THERMAL ANALYSIS OF MULTISTAGE SOLAR DISTILLER

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

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DECLARATION

I hereby declare that this project report is based on my original work except for citations and quotations which have been duly acknowledged. I also declare that it has not been previously and concurrently submitted for any other degree or award at UTAR or other institutions.

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APPROVAL FOR SUBMISSION

I certify that this project report entitled **"THERMAL ANALYSIS OF MULTISTAGE SOLAR DISTILLER"** was prepared by **QUEH ZHI XIAN** has met the required standard for submission in partial fulfilment of the requirements for the award of Bachelor of Science (Honours) Mechanical Engineering at Universiti Tunku Abdul Rahman.

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ABSTRACT

Fresh water is essential as it is the basic need of biological processes. The demand for fresh water also increases steadily as the global population increases. There are multiple types of desalination processes such as reverse osmosis process, freezing process, ion-exchange process, thermal process and etcetera. Solar distiller is one of the oldest desalination processes that works based on two scientific principles, evaporation and condensation. This research uses theoretical analysis to estimate the distillate output and thermal performance of multistage solar distillers with different number of stages. It was found that the efficiency of solar distiller improves as the number of stages increases, 5-stages solar distiller was found to be the optimal number of stage, as any further increment in number of stage will lead to insignificant improvement in efficiency (< 1.5%). The distillate output also followed the same pattern and reached an optimal number at 5-stages solar distiller. Cost analysis was also done and it was found that 4-stages solar distiller was the optimal selection with the least cost per litre distillate output of RM 0.261/L.

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LIST OF SYMBOLS / ABBREVIATIONS

$Q_{conv,w-c}$	Convective heat transfer from water to condenser (W/m^2)
$Q_{evap,w-c}$	Evaporative heat transfer from water to condenser (W/m^2)
$h_{conv,w-c}$	Convective heat transfer coefficient ($Wm^{-2}K^{-1}$)
$h_{evap,w-c}$	Evaporative heat transfer coefficienct ($Wm^{-2}K^{-1}$)
p_{sw}	Water saturation pressure above saline water (Pa)
p_c	Water saturation pressure below condenser (Pa)
T_w	Water Temperature (˚C)
T_c	Condenser Temperature (˚C)
I(t)	Solar Irradiance (W/m^2)
m_{yield}	Mass of Yield (kg)
S	Salinity of water
$h_{fg,w}$	Enthalpy of evaporation of water (kJ/kg)
$h_{fg,sw}$	Enthalpy of evaporation of saline water (kJ/kg)
E	Solar irradiation energy (kJ)
t	Time (second)
A_{total}	Total area of absorption (m^2)
PCM	Phase Change Material

Subscripts

w	water
sw	saline water
n	n^{th} stage
c	condenser
conv	convective
evap	evaporative

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CHAPTER 1

INTRODUCTION

1.1 General Introduction on Solar Distiller

Fresh water is essential as it is the basic need of biological processes. Due to the steady increase in global population, the demand for fresh water also rises rapidly. According to Reif and Alhalabi, 2015, 71 % of the globe's surface is covered with water, however, only roughly 4 % of the globe's water is considered fresh water, and it is approximated that the need for fresh water would be increased by two-fold every 20 years. Hence, methods of obtaining fresh water have constantly been improving, and new techniques have been developed to cope with the surging needs of fresh water.

Based on Figure 1.1 (Shatat and Riffat, 2014), the desalination processes have a few different types, one of the major processes is the thermal processes, thermal desalination is one of the earliest processes to convert saline water into fresh water. The water is extracted from the impurities by using the principles of evaporation and condensation, as impurities and water have different boiling point and evaporation properties, water would evaporate while the impurities are left behind (Shatat and Riffat, 2014). Thermal desalination processes include multistage flash distillation, multi-effect evaporation, vapor compression evaporation, co-generation and lastly, solar water desalination, the principle that a solar distiller used. The membrane process started being used in the 1960s with the limitation to municipal water treatment. However, as technologies improve and developments progress, membrane processes are also introduced to other chemical industries (Shatat and Riffat, 2014). Reverse Osmosis, Electrodialysis and Membrane Distillation are 3 main membrane desalination processes while Reverse Osmosis is one of the most popular ways to produce fresh water besides multistage flash and multi effect distillation.

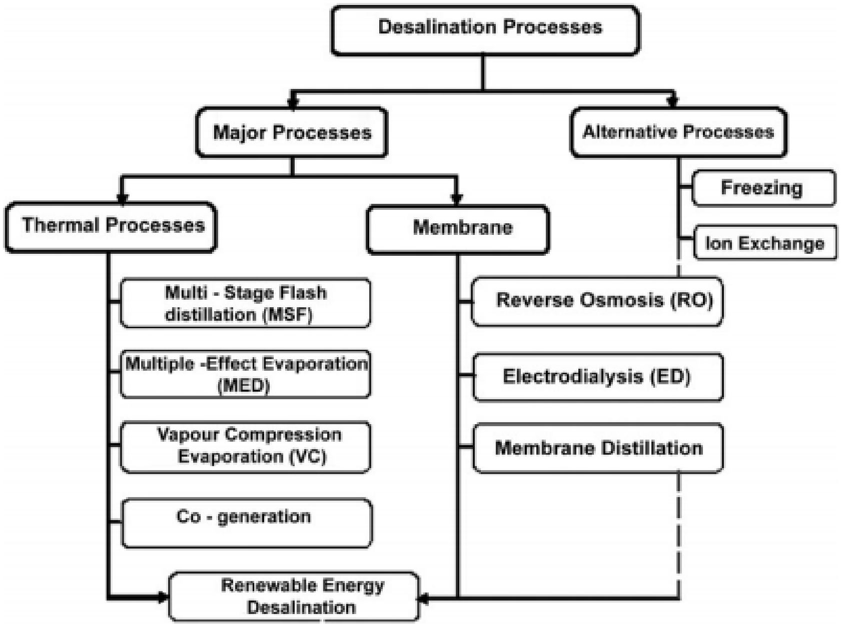

Figure 1.1: Classification of water desalination technologies (Shatat and Riffat, 2014)

Usually, the desalination process such as the Reverse Osmosis process requires a lot of electrical energy. However, global electricity is mostly generated by steam turbines or nuclear power plants with combustion of fossil fuels or nuclear reactions that would contribute to releasing harmful emissions. Hence, an alternative option such as utilizing renewable energy sources to produce fresh water needs to be enhanced. This is because desalination processes that continuously depend on non-renewable resources risk exhausting available energy sources and cause damage to the environment (Gude, Nirmalakhandan and Deng, 2010).

In this study, solar distillation would be further discussed. It is the principle used by the solar distiller and uses renewables sources, solar energy. Solar energy is one of the popular renewable sources because it is almost readily available around the globe. In addition, it is infinite, clean, and free to use for energy harvesting. Henceforth, solar distiller is economical to be used in areas with low population densities, less rainfall and plentiful accessible solar energy (El-Sebaii and El-Bialy, 2015).

The operation principle of solar distiller is based on two scientific principles, evaporation and condensation. Saline water inside the solar distiller absorbs energy from the sunlight, slowly increasing its temperature until it ultimately evaporates to become water vapour and condenses as pure water droplets. During this process, impurities such as table salt do not evaporate and would be left behind. In other words, the whole desalination process inside a solar distillation could be explained as mimicking the process of natural rain fall. Currently, there are two classifications of solar distillers, the active and passive solar distillers. In terms of passive solar distiller, the examples include Single Slope Solar Distiller with Passive Condenser, Tubular Solar Distiller, Double Condensing Chamber Solar Distiller, Vertical Type Solar Distiller, Conical Solar Distiller, Solar Distiller with Inverted Absorber, Wick Type Solar Distiller and etcetera (Ali, Fath and Armstrong, 2011). An active solar distiller is one that includes external operating components to help changing the parameters of the solar distiller such as using an external heater to heat up the saline water or using pump to reduce the internal pressure of the solar distiller. The productivity of a solar distiller is dependent on several parameters such as depth of water, insulation capability, wind velocity, ambient temperature, the intensity of solar radiation, temperature difference between glass and water, glass angle and design of the solar distiller and etcetera.

With the improvement of solar distiller in more than 400 years, there are several known pros and cons of using the solar distiller. The advantages of using solar distiller include that it is relatively cheaper and require minimal maintenance since there are no moving parts. Other than that, it has no energy cost because solar energy is readily available, and it does not cost to get solar energy. However, the disadvantage of it is that the rate of desalination is comparatively slow to other processes, therefore, it is not a suitable solution for the requirement of huge consumption needs. Also, because solar distillers will leave impurities behind as pure water evaporates, the contaminants will cause environmental pollution if it is not correctly disposed.

1.2 Importance of the Study

The study about thermal analysis of multi-stage solar distiller is crucial for multiple reasons. First, based on World Health Organization, 2019, 2 billion people globally drink water source that is contaminated with faeces. Most of the unfortunates without access to clean water are people in rural areas especially in under-developed countries, accompanied by poor accessibility to fresh water, electricity is usually lacking as well in these areas, thus, they would be left with less choice to desalinate saline water sources. Besides, sunlight is typically abundant in these areas. Also, other characteries of solar distiller such as low maintenance cost, no moving parts, cheap to construct and does not require high technology equipment make solar distiller the suitable device of water desalination for these people in need.

It is undeniable that the requirement of fresh water in this growing population and demand for fresh water by accelerating industrial advancement is increasing. Hence, to cope with the rising needs of fresh water, methods of producing fresh water have been becoming increasingly important. Although there are currently methods that are effective and efficient, such as the Reverse Osmosis process, but it requires much electrical energy to operate, which is polluting to the environment. Therefore, studying the efficiency of the solar distiller not only enhances the water supply but also helps to analyse method that produces fresh water using renewables energy.

Thus, it is essential to study thermal analysis of solar distiller as improving its efficiency means producing more fresh water for the people in need. Other than that, the efficiency of a process is of paramount importance as an advance of efficiency boosts greater productivity in a shorter amount of time while reducing wastes.

1.3 Problem Statement

The comparison of solar distiller with different number of stage while other parameters remain the same shows difference for its productivity. One of the most efficient ways to improve the productivity of solar distiller is by having additional stages as it could utilize the latent heat of condensation. However, there are still insufficient studies in Malaysia’s environment context found to be comparing the productivity of multistage solar distiller with conventional single-stage solar distiller. Therefore, this study aims to identify the thermal performance of multistage solar distiller.

1.4 Aim and Objectives

This study aims to identify the effect of utilization of latent heat through multiple staging of solar distiller toward its productivity. To achieve the overall aim, the following objectives need to be accomplished.

i) To identify the difference in distillate output of solar distiller ranges from 1-stage to 7-stages.
ii) To determine the theoretical water production rate of solar distiller in Malaysia's environment context.
iii) To analyze the energy efficiency of the solar distillers.
iv) To conduct an economic analysis for determining the optimum output from variable number of stages.

