYPE SOLAR STILL

Omar Bait & Mohamed SI-Ameur (2016) conducted a study on the numerical investigation of a multistage solar still and reported that in the initiation of the solar stills, they were constructed as simple conventional stills. The solar still consisted of a simple basin containing seawater and enclosed by a clear plastic or glass cover at the top. The solar energy from the sun would heat the seawater to the evaporation point and cause the seawater to vaporize. The condensate would then collect on the internal surface of the glass or plastic cover and trickle down towards the trough. The distillate is then gather in the trough.

The basin type solar still were both passive and consisted of less components to form a system. The components were the basin containing seawater, inclined clear glass or plastic, the trough to collect the distilled water and the distillate tank. The need to increase the amount of distillate output from the system raised the need for some additional equipment to be coupled with the still. The solar collector was one of the equipment coupled with the still and the integration of the still with the collector is explained later in the section.

In the review study by Kumar et al., (2015) it is reported that the productivity of the still depends on the solar radiation and the ambient conditions. If the solar intensity is less, the amount of distillate produced by the still will be less. If the solar intensity is increased, the amount of distillate will increase. The ambient conditions plays a huge role in the production of the distillate and these conditions will be discussed later on in the chapter. This suggests that when the basin type solar still is designed accordingly and vapour tightness is achieved, the still can yield considerable amount of distillate when high solar radiation is prevalent. This however, does not mean large amount of water. Lal et al. (2017) in a comprehensive study of the different parameters of solar still reports that the distillate output from the passive basin type solar still is only 2-3 litres per day. This is due to a number of factors and these factors are described below.

The angle at which the inclined condensing cover is tilted, contributes towards the still's productivity. Tiwari and Tiwari (2007) conducted a study on an annual performance analysis and thermal modelling for different inclination of condensing cover. The conclusion reported that the optimum angle of 15° was found to be the best in summer and rainy seasons for a single sloped solar still while the 45° was much better in winter. This study shows that the angle of the solar still needs to be positioned correctly for maximum performance. In addition to that the depth of seawater in the still determine the evaporation rate of seawater in the still as described below.

The depth of seawater in the basin type solar still is one of the factors which enhances the system's productivity. In all the literature consulted, there is no definitive depth of seawater in the still as the level of seawater differs from one researcher to the next. Some of the researchers who had the studies with the focus on the depth of water are (Singh et al., 2013; Kumar et al., 2014; Lal et al., 2017). The seawater level was different in their basin type solar stills. The difference in water depth does not significantly affects the distillate yield as their results were not far off from each other.

Integrating the still with the solar collector plays a role in increasing the stills output. The review conducted by Sathyamurthy et al. (2016) focused on an integration of a solar collector with a solar still. Comparisons were made to different configurations and the most productive and efficient basin type solar still is that which is coupled with the collector. The amount of distillate produced by the active solar still is much higher than that of the passive type solar still. This still above is no longer a passive but rather an active one and hence it productivity was improved. The type of a system that is coupled with the collector is called active solar still and those that are not coupled with the collector are passive solar stills. During a comparative study conducted by Manokar et al., (2018) on two basin type solar stills, it was discovered that the active system was more productive than the passive type. The passive type solar still daily yield was 4.8 kg of distillate while the active was producing 7.9 kg of distillate daily.

Figure 2.1 shows a typical basin type solar still which is the most common. Lal et al., (2017) conducted a study for different parameters of solar stills and stated that there are different factors which affects the performance of a solar still. Amongst other factors, the absence of the insulation on the outer body of the still affects the stills performance. The type of insulation used on the still determines how much the system is isolated from the outside elements. The productivity of the still is therefore largely relying on the design parameters of the still. The ambient, operating and design condition are further broken down below.

The factors influencing the productivity of the solar still are explained by Muftah et al., (2014) in a review study as three elements. They are ambient, operating and design condition, they are further broken down in this manner. The ambient condition are made up of the ambient temperature, isolation and wind velocity. This is true as the design of the system determines how much the internal of the system is isolated from the outside elements. The operating conditions are the water depth in the still, the inlet temperature of seawater as more thermal energy is used in heating up cold water, whether the walls are painted with either a black paint or other colours but most importantly, the orientation of the still. This may greatly affect the yield of the still if not positioned accordingly. The last condition described is the design, how the system is protected from the outside and is the system not losing lot of heat due to its poor design.

Elango and Murugavel (2014) conducted a study on double basin double slope still and single slope still. A comparative study was done based on the insulated and un-insulated basin. The result found that the un-insulated solar still produced more water during the day time with a minim level of water at 1 cm. However, the un-insulated still was much better during the day but was unable to produce as much in the night. The insulated still had produced more distillate as it was able to work productively both during the day and night, as a result the insulated solar still had the highest overall production.

In research, there are different material used for experimentation purposes but yet the most common materials are aluminium and galvanised iron sheet. Selvaraj and Natarajan (2017) conducted a review study on the factors influencing the performance and productivity of solar stills and stated that for experimental purposes most researchers prefer to use either the galvanised iron sheet or aluminium. In most regions, these material are available locally and relatively cheap.

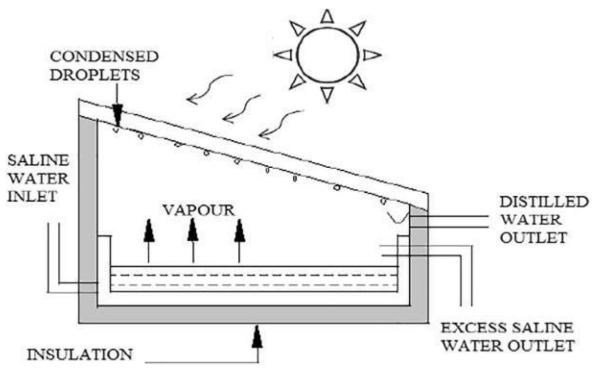

Figure 2.1: Basin type solar

(Selvaraj & Natarajan, 2017)

2.2 MULTISTAGE SOLAR STILL

Solar desalination systems which consisted of a multi-stage layout and their performance compared to simple solar stills have been extensively studied over the years. Figure 2.2 shows a typical multistage solar desalination system, the system had water bed in each stage, used a closed loop circuit supplied by the evacuated tube solar collector. The explanation of how the system works is given in various ways but the most common is given below.

The thermal energy which is used to heat and evaporate seawater is supplied by the evacuated tube solar collector. The heat exchanging process of a closed loop thermal siphon circuit with a heat transfer fluid is explained in the following manner. The solar radiation hits the collector, the working fluid (an oil) is heated up and moves by natural convection to the highest point of the system where a heat exchanger is located. The oil flow releases its sensible heat to the salty water on the other side of the equipment. The heat exchanger works as the first stage of the desalination unit. As the oil flow cools, it returns to the solar collector, completing a thermal siphon circuit (Schwarzer et al., 2000).

Since the system had a heating source in the first stage and water bed in the stages, heat is transferred by means of latent heat of condensation to the rest of the stacked stages. In the study conducted by Chandrashekara and Avadhesh (2016) which was a multi-effect distillation (MED) system, the latent heat of condensation was transferred to the next stage to preheat saltwater in the subsequent stage. All the system encountered in the literature used the same method to transfer the heat to the rest of the stages. Thus, this means that the rest of the stages, except the first stage of the system are not directly supplied with the heat but rather rely on the latent heat of condensation from the previous stage. Also, each stage except for stage one at the bottom is dependent on the preceding stage for thermal energy to heat and evaporate the seawater bed in that stage.

A multistage that is a passive solar still desalination system has not been found in the literature reviewed. Ahmed et al., (2008) conducted a study on a multistage solar desalination system. The aim was to improve the distillate collection of the solar still and the conclusion was that the output was three times that of the conventional type solar still. It is thus evident that the multistage solar still desalination system out-performs the passive basin type solar still. The design and construction of the multistage system are clearly more than that of the passive basin type solar still in terms of costs. This is due to the fact that more components are required to form a multistage as opposed to the simple basin type solar still. The high cost is justified by the high output of the multistage system compared to a basin type solar still as described below.

In addition to designing and constructing a conventional multistage solar still desalination system, there are ways to maximize the output of the system by modifying the system to reuse the heat generated by the system. Zhen-hua Liu et al., (2013) conducted a study on a novel integrated solar desalination system with multistage evaporation/heat recovery processes. The study reiterates that the combination of good solar collection and the concept of recovering the latent heat of condensation can increases the efficiency of the system if both are done accordingly. Also, employing the method of heat recovery using brine has some outstanding performance to the system, not only heat is recovered from the vapour but three objectives are achieved at once. These objectives are cooling the vapour down and subsequently reducing its pressure, recovering the heat from the vapour and raising the temperature of the seawater.

Morad et al., (2017) conducted an experiment on a solar-powered desalination system, using a condenser integrated with a flat-plate solar collector and a vacuum pump. A saline water tank situated on top of the stacked stages and this saline water was used as a coolant and it was noted that this water provides sufficient cooling for the vapour to condense completely and the vacuum pump enhanced its productivity. It is evident that the cold seawater in the tank on top of the stacked stages is playing a huge role in condensing the vapour. The concept of allowing the cold seawater to cool the vapour can be applied in different ways by employing alternative flow patterns.

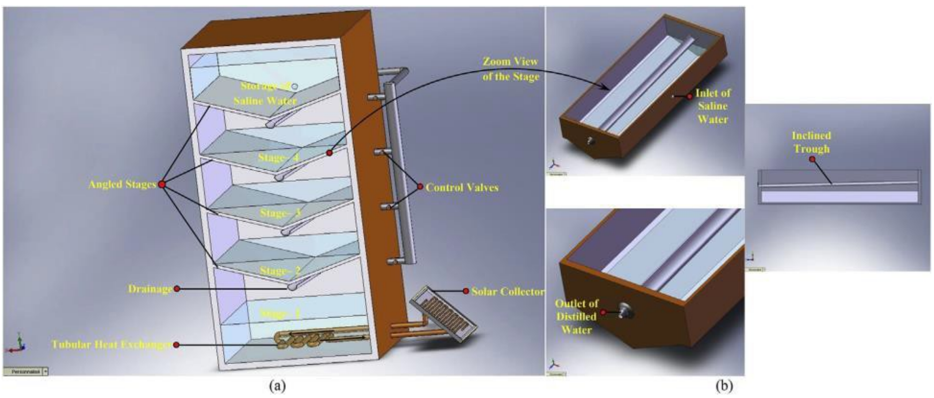

Figure 2.2: Design of a multistage solar desalination system

(Omar Bait & Mohamed Si-Ameur, 2016)

2.3 EFFICIENCY AND PRODUCTIVITY

The efficiency of the multistage solar still desalination system is not just dependent on the thermal energy supplied by the collector but the reusing of this energy as well. Sharshir et al., (2016) concluded that reusing rejected hot brine to preheat the incoming salt water enhances the system performance by 50% and increases its efficiency to about 90%. The recovered heat assist in reducing the amount of thermal energy required to heat and evaporate the seawater in the system. The heat recovered needs to be kept inside the system and the insulation on the body of the assembly can enhance that. Researchers have used different insulation on the assembly and different results have been achieved.

Feilizadeh et al., (2015) investigated the outdoor performance of the basin type multi-stage solar still as well as the effect of the collector over the basin area, using a 10 cm of polystyrene for insulation which was found to be sufficient for insulation seasonally. Saint-Gobain Isover South Africa, n.d. explains that polystyrene is cheap, has excellent thermal insulation properties, easy to handle and can be reused. This material has the qualities to lessen heat loss from the system. Also, Ahmed et al., (2008) conducted a study on the characteristic of multistage evacuated solar desalination and a thick layer of an insulation was used to prevent heat losses from the system. The study concluded that the output from the system was three times that of the basin type solar still.

The production of the distillate is not enough if the collection mechanism is designed badly. The trays in the stage must be able to collect and deliver the distillate to the distillate pipe and to its tank. The required angle of the trays was experimentally determined by Estahbanati et al., (2014) in an experimental investigation of a multi-effect active solar still on the effect of the number of stages. The angle was experimentally found to be 5° but the angle of 8° was used to ensure that the distillate produced is collected sufficiently. The multistage trays at an angle as shown on figure 2.3. This means that the trays are not totally horizontal but are tilted at an angle of 8° from the horizontal. The distillate will therefore be able to flow in one direction under the influence of gravity. The angle at which the plate are inclined at influences the collection of the distillate at the lower end of the tray under the influence of gravity.

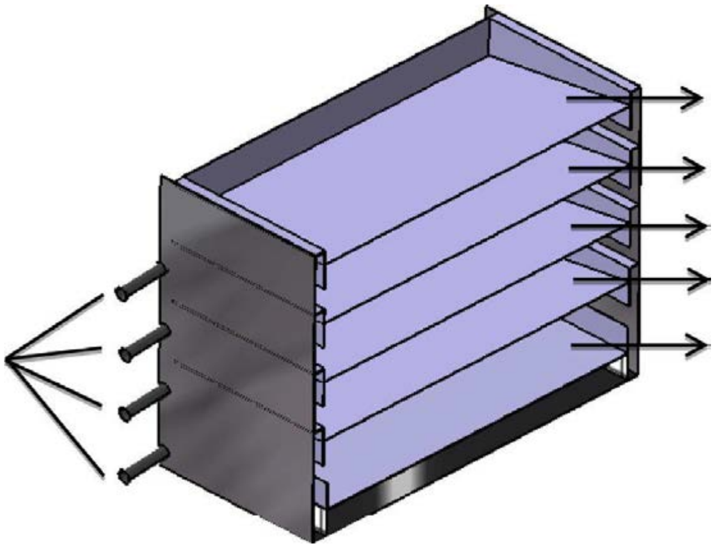

Figure 2.3: Stage trays at 8° from the horizontal

(Estahbanati et al., 2014)

Feilizadeh et al., (2015) conducted a study on the effect of the amount and mode of input energy on a multistage solar still desalination system. The results on the impact of the input energy amount showed that the distillate production increases with the increase in the amount of energy input into the system. The stages of the still produced different amounts as fraction of the total output as presented. Stage 1 to stage 4, the distillate was 36%, 26%, 20% and 18% respectively. This means that the lower stages produces more distillate than the stages at the top of the assembly. The heat intensity is more at the bottom than in the top stages.

Jubran et al., (1999) explains the construction of a multistage solar desalination unit with the orifice to transfer the vapour to the subsequent stage and the perfect sealing between different stages. The study stated that the orifice enabled the vapour to access the following upper stages in the assembly. All the surplus vapour which did not condense in a particular stage is transferred to the following stage. The orifice in a stage prevents the build-up of pressure and thus allowing the stage to remain at lower temperature. The difference in temperature between the vapour and the stage walls encourages condensation in a stage.

Abdessemed et al., (2018) conducted a study on the effects of the tray shapes in the stages. The comparison was made between the A-shaped trays and V-shaped trays. The V-shaped trays shown on figure 2.4 experimentally proved to be more efficient than those of an A-shape shown on figure 2.5. In addition to the shape of the tray, the material used to construct the stage trays was galvanised iron sheet. From the angle of 8° reported by Estahbanati et al., (2014) and the V-shape trays, firstly, allows the condensate to collect at the middle of the tray and then to flow to the lowest part of the trays and thus the shape and the angle influences the collection of the distillate positively.

Figure 2.4: V-shaped stage trays

(Abdessemed et al., 2018)

Figure 2.5: A-shaped stage trays

(Abdessemed et al., 2018)

According to the study conducted by Reddy et al., (2012), where the analysis of the evacuated multistage solar water desalination was done. It was suggested that for maximum performance of the collector, the collector must be positioned at an angle equal to the latitude of the area where the study is conducted. Setting the collector to the inclination equal to the area where the study is conducted increase the performance of the still. In addition to that, it was concluded that the optimum number of stages is 4 for that particular design. Chen et al., (2016) designed a multistage system with the evacuated tube collector and the position was equal to the altitude of the area. It is important to consider the angle as this will give maximum performance.

2.4 FACTORS AFFECTING THE EFFICIENCY AND PRODUCTIVITY OF SOLAR STILL

In the solar still, the boiling of the seawater in the stages reduces the efficiency and the productivity of the still. Taghvaei et al., (2014), conducted an investigative study on different brine depths, the study suggests that boiling of the brine negatively affects the productivity and the efficiency of the still. The saltwater depth is directly proportional to its temperature. Temperature must be high enough to evaporate the saltwater but lower than its boiling point.

The multistage solar still with water bed in each and every tray of the system are vulnerable to be affected by the seawater in the stages. In the study conducted by Adhikari et al., (1995) where the simulation study was conducted on the multistage with stacked trays. It was reported that the salt deposits from the seawater get stuck in the basin liner and affecting the ability of to absorb the solar energy from the sun. Also, the latent heat of condensation released by the last stage of the assembly is lost to the atmosphere. Chandrashekara and Avadhesh (2016) studied a multi-effect distillation (MED) system, it is reported that the evaporation and condensation of seawater is induced by the temperature difference existing inside the enclosure. Therefore, the condensation in the stage is caused by the lower temperature on the bottom tray of the subsequent stage and the walls of the assembly. The high temperature of the wall would affect the condensation rate of the vapour in the stage.

Rajamanickam and Ragupathy (2012) on a study conducted to determine the influence of the water depth on internal heat and mass transfer in a double sloped solar still. The conclusion was that, the increase in water depth in the basin type solar still decreases the efficiency and the productivity of the solar still. The output from the solar still was 3.07 litre per square meter per day when the depth of water was 10 mm. When the depth of water in the basin was increased to 75 mm, the total output for the day was 0.67 litre per square meter per day. The increase in depth of water in the basin does affect the performance of the still.

The angle of the condensing cover on the basin type solar still can affect the amount of distillate collected if not positioned at an adequate angle as reported by Tiwari and Tiwari (2007). The condensate droplets will not be collected as required by the trough if the cover does not allow them to flow to the lowest part of the still where the trough is located. In addition to the above the ambient conditions can greatly affect the efficiency and the productivity of the still.

Since the ambient condition includes the isolation of the still from the outside elements. The lack of insulation of the outside of the still can cause the still to underperform as reported by Elango and Murugavel (2014). The ability to conserve thermal energy in the still will be greatly affected by the atmospheric conditions interfering with the still and thus the still cannot perform as it should. Also, the type of material such as galvanised iron sheet, aluminium sheet or other material as some materials do not have good heat conducting properties.

2.5 SUMMARY

In all the literature reviewed, the multistage solar still desalination systems used the water bed in the stages to supply the heat to the following stages. This is done by means of latent heat of condensation from the previous stages. The present study however, proposes a direct vapour input into each stage from the evaporator by means of the vapour make-up tubes. In addition to the direct vapour input into each stage, there are number of things that have not been found to exist in both the present and previous multistage solar still desalination systems.

Firstly, it was discovered that none of the systems are self-regulatory in terms of seawater flow in the system by means of a float valve or any other device. The present study uses a float valve located inside the secondary seawater tank to control the flow of seawater in the system. The seawater tank stores the seawater and transfers it to the evaporator.

Secondly, the flow patterns of seawater in a zig-zagged seawater tube has not been found. The tube is made from copper material and serves a number of purposes, it directs the flow of seawater from the basin type solar still at the top of the stacked stages to the secondary seawater tank. It recovers the latent heat of condensation from the condensing vapour and lastly, it transfers that heat to the seawater flowing inside it since it is made from copper material. The material is known to have good heat transfer qualities.

Thirdly, the integration of the multistage solar still desalination system with the basin type solar still have not been found. This study proposes to experiment on the integrated system.

Fourthly, the method employed to circulate the seawater between the evacuated tube solar collector and the evaporator as well as the way the thermal energy is supplied from the collector to the evaporator and ultimately to the stages has not been found. This system proposed in this study experiments this method.

CHAPTER THREE

CONSTRUCTION OF A MULTISTAGE SOLAR DESALINATION SYSTEM

A detailed construction process of the main components is discussed in this chapter. It presents the list of all materials and equipment used in the construction of the system. It then goes on to details the construction of each of the components of the system and lastly, it describes how the whole system was put together to form one assembly.

3.1 LIST OF MATERIALS AND EQUIPMENT USED IN CONSTRUCTION OF THE SYSTEM

The following is the list of materials and equipment used in constructing the solar still system:

- Galvanised iron sheet with 1 mm thickness.
- Clear perspex sheet with 0.5 m x 0.5 m x 3 mm dimensions.
- Counter sunk eureka machine screws and nuts with 5 x 12 mm dimensions.
- Counter sunk eureka machine screws and nuts with 4 x 40 mm dimensions
- Cistern float valve inlet and a ball float.
- 1 litre Duram black paint.
- Galvanised square tube with 19 x 19 x1 mm dimensions.
- A 22 mm inlet non-return valve.
- U-channel galvanised iron
- Mild steel sheet with 3 mm thickness
- Alcolin silicone neutral cure 280 ml.
- Copper tube with 9.6 mm external diameter.
- Copper tube with 6.4 mm external diameter.
- Copper tube with 15 mm external diameter.
- Copper crossover tubes (T-shaped tubes).
- Copper crossover tubes(U-shaped tubes)
- 90° elbow with 15 mm external diameter.
- 90° elbow with 22 x 15 mm external diameters.
- Black foam sealing strip with 10 x 10 mm dimensions.
- Hose clamps.
- Eureka aluminium rivets with 4 x 8 mm dimensions.
- Clear tubing with 1.5 mm wall thickness.
- Guillotine machine
- Bending machine
- Angle grinder

- Hand drill machine
- Acetylene gas welding unit
- Mallet hammer
- Ball peen hammer
- Centre punch
- Screw drivers
- Marking-off tools
- Tape measure
- Vernier calliper
- Pliers
- Tin snip
- Protractor
- Copper welding rods
- Bench vice
- Engineers square
- Steel rule
- Scriber
- File
- Pop rivet gun
- Marking-off spray

3.2 A DETAILED CONSTRUCTION OF THE SYSTEM

3.2.1 Side covers

Most of the components of the system were made from a 1 mm thick galvanised sheet. The sheet was used because it had a certain degree of resistance to corrosion since it was galvanised. It thickness meant that the sheet was relatively cheap as compared to larger thicknesses of the same material. In addition to that, it is understood that the material is not a food grade material but it was preferred because the study was for experimental purposes only. Selvaraj and Natarajan (2017) on a review study reports that for experimental purposes most researchers prefer to use either the galvanised iron sheet or aluminium. In most regions, these material are available locally and relatively cheap. The side covers of the assembly shown on figure 3.1 were measured and marked-off using the measuring tape, scriber, engineers square, steel rule and the marking-off spray. The sizes of the side covers were 1450 x 350 mm in length and width. The cutting of the sheet was done by the Guillotine machine. There are two of these sheets and for attaching them on the system, the lips were measured as above. Their measurements 25 x 25 mm and they were cut all around the edges of the galvanised sheets using a tin snip. A centre punch and a ball peen hammer was used in punching the centre hole to accommodate the drill bit. A 4 mm drill bit and a hand drill were used to drill the holes which will be later used to secure the cover onto the skeleton structure. The lips were spaced at 280 mm from each other on the longest side. The total number of lips was 4 on each side of the sheet. Along the width they were 3 lips spaced 50, 250 and 50 from one end to the other. Side cover 2 was further reduced to 1112 mm to form a triangular shape shown on the figure. The shape created the passive basin type solar still at the top of the whole assembly.

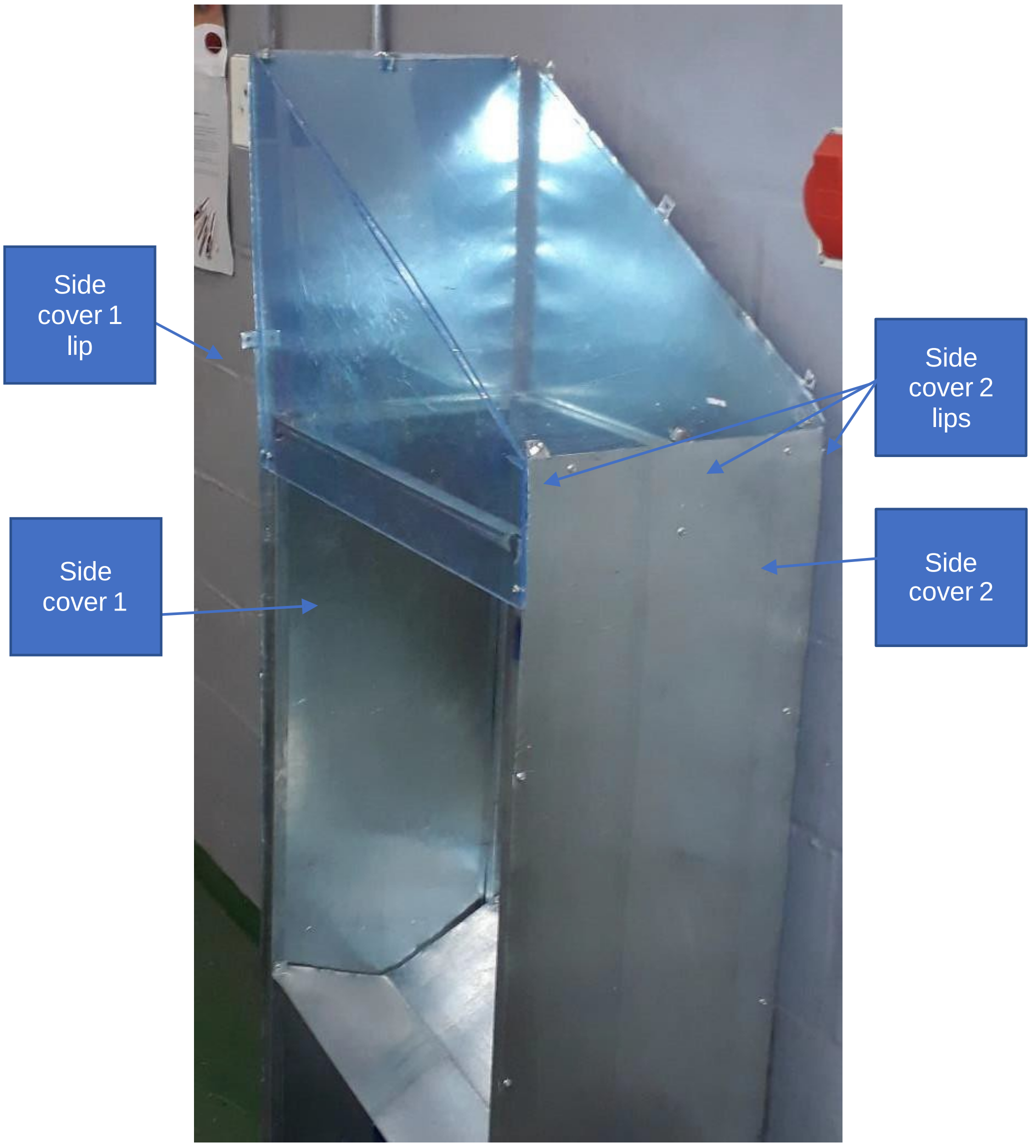

Figure 3.1: Side covers

3.2.2 Back cover

The back cover was measured and cut to dimensions using the same procedure used on the side covers. It dimensions were 1450 x 650 mm before the 25 x 25 mm lips were cut all around it edges. A protractor was used to measure an angle of 33° from the horizontal and a tin snip was used to remove the top part. Figure 3.2 shows the back cover fixed onto to the skeleton structure. The cover runs from the top to the bottom of the assembly. The lips and the holes around the edges of the cover were achieved using the same procedure used on 3.2.1

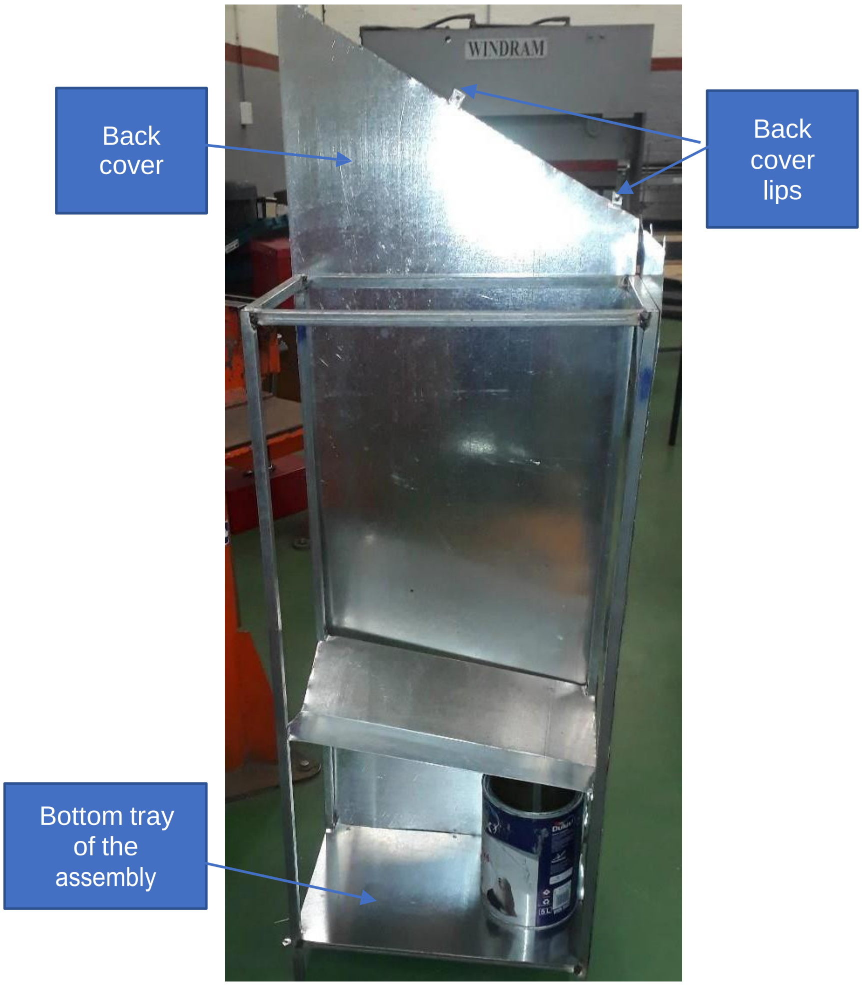

Figure 3.2: Back cover

3.2.3 Bottom tray of the assembly

The bottom tray shown on figure 3.2 was measure as in 3.2.1 above and cut using the Guillotine machine. The sizes of the tray were 300 x 600 mm and a 15.5 mm hole was drilled 150 mm from one end. A centre punch and a ball peen hammer were used to punch a centre hole for the drill bit. A hand drill and a 15.5 mm drill bit was used to drill the hole. This hole was later used to inter-connect the evaporator and the brine tank through the brine over flow tube.

3.2.4 Top tray of the assembly

The bottom tray shown on figure 3.3 was measure as in 3.2.1 above and cut using the Guillotine machine. The sizes of the tray were 300 x 600 mm and a 15.5 mm hole was drilled 150 mm from one end. A centre punch and a ball peen hammer were used to punch a centre hole for the drill bit. A hand drill and a 15.5 mm drill bit was used to drill the hole. This hole will later be used to inter-connect the fifth stage and the basin type solar still.

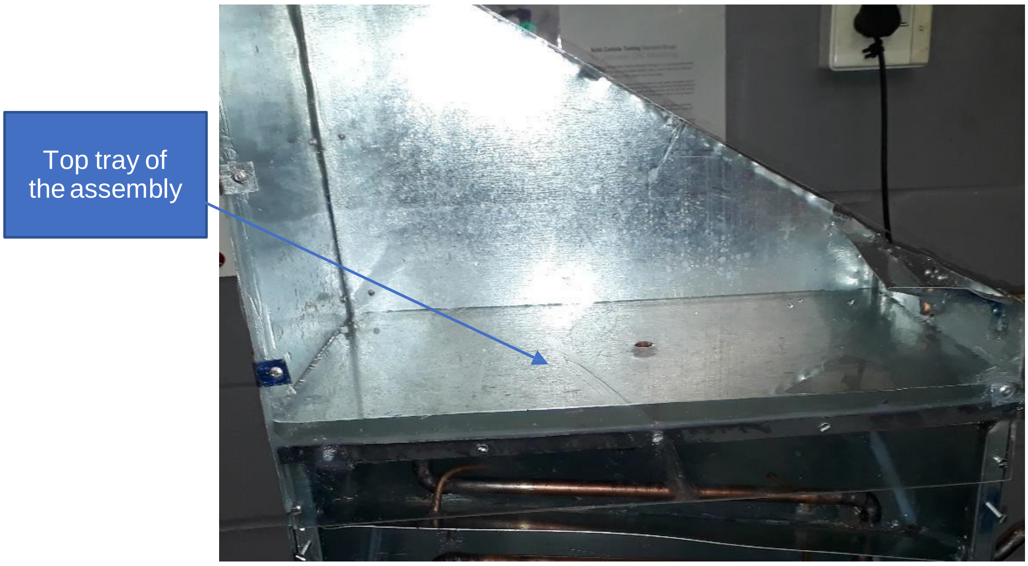

Figure 3.3: Top tray of the assembly

3.2.5 Skeleton structure

The galvanised tubes were preferred for the same reason discussed above in 3.2.1. The skeleton structure shown on figure 3.4 was made from galvanised iron square tubes with the dimensions of 19 x19 x1.6 mm dimensions. The tubes were measure and marked-off using the measuring tape, a scriber and a marking-off spray to the required sizes. A hacksaw was used to cut the square tubes and a file was used to clean the edges of the tubes. The arc welding was used in joining the structure together at an angle of 90° to each other. These tubes were then drilled using a 4 mm drill bit and a hand drill, the hole were used to accommodate the pop rivets.

Figure 3.4: Skeleton structure

3.2.6 Separator plate

The separator plate shown on figure 3.5 is made from the galvanised iron material and was measured and marked-off using the protractor, steel rule and the scriber to mark all the relevant points. The angle of 15° was measure on both sides of the centre of the tray. The V-shape was cut at the centre to accommodate the first stage bottom tray. A steel rule and a scriber was used in measuring and marking-off a 15 mm hole. A centre punch and a ball peen hammer was used in punching the centre point and a hand drill was drilled used in drilling the hole. The 15 mm hole was later used to inter-connect the secondary seawater tank and the evaporator by means of the seawater transfer tube. The full view is shown on figure B7 under appendix B

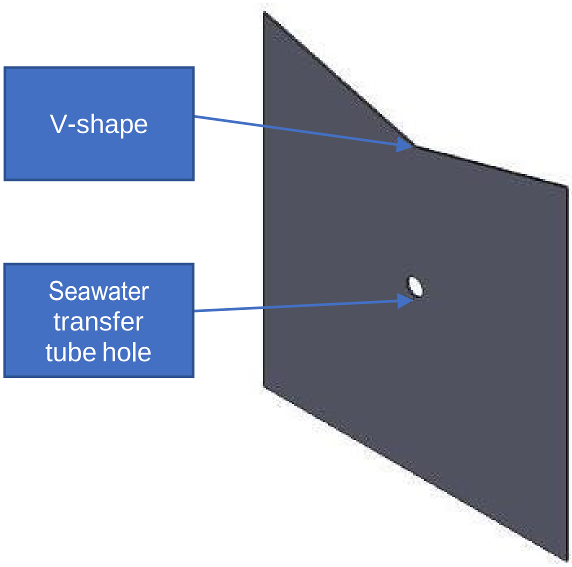

Figure 3.5: Separator plate

3.2.7 The evaporator

A paint container was used as the evaporator, since the configurations of the system were relatively new in the solar desalination. It was unclear how the system will perform and therefore to save costs, the paint container was used which was obtained for free. The evaporator is a component inspired by the domestic house hold kettle, the evaporator is shown of figure 3.6. The evaporator rejects heat as it operate through its body, this heat is then transferred to the surroundings though radiation. Radiation is the energy emitted by the matter in the form of electromagnetic waves (or photons) as a result of the changes in the electronic configuration of the atoms or molecules (Çengel, 1998).

It has a capacity of five (5) litres and an external diameter of 200 mm. It is connected to a number of tubes that have different purposes. In measuring and marking-off the holes in the evaporator, the steel rule, ball peen hammer and centre punch was used. The seawater transfer tube is 45 mm long with a 15 mm diameter. The evaporator was drilled onto its side using a 14.5 mm drill bit and a hand drill. The seawater transfer tube was forced through the side of the evaporator. The brine overflow tube was drilled at the bottom centre of the evaporator using the hand drill and the drill bit of 15 mm. The open loop circuit holes was also drilled on the side of the evaporator using the same method as above. All the holes were sealed off using the Alcolin sealant to prevent water from leaking.

The 6 x 9.5 mm vapour make-up tubes holes were on the top side of the evaporator, the hole were drilled equally around the circumference of the evaporator. The vapour make-up tubes holes were drilled using a 9.5 mm drill bit and the hand drill, a 60° interval was used in laying out the holes on top of the evaporator, therefore the holes are equally spaced. A 15 mm hole was drilled on the side of the evaporator to make a sight glass. The inside of the evaporator is shown on figure 3.7. A 40 x 30 mm perspex sheet was used as a sight glass. The full view of this evaporator is shown on figure B1 under appendix B.

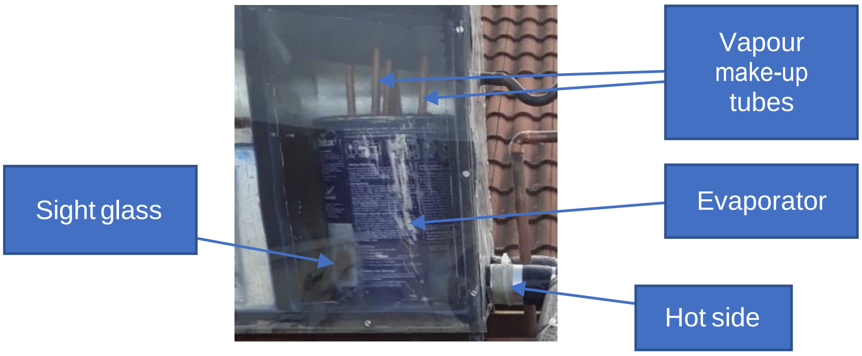

Figure 3.6: The evaporator, vapour make-up tubes and the sight glass

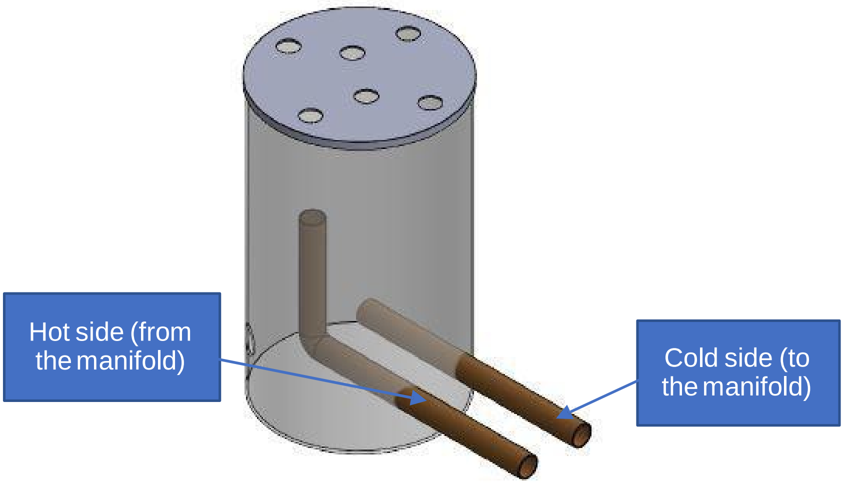

Figure 3.7: The inside of the evaporator

3.2.8 V-shape stage trays

The stage trays were made from the same galvanised sheet described under 3.2.1. The trays shown on figure 3.8 and figure 3.9 are made from a galvanised sheet and the same process in 3.2.1 was used in measuring, marking them off and cutting them. The bending of the trays was achieved through the use of the banding machine. The trays were bent at 15° from each side to form a V-shape. A 15 mmm drill bit and a hand drill was used in drilling the zig-zagged seawater tube hole. In drilling the hole, a steel rule, marking-off paint and a scriber was used to mark the centre of the hole. The centre punch and a ball peen hammer was used to punch the centre hole so that the drill bit can be accommodated. In drilling the vapour make-up tubes hole, a 9.8 mm drill bit was used in drilling them and the same procedure was used as in drilling the 15 mm hole. All the stage trays were done using the same procedure depending on which stage the tray belonged to the holes would differ. On table 3.1, the number of holes per tray and tray dimensions are shown. Also, on figure 3.10, the stage trays at an angle are shown. A full view with dimensions is shown on figure B4 under appendix B.

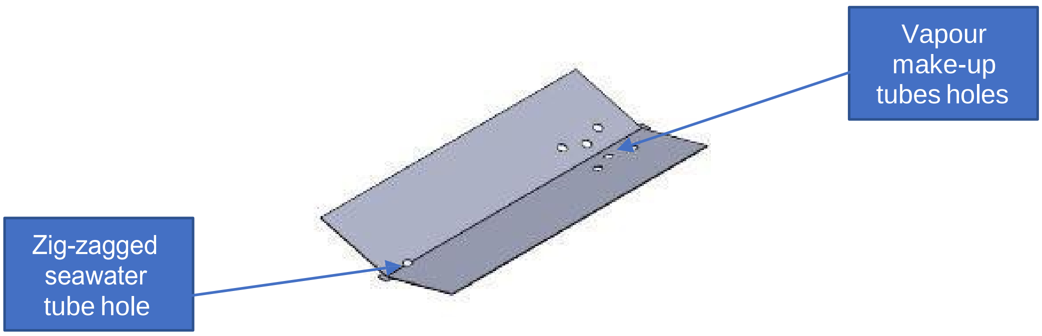

Figure 3.8: Stage one V-shaped tray

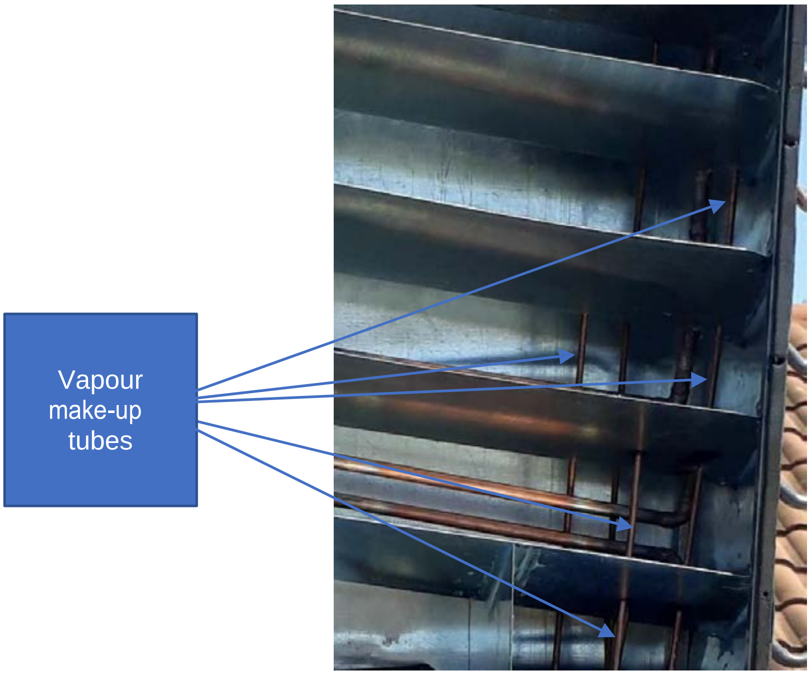

Figure 3.9: V-shaped stage trays with vapour make-up tubes protruding through them

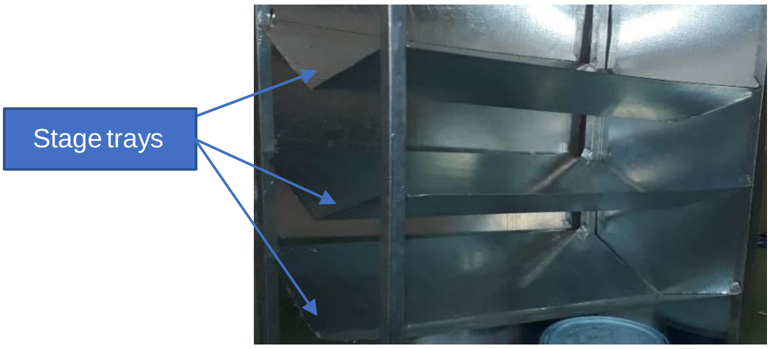

Figure 3.10: V-shaped trays positioned at 8° angle and bent in the middle at 20°

Table 3.1: Make-up vapour holes

Stage number	Number of make-up tubes holes	Tray dimensions L x W x T (mm)
1	6	580 x 300 x 1
2	4	
3	3	
4	2	
5	1	

3.2.9 Zig-zagged seawater tube

This tube was made from a copper material which is a non-ferrous material. These materials are known to be good heat conductors. Çengel (1998) states that non-ferrous materials such as copper are very good heat conductors. This tube has three functions in the system, firstly, it transport the raw seawater from the top of the assembly to the bottom as shown on figure 3.11. Secondly, it recovers the latent heat of condensation from the condensing vapour in all stages. The heat recovery process occurs a number of times and the heat transfer between the vapour and the tube happens through convection. Convection is the mode of heat transfer between a solid surface and the adjacent liquid or gas that is in motion, and it involves the combined effect of conduction and fluid in motion (Çengel, 1998).

Since the tube's thickness is very small, the temperature gradient between the inside of the tube where the cold seawater is flowing and the outside where the hot vapour comes into contact with the tube, is big. The small thickness of the wall causes the temperature gradient in that direction to be larger (Çengel, 1998).The heat then flows from the outside cylindrical wall of the tube to the inside though conduction. Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent, less energetic ones as a result of interaction between the particles (Çengel, 1998).

This tube is made from a 15 mm external diameter copper material. This tube travel through all the five stages and figure 3.12 illustrate how the seawater tube runs from the top to bottom through the stages. A 15.5 mm hole was drilled through at the centre of each stage tray from stage 1 to the basin type solar still using a hand drill and a 15 mm drill bit. The length of the passes are equal at 410 mm along the length of the stage trays. The 90° elbows also made from copper material were used to achieve multiple passes in a stages. The elbow were joined together using the acetylene gas welding and the copper welding rods by means of brazing.

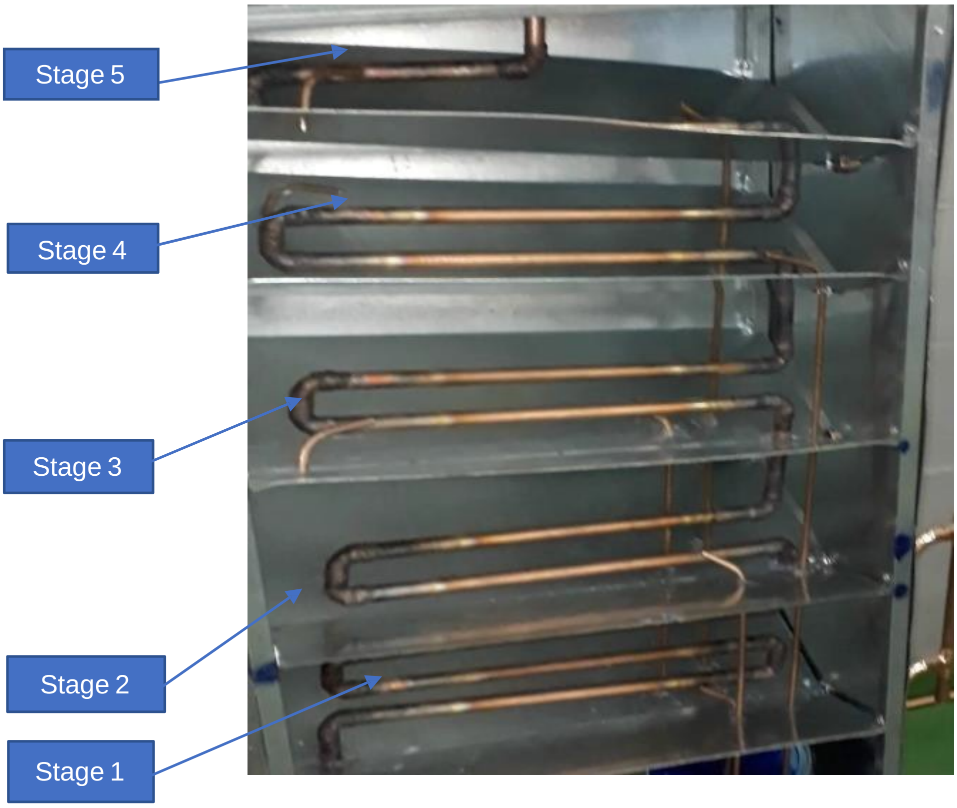

Figure 3.11: Zig-zagged seawater tube

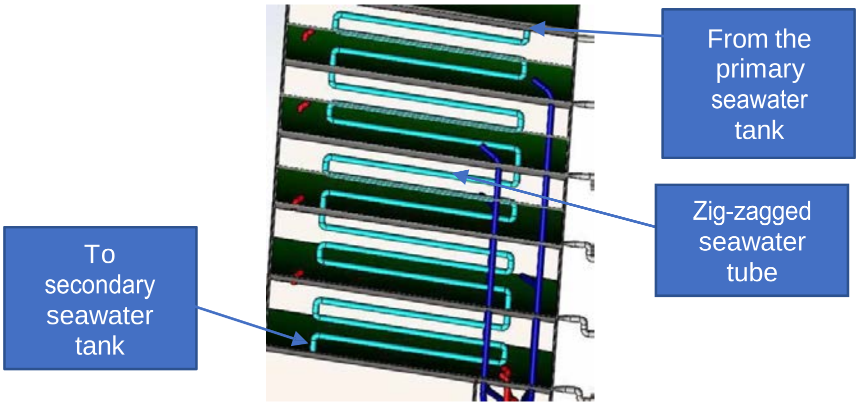

Figure 3.12: Zig-zagged seawater tube

Figure 3.13 shows stage one zig-zagged seawater tube in 3D drawing. A full drawing with dimensions is shown on figure B5 under appendix B.