1.5 Scope and Limitation of the Study

The scope of this study focuses on the impact of solar distillers' efficiency caused by different number of stage of the design, where the other variable parameters are omitted and will not be part of the consideration in this study. Other than that, this project is limited to theoretically studying desalination of saline water from one source with the salinity of 35000 ppm, and analysis would only be considered for day time (9 A.M. to 5 P.M). Economical analysis is based on location at Petaling Jaya, where cost such as rental and principal cost are closely related. Lastly, there will be no active components considered in this project to reduce the complexity of the study and allow focusing on the observation of the difference on efficiency between solar distiller of different number of stage. Lastly, another limitation is that the imperative relationships between the temperature of various stages and components by analyzing experimental data of previous studies are merely an approximation.

1.6 Contribution of the Study

This study contributes to identify the thermal performance of multistage solar distiller, and it would also suggest the optimal number of stages in economical context. With the result, researchers of future works could utilize the concluded optimal number of stage to build the solar distiller.

1.7 Outline of the Report

A total of 5 chapters are included in this report. Chapter 1 explains the introduction on solar distiller, concepts of desalination and the objectives of this research. Chapter 2 discusses the literature review regarding about historical background of solar distiller, operation principle, the parameter affecting the productivity of the solar distiller and reviews experiments that had been done regarding multistage solar distiller. Research methodology would be explained in Chapter 3, and the obtained result would be discussed in Chapter 4. Lastly, Chapter 5 concludes the finding of this research and recommend suggestion on future research.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction to Literature Review

In this chapter, the literature review will be based on 5 major scopes. The first 2 discussed scopes include the history background of solar distiller, operation principle of solar distiller. Then, in section 2.4, the factors affecting the productivity of the solar distiller including addition of active and passive components is discussed. Next, the impact on water productivity by having multistage design and various different design would be stated in section 2.6. Lastly, previous experiments with multistage solar distiller would be reviewed in section 2.7.

2.2 History of Solar Distiller

The first sign of desalination concept can be traced back to about 1500 BC, where it was first written in Old Testament (Vetus, M.Dc. XXVIII) (Delyannis, 2003). However, even with the idea of desalination described, there were no apparatus or application that utilizes the solar energy for desalination until medieval times (Delyannis, 2003). As research and technology evolve until later during Renaissane, one scientist named Giovani Batista Della Porta (1535-1615) wrote books mentioned about 7 methods of desalination, most crucially was the reference in the 19th volume of his book, Figure 2.1 below shows the solar distillation unit to obtain freshwater by converting saline water (Delyannis, 2003).

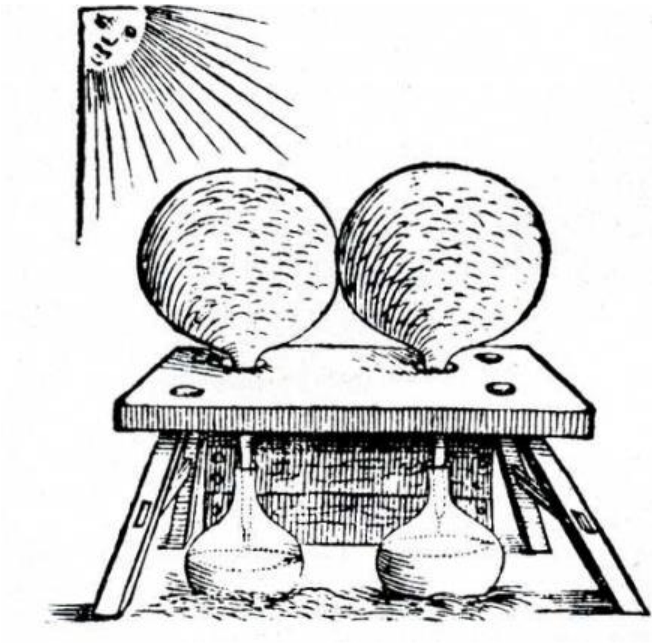

Figure 2.1: Solar distillation unit according to Della Porta (Gioda, 1999)

After the published idea by Della Porta, there was no important update on solar distillation application until the Americans, Wheeler and Evans obtained the patent on solar distillation that was granted in 1870 (Delyannis, 2003). In 1872, the first solar distillation plant was built by Carlos Wilson near a saltpeter mine and silver mining area in Las Salinas, Chile, the 64-bay solar distiller was in operation for roughly 40 years and it was capable of providing 22.70 m^3 of fresh water daily to the workers and their families (Delyannis, 2003).

2.3 Operation principle of Solar Distiller

Solar distiller works on two essential principles, which are evaporation and condensation. Figure 3 shows the schematic diagram of a simple solar distiller. Initially, for a simple solar distiller, ambient temperature saline water flows into the basin, where the depth of the water is controlled. Then, with solar radiation, the energy is absorbed by the saline water, increasing the its temperature and evaporation rate, when the saturated air with water vapour comes in contact with the relatively lower temperature surface of transparent glass, water vapour condenses into water droplets (Sharshir et al., 2016). As the transparent glass is tilted, the condensed droplets would flow to the direction of distilled water outlet as shown in Figure 2.2. Usually, the basin would be covered by insulative material to prevent heat loss of the saline water, also, as the water evaporates, the contaminant left behind would be required to be removed with a brine tank, similar to the component as shown in Figure 2.3.

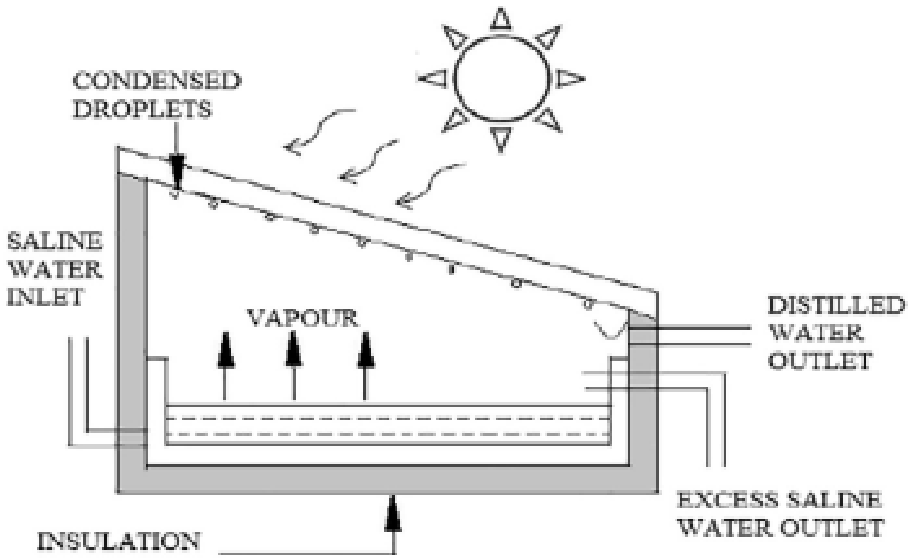

Figure 2.2: Schematic diagram of single basin solar distiller (Selvaraj and Natarajan, 2018)

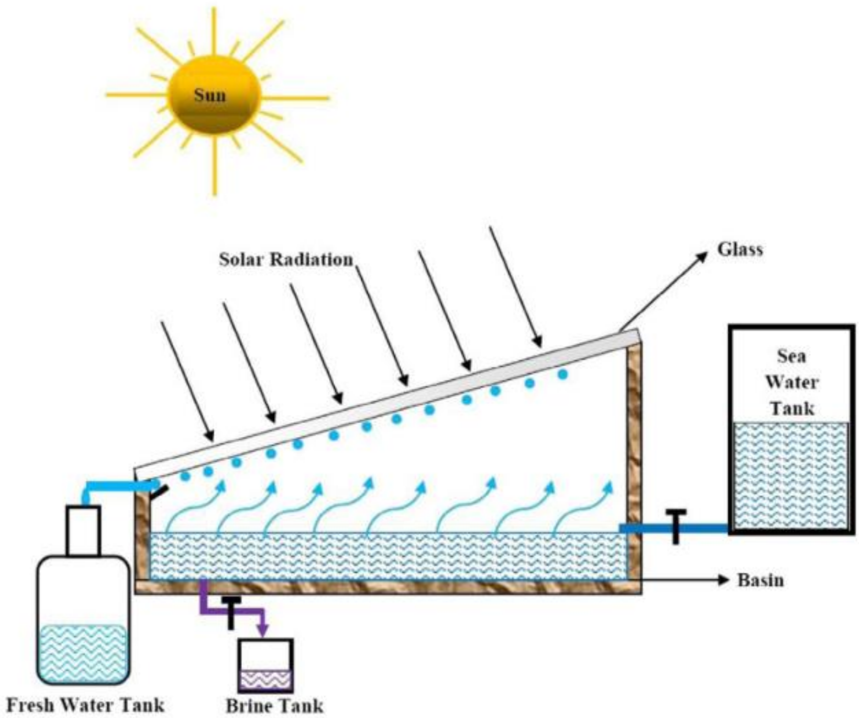

Figure 2.3: Schematic diagram of a simple solar distiller (Sharshir et al., 2016)

2.4 Factors affecting productivity of Solar Distiller

The productivity of the solar distiller is sensitively affected by numerous parameters including solar radiation intensity, wind velocity, ambient temperature, temperature difference between condensation cover plate and water, inlet of the water temperature, area of the solar distiller that receives the solar radiation, glass cover angle and thickness, insulation of the basin, the pressure inside the solar distiller and depth of water. However, there are certain factors that cannot be controlled such as solar radiation intensity, ambient temperature and wind velocity because they are metrological parameters (Sharshir et al., 2016).

2.4.1 Solar Radiation Intensity

As the name, solar distiller stated, the energy provided by the sunlight greatly affect the productivity of solar distiller. In case of passive solar distiller, solar radiation is usually the only energy source for the solar distiller.

From an experiment of desalination process with seawater using inclined stepped solar distiller, it was found that increase in solar radiation intensity will affect other parameters such as ambient temperature, temperature difference between cover and water vapour. In short, the higher the solar radiation, the better the productivity of the solar distiller (Abujazar, Fatihah and Kabeel, 2017). This statement is also in good agreement with research done by Badran and Abu-Khader (2007) where they performed experiment with a single slope solar distiller and figure out that during afternoon time around 12 P.M. to 1 P.M. when the solar intensity is the strongest, the productivity of the solar distiller increases rapidly, Figure 2.4 below shows the relationship between solar radiation intensity and productivity of the solar distiller. Furthermore, another group of review study had concluded that solar distiller productivity is directly proportional to the solar radiation intensity as well (Sharshir et al., 2016).