Figure 3.13: Stage one zig-zagged seawater tube

The number of passes of the zig-zagged seawater tube in each stage are shown on the table 3.2.

Table 3.2: Zig-zagged Seawater tube passes

Stage number	Number of passes
1	3
2	2
3	2
4	2
5	1.5

3.2.10 Basin type solar still

The basin type solar still shown on figure 3.14 is situated at the top of the system and has a transparent perspex sheet on one side and on top. The perspex is 3 mm thick and forms a triangular shape on one side and the other perspex is on top of the stage at an angle of 33° and facing to the north. The other two sides are made of a galvanised sheet and the stage is painted black inside. The highest side is 400 mm high with a width of 300 mm and 500 mm long.

A protractor was used in marking-off the angles of the perspex sheet and the galvanised sheet at 33° from the horizontal. The sides and the holes along the edges of the sheet were measured using the measuring tape, scriber and engineer's square. The cutting of the perspex sheet was done using the hacksaw and a fine file was used to smoothen the rough edges of the sheet. The holes along the edges were drilled using the hand drill and were used to fasten the perspex sheet onto the skeleton structure of the system.

The 5 x 12 mm counter sunk screws and nuts were used in securing the perspex sheet and 4 x 8 mm pop rivets and pop rivet gun were used to fasten the galvanised sheet and form a triangular structure. A 320 long and 20 mm width galvanised iron strip was bent 15° in the middle to form a trough shown on figure 3.15. A 15 mm hole was drilled on the side of the basin type solar still to accommodate the distillate collecting tube. A 90°, 15 mm elbow was used as a filling hole of the basin type solar still on the highest side as shown on figure 3.16. The basin type solar still internal walls was then painted black with the Duram black paint to increase absorptivity of the wall of the basin type solar still.

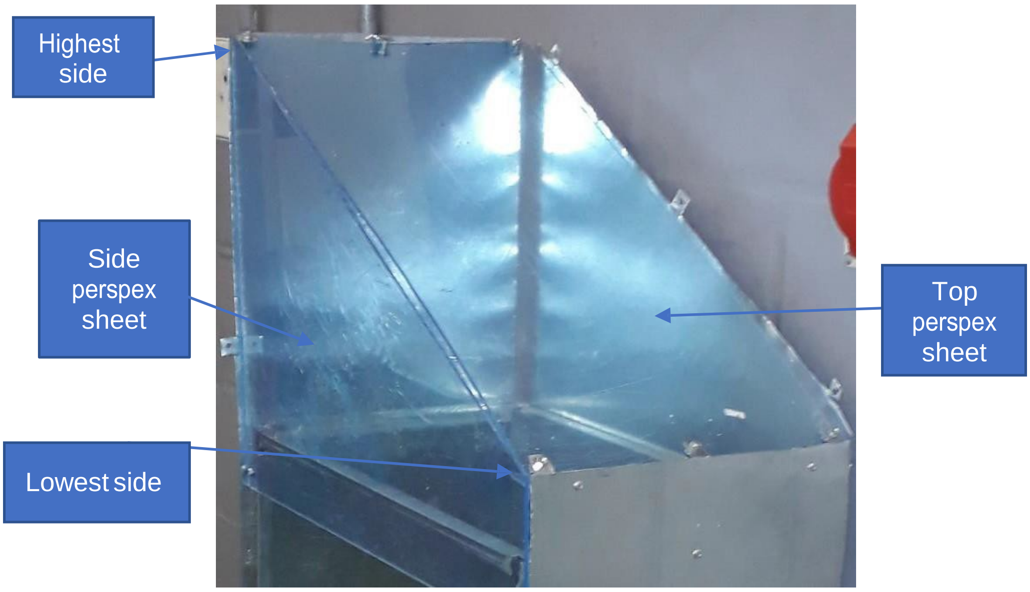

Figure 3.14: Top and side perspex sheets

Figure 3.15: Trough

Figure 3.16: Filling hole

3.2.11 The front cover perspex sheet

This sheet was not cut as the dimensions of the front of the system were made to accommodate it. The sheet had dimensions of 1000x 500 x 3 mm and it is shown on figure 3.17.

Figure 3.17: Front view of the multistage covered with perspex sheet

3.2.12 Evacuated tube solar collector

Table 3.3 shows the evacuated tube solar collector's information as supplied by the manufacturer. The collector shown on figure 3.18 was elevated at an angle equal to the area using the galvanised square tubes. The tubes were measured and marked-off using the measuring tape, engineer's square and the scriber. They were cut using the hacksaw and a file was used to smoothen the edges. The tubes with 19 x19 x 1.6 mm dimensions were used in elevating the collector. Two of 32 x 10 x 1.6 mm galvanised iron U-channel were used as support for rigidity of the structure and 32 x 3 mm thick mild steel strip was used to stabilise it. A side view of the system is shown on figure A2 under appendix A. According to Reddy et al., (2012) for maximum performance the collector must be placed at a latitude equal to that of the area. In this present study, since South Africa is in the southern hemisphere, the collector is facing north. The latitude and longitude of Cape Town are 33.925°S and 18.4241°E respectively Latitude Longitude, n.d. The collector is positioned in a sloped position according to the latitude of the area.

Low grade solar panels were chosen because the intensity of solar radiation is very high in the Southern African country and therefore they it is suitable for such conditions. South Africa.

Department of Energy (2003:20) explains that South Africa is one of the countries in the world that receives high solar radiation. This solar radiation ranges from 4.5-6.5 KWh/m^2 compared to other countries such as United States of America which receives only 3.6 KWh/m^2.The sun intensive is immense and can be harness to produce fresh drinking water through thermal desalination means. The evacuated tube solar collector has 12 tubes and the heat transfer fluid inside the heat pipe is called acetone.

Table 3.3: Evacuated tube solar collector

Tube quantity	Dimensions (mm) L x W x H	Weight (kg)	Absorption (%)	Emission (%)
12	1056 x 1983 x 130	51	93	10

Figure 3.18: Evacuated tube solar collector at 33° from the horizontal

3.2.13 Open loop circuit

The open loop circuit shown on figure 3.19 was formed using the 15 mm, 90° x 15 mm elbows and 90 ° x 22 x 15 mm elbows, all of which are made from copper material. These tubes were used in conjunction with the 22 mm non-return valve shown on figure 3.20, 22 mm flexible hose, hose clamps and a 9.6 mm pressure relief plug tube. The flexible hoses were used to connect the hot and the cold side on to the collector. The hose clamps were used to secure the connections and flat screw drivers were used in securing them in place. A steel rule was used in measuring them and a box cutter used in cutting them to required sizes. A 10 mm thick polystyrene insulation was used to cover the tube as shown on figure 3.21. A 22 mm non-return valve was fitted on the hot side of the circuit since the manifold has 22 mm diameter tubes. A 22 x15 mm, 90° elbow was used connect the flexible hose from the non-return valve and the 15 mm tube on the hot side. The rest of the connections were done using a 15 mm diameter tubes and 90° elbows. The connections of these tubes were welded with the acetylene unit and the copper welding rods.

Figure 3.19: Open loop circuit and non-return valve

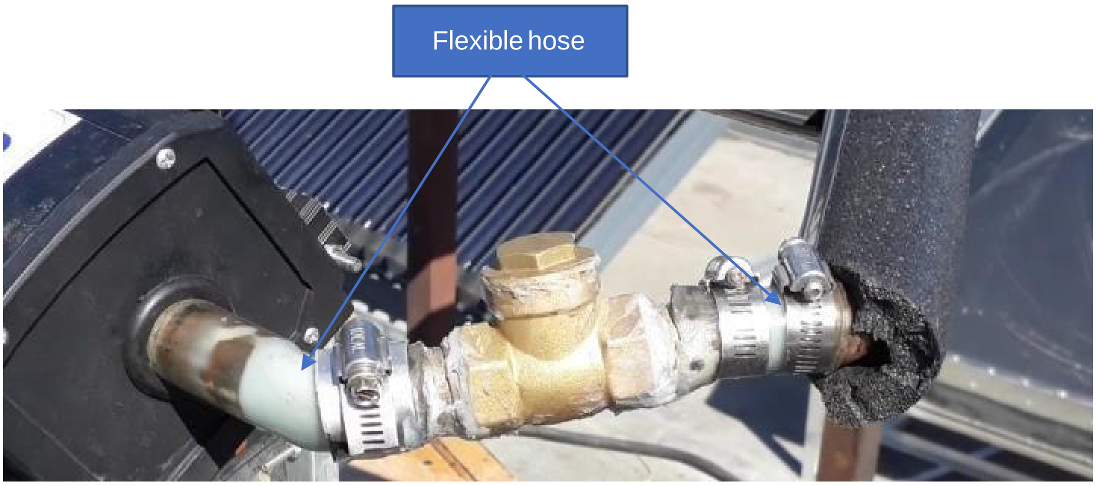

Figure 3.20: Non-return valve

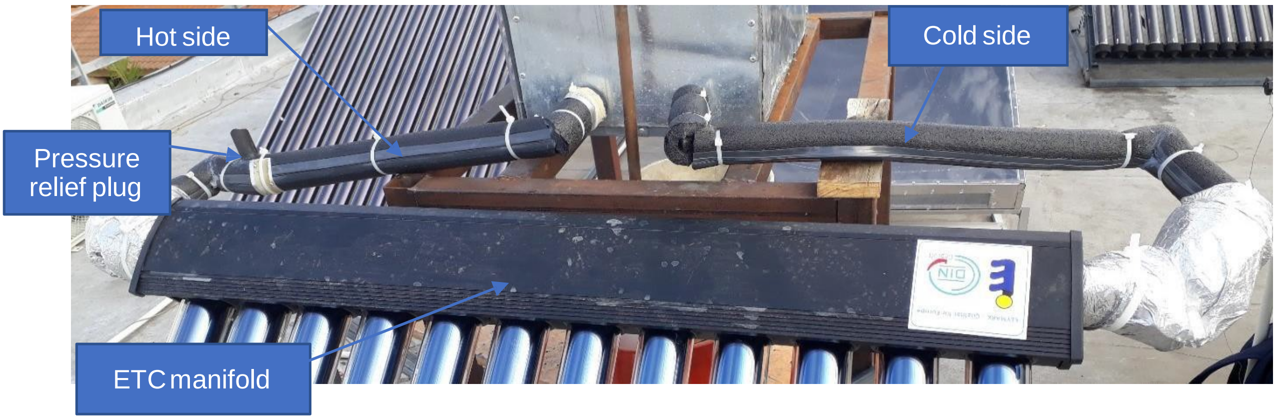

Figure 3.21: Open loop circuit with insulation

Figure 3.22 shows a pressure relief plug; this plug was welded onto the hot side of the open loop circuit using brazing. On the hot side, a 9.8 mm diameter hole was drilled perpendicular on the tube's cylindrical surface and a 70 mm long and 9.6 mm in diameter copper tube was welded on to it. A plastic insert was pressed inside the 9.6 mm tube.

Figure 3.22: Pressure relief plug

3.2.14 Vapour make-up tubes

The vapour make-up tubes are equally spaced on the diametrically top of the evaporator. The hole of the tubes was drilled through the cap of the evaporator at equal intervals. There are 6 make-up tubes in total and these tubes are made of 9.6 mm external diameter copper tube. The tubes were measured and marked-off using the measuring tape and the scriber to mark the size. A hacksaw was used to cut the tube and a fine used to clean the edges. The tubes are bent at 45° in each stage as shown on figure 3.23, the pipe bender was used to achieve the angle. These tubes have different sizes in length depending on which stage they are supplying the vapour to. A 3D view is shown on figure A6 under appendix A.

Figure 3.23: Vapour make-up tubes

The vapour make-up tubes lengths are shown on table 3.4.

Table 3.4: Vapour make-up tubes

Stage number	Number of tubes per stage	Length (mm)
1	2	125
2	1	255
3	1	450
4	1	600
5	1	750
Total	6	2180

3.2.15 Secondary seawater tank

The secondary seawater tank shown on figure 3.24 and figure 3.25 are designs which were inspired by the float valve of a domestic cistern toilet found in a house hold. The tank is made from galvanised sheet with a thickness of 1 mm and has dimensions of length, width and height of 300 x 110 x 150 mm. This tank is made in a rectangular shape and has a sight glass. The measuring, cutting and bending of the galvanised sheet was achieved by the steps under 3.2.1. A 20 mm hole was drilled on the side of the tank to accommodate the zig-zagged seawater tube. A float valve was modified using the hacksaw and the pliers to bend it to suit the tank's position. It was then installed by joining the male and female threaded parts and was secured in place. A 4 mm hole was drilled on the side using the hand drill to allow the tank to vent the pressure. The sight glass slot was cut and a 120 x 30 mm perspex sheet was measured using the steel rule and marked-off using a scriber. The cutting was done using a hacksaw. The perspex was sealed off and secured in place using the Alcolin sealant. See figure B2 and figure B3 under appendix B for a detailed drawing of the components.

Figure 3.24: The evaporator, vapour make-up tubes and the secondary seawater tank

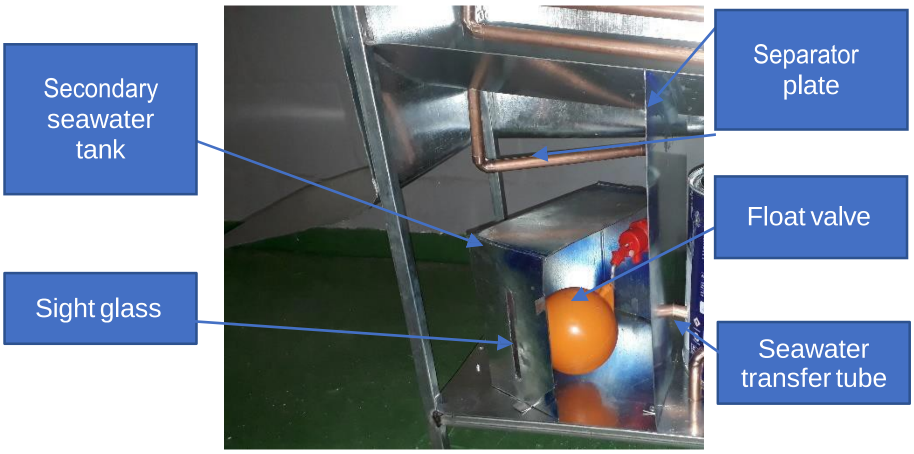

Figure 3.25: Seawater tank and float valve

3.2.16 Brine tank

The tank is made from the same material as in 3.2.1 and the location of the tank encourages heat transfer from the hot brine to the relatively warm seawater in the secondary seawater tank. The brine tank has the dimensions of length, width and height of 450 x 200 x 20 mm. This tank is also made in a rectangular shape. The brine tank is shown on both figure 3.26 and figure 3.27 and has a brine discharge tube on the underside which is 15 mm external diameter and 45 mm long. The tube was made from welding a 90° elbow and a 15 mm copper tube using acetylene gas welding. Figure A5 under appendix A show how the brine tank is located.

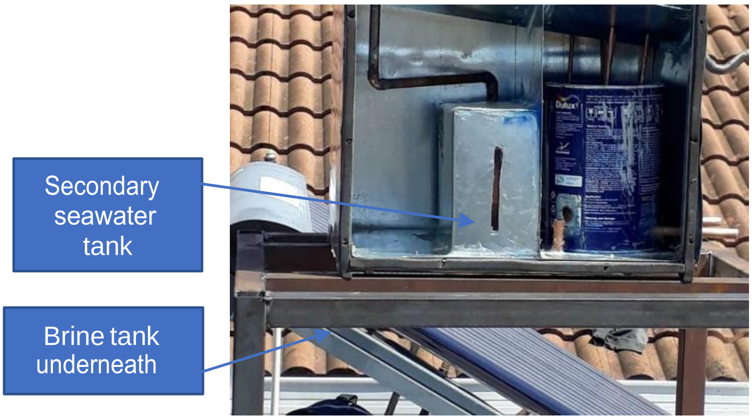

Figure 3.26: Secondary seawater tank and brine tank

Figure 3.27: Brine tank located on the underside of the system

3.2.17 The main distillate tube and the U-shaped tubes

The main distillate tube shown on figure 3.28 and figure 3.29 was made of a copper tube with external diameter of 15 mm and 90° T-shaped fittings were used to create right angle joints. The U-shaped tubes with a corresponding diameter were used to connect the tube to the multistage unit. The tube was 1.051 m in length and connected to U-shaped tube which each had a length of 80 mm. The tube was measures and marked-off using the measuring tape and a scriber, they were cut using the hacksaw and a file used to flatten the rough edges. The joints on the tube were achieved through gas welding. See figure B6 under appendix B for full dimensions.

Figure 3.28: Main distillate tube

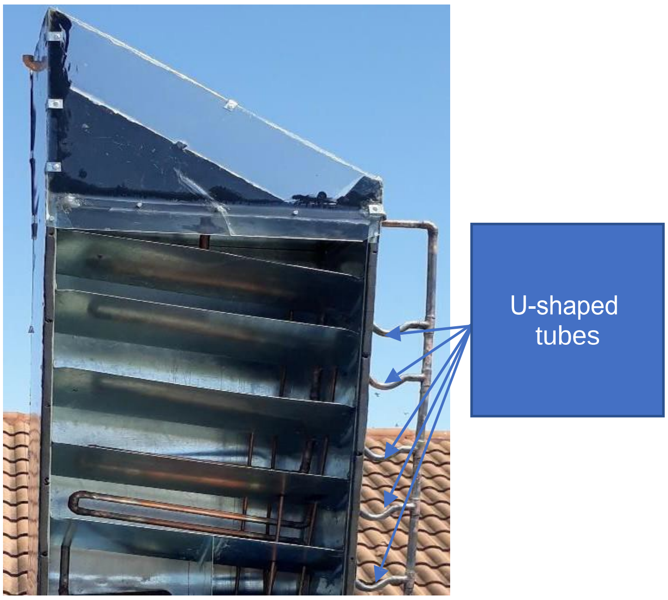

Figure 3.29: Skeleton structure

3.2.18 Vapour transfer tubes

The vapour transfer tubes shown on figure 3.30 were made from copper material with 6.4 mm diameter. They were measure, marked-off using the steel rule and a scriber, they were cut using the hacksaw and a file was used to flatten the rough edges. They were bent at 45° towards the zig-zagged seawater tubes using a pipe bender so that they spray the vapour directly on the tube. Each tube is 75 mm in length

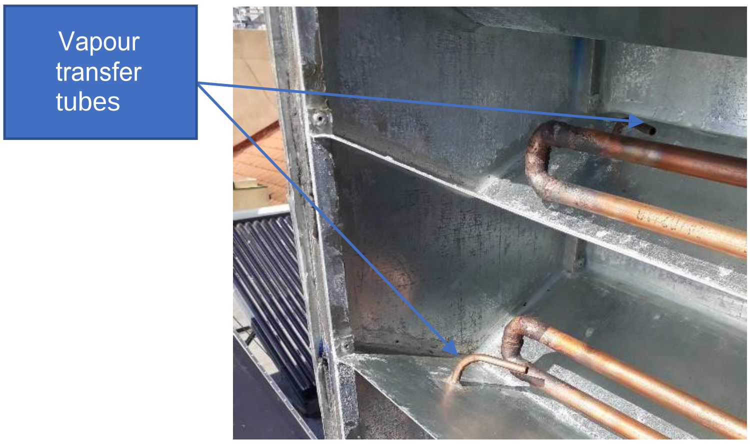

Figure 3.30: Vapour transfer tubes

3.2.19 Multistage stand

The stand shown on figure 3.31 is made from a 40 x 40 mm square tube and there are two transversal tubes on which the multistage is mounted. Each transversal tube has two square holes cut through them along its length. For rigidity, the legs of a multistage are inserted through these holes and the stand is bolted down on the floor to stabilise it. Dimensions of the stand are 700 x 660 x 380 mm, height length and width respectively. The stand was welded using arc welding.

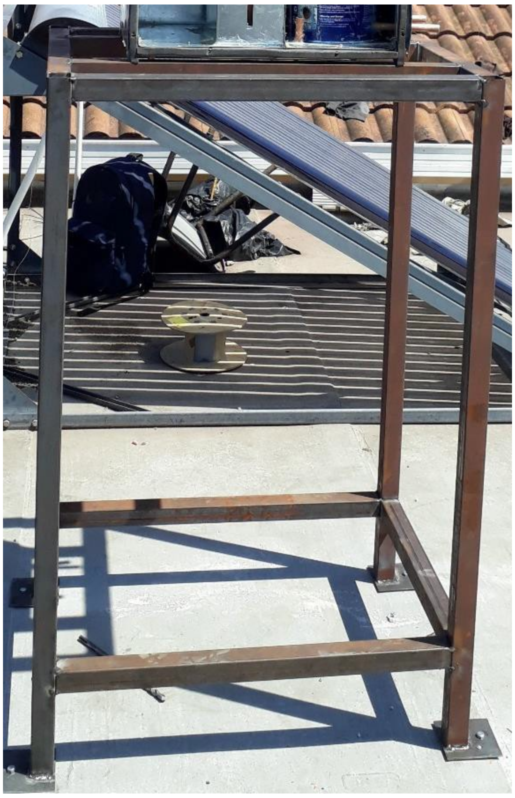

Figure 3.31: Multistage stand

3.3 THE CONSTRUCTION OF THE MULTISTAGE SOLAR STILL

The complete system is shown on figure 3.32. The construction of the assembly was started with the skeleton structure and the galvanised sheets. The bottom tray of the assembly was fixed on the lower end on the skeleton structure by means of 4 mm pop rivets and the pop rivets gun. The back cover was then installed thereafter, fixing it with the rivets as by using the 25 x 25 mm lips. The side covers were then installed afterwards onto the structure and secured using the same method. The evaporator was then inserted into the assembly and aligned with the brine over flow tube which connect the evaporator and the brine tank. The seawater transfer tube was also aligned with the secondary seawater tank. Alcolin sealant used to seal the gap between the tube and the evaporator opening.

Figure 3.32: Multistage solar still desalination system

The open loop circuit tubes were inserted into the evaporator in their positions and the sealant was also used to seal the gap off. The separator plate was then installed close to the evaporator at 250 mm from one end along the length of the skeleton structure and the seawater transfer tube inserted through the separator plate hole. The sealant was the used to seal it off. Figure 3.33 shows a 3D view of the system. The full view of the system is shown on figure A3 under appendix A. The secondary seawater tank was installed against the separator plate and secured using the 4 mm pop rivets. The zig-zagged seawater tube was then attached to the float valve in the secondary seawater tank and sealed off with the sealant. The vapour make-up tube were inserted on top of the evaporator and sealed off as well to prevent vapour leaks. The first stage tray was then installed allowing the vapour make-up tubes as well as the zig-zagged seawater tube to pass through it.

The tray was then fixed in place using the 4 mm pop rivets and the pop rivets gun. The tray was positioned at 8° from the horizontal and secured in place using the 4 mm pop rivets. Stage 2, 3, 4 and 5 trays were installed using the same procedure as that of stage 1. The trays were placed 150 mm from each other to form a multistage. The Alcolin sealant was used to seal off each stage so that all the stages are vapour tights. The vapour make-up tubes were allowed through each tray depending on the tube’s destination. The opening between the tube and the vapour make-up tubes was sealed off using the sealant. The zig-zagged seawater tube was then positioned to allow seawater from the basin type solar still to flow down. The sealant was also used to seal off the gap between the zig-zagged seawater tube and the top tray of the assembly.

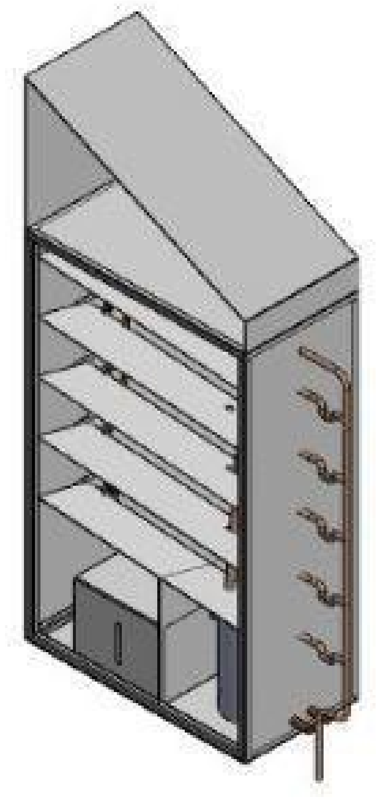

Figure 3.33: 3D view of the multistage solar still desalination system

The vapour transfer tubes were then installed in each stage from stage one to stage five. The tubes were positioned in such a way that they face towards the zig-zagged seawater tube. This was done so that the vapour will be sprayed directly onto the tube. The gap between the trays and the tube was sealed off using the sealant. The main distillate tube was then inserter on the side of the side cover and the gap sealed off as well, refer to figure 3.34 for the main components of the system. The full front view of the system is shown under figure A4 on appendix A. The basin type solar still covers was the put in place and made vapour tight by means of the sealant. The brine tank was then installed on the underside of the assembly by means of the 4 mm pop rivets and pop rivets gun. The Alcolin sealing agent was used to seal the edges of so that the bine does no leak.

A 16 mm diameter clear tubing was attached at the bottom of the brine discharge tube and secured using the hose clamps and the screwdriver. The 16 mm tube was inserted at the bottom of the main distillate tube and secured with the hose clamps as well. A black foam sealing strip was the used on the front perspex cover was which will seal off the stages from the outside. On the roof top of Mechanical Engineering building, the multistage system was mounted on top of the multistage stand. The stand had 4 square hole measured precisely to fit the legs of the skeleton structure. The open loop circuit was then connected to the evacuated tube solar collector. The front perspex cover was put in place just before the tests commenced.

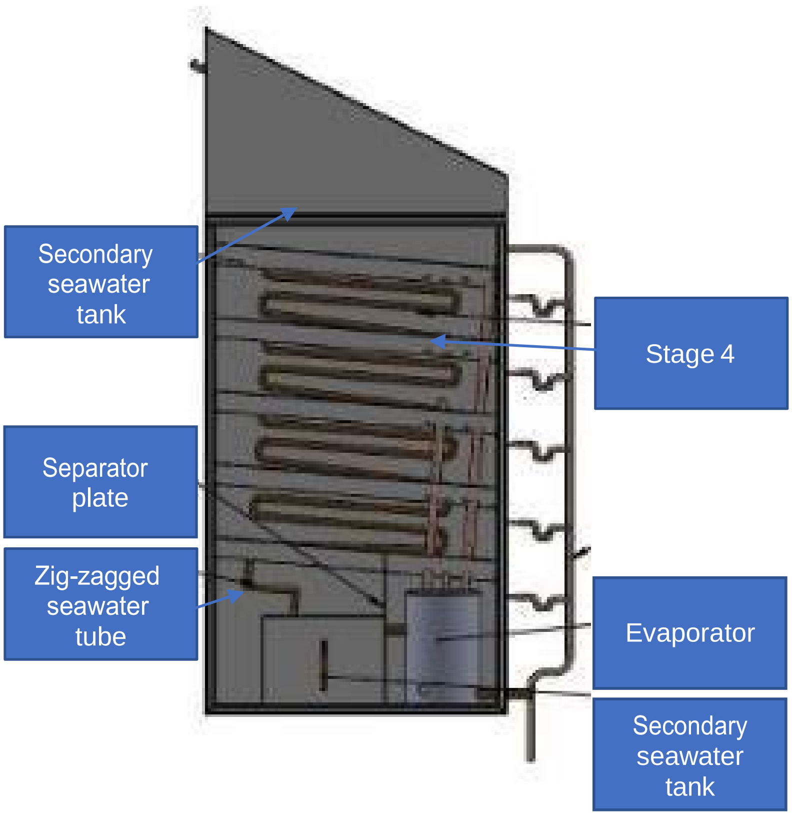

Figure 3.34: Front view of the multistage solar still desalination system

CHAPTER FOUR
EXPERIMENTAL PERFORMANCES

The procedures on how the experiment was prepared, set-up and carried out are presented in this chapter. It gives a sequence from the start to finish, taking into account all aspect that may influence the study. This experiment focused on maximizing distillate outlet from the system while reducing the losses which could ultimately deem the system inefficient. The data obtained through researching with regards to orientation, depth of water, sun intensity etc. was implemented to achieve the best possible results.

4.1 EXPERMENTAL PERFORMANCE

After the construction of the stand, a multistage desalination system and the evacuated tube solar collector as well as confirmation of the entire structural integrity, tests were conducted. The system was put into operation and monitored for any water leaks and other defect.

Figure 4.1 shows the whole set up of the multistage solar still desalination system.

Figure 4.1: Multistage solar desalination system

4.1.1 Testing apparatus

The following were used during testing and measuring the distillate output from the system.

a) Distillate collecting container
b) Brine collecting container
c) Seawater
d) Graduated cylinder

Figure 4.2: Distillate and brine collecting containers

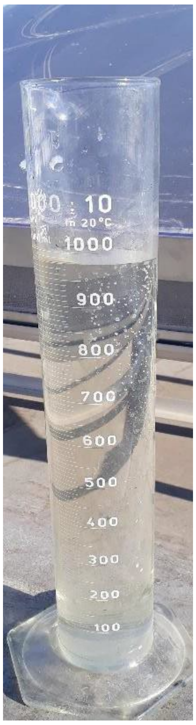

Figure 4.3: Graduated cylinder

4.1.2 Testing procedure

The seawater was collected from the sea prior to commencing the tests. Initially, the system was tested for few hours in each day, there was a day and a night time tests. The day time tests were monitored while the night time test were not. When starting up the system, the fresh drinking water was poured on all the stage trays so that all the U-shaped tubes are full of water. This was done on one stage at a time and water monitored until it flowed out of the main distillate tube. The water in the U-shaped tubes prevents the vapour from escaping the unit and once the water flows out of the main distillate tube, it confirmed that the U-shaped tubes are full.

After that, the sea water was then poured in the basin type solar still or primary seawater tank at the top through a filling hole discussed under figure 2.1 until the flow was observed from the brine discharge tube of the brine tank. The seawater from the primary seawater tank flowed under the influence of gravity as there were no pumps installed to the system to circulate it. The flow through the brine discharge tube indicated that the zig-zagged seawater tube, the secondary seawater tank, the evaporator, the brine tank, the open loop circuit and the collectors manifold were full of water. In addition to that, the secondary seawater tank and the evaporator had sight glasses and thus the water level could be seen through them. The filling hole in the primary seawater tank was then sealed off and ensured that it is air tight.

The perspex front cover shown on figure 3.17 under chapter three was secured in place by the screws and ensuring vapour tightness. The seawater from the brine tank continued to leak off until the system had just enough water in the evaporator and no over flowing was occurring. The system was then allowed time to stabilise and after about thirty minutes the vapour started condensing on the inside of the perspex sheet cover. Distillate collecting container on was placed under the main distillate tube to collect the distillate and the brine collecting container placed under the brine outlet tube to collect the brine, this container is shown on figure 4.2. The system required that every hour, seawater be refilled through the primary seawater tank. This was due to the fact that the float valve would open every time the water level drops. The seawater in the evaporator was observed through the sight glass.

The tests were carried out during the day and night, the number of hours the system ran fluctuated from day to day. The distillate produced was then collected after the testing time had elapsed. The details about the day to day fluctuation of hours is further discussed under chapter five. The graduated cylinder on figure 4.3 was then used to measure how much distillate has been produced. Thereafter, the night tests would commence and ran throughout the night without monitoring. However, after four days of testing it was discovered that the night tests are rather problematic at best. It was then decided that the system be shut down during the night but in the morning small quantities of distillate were found in the distillate tank. The details of the night tests will be discussed under chapter five as well.

CHAPTER FIVE
TEST RESULTS AND DISCUSSION

The main aim of the project was to test the performance of the newly developed multistage solar still. The results presented in this chapter focused on the amount of the distillate produced, the ambient conditions the system operated under and the quality of distillate produced. The tests were done on the roof of Mechanical Engineering Department of Cape Peninsula University of Technology in Bellville. The day time tests are presented and discussed and then the night time tests. The resistance results in the distillate produced by the system are discussed in comparison with seawater and the tap water. The daily weather conditions during the tests are presented.

5.1 DAY TIME EXPERIMENTAL TESTS AND DISCUSSION

The tests were conducted between 08h00 in the morning and 17h30 in the evening, local South African time. They ran from the 18th of October 2018 to 27th October 2018. On the 24th of October 2018, the system did not operate as repairs were under way and hence the total number of tests was nine days. Figure 5.1 shows the variation of the distillate produced by the system in each day of the tests. The variation was caused by the minor repairs that were supposed to be performed to the system prior to the tests. The leakages were the only repairs experienced on the base of the system, specifically the evaporator. The constant leakage of the evaporator was caused by the material used in constructing the evaporator. The system produced between 1110 and 1430 ml of distillate when there were no repairs to be performed before tests were conducted. The system produced between 225 and 910 ml when repairs were performed before tests. The repairs performed to the system impacted the distillate collection during the tests and hence low distillate corresponds with short collection periods.

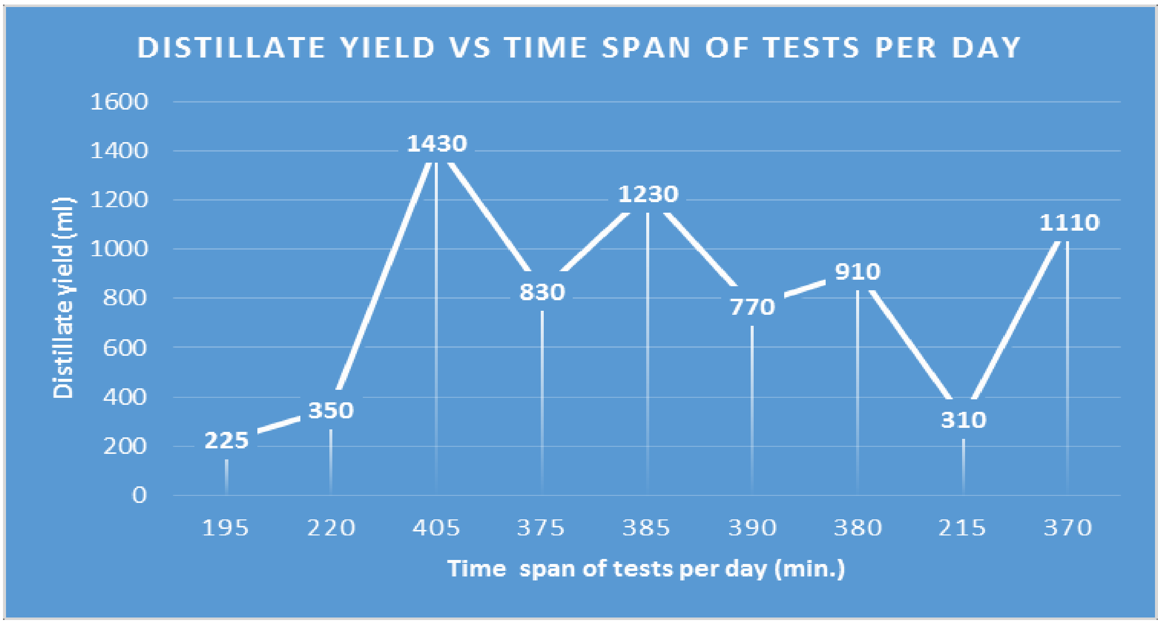

Figure 5.1: Distillate volume vs time span of tests per day

Figure 5.2 shows the temperature from day one to the last day of the tests. It can be clearly seen that the temperature was rather favourable to the tests and the system performance could not have been affected by it. In fact, 1430 ml was produced when the temperature was only 28°C on the day. The weather conditions data were collected from the weather station located next to where the tests were conducted.

On very hot days, it was apparent that the heat from the collector became too unbearable for the sealant and the evaporator since the sealant would resist a temperature of up to 120ºC. The evaporator would start leaking and the sealant loses its adhesiveness. The system had to be shut down and allowed to cool down because the seawater was too hot. This problem was mainly due to the fact that some of the materials used in the construction of the system were not suitable for the working conditions. The evaporator was one of the components created from the unsuitable materials. Firstly, the heat from the collector was too high for the paint container (the evaporator) and it started showing signs of leakages. The other factor which affected the evaporator was the salinity in the seawater, great amount of rust started showing and that contributed in its failure. Based on the observations made, the system had an even greater potential and can easily out perform these current results if all the components were to be appropriate for the working conditions.

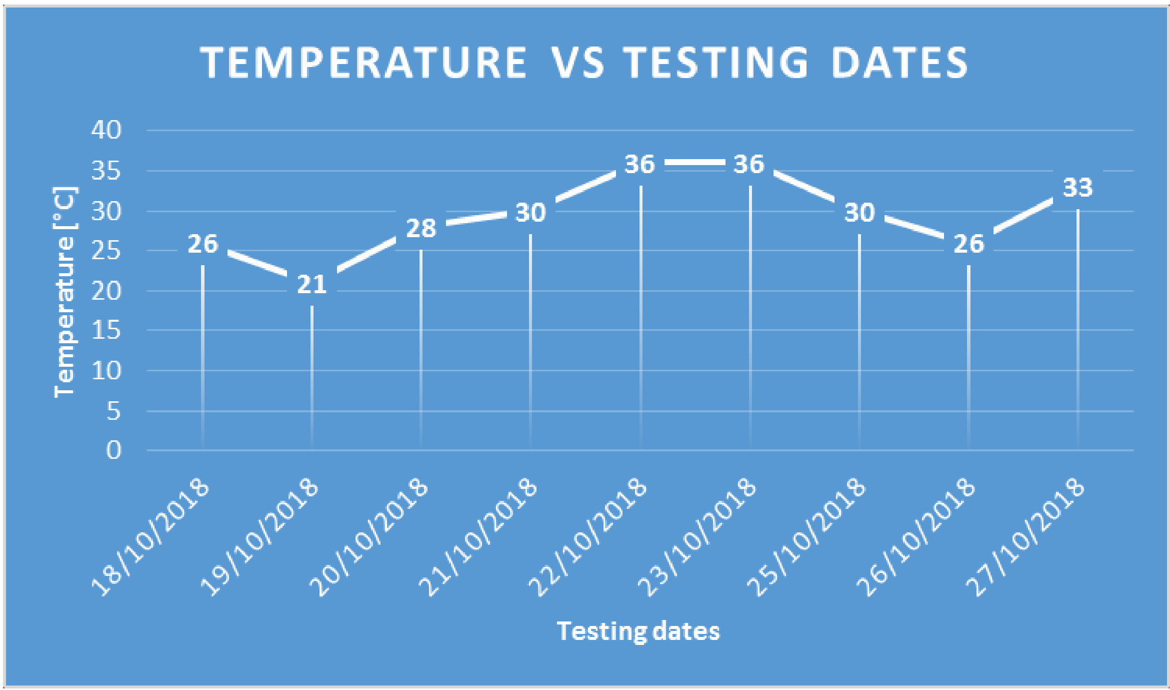

Figure 5.2: Temperature vs testing dates

Figure 5.3 shows the combination of the duration of each test for each day, the distillate yield per day and the days the tests were conducted. The figure below serves to show the distillate produced relative to the running time on the dates of the experimental tests. The distillate yield increases with the increase in time. The system showed that the vapour tightness was very important in producing the distillate. When the perspex front cover was slightly opened and the stages exposed to the atmosphere they would not yield any distillate. The maintaining of the temperature in the stages was very important since the system had no water bed in the stages. This is especially the case when operational data is to be collected. It would take up to 30 minutes for the condensate to show on the perspex cover shown on figure 5.4 when the cover was opened. For this reason, the vapour tightness had to be ensured at all times.

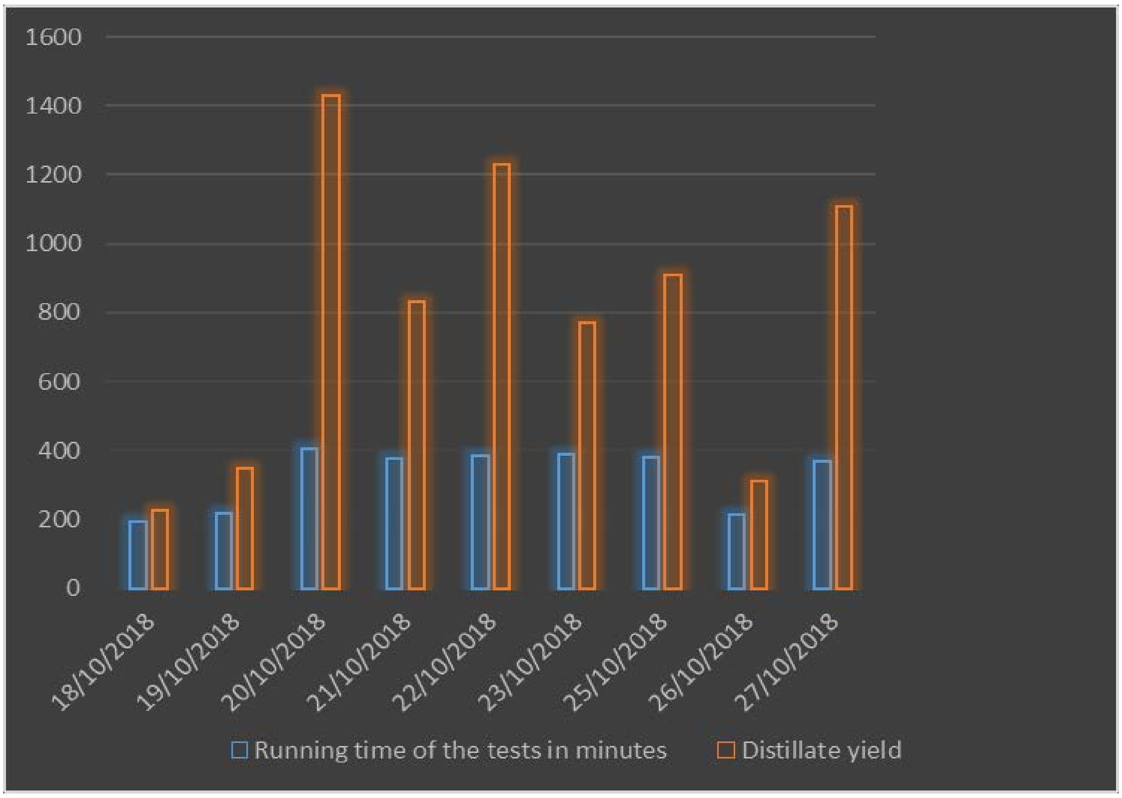

Figure 5.3: Distillate yield and running time vs date of experimental tests

Table 5.1 shows the dates the tests were conducted, the number of hours the tests were conducted, the start and finish times and the amount of distillate yield on each day.

Table 5.1: Day time experimental test results

Tests date in October	Number of hours (Hours, minutes)	Start time	Finish time	Distillate yield (ml)
18	3,15	12h00	15h15	225
19	3,40	13h20	17h00	350
20	6,55	10h20	17h15	1430
21	6,10	09h35	15h45	830
22	6,25	11h00	17h25	1230
23	6,30	10h00	16h30	770
25	6,20	10h40	17h00	910
26	3,35	14h00	17h35	310
27	6,10	08h20	14h30	1110

The phenomenon of not boiling the seawater has proven to be insufficient in the production of the distillate. Taghvaei et al., (2014) reported that boiling of seawater will have an adverse effect on the production of the distillate.

In the present study however, it was observed that when seawater was not boiling, insignificant amount of condensate would be seen on the perspex front cover. When the seawater was boiling though, considerable amount of condensate would be seen on the front perspex sheet shown on figure 5.4.

While it is true that 4 to 5 stages are adequate as promulgated by Reddy et al. (2012) for that type of set-up, the optimum number of stages for the present design are yet to be experimentally determined. It is acknowledged that for a conventional basin type solar still situated at the top of the multistage in this present study, the number of stages may be limited. However, the direct vapour injection into the stages using vapour make-up tubes proves to be effective for all five stages, in fact the fifth stage operated just like any other stage in the unit. There was no evidence to suggest that the stage was either producing less or not at all.

According to observations made, the system did not show any difference in producing the distillate from stage one to stage five. The number of stages in the current study did not affect the yield of any of the stages. It is the view of this study that an additional stage or stages may be added without affecting the optimal operation of the whole system. The stages started producing the distillate almost simultaneously and equally. In fact, stage five seemed to be producing just as much condensate as the first stage. This may have been induced by the cold seawater in the basin type solar still. The vapour was condensing on the underside of the basin type solar still bottom tray which is the top tray of the system and it is shown on figure 3.3. The amount of distillate the system produced was over and above any of the expectations. The system started producing the distillate in weather conditions as low as 15°C, this was noted during pre-trail tests. However, only small amount of distillate can be produced under these weather conditions. It was noted that with regards to weather conditions, the higher the temperatures, the higher the distillate yield from the system.

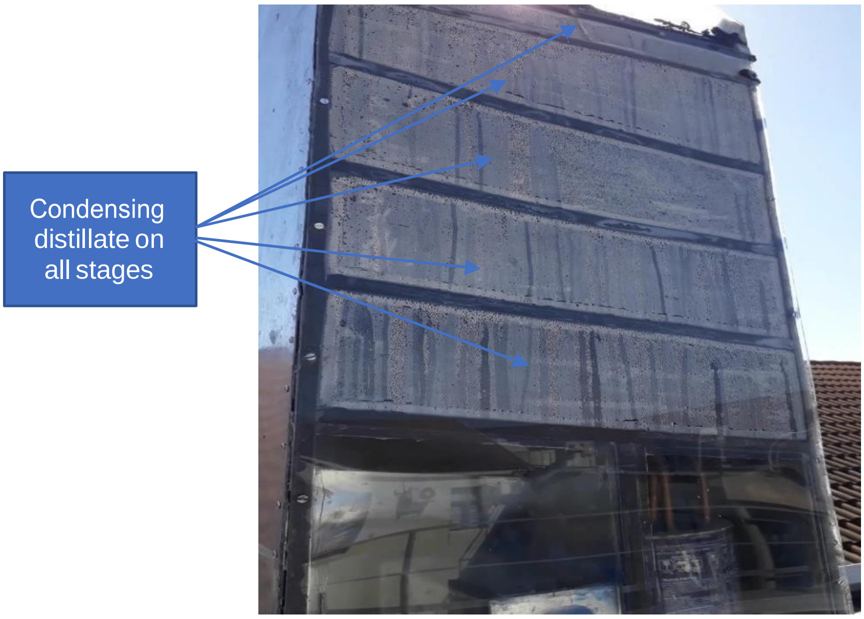

Figure 5.4: Condensing distillate

5.2 NIGHT TIME EXPERIMENTAL TESTS RESULTS AND DISCUSSION

The study aimed at running the experimental tests for 24 hours a day, it worked well for the first four days as shown on figure 5.5. The distillate yield was relatively stable but lower in comparison with the day time tests. This was attributed to the low solar radiation during the night and understandably, the yield could not be the same in the night and day. The evaporator showed signs of leaks in the mornings when the day time tests were commenced, this happened from the morning of the 19th October 2018 until it was decided to shut down the system during the night from the 22nd October 2018 onwards. This can be seen on the graph as the distillate decrease from 45 ml to 8 ml a night.