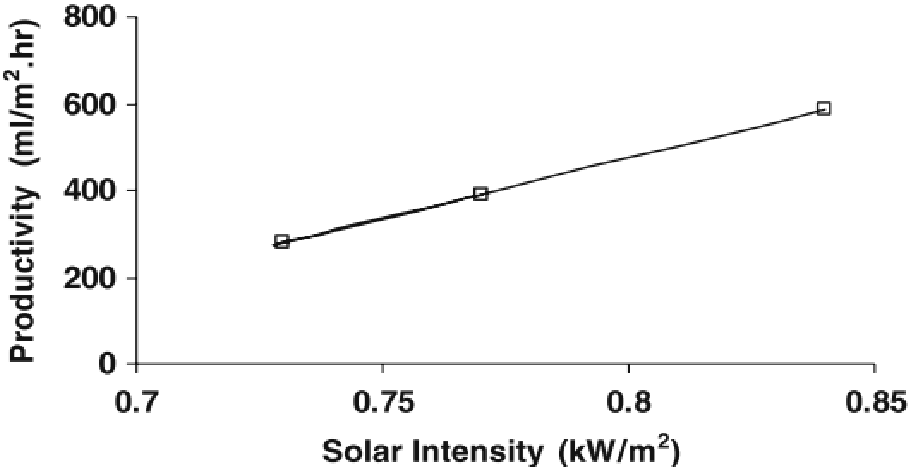

Figure 2.4: Relationship between solar radiation intensity with productivity (Badran and Abu-Khader, 2007)

2.4.2 Ambient temperature

Ambient temperature is another critical factor that affects productivity of the solar distiller, as it is closely related to the solar radiation intensity, they are often studied together. This is because as the ambient temperature increases, the initial temperature of the saline water would be increased, besides that, the heat loss of the basin would also be decreased. However, it would cause the temperature difference between the condensation cover plate and water vapour to be lower. Thus, considering all these effects that ambient temperature brings, a study 2007 using single slope solar distiller showed that the increase in ambient temperature would lead to an increase in productivity (Badran and Abu-Khader, 2007).

2.4.3 Wind velocity

There are several different findings obtained for the effect of wind velocity to the solar distiller productivity. Theoretically, an increase in wind velocity will promote the convection heat transfer between the solar distiller and the ambient, which has both positive and negative effect. The positive effect is that it will increase the temperature difference between the condensation cover plate and water vapour, increasing the condensation of distillate In contrast, the disadvantage is that it will raise the heat loss of the saline water to the ambient. Hence, would the increase in wind velocity have more positive impact than negative impact on the productivity of the solar distiller? El-Sebaii, 2000, states that the saline water and cover temperature both drop as wind velocity increases due to higher convective heat transfer However, the effect of have both temperatures drop is less significant than the effect of increase in temperature difference between the condensation cover plate and water, thereby increasing the productivity. It was also concluded that the optimal value of wind velocity is between 8 m/s to 10 m/s independent of the design of still and properties of saline water (El-Sebaii, 2000).

Moreover, it was figured out that multi-effect passive solar distiller has obvious advantage by placing it in high wind velocity location because the top basin well protects the lower stages basin water from heat loss (El-Sebaii, 2004). Finally, the effect of wind velocity on the productivity of solar distiller is found to be closely related to the depth of the saline water, whereby if the depth is lower than the critical value of 4.5 cm, the increase in wind velocity will reduce the productivity of the solar distiller (El-Sebaii, 2004).

2.4.4 Temperature difference between condensation cover plate and water

The temperature difference between the condenser cover plate and water is essential because it causes the natural circulation of the water vapour and air inside the solar distiller, enhancing the evaporative and convective heat transfer from the water to the cover plate (Sharshir et al., 2016). Productivity of the solar distiller depends heavily on the temperature difference between the condensation cover plate and saline water, such that the productivity increases with higher temperature difference (Muthu Manokar, Kalidasa Murugavel and Esakkimuthu, 2014). Another study done by researchers obtained similar result, from the two circled legends in Figure 2.5. Legend circled in red shows the temperature difference and legend circled in blue shows the productivity, the pattern of increase in temperature difference increases the productivity could be observed (Abujazar, Fatihah and Kabeel, 2017).

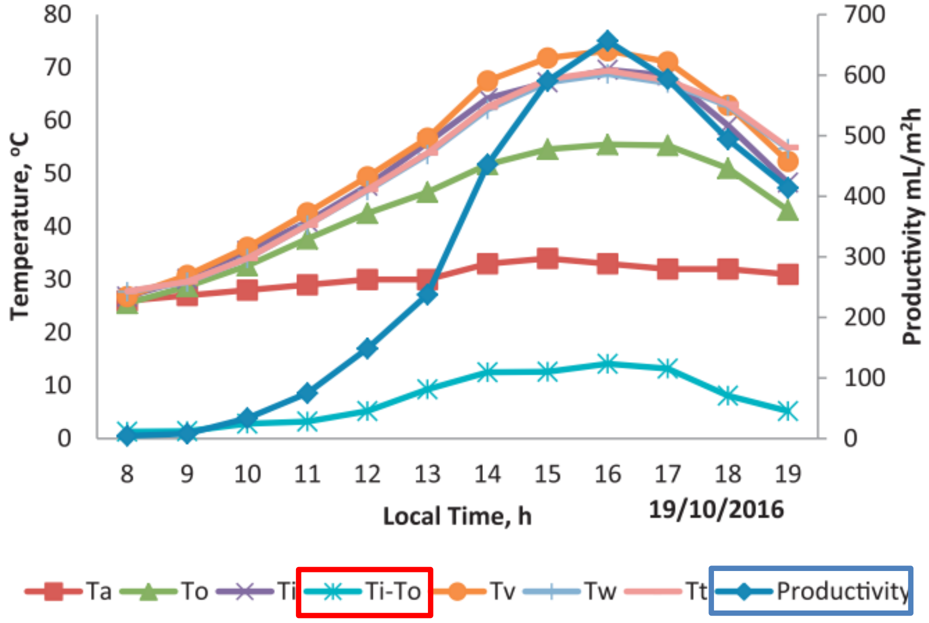

Figure 2.5: Effect of temperature difference on productivity (Abujazar, Fatihah and Kabeel, 2017)

2.4.5 Angle, material and thickness of condensation cover plate

Dust accumulation has an indirect effect on the productivity of the solar distiller because the dust would reduce the transmittance of solar radiation. In fact, the ease of dust accumulation is directed related to the cover plate material and its angle (Muftah et al., 2014). Thus, the larger the angle of cover plate, the harder for the dust to accumulate, also, other researches showed issues beside dust accumulation. It was found that the relationship between cover plate angle and geographical location of the experiment also significantly impacts the solar radiation received.

Akash, Mohsen and Nayfeh, 2000, conducted an experiment in Jordan at a latitude of 31.57°, in May 2000, investigating the water production with several cover plate angles of 15 °, 25 °, 35 °, 45 ° and 55 ° , they obtained a conclusion that the best tilt angle is 35° with maximum water production. However, by analysing annual yield in Delhi climatic condition at latitude of 28 °N, it was observed that the optimal angle of cover plate is found to be 15 ° (Kumar, Tiwari and Singh, 2000). Another study using numerical method to analyse the impact of cover plate angle on the productivity in Delhi at a latitude of 28.36°N, the study concluded that 45 ° is the optimum angle (Dev and Tiwari, 2009). Mathematical modelling analysis from Jubran, 2003, indicated that the productivity of solar distiller in Omani at latitude of 23.36 ^{o}N increase with decreasing cover plate angle during summer, and the relationship is in a reverse manner in winter.

Combining the conclusion made by several studies reviewed above, it is convinced that the optimum angle of condensation cover plate is in close relationship with the angle of latitude of the location. The tilting angle of the cover plate is dependent on the direction of cover is facing and the angle of latitude of the location. This is because when the angle of inclination is equal to the latitude angle, the solar distiller will receive close to normal solar radiation throughout the year (Muftah et al., 2014). The statement "The optimum inclination of the flat-plate collector is equal to the latitude of New Delhi as in the case of the passive solar distiller for the condensing cover inclination" shows a good agreement for the relationship between optimum angle and latitude of the location (Singh and Tiwari, 2004). As a matter of fact, 3 Malaysian works on solar distiller at the location of Bangi by Abujazar *et al.* (2018), Zarasvand Asadi *et al.* (2013) and Abujazar, Fatihah and Kabeel (2017) all used a 30 ^{o} as the inclination angle of condensation cover plate.

Regarding the material of the condensation cover plate, the material selection usually emphasizes the solar transmittance for different angles of cover plate, where materials like plastic and glass are often flavoured (Sharshir et al., 2016). Begum, Yousuf and Rabbani in 2018 experimented to analyse the difference in productivity of solar distiller using PVC and Glass as cover plate material, the result showed that the performance of solar distiller was 58 % poorer by using PVC sheet cover plate. The thickness of the cover plate also affects the heat transfer rate, where the thinner the cover plate, the greater the thermal conductivity. An experiment in year 1998 showed that the productivity of the solar distiller increased by 16.5 % when the glass thickness was reduced to 3 mm from 6 mm (Mink et al., 1998). Another analysis result using software comparing 3 solar distillers with glass cover plates of thickness 3 mm, 5 mm and 6 mm discovered that glass cover plate with 3 mm have the best performance where the productivity is 15.5 % higher than 6 mm (Ghoneyem and Ileri, 1997).

2.4.6 Collector's surface coating and area of the solar distiller

A larger area of the collector allows more absorption of solar radiation which subsequently rises the water temperature and productivity of the solar distiller. Velmurugan and Srithar (2011) discovered that by adding fins to the collector surface to increase the absorption area had led to an increase in productivity by 30 %. A matte or flat black paint for surface coating could increase the absorption of solar radiation that results in increased productivity (Selvaraj and Natarajan, 2018). Prakash, 2012, experimented with black chrome coating, matt black coating and solchrome coat, he concluded that black chrome coating has the higher thermal efficiency. Hence, it can be presumed that the performance of the solar distiller increases by enlarging the area of the solar collector and having black surface coating.

2.4.7 Insulation of the basin

Having proper insulation can minimize the heat loss of the saline water to the surrounding, solar distiller with 60 mm insulation thickness increased the productivity by 80 % compared to solar distiller without insulation (Muftah et al., 2014). Another study analysed the productivity of solar distiller with 30 mm of bubble wrap as insulation system, after experimenting for 3 months, the average productivity of the solar distiller with bubble wrap as insulation have 21.1 % higher output as compared to solar distiller without insulation (Arunkumar et al., 2018). Other than that, Jubran (2003) confirmed the relationship between insulation and productivity, based on Figure 2.6, it indicates that by increasing the insulation thickness, the solar distiller productivity raises. Data obtained by Badran and Abu-Khader (2007) as plotted in Figure 2.7 also shows strong agreement with the result obtained by Jubran (2003).