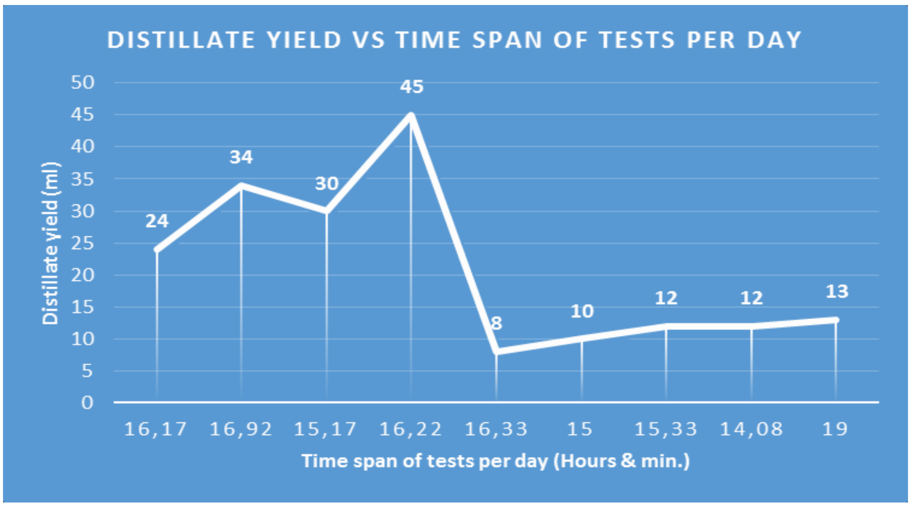

Figure 5.5: distillate yield vs time span of tests per night

The tests were not monitored during the night and the cause of the downtime on the system was that the seawater level in the basin type still had to be kept at a minimum to ensure optimum evaporation. Raj and Manokar (2017) reported that the minimum level of water in the still enhances evaporation and thus the water level was pre-determined in our study. While the level of seawater in the basin type solar still played an important role in ensuring optimal evaporation, the seawater level in the evaporator diminished faster due to evaporation. Once the seawater was finished, the temperature in the system increased drastically as there was no seawater to cool it down. In the mornings, it was noted that the evaporator was totally empty and the sealant burnt. This made the shutdown of the system a necessity and after the shutdown it was expected that no distillate will be collected. On the contrary, the amount of distillate collected was steadily increasing as shown on figure 5.5. However, the damages sustained by the evaporator were still there and the leaks occasionally appeared.

There is a notable increase in distillate shown in figure 5.5 after the system was shut down. This increase is suggested to be caused by the ambient temperature decrease (see figure 5.6) which contributes towards the condensation.

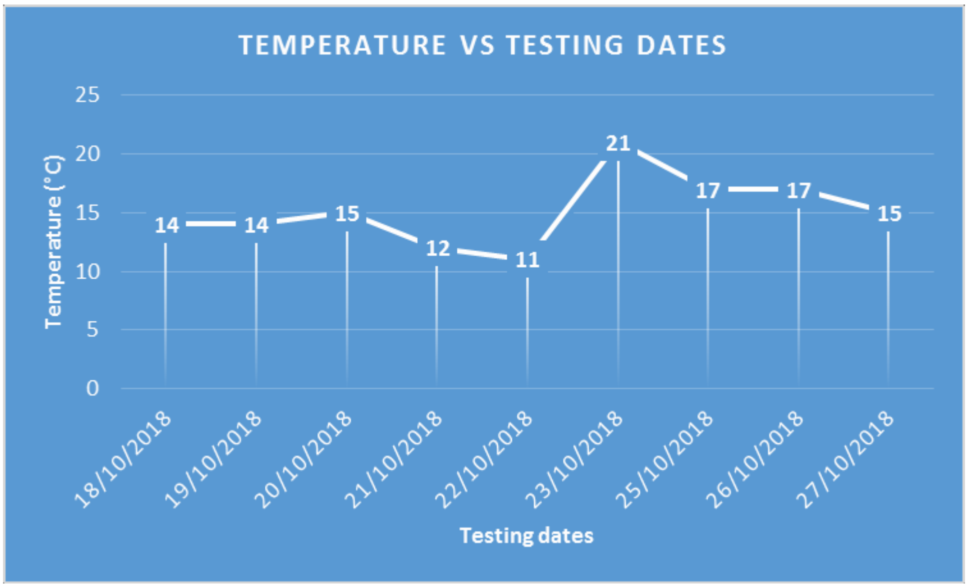

Figure 5.6: temperature vs testing dates

Figure 5.7 shows the distillate collected against the time of collection in each night. It can be seen that the time does not fluctuate as much as it does during the day time tests. However, the distillate does and it is the shutting down of the system that made an apparent difference between the first four days and the last five days. On the 21th October 2018, 45 ml of the distillate was produced and it was the highest yield. The tests on this day finished at 15h45 in the afternoon, this test was finished earlier compared to other tests. Since the solar radiation was still relative higher, the distillate was able to be more than other days. This was the indication that the presence and the intensity of solar radiation plays a huge role in producing the distillate.

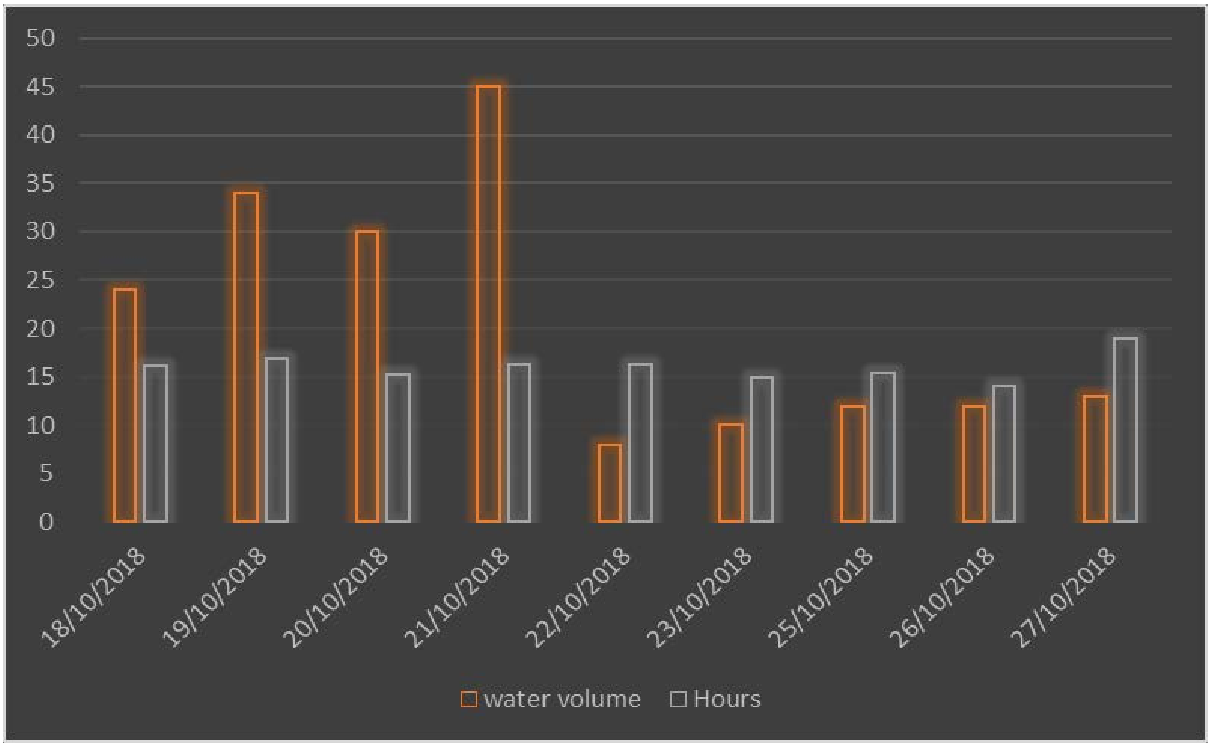

Figure 5.7: Distillate yield and running time vs dates of experimental tests

Table 5.2 shows the dates the tests were conducted, the number of hours the tests were conducted, the start and finish times and the amount of distillate yield on each night.

Table 5.2: Night time experimental test results

Tests date in October	Number of hours (Hours, minutes)	Start time	Finish time (following day)	Distillate yield (ml)
18	16,10	17h35	09h45	24
19	16,55	17h20	10h15	34
20	15,10	17h20	08h30	30
21	16,13	15h47	08h00	45
22	16,20	17h30	09h50	8
23	16,20	17h00	08h00	10
25	15,20	17h10	08h30	12
26	14,05	17h40	07h45	12
27	19	15h00	10h00	13

5.3 RESISTANCE RESULTS

Three different samples of water were taken and tested for electrical resistance using a multi-meter. The samples included the distillate produced by the multistage system, tap water and seawater. The seawater is known to have a high quantity of metallic elements and this suggest that its resistance is low while its conductivity is high. The tap water should have high resistance which means its conductivity is low. The distillate water had to be tested its resistance compared with the two samples. The seawater recorded an electrical resistance of about 1.919 k Ω (see figure 5.8). The tap water recorded an electrical resistance of about 32.8 k Ω (see figure 5.9). The distillate recorded an electrical resistance of about 52.7 k Ω (see figure 5.10). This is apparently clear that the water produced by the system has much less metallic components compared to the tap water. This then suggests that there will be no further processing of water produced by our system.

Figure 5.8: Distillate tested sample

Figure 5.9: Drinking water tested sample

Figure 5.10: Seawater tested sample

These tests were conducted so as to get an idea of how clean the distillate is in comparison with the tap water. These results are not meant to make a concrete conclusion about the quality of the distillate. The quality of distillate can be done using the relevant equipment so as to draw the concrete conclusion.

5.4 DAILY WEATHER CONDITIONS

This section discusses the day by day solar radiation received by the collector as well as the temperature and the wind speeds of each day.

5.4.1 First day of the experimental tests

Figure 5.11 below shows the solar radiation captured by the collector against time of the day. The radiation is evidently fluctuating throughout the day. It diminishes as the day draws to a close and towards sunset. The tests were started at 12h00 in the afternoon and finished at 15h15, the amount of distillate yield during this time period was 225 ml. The solar radiation peaked at 505 W/m^2 on that day. The graph shows that the radiation during the night between 20h00 and 06h00 in the morning was almost zero. The amount of distillate produced during the night was 24 ml and the system was not shut down.

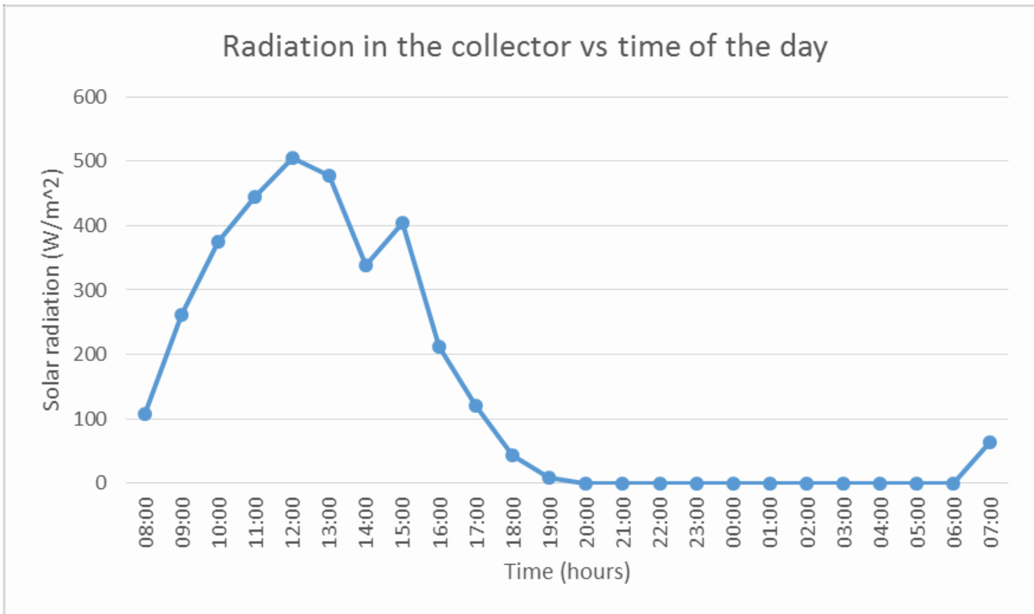

Figure 5.11: Solar radiation captured by the collector on the first day of the tests

The temperature and the wind speed on the day of the tests are shown below on figure 5.12. The graph shows that the temperature was at its highest at the start of the tests but slowly faded away as the day went on. The temperatures went as high as 37 °C that day and the maximum wind speed was 3.8 m/s

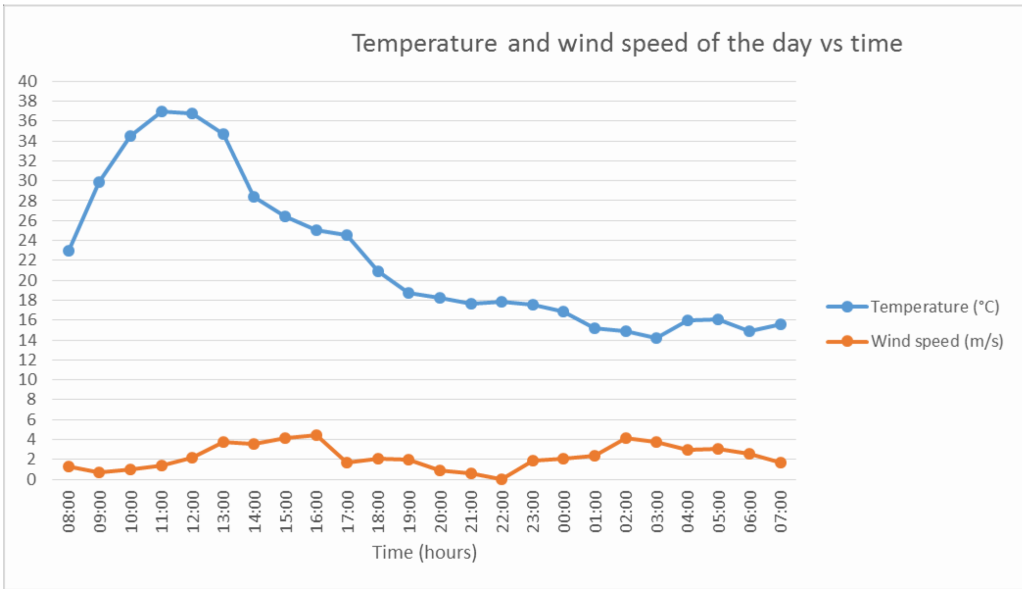

Figure 5.12: The temperature and the wind speed on the first day of the tests

5.4.2 Second day of experimental tests

On the second day of experimental tests, the graph below on figure 5.13 shows that the maximum solar radiation captured by the collector was at 530 W/m^2. The yield of the system was 350 ml in total for the day. On this day, the tests were commenced at 13h20 and finished at 17h00. In the night, between 20h00 and 06h00 there is no solar radiation reaching the collector. The night distillate yield of the system was 34 ml.

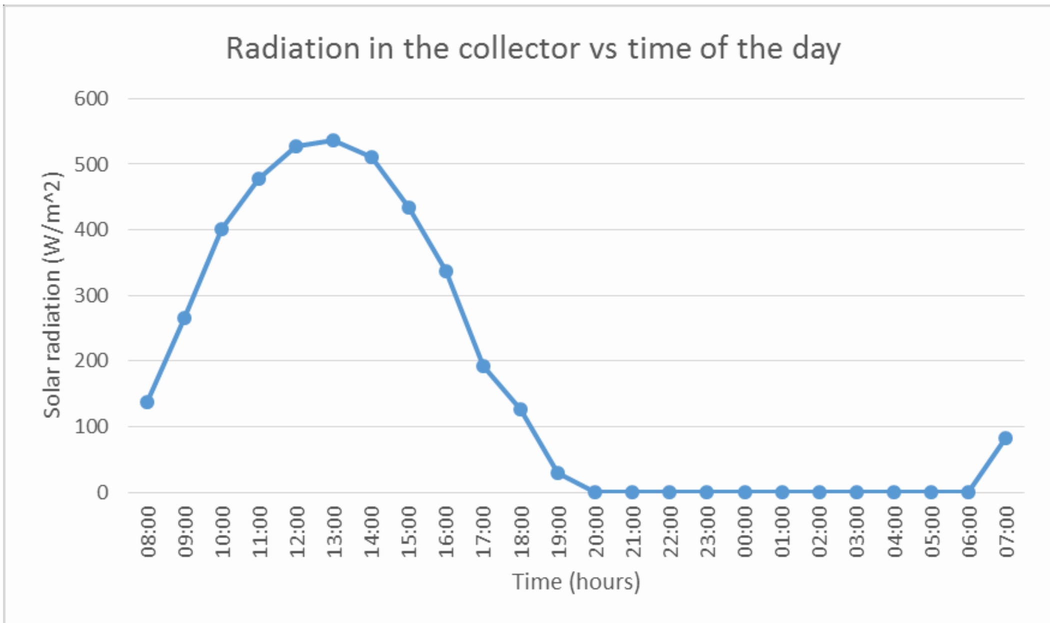

Figure 5.13: Solar radiation captured by the collector on the second day of the tests

The temperature reached the highest of 28.5 °C on this day as shown by the graph below on figure 5.14. It is noticeably lower than that of the first day. The wind speed was rather higher as they peaked at 7.6 m/s.

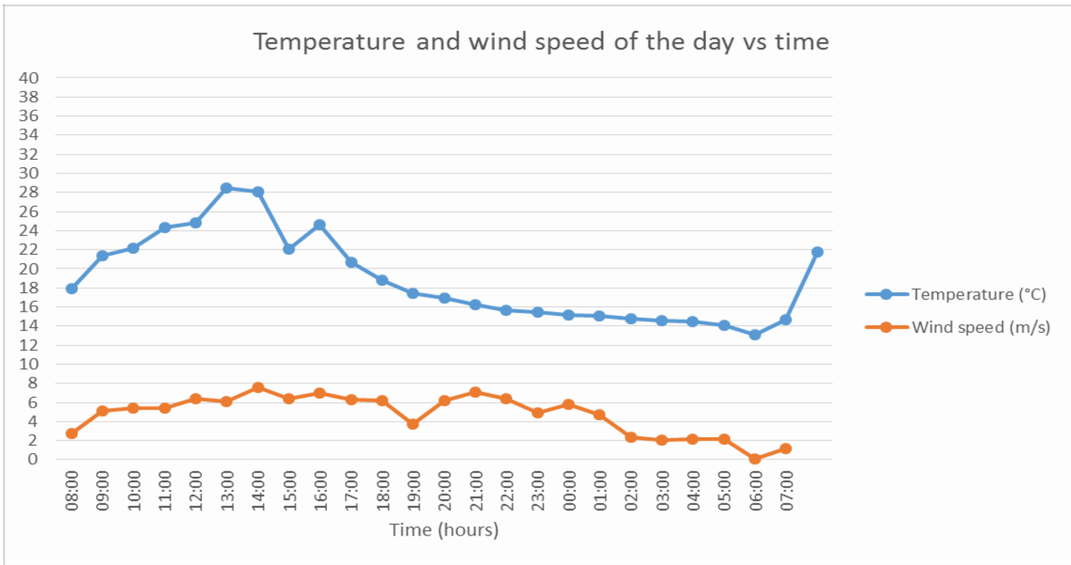

Figure 5.14: Temperature and wind speed on the second day of the tests

5.4.3 Third day of experimental tests

The solar radiation shown on figure 5.15 was momentarily higher around midday and rapidly went down later in the day. The maximum was 527.7 W/m^2 for a short while, the tests were commenced at 10h20 in the morning and ran through the day. They finished at 17h15 in the evening and the daytime yield was 1430 ml. On this day the distillate yield was the highest despite the diminishing solar radiation. Also, as it can be seen from staring to finishing time, the tests ran the longest on this day. The night distillate was 30 ml.

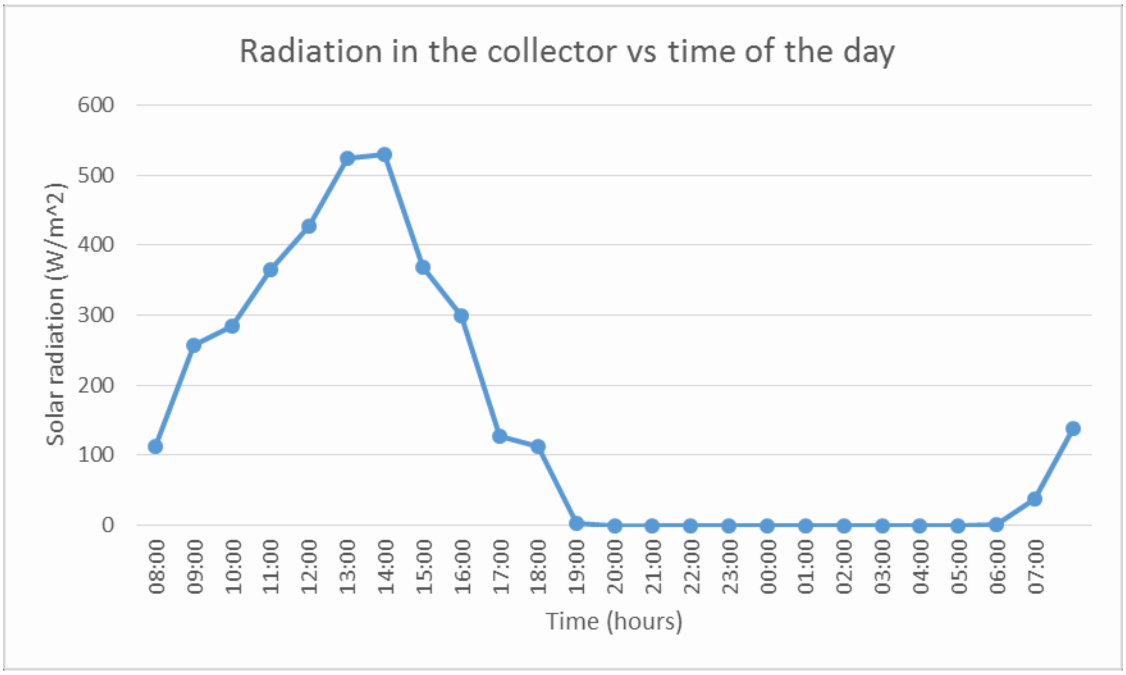

Figure 5.15 Solar radiation captured by the collector on the third day of the tests

The temperature was very high on this day and it remained in that region for a while even though there were fluctuations. Figure 5.16 shows the highest recorded temperature by the weather station at 43.22 °C but it decreased during the night. The wind speed peaked at 5.2 m/s.

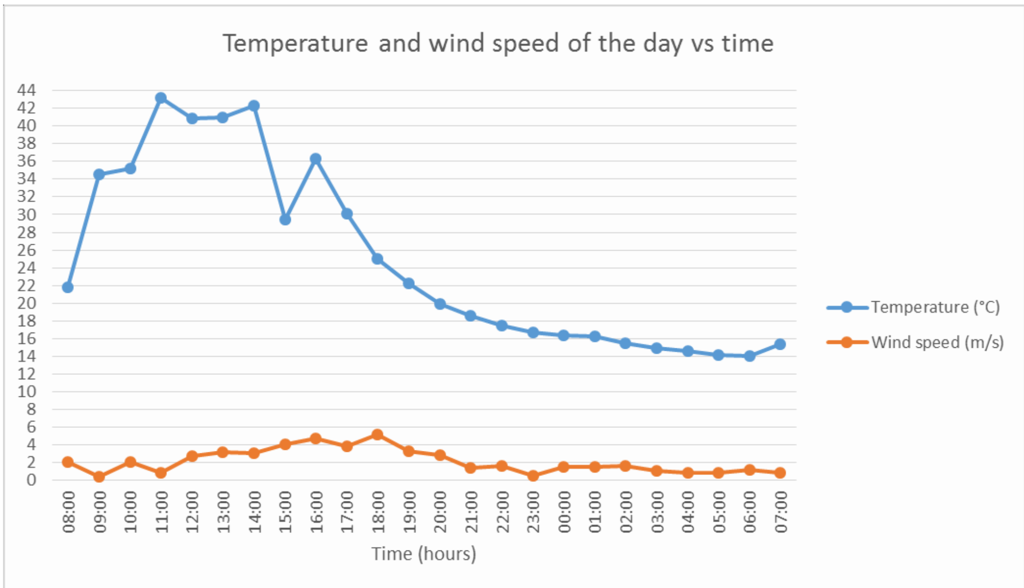

Figure 5.16: Temperature and the wind speed on the third day of the tests

5.4.4 Fourth day of experimental tests

On this day the tests started at 09h35 in the morning and finished at 15h45 in the afternoon. The solar radiation was constantly fluctuating but the distillate yield was 830 ml. The highest it reached on that day was 547 W/m^2 as shown on figure 5.17. The same trend of zero solar radiation at night is still showing and it common to all the days so far. The night distillate produced was 45 ml, this distillate was the highest. This was because the day time tests finished earlier than usual.

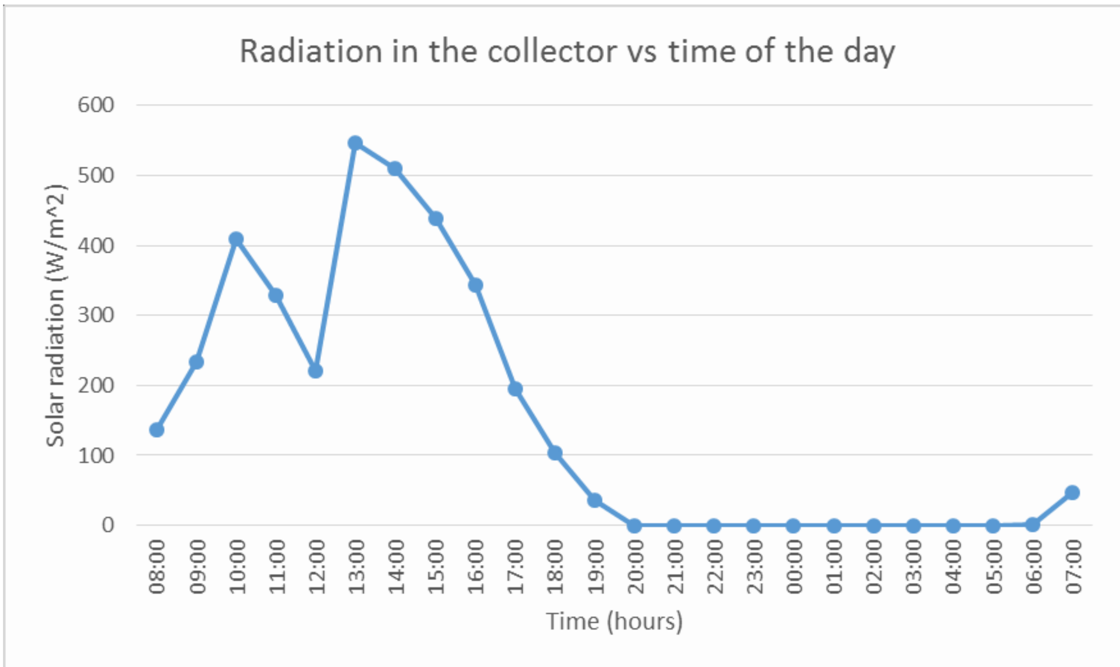

Figure 5.17: Solar radiation captured by the collector on the fourth day of the tests

The temperature was mostly higher on this day around the region of 40 to 45 °C which was the maximum, as shown on figure 5.18. The wind speed was relatively lower compared to the other past days and the maximum for this day was 3.2 m/s which played a role in high solar intensity.

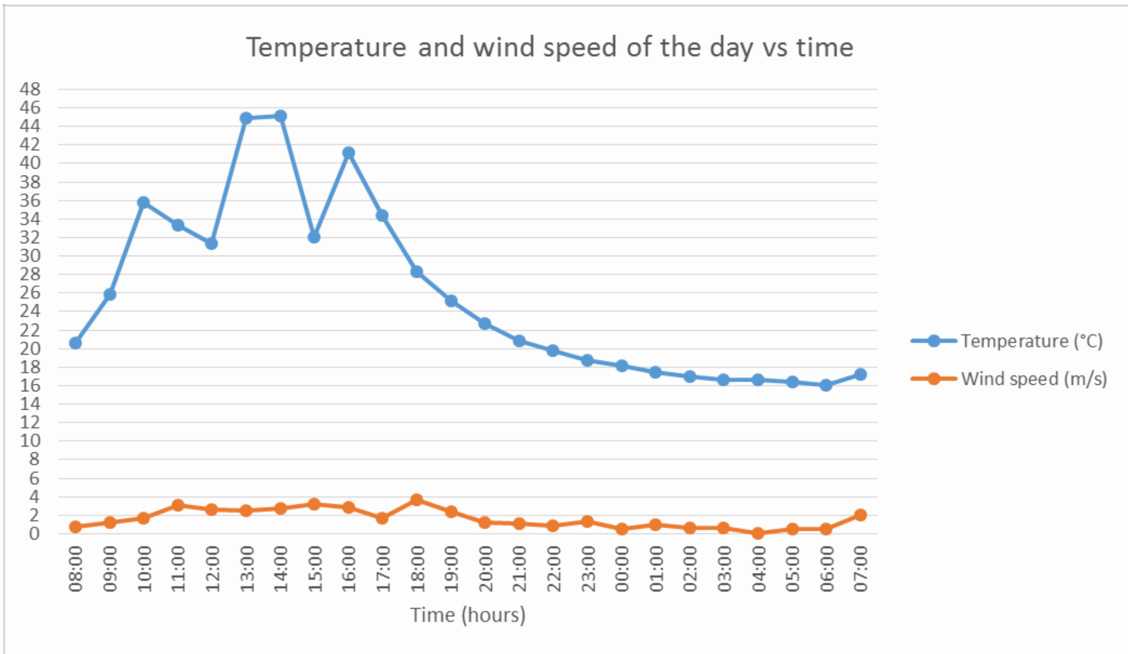

Figure 5.18: Temperature and wind speed on the fourth day of the tests

5.4.5 Fifth day of experimental tests

The tests on this day commenced at 10h00 and were concluded at 17h25 in the evening. The solar radiation peaked at 511.6 W/m^2 at around midday (see figure 5.19). The amount of distillate produced during this time was 1230 ml and this is the second highest after the third day yield on 5.3.3. The night time yield of the distillate was the lowest at 8 ml, this was because the system was shut down for the night because of the problem it faced. Even though the system was shut down it is evident that it can still produce water.

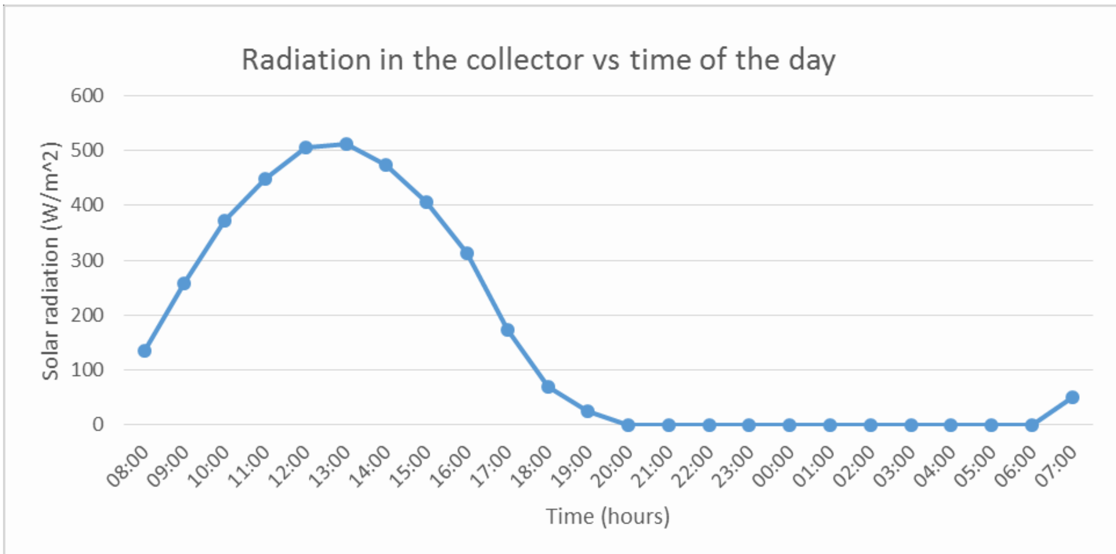

Figure 5.19: Solar radiation captured by the collector on the fifth day of tests

Figure 5.20 show the temperature conditions and the wind speed of the fifth day of the tests. On this day, the temperature was as high as 49.98 °C around midday and completely fell to zero at midnight. The high temperature contributed hugely in the amount of distillate that was produced on this day. The wind speed was maximum at 3.6 m/s at around 15h00 in the late afternoon.

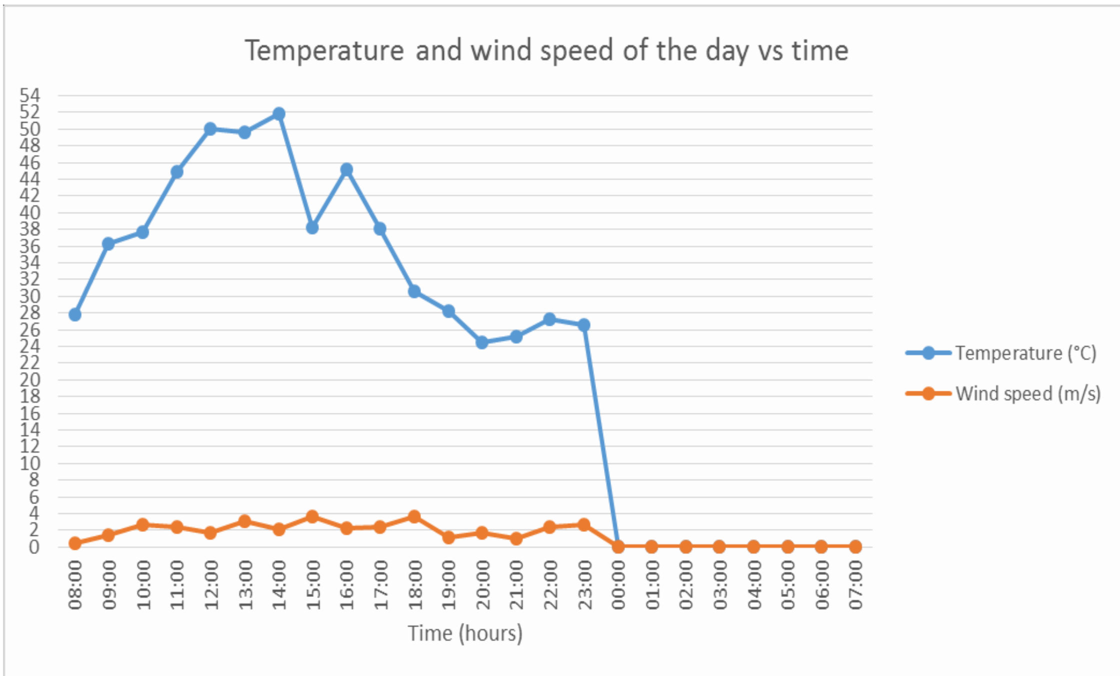

Figure 5.20: Temperature and wind speed on the fifth day of tests

5.4.6 Sixth day of experimental tests

The sixth day was the second longest test after the test conducted on the third day. Figure 5.21 shows a solar radiation graph against time, the tests were started at 10h00 in the morning and concluded at 16h30 in the afternoon. The maximum solar radiation received by the collector was 502.5 W/m2. This maximum solar radiation occurred at around 13h00 and even though it was slightly lower compared to other days, it took a parabolic shape which made it last a bit longer. The distillate yield from the system was 770 ml and the night yield was 10 ml.

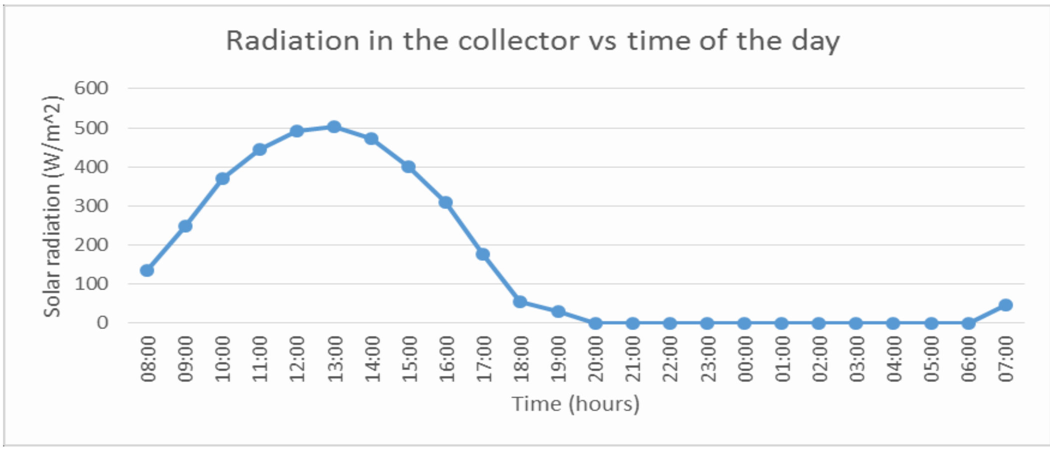

Figure 5.21: Solar radiation capture by the collector on the sixth day of tests

The temperature reached a maximum of 45.3 °C as indicated by figure 5.22 on graph. It stayed higher throughout the night as it was in the region above 20 °C. The accompanying wind speed was maximum at 5.5 m/s around midday but was mostly lower throughout the day.

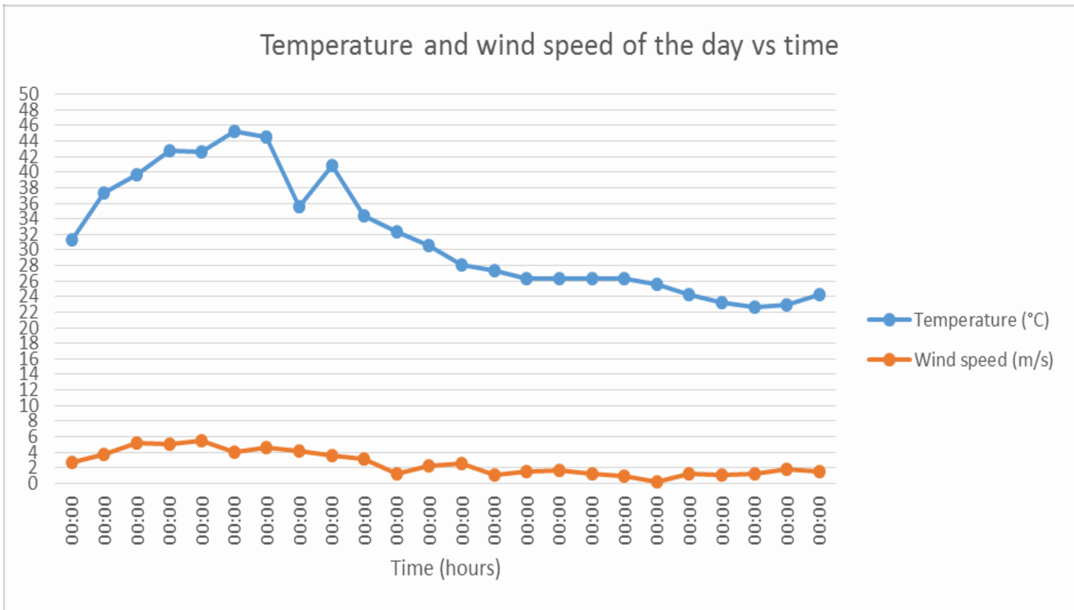

Figure 5.22: Temperature and wind speed on the sixth day of the tests

5.4.7 Seventh day of experimental tests

The seventh day of experimental tests was on the 25th of October as the 24th was skipped due to some repairs carried out on the system. Figure 5.23 shows the path the solar radiation of the day took. The radiation received by the collector was rather lower at 497 W/m2 but it steadily rose to reach the maximum and descended, which means the collector received a great deal of it. The distillate yield of the day was at 910 ml. The tests started at 10h40 and finished at 17h00 in the evening. The distillate produced during the night was 12 ml and according to the graph below, the solar radiation was available between 17h00 and just before 20h00 in the evening. It then comes back again in the morning just after 06h00. It therefore, suggests that the distillate from the multistage system was produced between those times.

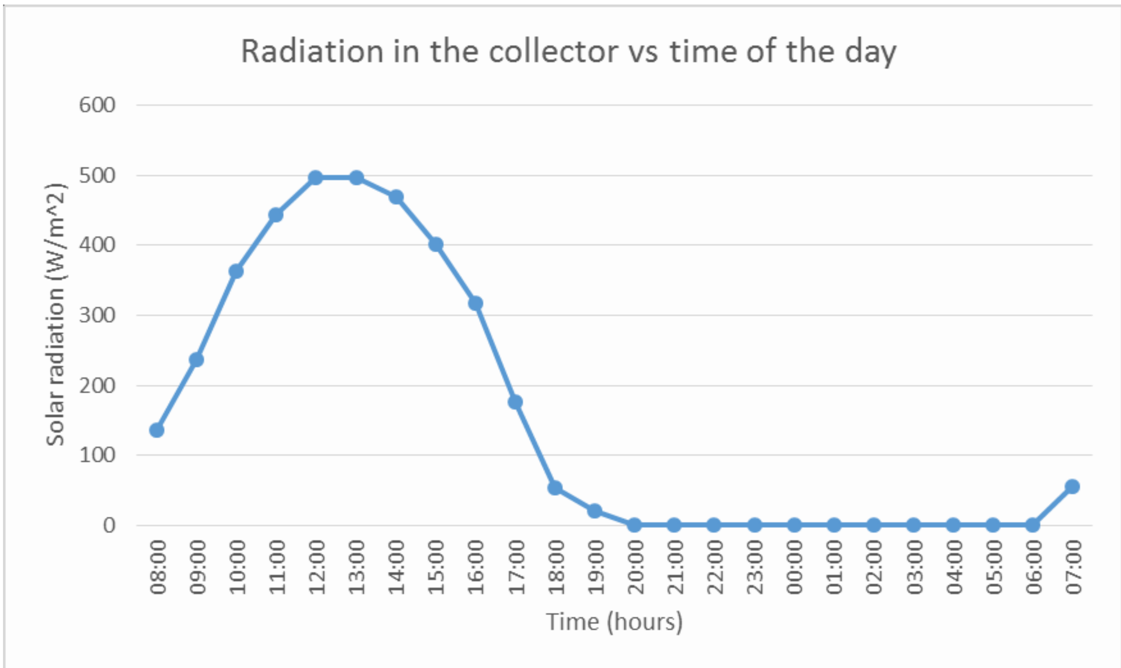

Figure 5.23: Solar radiation captured by the collector on the seventh day of tests

On this day, the temperature reached 48.8 °C as shown by the graph on figure 5.24. This maximum was however, for a brief moment at around 13h00 and it started the decline from there onwards. For the most part of the day whilst tests were running, the temperature was fairly high and it was at 26.6 °C at 17h00. The wind speed was maximum at 4.3 m/s around 16h00. The wind speed remained below 4 m/s throughout the night.

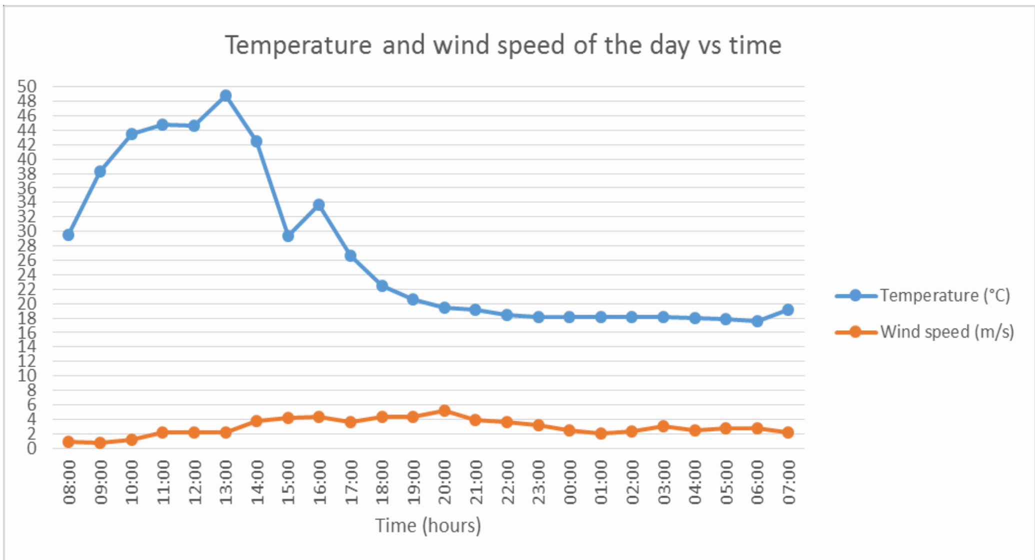

Figure 5.24: Temperature and wind speed on the seventh day of the tests

5.4.8 Eighth and ninth day of experimental tests

These two day were combined because the ninth day was the last day and the tests were concluded at 15h00 on the 27th October. On the eighth day the maximum solar radiation was 510.8 W/m^2 at around 13h00 in the afternoon. The solar intensity did not stay constant very long as shown of figure 5.25. The tests were not started until 14h00 on this day and were concluded at 17h35 in the evening. The distillate yield under these conditions during the day time tests was 310 ml. The night time tests yield was at 12 ml. On the last day of the tests, the day time tests started at 08h20 and finished at 14h30. The solar radiation peaked at 510.2 W/m^2 which was a bit lower than the previous day. The distillate output was higher at 1110 ml during the day and 13 ml during the night.

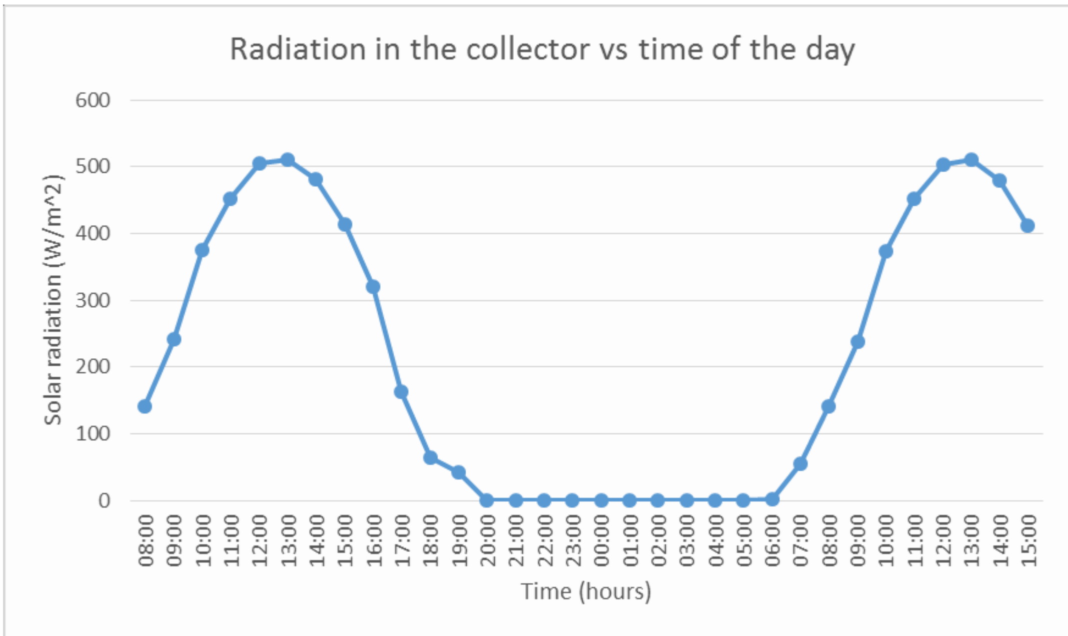

Figure 5.25: Solar radiation captured by the collector on the eighth and ninth day of the tests

The temperature on the eighth day was maximum at 41.4 °C as shown on figure 5.26. The wind speed was maximum at 4.06 m/s around 13h00 in the afternoon. On the last day the temperature was at 47.4 °C at 14h00 just before the tests were concluded. The accompanying wind speed was at 1.8 m/s maximum for the remainder of the tests.