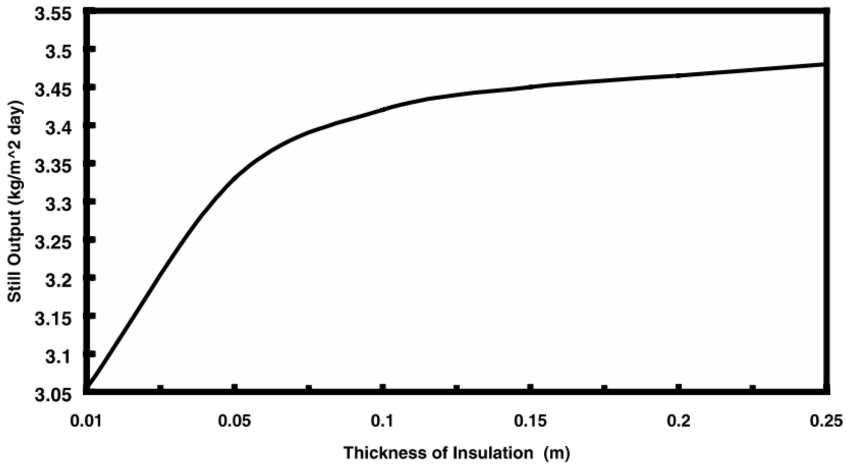

Figure 2.6: Effect of insulation thickness on productivity (Jubran, 2003)

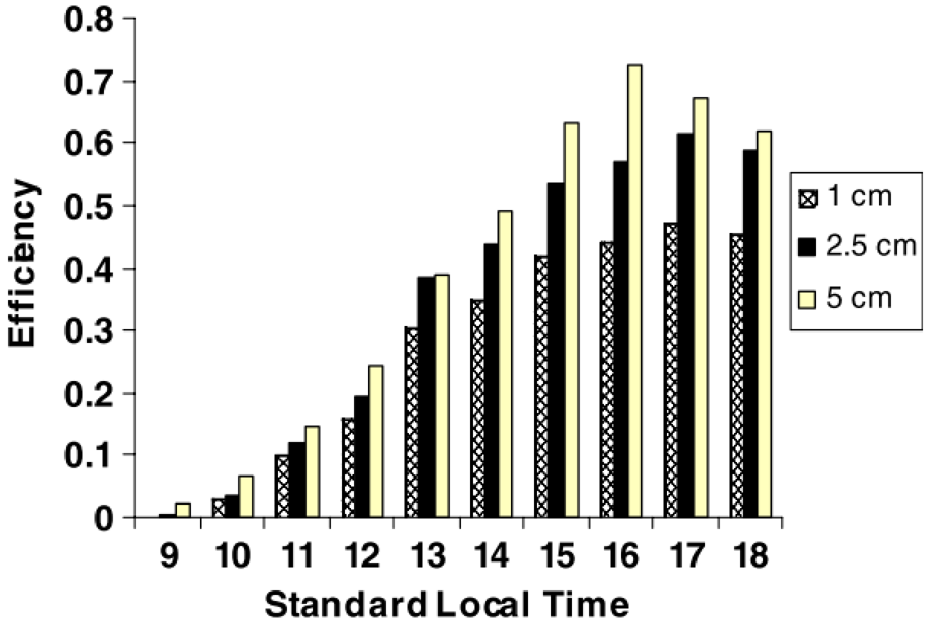

Figure 2.7: Effect of insulation thickness on efficiency (Badran and Abu-Khader, 2007)

2.4.8 Depth of the water

One of the significant factors affecting the productivity of solar distiller is the depth of the saline water. Figure 2.8 shows experimental results comparing 2 cm water depth and 3.5 cm water depth, the graph reveals that 3.5 cm water depth has lower productivity than 2 cm water depth in general. This is due to the increase in water depth also means an increase in water mass, subsequently increasing the total heat capacity of the water that would cause slower temperature rise and therefore lower evaporation rate (Badran and Abu-Khader, 2007). A statement “It was found that a lower water depth gives better efficiency, which is in agreement with many investigators” by Dev and Tiwari (2009) also agrees with the relationship between water depth and productivity conclusion obtained by Badran and Abu-Khader (2007).

In conclusion, the productivity of the solar distiller has inversely proportional relationship to the water depth, if the water depth increase, the evaporative heat transfer rate decreases, reducing the productivity of the solar distiller (Muftah et al., 2014).

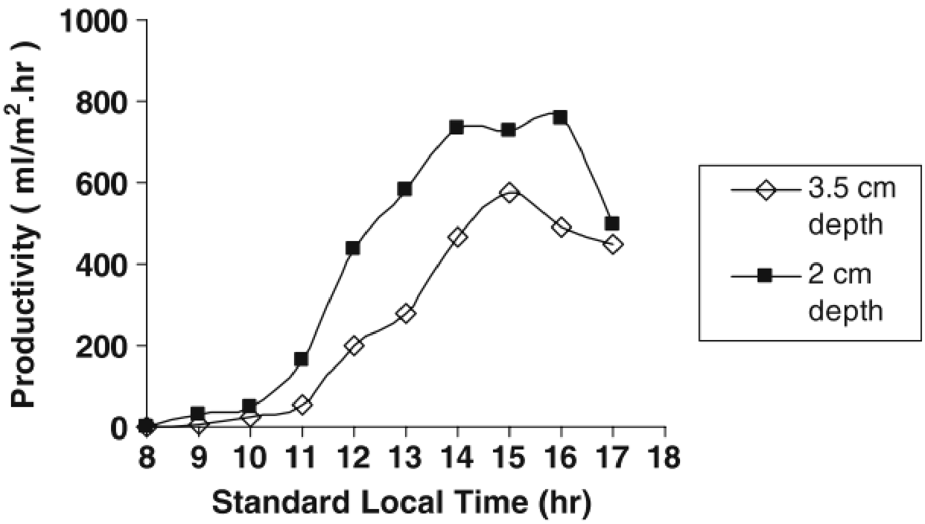

Figure 2.8: Effect of water depth on productivity (Badran and Abu-Khader, 2007)

2.5 Components used to improve Solar Distiller’s productivity

To improve the productivity of solar distiller, multiple concepts that include active or passive components have been used in solar distiller, for example, using a pump to reduce the pressure of the solar distiller or using a heat exchanger to enhance the rate of temperature increase of the saline water. In this section, both active and passive components used to improve solar distiller’s productivity will be discussed.

2.5.1 Active components

Active components are components that require energy input to operate such as a vacuum pump, solar tracking system and heat exchanger that would be discussed in this section.

Improvement in the productivity is observed when a vacuum pump is used to reduce the pressure inside the solar distiller. It is because by reducing the pressure, the heat loss due to convection would be reduced, and the heat loss would be left with evaporation and radiation only, it was found that by applying a vacuum in the solar distiller, the productivity increased about 100 % (Al-Hussaini and Smith, 1995). Other than the reduction in heat loss, another benefit of lowering the operating pressure with the use of vacuum is the reduction of the water vapour saturation temperature, improving the evaporation rate of the water (Reddy and Sharon, 2016). Vacuuming also assists in removing unwanted gases inside the solar distiller (Reddy and Sharon, 2016). From an experiment, it was found that the average productivity increased by 164.31 % by operating the solar distiller at a pressure of 0.25 bar, as compared to productivity with operating pressure of 1 bar (Reddy and Sharon, 2016). However, although vacuum pump has positive impact on the productivity, it requires electricity and cost money, which might not be suitable to be used in urban area.

As the temperature of the saline water extensively affects the productivity of the solar distiller, sun tracking system is integrated with solar distiller to increase the solar energy absorbed, thereby increasing the temperature of saline water. Sun tracking system is one of the many components used to keep track of the movement of the sun to obtain optimal solar radiation at all time, and it was reported that by using a two-axes sun tracking device, the productivity of the solar distiller increased by almost 42 % (Abdallah and Nijmeh, 2004). Moreover, heat exchanger is also a commonly used system to provide additional thermal energy to the saline water, often, waste heated fluid such as heated coolant from power or chemical plants could be used to serve as the working fluid (El-Sebaii and El-Bialy, 2015).

2.5.2 Passive components

Passive components reviewed here are components that do not require input of energy, for example, it includes placing a reflector to increase solar radiation to the solar distiller, using energy absorption and storing materials like phase changing material, addition of fins to improve the heat conductivity and etcetera. In terms of reflectors, it works by redirecting the sunlight into the water, increasing the solar radiation energy. With the implementation of internal or external reflectors to a typical basin type solar distiller, the productivity would increase by 70-100 % (Sharshir et al., 2016). Tanaka and Nakatake (2006) performed numerical analysis on solar distiller with internal and external reflectors found that single-slope basin type solar distiller with both reflectors had an improvement of 48 % in productivity.

Phase change material (PCM) has recently been used as energy absorbing and storing components, with the principle of storing heat as latent heat. Initially, PCM exists as solid, absorbing solar energy during day time until it gains excessive energy, melts and changes into liquid phase, after that, PCM continues to absorb energy as liquid until solar radiation intensity drops until the PCM has higher temperature than the saline water, then, the PCM starts releasing the energy it absorbs, heating the saline water (Naim and Abd El Kawi, 2003).

Next passive component is addition of fins, fins are typically made of highly conductive material to increase the heat transfer rate. An experiment was carried out comparing the productivity of single basin solar distillers that were equipped with and without fins, it was found that when fins were used, the distillate output increased by 45.5 % (Velmurugan et al., 2008).

2.6 Multi-stage and various design

Various designs of solar distiller with different shapes and sizes have been proposed and studied. Some of the common designs' idea are hemispherical solar distiller, pyramidal solar distiller, vertical solar distiller, tubular solar distiller, and multistage solar distiller. Different designs and features that are commonly added would be reviewed in this section.

2.6.1 Hemispherical Solar distiller

Arunkumar et al. in 2012 constructed a hemispherical solar distiller to study the impact of flowing cold fluid over the cover towards the productivity. The diameter of the hemispherical solar distiller basin was 0.95 m and had 0.10 m in height, while top covering hemispherical cover plate with 0.945 m in diameter and 0.20 m in height was constructed with a transparent acrylic sheet with 88 % solar transmittance. Figure 2.9 shows the cross-sectional view of hemispherical solar distiller constructed by Arunkumar et al. (2012), experimental result showed that efficiency increased by 8 % with water flowing over the cover.

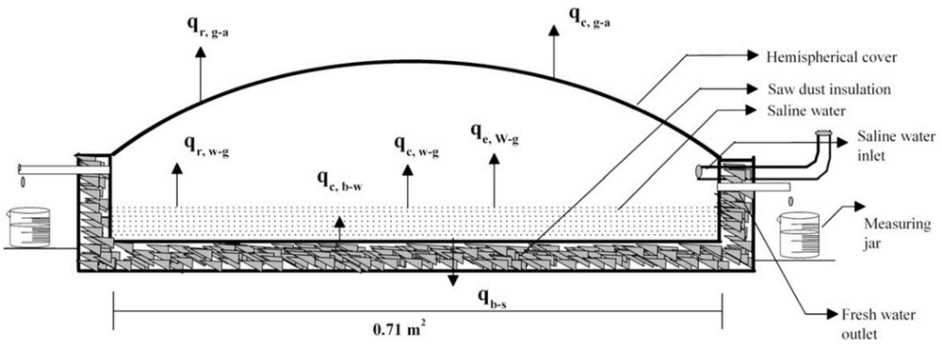

Figure 2.9 : Cross-sectional view of hemispherical solar distiller (Arunkumar et al., 2012)

A transportable hemispherical solar distiller was designed and experimented for its performance, the constructed solar distiller had 0.5 m^2 in surface area basin that contained an aluminum plate to work as an absorber. It also had hemispherical transparent cover, a conical-shaped aluminum distillate collector and a transportable frame support, Figure 2.10 shows the schematic diagram of the solar distiller (Ismail, 2009).

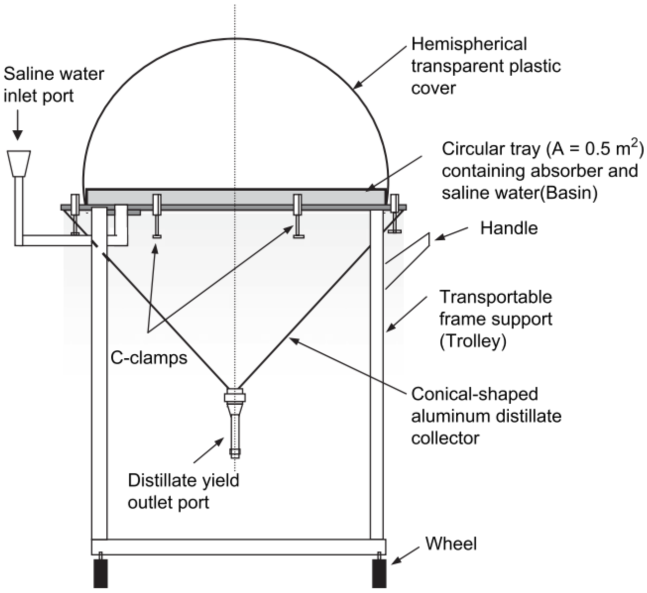

Figure 2.10: Transportable hemispherical solar distiller (Ismail, 2009).

2.6.2 Pyramidal Solar Distiller

Figure 2.11 shows the solar distiller with a basin area of 0.95 m^2 and pyramid-shaped glass cover, this experiment determined the productivity of the solar distiller with and without fan, that productivity was found to increase by 25 % with forced convection with the usage of fan (Taamneh and Taamneh, 2012).

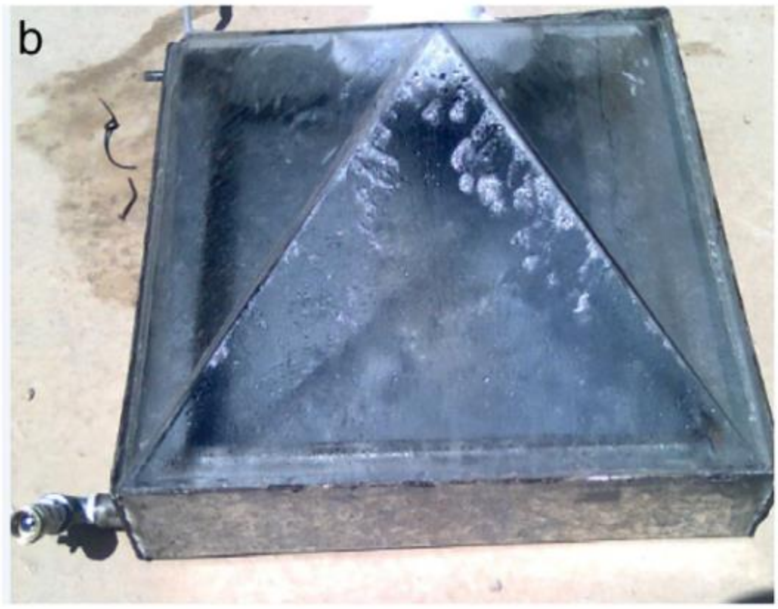

Figure 2.11 : Solar distiller with pyramid-shaped glass cover (Taamneh and Taamneh, 2012).

Abdelal and Taamneh (2017) investigated the productivity enhancement on pyramid solar distiller with the usage of CNT-modified epoxy composites as absorber plates, the setup was as shown in Figure 2.12. From the result obtained, using graphene nanoplates in epoxy matrix as absorber plates would effectively increase the productivity of the pyramid solar distiller by 30 % (Abdelal and Taamneh, 2017).

Figure 2.12 : 4 Solar distillers with pyramid-shaped glass cover (Abdelal and Taamneh, 2017).

2.6.3 Vertical Solar Distiller

In high population density cities, land area is costly, hence as basin type solar distiller requires much space, it is not suitable. Thus, the idea of vertical solar distiller emerged to save space and be conveniently used. Boukar and Harmim (2004) in Adrar constructed and experimented a vertical solar distiller from May to July 2003, obtaining a conclusion that productivity of the vertical solar distiller is highly dependent on the solar orientation and radiation as well as the ambient temperature. Throughout the 4 months experiment, a maximum productivity using vertical solar distiller of 2.3 kg/m^2 was obtained (Boukar and Harmim, 2004).

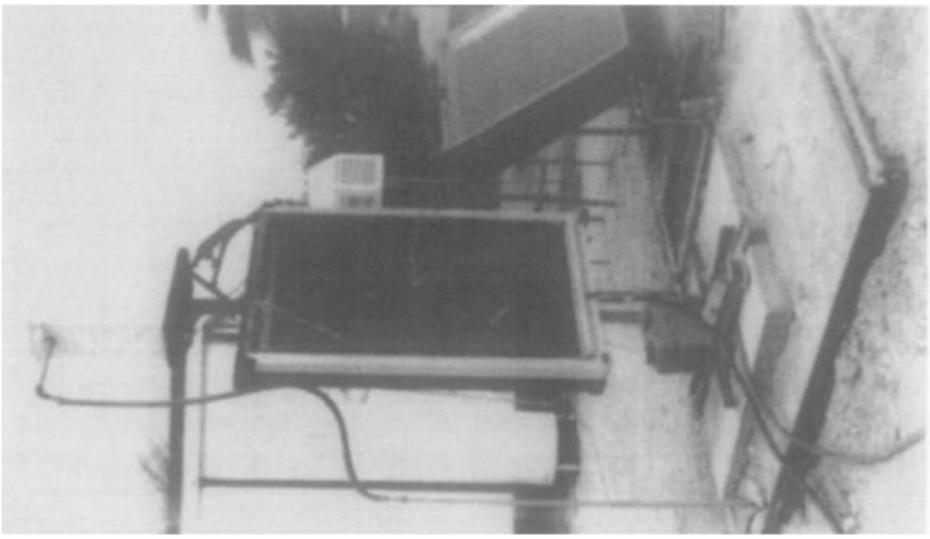

Figure 2.13: Photograph of vertical solar distiller, titled 90 degrees to the left to save space (Boukar and Harmim, 2004)

2.6.4 Tubular Solar Distiller

Tubular solar distiller is reported to be suitable for the use with water distribution network for desert plantation. The distiller could be set up directly on the ground with pipes connecting saline water, then the distillate is not collected by a tank but instead is supplied to the plant directly (El-Sebaii and El-Bialy, 2015).

Figure 2.14 shows the schematic diagram of tubular still, Ahsan *et al.* in 2012 analyzed the tubular solar distiller with proposed improved material selection where the material is cheaper, lighter and can be easily machined, from the result obtained, the tubular solar distiller built with new material had a reduce cost and weight by 92 % and 61 % respectively while having the similar productivity as using the old material.

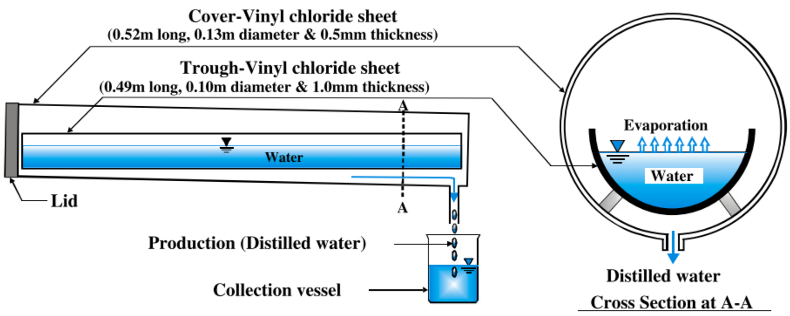

Figure 2.14: Tubular Solar Distiller (Ahsan et al., 2012).

2.6.5 Multistage basin Solar Distiller

The solar radiation transmits through the upper covers and gets received directly by the lowest basin water while the upper stages of multistage solar distiller utilize the latent heat of condensation from the previous stage to heat up the saline water. In a conventional multistage passive basin solar distiller, the only energy that the lowest basin water obtains is from solar radiation. Based on research, the productivity of solar distiller increases rapidly as the number of stages increases from 1 to 3, however, the maximum optimum number of stages for inverted absorber solar distiller is seven (El-Sebaii and El-Bialy, 2015).

Al-Karaghouli and Alnaser in 2004 performed a 5-month experiment that compared the productivity of single-stage solar distiller with double-stages solar distiller. The experiment found that the average daily performance of double-stages solar distiller is 40 % higher. Figure 2.15 shows the schematic diagram of the single-stage solar distiller while Figure 2.16 shows the double-stages solar distillers.