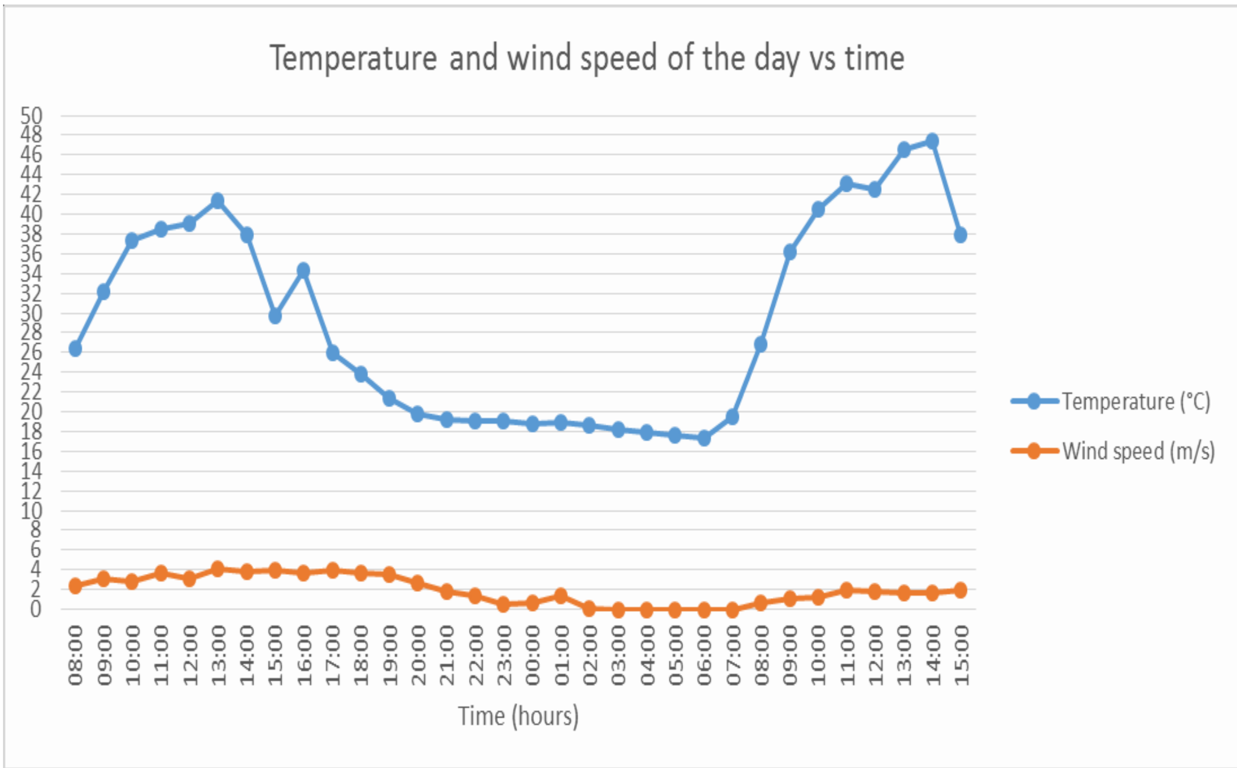

Figure 5.26: Temperature and wind speed on the eighth and ninth day of the tests

It is evident from the results presented above that during the night there is little to no radiation. This is especially the case between 20h00 and 06h00 in the morning. It should be noted that for all the testing days, the night distillate was produced just before the 20h00 in the evening and just after 06h00 in the morning. The earliest time the daytime commenced was 08h00 which meant that some of the distillate was already produced. From the details presented on 5.1 and 5.2 it is important to note and understand that, had it not been for the technical challenges which was mainly due to the evaporator leaks. The system would have worked continuously and consistently without any problem. Given the temperature ranges during the tests both in the night and day, the fluctuation in distillate production would have been very small to negligible.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The study was based on the experimentation of a multistage solar still desalination system. The multistage with similar configurations to the current study has not been found and thus the design is a new approach to the solar desalination systems. The experimental tests were carried out to determine how much distillate can be produced by the multistage system with direct vapour input into each stage. The system developed in our study has multiple saltwater pre-heating, multiple heat recovery from the latent heat of evaporation, self-regulatory of seawater and a combination of a multistage and a basin type solar still. The system uses the advantage of gravity and float valve in controlling the flow of seawater to the evaporator. The system is independent of pumps and electrical connections.

The multistage solar desalination system produced a total of 7.2 litres of distilled water in the space of 49 hours. These hours is the total number of running hours of the system during the day time tests of 9 days. The night time tests yielded 188 ml of distilled water over a time span of 143 hours and the 143 hours occurred over a period of 9 days. During the night time tests, the system was either not operating optimally because there was not enough water in the system or was shut down during the night. Ultimately, the system showed a great potential in producing the distillate especially on a small scale. The challenges experienced during the tests were noted and were not inherent into the system, rather a technical glitch on a design side. Other than the problem with the evaporator, the system worked perfectly.

The direct vapour input into each stage showed that the method is very effective and can yield great amount of distilled water. The distillate from the main distillate tube almost took a flow mode rather than droplets of water dripping down. In addition to that, employing the concept of boiling seawater in the manifold of the collector proved to be a positive contribution to the system. The amount of heat from the heated seawater was able to produce the vapour at a higher rate and thus producing more distillate. The heat did not only produce the distillate but it aided in maintaining the temperature of the system internally to prevent premature condensation in the vapour make-up tubes.

The pre-heating of seawater from the basin type solar still to the zig-zagged seawater tube and to the secondary seawater tank just before the evaporator was successful. The float valve played a major role in limiting the flow of seawater so that the seawater can be pre-heated by the latent heat of condensation in the stages. The seawater temperature between the inlet into the basin type solar still and secondary tank was noticeably different. In addition to that, the seawater circulating between the evaporator and the collector was always hot and it contributed positively to constant production of the distillate. The vapour in stage 5 of the system was pre-heating the seawater in the basin type by condensing on the underside of the basin type solar still bottom tray and releasing its latent heat of condensation.

Heat recovery from the latent heat of condensation by the walls of the stages and the zig-zagged copper tube proved to be enough to condense the vapour completely in to each stage. The outside wall of the system all around were very hot due to the vapour releasing its latent heat. The brine from the brine tank was constantly hot, so hot that it cannot be touched by a bare hand without getting burnt. From there, the heat was transferred to the seawater in the secondary seawater tank.

The results of combining the basin type solar still and the multistage unit cannot be conclusively drawn individually since there was no individual analysis performed on them. This was not done since it was outside the scope of this study. The overall performance of the system was unexpectedly higher and it paved a way to better improvements. However, there are improvements required which will be covered under recommendations.

Coupling the integrated system with the evacuated tube solar collector enhance its productivity. The collector proved to be enough to supply the thermal energy required by the system. For this type of set-up there is no additional collector required as one collector is enough. In fact, the heat generated by the collector was unbelievable even under moderate weather conditions.

6.2 RECOMMENDATIONS

Since this was a relatively new configuration into the multistage set-up, there is number of improvements recommended to further enhance the system's productivity and efficiency. Firstly, the evaporator should be made from a material that can handle higher temperatures over a long period of time. It should also be the kind of material with high tolerance to seawater. The shape of the evaporator should change, a shape that will encourage the more vapour to reach the stages should be used. A cone shaped design at the top where the vapour make-up tubes are connected. Lastly, the material whose heat conducting ability is very good, such as a rubber, wool or polystyrene should be used to separate the evaporator from the floor of the system. The evacuated tube solar collector should be placed much closer to the evaporator to eliminate the heat losses due to the length of the tube between the two. This will improve its productivity.

While it is to the design's benefit of the system in terms of distillate yield to incorporate the basin type solar still at the top of the assembly, the restriction on water level in it affects the whole system's operation. Additional external tank may be incorporated into the system to supply the basin type solar still with seawater, preferably, the seawater from the external tank should be self-regulated by a float valve or similar device. The external tank should be much larger that the basin type solar still so that it replenishes it throughout the night. The insulation should be used on the outside walls of the basin type solar still in future. A fluorine doped tin oxide (FTO) glass should be used on the basin type to trap more solar radiation inside the basin type solar still and enhance its productivity.

El-Baily et al. (2016:29) conducted a study on cost analysis for several solar desalination systems and concluded that in active solar still it is better to use a concertation mechanism as this produces relatively high distillate per capital cost. A sun tracking device or similar may be incorporated in this study to generate more thermal energy without having to add anymore collectors to the system. The thermal energy generated by the collector was not regulated. Using such mechanism can prevent the system from being damaged by overheating, especially during the night times when the system is not monitored. This will also control the amount heat reaching the evaporator.

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APPENDICES

APPENDIX A

MULTISTAGE SOLAR STILL DESALINATION SYSTEM

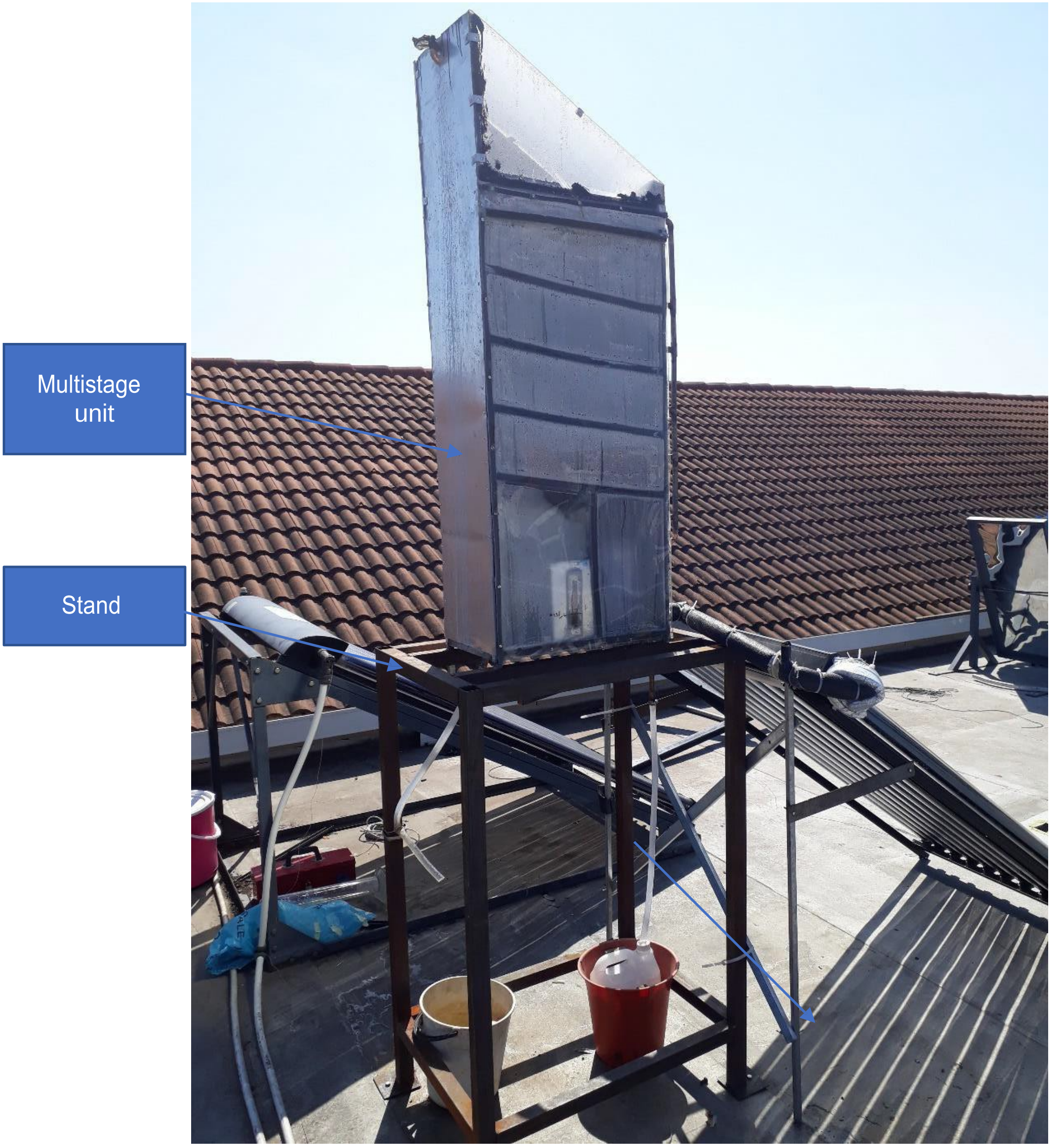


Figure A1: Front view of the assembly

FigureA2: Side view of a multistage still solar desalination system

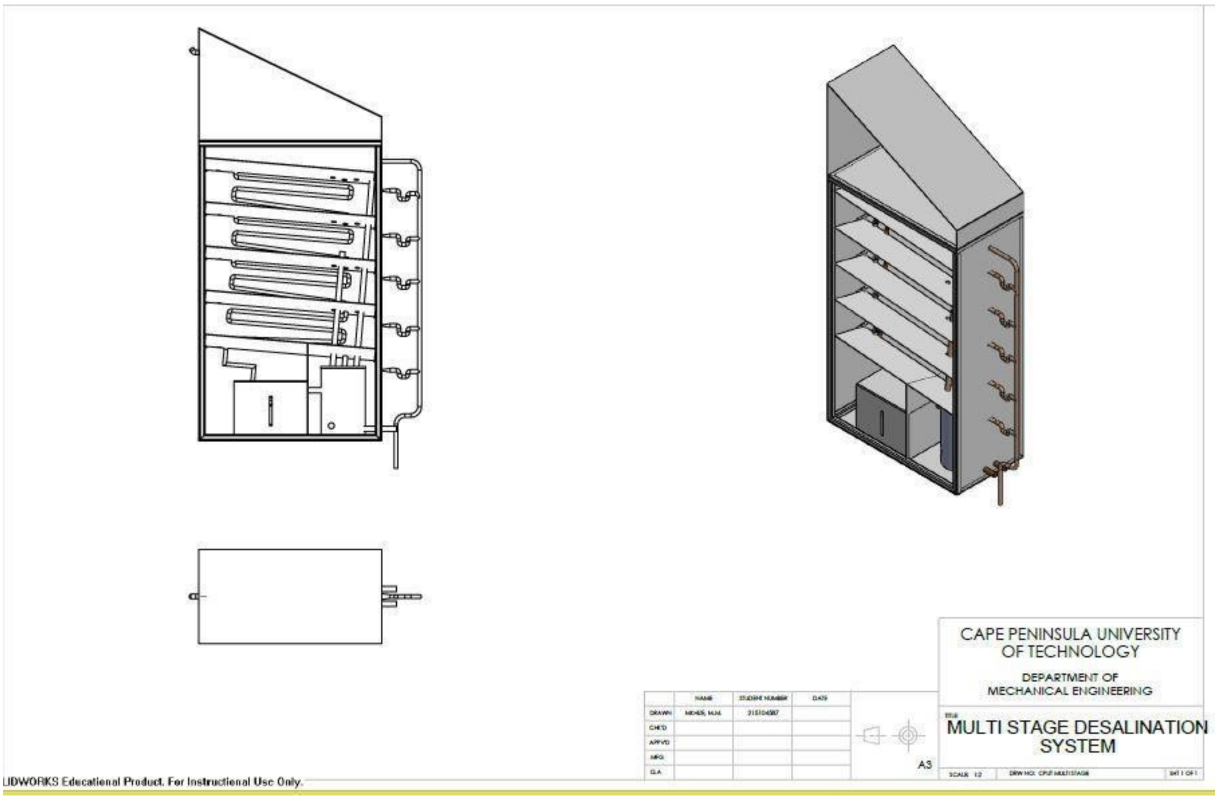
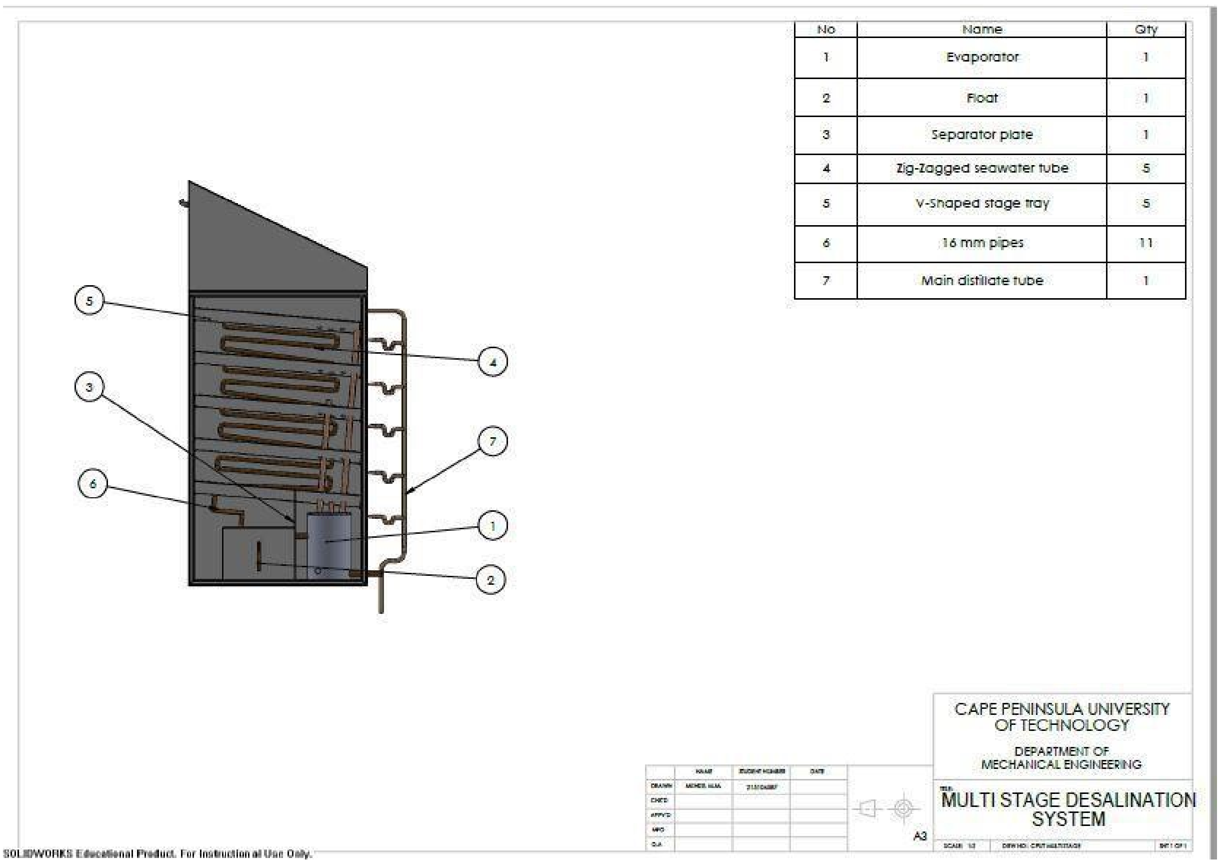


Figure A3: 3D design of the multistage solar desalination system



No	Name	Qty
1	Evaporator	1
2	Float	1
3	Separator plate	1
4	Zig-Zagged seawater tube	5
5	V-Shaped stage tray	5
6	16 mm pipes	11
7	Main distillate tube	1