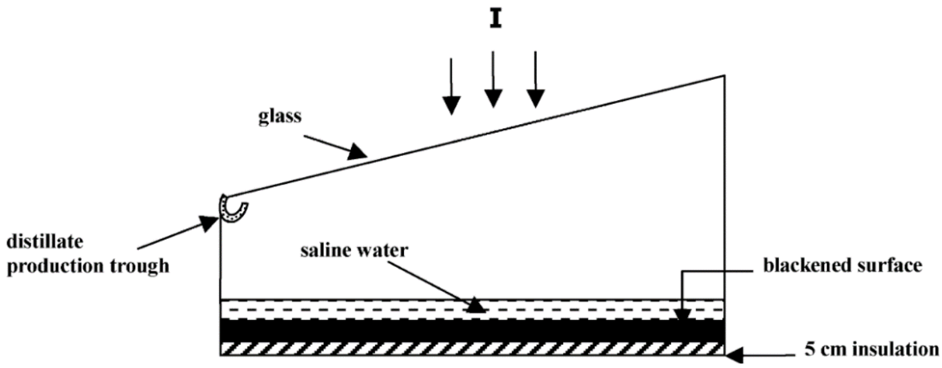

Figure 2.15: Schematic diagram of the single-stage solar distiller (Al-Karaghouli and Alnaser, 2004)

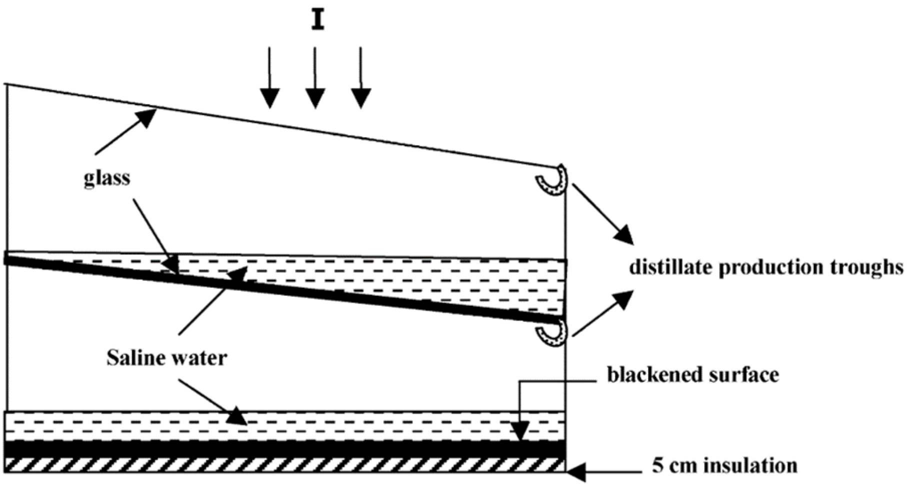

Figure 2.16: Schematic diagram of the double-stages solar distiller (Al-Karaghouli and Alnaser, 2004)

Another research compared the performance of single-stage double slope solar distiller and double-stage doubles slope solar distiller, the schematic diagrams are as shown in Figure 2.17. The experiment realized that by adding mild steel pieces as energy-storing components for both the solar distillers, the productivity increased by 85 % (Rajaseenivasan, Elango and Kalidasa Murugavel, 2013).

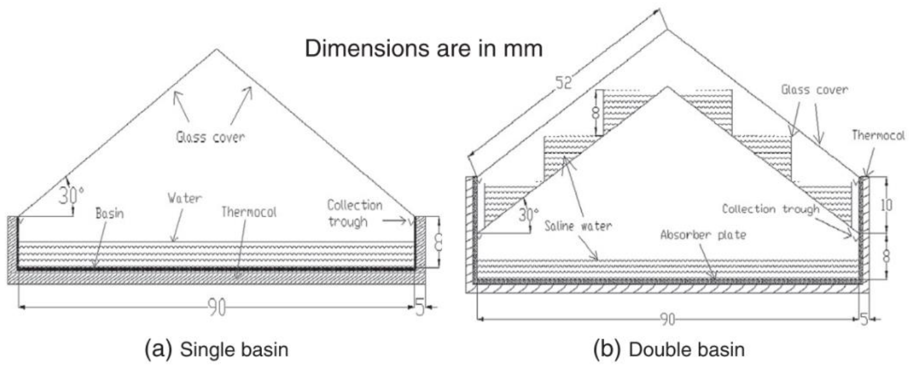

Figure 2.17: Schematic diagram of the 2 double slopes solar distiller (Rajaseenivasan, Elango and Kalidasa Murugavel, 2013)

Al-Hinai, Al-Nassri and Jubran (2002) used mathematical model to analyze the difference in cost required to produce fresh water between single-stage and double-stages solar distiller, the result indicated that in Oman, the cost to produce freshwater is 15.7 % cheaper by using double-stages solar distiller.

Triple-stages solar distiller even further utilize the latent heat. In Amman, Hamdan, Musa and Jubran (1999) compared the performance difference between single, double and triple stages solar distiller, it was shown that the performance of triple stage solar distiller is 5.8 % higher than double-stages solar distiller and 24 % higher than single-stage solar distiller. Figure 2.18 shows the schematic diagram of triple-stages solar distiller of El-Sebaii (2005), the experiment analyzed the impact on productivity of the solar distiller by changing the water mass and wind velocity, it was found that at optimal parameters on a summer day, the daily productivity of the solar distiller reached a maximum of 12.635 kg/m^{2}day.

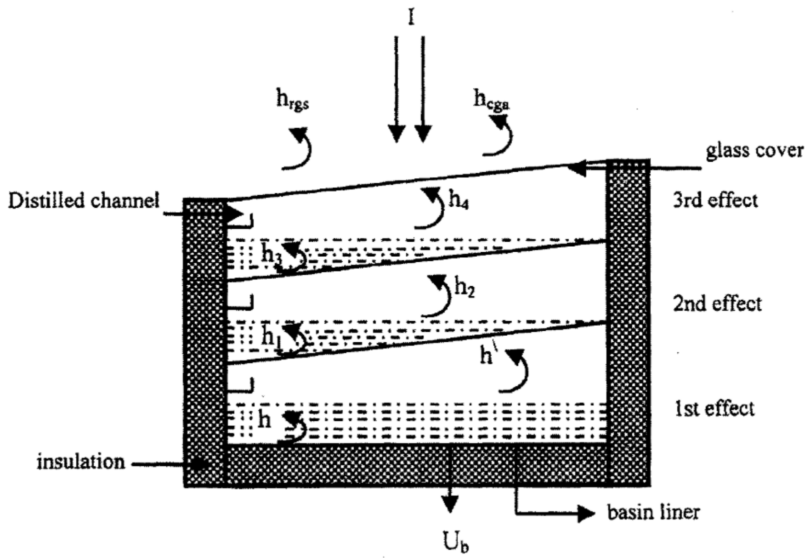

Figure 2.18: Schematic diagram of the triple-stages solar distiller (El-Sebaii, 2005)

Younas, Banat and Islam in 2016 built a triple-stages solar distiller as shown in Figure 2.19 to perform analysis on seasonal behavior and performance of the solar distiller in The Petroleum Institute, Abu Dhabi. The researchers developed transient mathematical model to analysis the solar distiller, they found out that theoretical analysis had an average deviation of 8.8 %, 9.3 % and 13.6 % in daily yield as compared to experimental result for 1st, 2nd and 3rd stage respectively. It was discovered that in May and June, the solar distiller has maximum productivity of 10 kg/m^{2}day, in contrast, the system has least productivity of 4.8 kg/m^2 day in the month of December (Younas, Banat and

Islam, 2016). The triple-stage solar distiller also had the amount distillate output of nearly 3 times better a single-basin solar distiller, yet, 5 stages solar distiller was found to have the optimal distillate output in terms of number of stage (Younas, Banat and Islam, 2016).

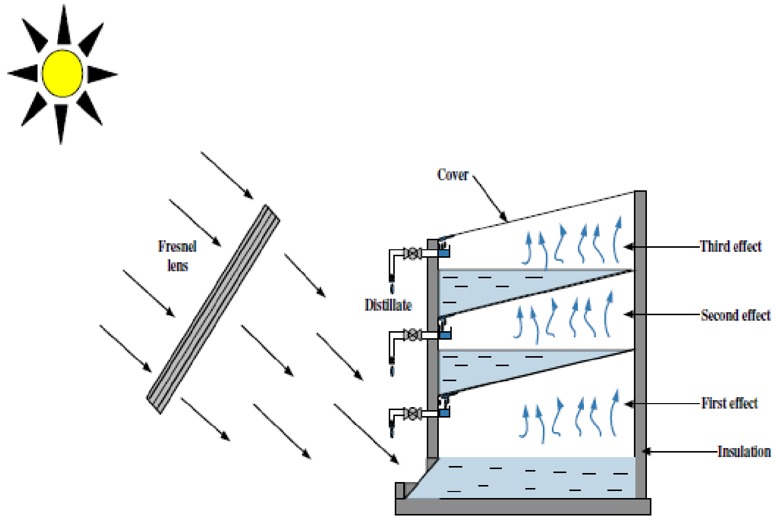

Figure 2.19: Schematic diagram of the triple-stages solar distiller with Fresnel lens (Younas, Banat and Islam, 2016)

2.7 Multistage Solar Distiller Experiments

Multistage solar distillers from different researchers are discussed and reviewed here, the experimental and simulation data from their articles are obtained, listed and cited in this section. Then, a computer software named “Get Data Graph Digitizer” is used to extract the experimental data from graph accurately. The experimental data extracted in this section would be used as reference in Chapter 3 and 4 to conduct theoretical analysis.

Figure 2.20 shows the data obtained of experiment performed in China on 3-stages solar distiller that was equipped with 7-tubes solar collectors with a total area of 0.9 m^2, considering the latitude of the location, optimal tilt angle of 30 ^{o} was chosen by the researchers (Chen et al., 2017).

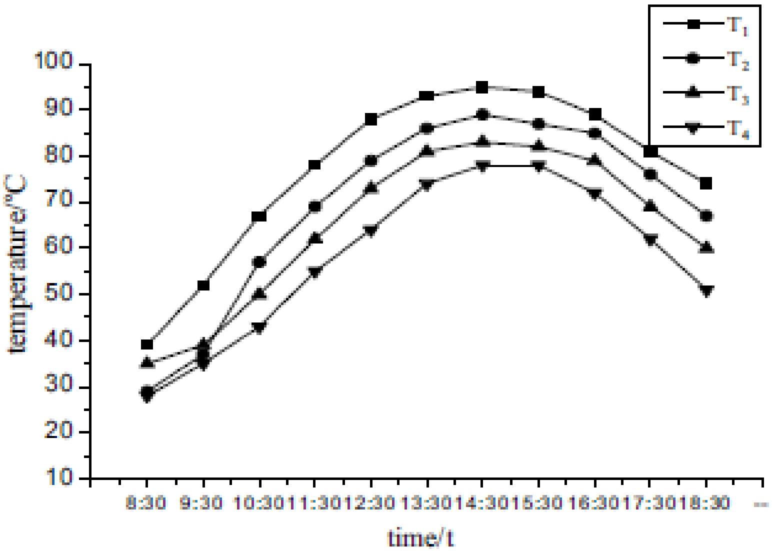

Figure 2.20: Experimental data of variation of water temperature at different stages and glassic roof (Chen et al., 2017).

Figure 2.21 shows the data obtained of experiment performed at Durham University on 4-stages solar distiller that was equipped with 20-tubes heat pipe, a frame with an array of 110 halogen floodlights were used to simulate solar irradiation. Besides, insulation material used was mineral wool with 150 mm in thickness with low heat conduction coefficient of 0.044 W/mK (Shatat and Mahkamov, 2010). In this experiment, they conducted full thermal insulation and partial thermal insulation model, the full thermal insulation completely insulated the solar distiller even from the top condenser part where it was designed to release heat energy. Experiment discovered that using full thermal insulation would cause the solar distiller to experience “thermal damage” such that the condenser surface had higher temperature than the water evaporation surface (Shatat and Mahkamov, 2010). Hence, only the experimental data of partial thermal insulation model where the top part of the solar distiller is left uninsulated is extracted and used.

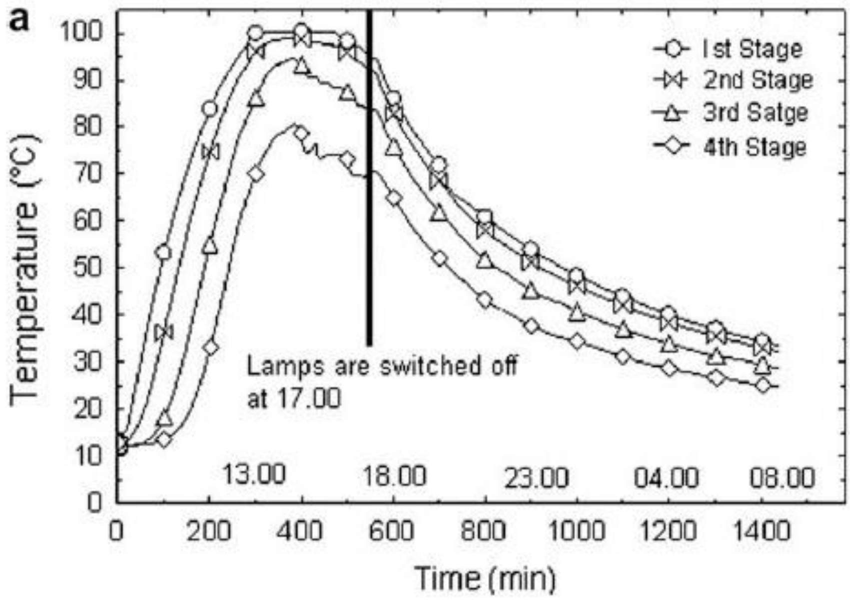

Figure 2.21: Experimental data of water temperature at different stages of experiment on 4 stage solar distiller performed at Durham University (Shatat and Mahkamov, 2010).

The temperature of the condensers are calculated using the following equations (Shatat and Mahkamov, 2010).

$$T_{C1} = T_{S2} - 2\ \mathrm{K} \tag{2.1}$$

$$T_{C2} = T_{S3} - 2.7\ \mathrm{K} \tag{2.2}$$

$$T_{C3} = T_{S4} - 1.11\ \mathrm{K} \tag{2.3}$$

$$T_{C4} = T_{S4} - (0.00007\ \times T_{S4}{}^{3} - 0.015\ \times T_{S4}{}^{2} + 0.9763\ \times T_{S4} - 10.324) \tag{2.4}$$

Figure 2.22 shows the data obtained from a research that utilized computer simulation model to solve energy balance equations of a 7-stages inverted absorber solar distiller based on Runge-Kutta 4th order method (Suneja and Tiwari, 1998). As the temperature of the condensers is not given except for the top condenser, the temperature of the condenser is assumed to be identical to the upper stage water temperature, for example, the condenser temperature at stage 2 is assumed to have same temperature with water at stage 3, because the condenser at stage 2 works as a basin to the water at stage 3 and they are physically in contact.

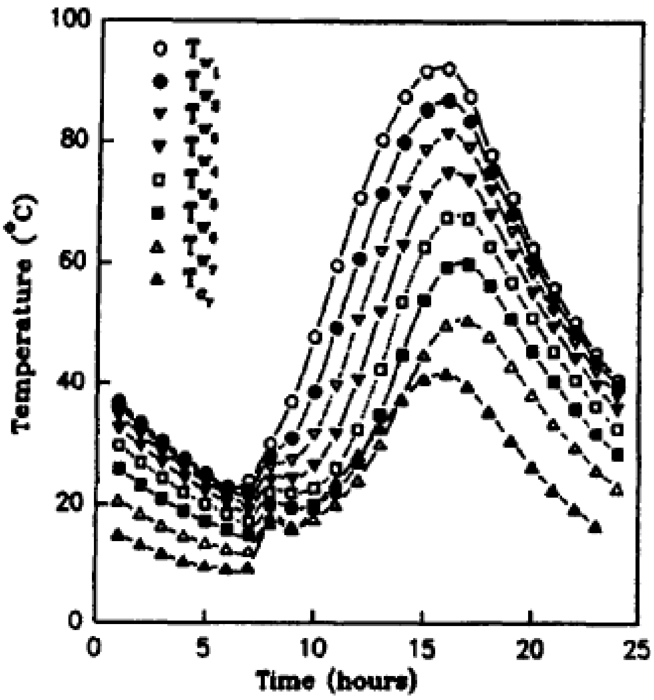

Figure 2.22: Computer simulation data of water temperature at different stages and top condenser temperature of simulation Runge-Kutta 4th order method on 7-stage solar distiller (Suneja and Tiwari, 1998)

Figure 2.23 and Figure 2.24 show the data obtained of predicted temperature based on data obtained during the experiment performed at Kirkuk, north of Iraq, at 43.39 ^{o} longitudinal and 35.17 ^{o} latitude on 3-stages solar distiller that was equipped with solar collector and circulation pump to keep the flowrate at 1.5 L/min. (Abed, Kassim and Rahi, 2017)

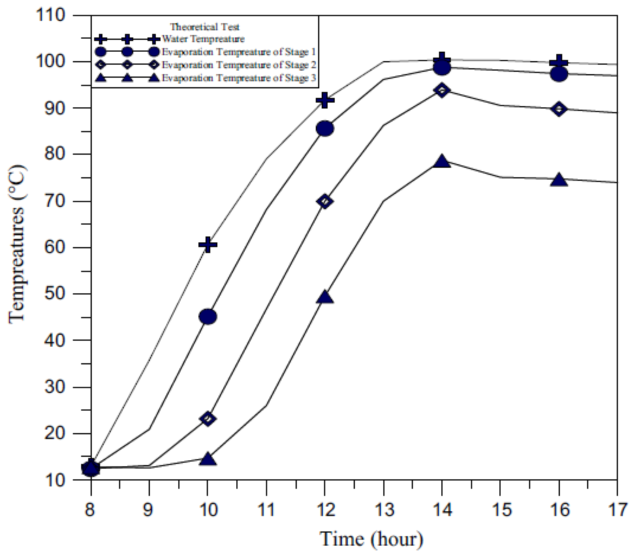

Figure 2.23: Water temperature of three stages with time (Abed, Kassim and Rahi, 2017)

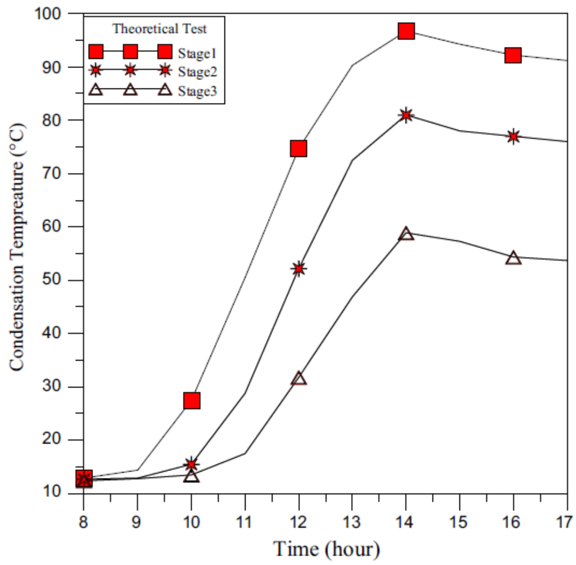

Figure 2.24: Condenser temperature of three stages with time (Abed, Kassim and Rahi, 2017)

Figure 2.25 and Figure 2.25 show the experimental data obtained for the experiment of a double-stages solar distiller, utilizing an electric heater to mimic the effect of solar irradiation. (Kalbasi, Alemrajabi and Afrand, 2018).

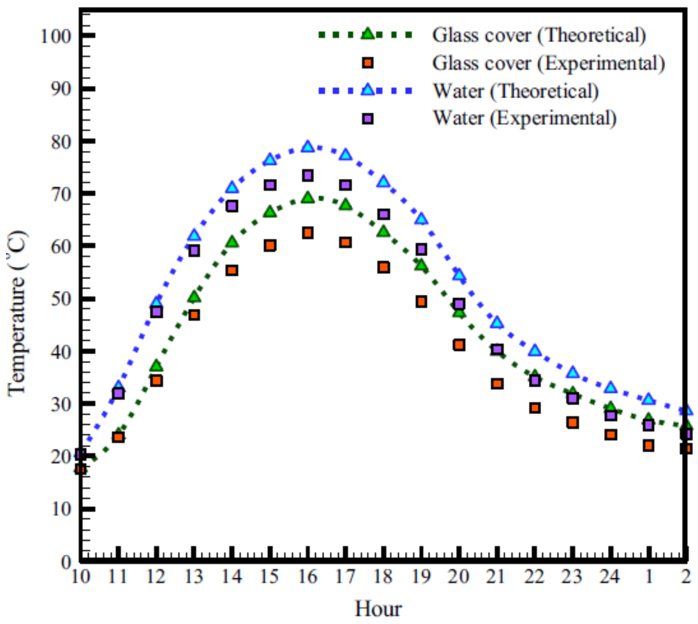

Figure 2.25: Water and condenser temperature of the lower stage with time (Kalbasi, Alemrajabi and Afrand, 2018)

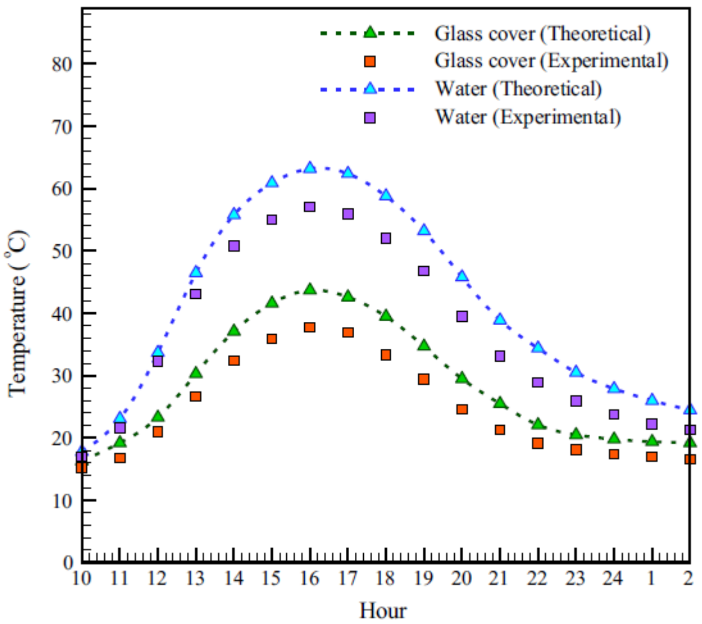

Figure 2.26: Water and condenser temperature of the upper stage with time (Kalbasi, Alemrajabi and Afrand, 2018)

Figure 2.27 shows the experimental data obtained for the experiment of a triple-stages solar distiller, utilizing an electric heater of constant power of 358 W to mimic the effect of solar irradiation (Adhikari and Kumar, 1993). As the temperatures of the condensers are not given except for the top condenser, the temperature of the condenser is assumed to be identical to the upper stage water temperature, for example, the condenser temperature at stage 2 is assumed to have same temperature with water at stage 3, because the condenser at stage 2 works as a basin to the water at stage 3 and they are physically in contact.