Figure A4: Multistage system major components

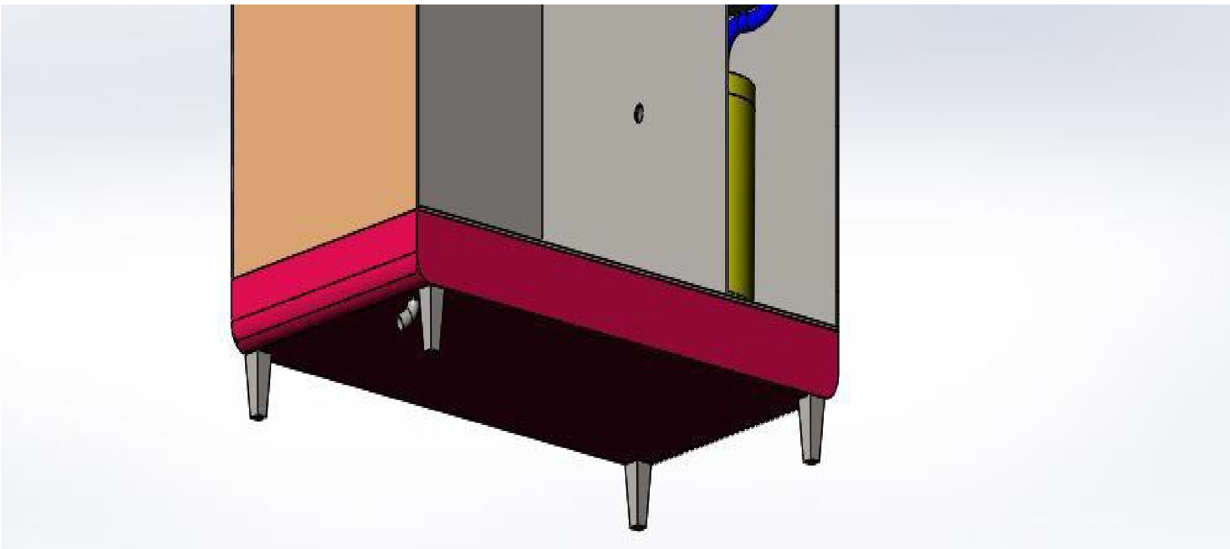


Figure A5: Lower view of the multistage unit with the brine tank

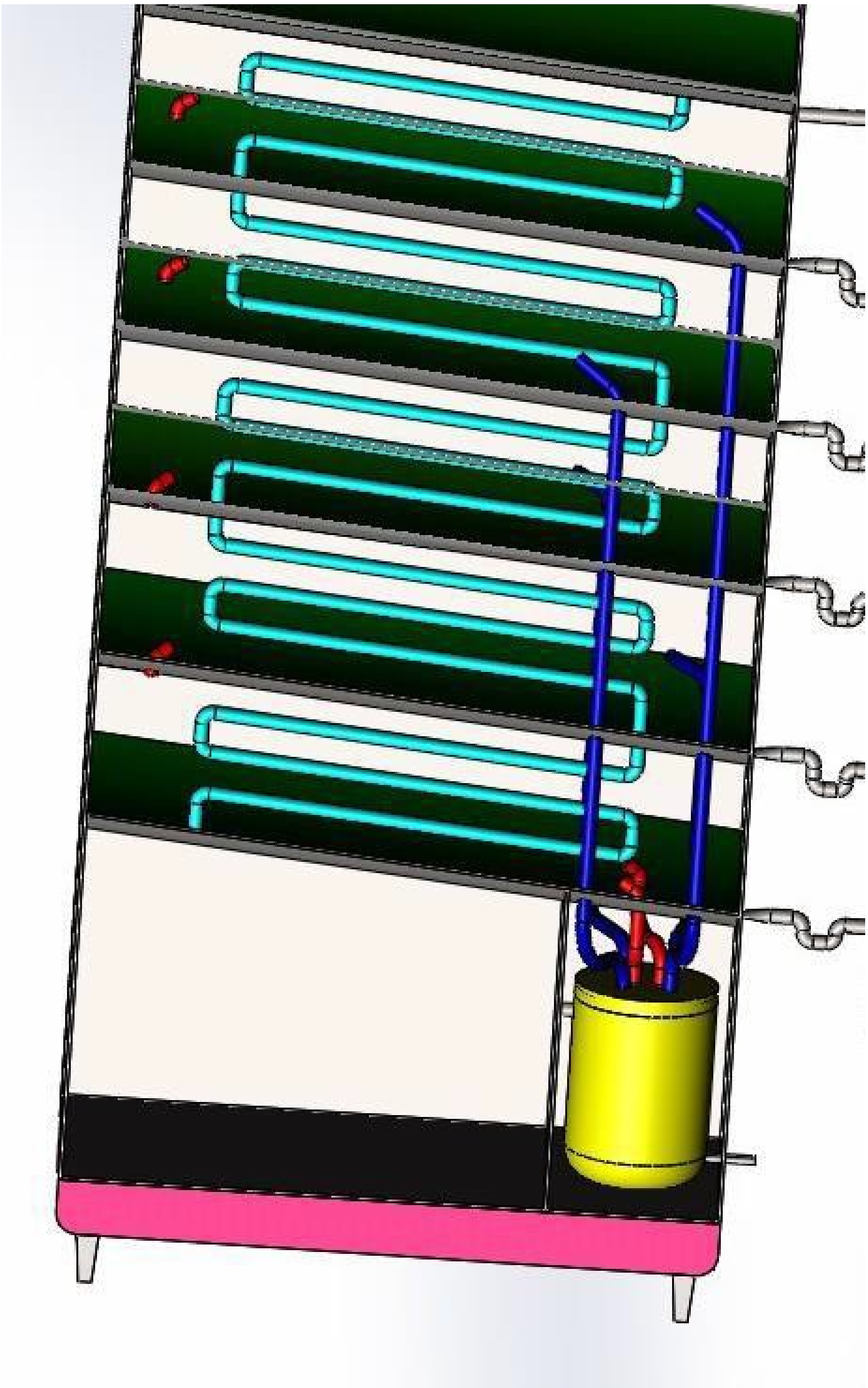


Figure A6: Front view of the multistage desalination unit with various tubes

APPENDIX B

MAJOR COMPONENTS OF THE SYSTEM

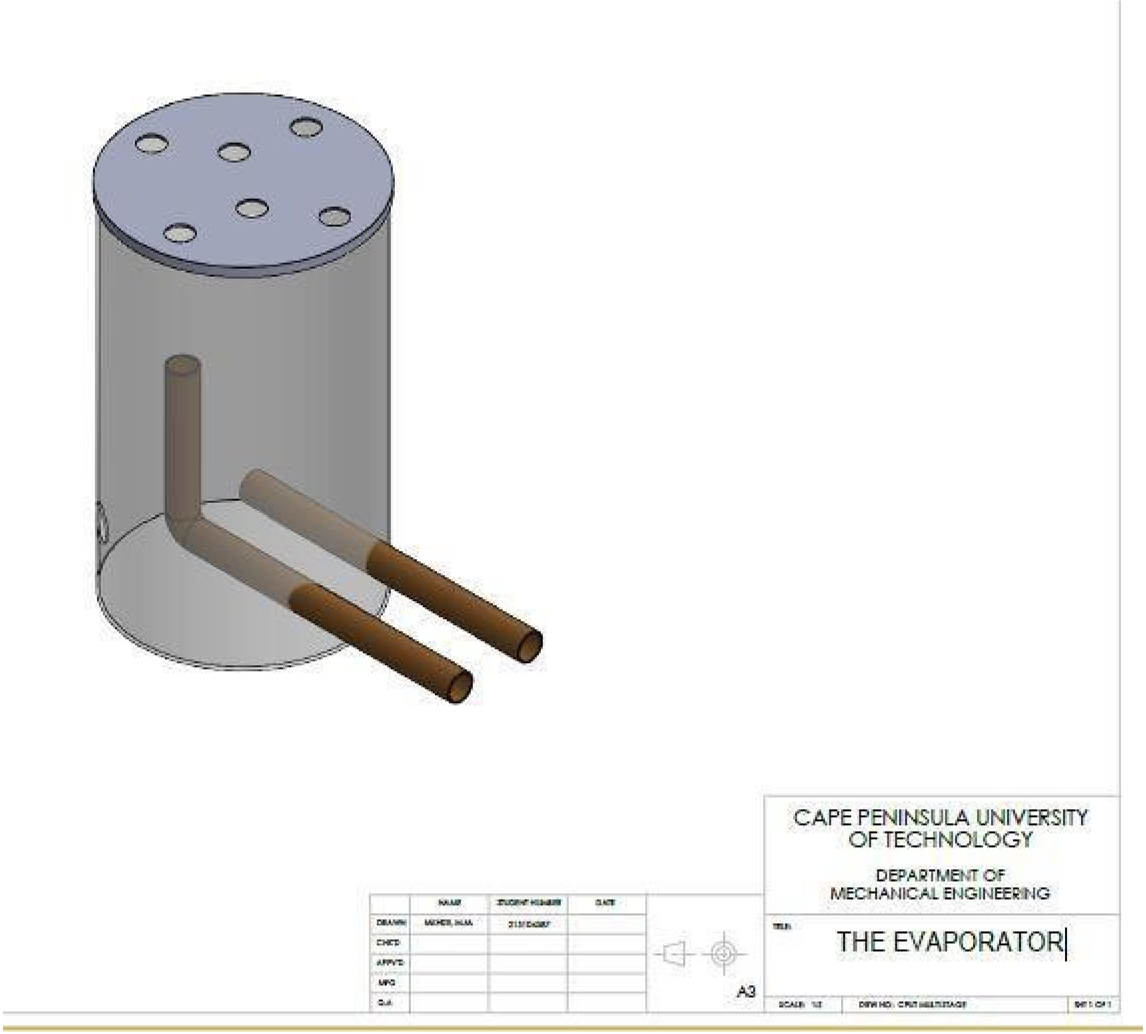


Figure B1: The evaporator with open loop circuit tubes

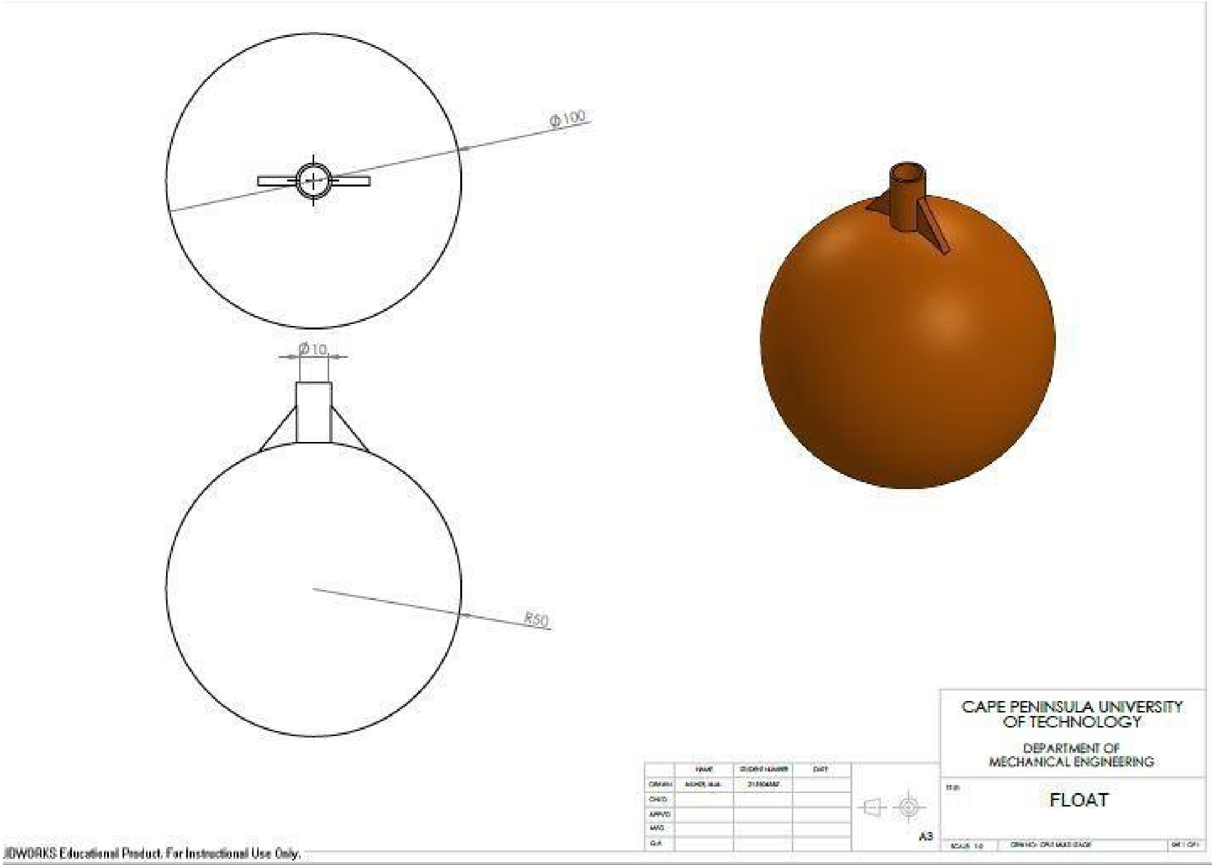


Figure B2: Float

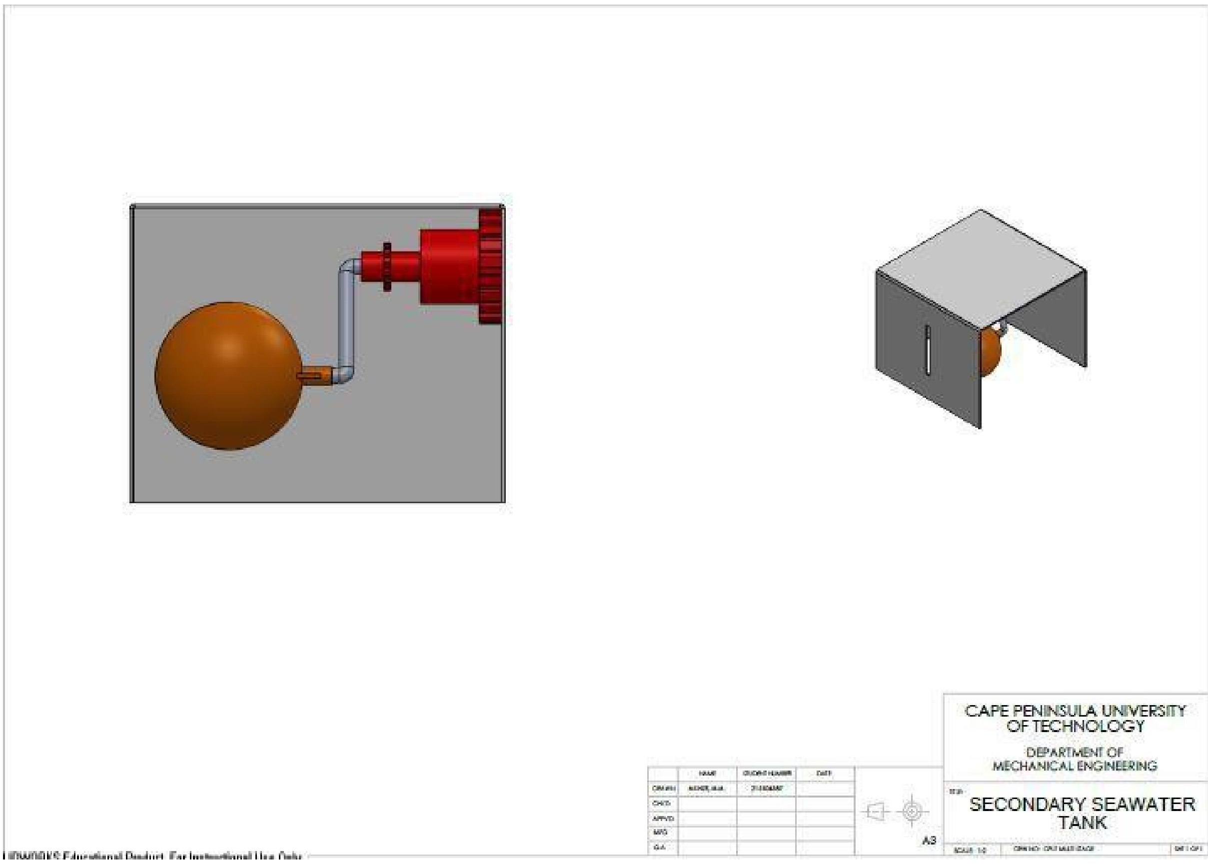


Figure B3: Secondary seawater tank

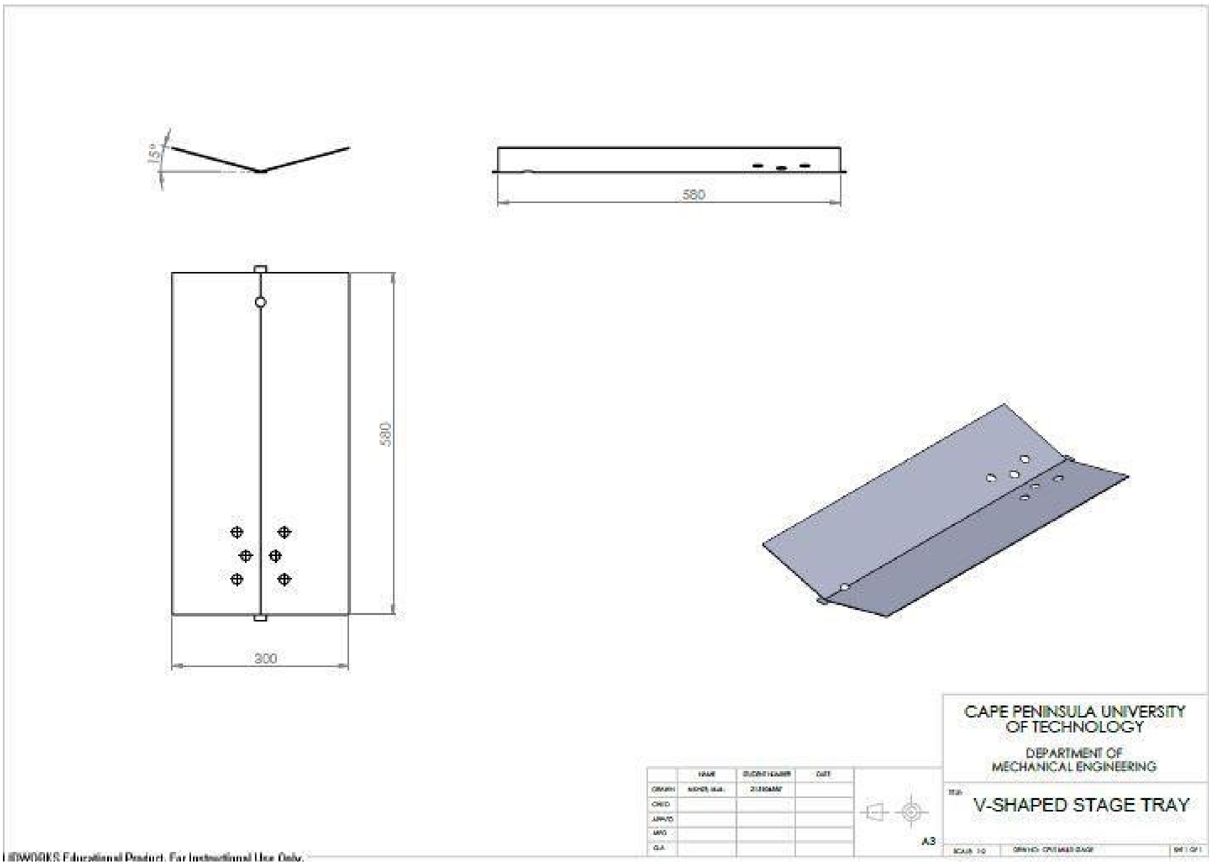


Figure B4: Stage tray

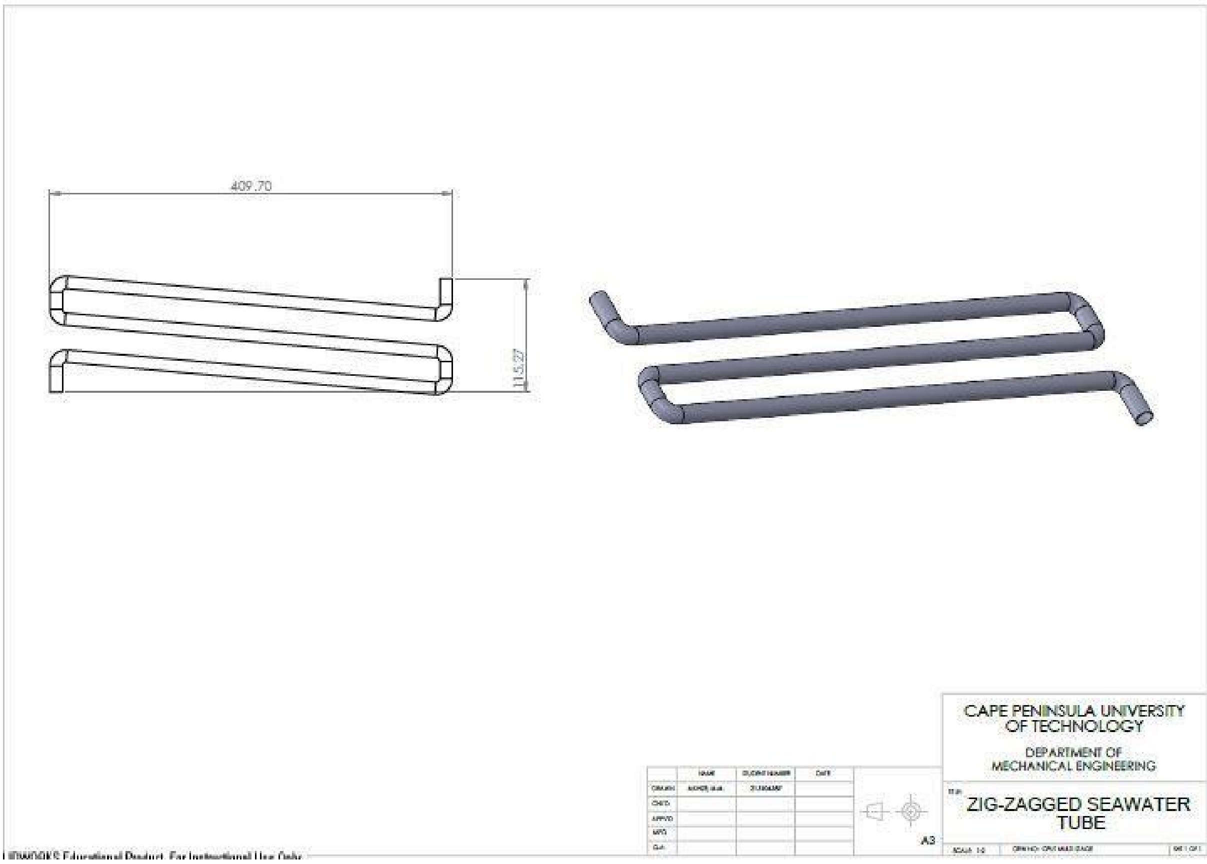


Figure B5: Stage one zig-zagged seawater tube

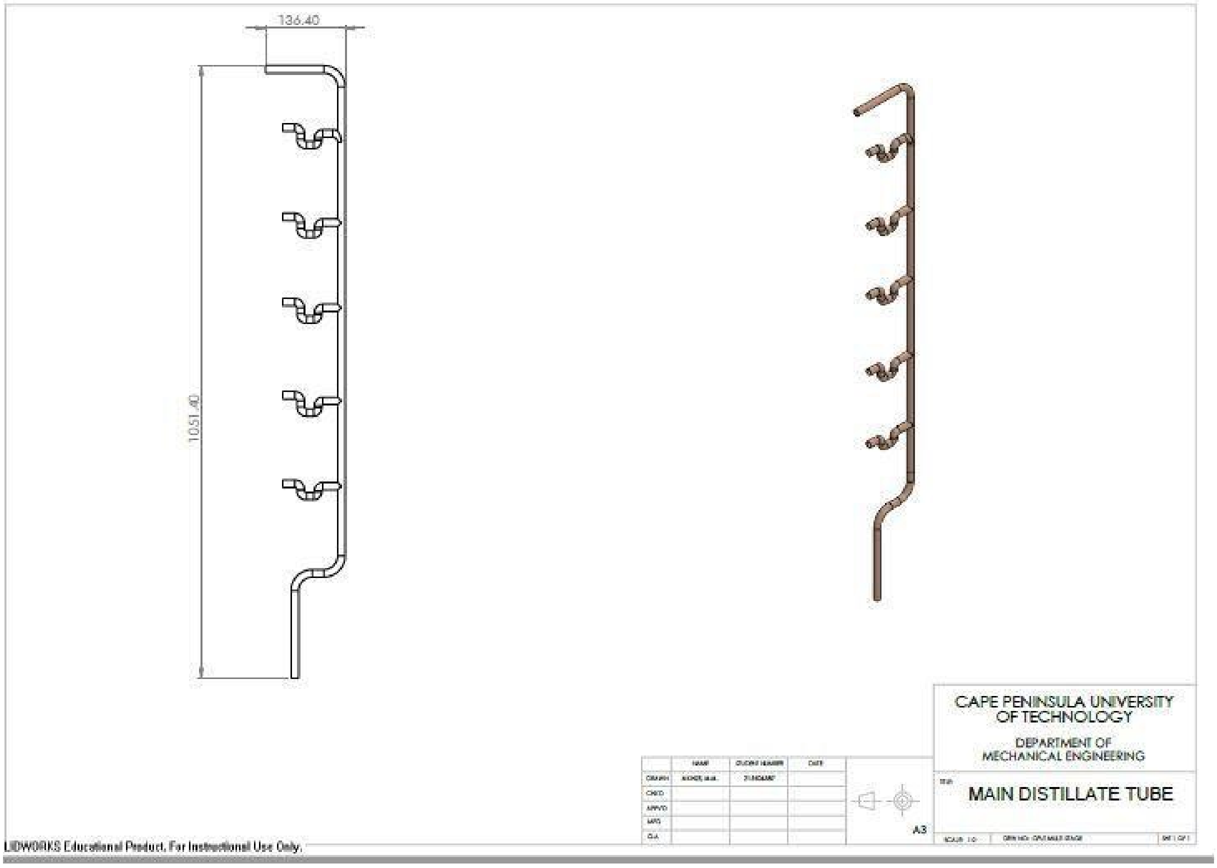


Figure B6: Main distillate tube with U-shaped tubes

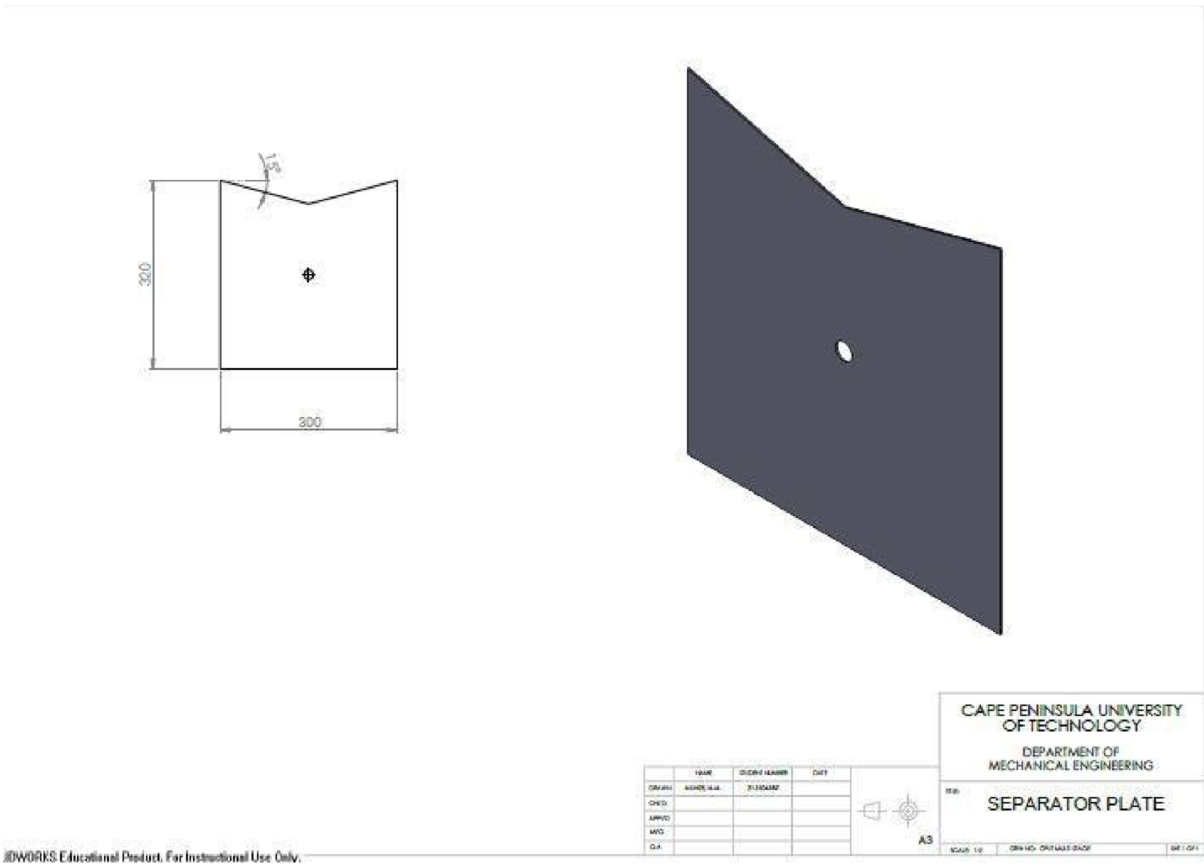


Figure B7: Separator plate