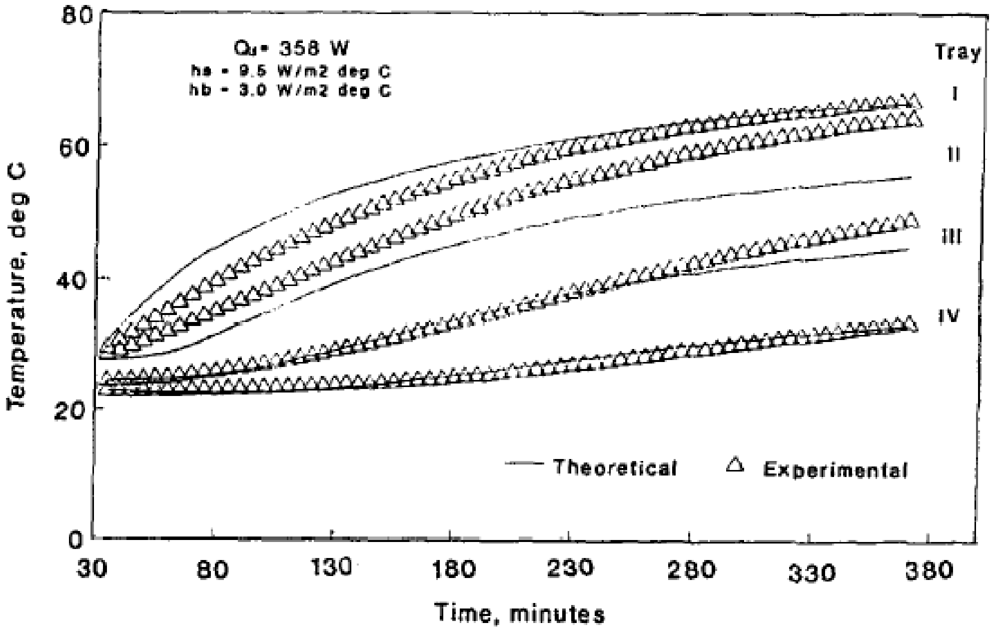

Figure 2.27: Water and condenser temperature of triple-stages solar distiller with time (Adhikari and Kumar, 1993).

Table 2.1 shows the recorded experimental data of research conducted by Ho (2021), the experiment was carried out during the period of April 2019 to September 2019, at the location of UTAR Sungai Long Campus. Data from this experiment would be used as the water temperature at stage 1 in this research.

Table 2.1: Recorded experimental data in UTAR Sungai Long Campus during April 2019 to September 2019 (Ho, 2021).

Time	Irradiance (W/m2)	Temperature of Feed water (°C)
9:00 AM	1065.2	27.75
9:30 AM	1194.4	30.85
10:00 AM	939.1	38.35
10:30 AM	1164.0	39.85
11:00 AM	1282.5	50.55
11:30 AM	1313.0	54.05
12:00 PM	1310.6	64.15
12:30 PM	1300.2	67.75
1:00 PM	1301.8	74.45
1:30 PM	1262.4	75.05
2:00 PM	1211.2	79.05
2:30 PM	1270.8	79.65
3:00 PM	1292.3	80.75
3:30 PM	1327.3	83.65
4:00 PM	1251.8	79.95
4:30 PM	1264.3	76.25
5:00 PM	231.3	66.15

2.8 Summary

This section explains that solar distillers work on the scientific principles of evaporation and condensation. In terms of factors affecting productivity, there are two categories of factors. Firstly, it is the metrological parameters like solar radiation intensity, the ambient temperature and wind velocity. Then, the second type of factor is modifiable design parameters including temperature difference between water and cover plate, inclination angle of the condenser, insulation of the solar distiller, depth of the saline water and multistage design to reuse enthalpy of vaporization. In the context of "multistaging" which is related to the title of this study, it was found that as the number of stages of solar distiller increases, the productivity improves as well.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

In this section, the methodology and work plan of this project will be discussed. Mathematical modelling, relevant formula, materials and equipment, and other required information to perform the experiment will be stated. By performing this project, it aims to study the thermal and cost analysis of the multistage solar distiller, primarily by using the performance of a single-stage solar distiller as our referencing and comparing value.

3.2 Proposed Designed

3 sets of different proposed designs with descriptions to be used in this project are stated in this section.

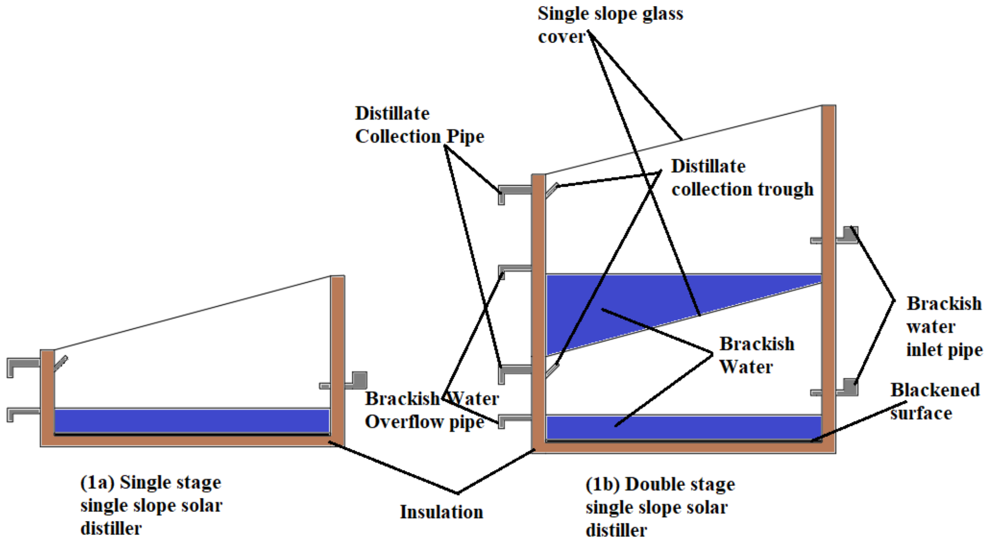

Figure 3.1: Single Slope Solar Distiller used in this project (Design 1)

Figure 3.1 shows the first proposed design, which is a single-slope solar distiller, where 1a is single-stage, and 1b is double-stages. The output of the distillate can be collected separately.

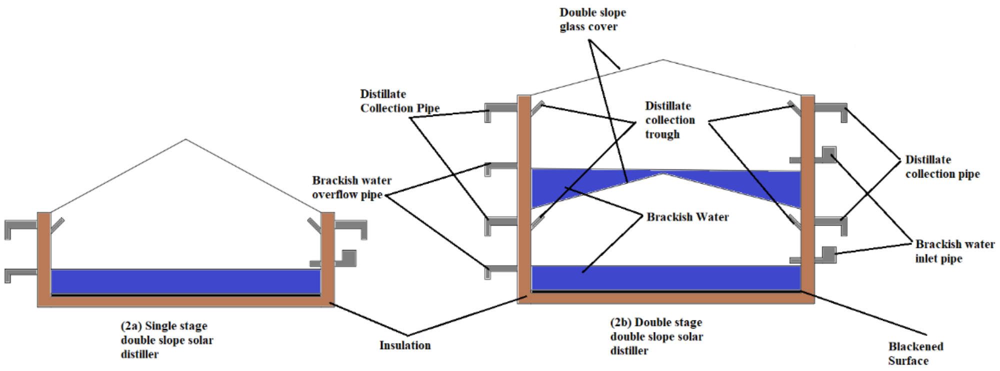

Figure 3.2: Double Slope Solar Distiller used in this project (Design 2)

Figure 3.2 shows the second proposed design, which is a double-slope solar distiller, where 2a is single-stage, and 2b is double-stages. The output of the distillate can be collected separately.

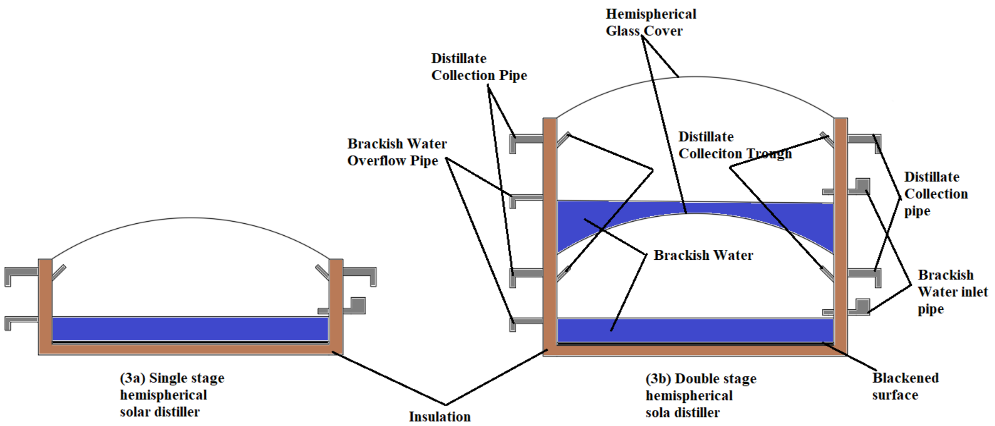

Figure 3.3: Hemispherical Solar Distiller used in this project (Design 3)

Figure 3.3 shows the third proposed design, which is a hemispherical solar distiller, where 3a is single-stage, and 3b is double-stages. The output of the distillate can be collected separately.

Proposed design 1 is selected for the experiment because it is cheaper and the easiest to construct among all 3 designs. Other than that, it is enough to serve the purpose of achieving the objectives of this study.

3.3 Parameters for proposed design

The experimental is planned to be conducted with the proposed design 1. The planned location, time and duration are UTAR Kampus Sungai Long, Kajang, Selangor, in June and from morning 9 A.M. to 5 P.M. Based on the literature review, the proposed designed parameters are stated in Table 3.1 below.

Table 3.1: Design parameter for the project

Design Parameter	**Value**
Basin Area (Length x Width)	0.25 m^2 (0.5 m x 0.5 m)
Insulation Thickness	5 cm
Insulation Material	Polystyrene
Cover plate material	Glass
Cover plate thickness	3 mm
Angle of inclination of cover plate (Both stage)	15 ^{o}
Depth of saline water (Both stage)	2 cm

Table 3.2 below shows the expected metrological parameters at Kajang, Selangor, based on June 2020 weather record data from 9 A.M. to 5 P.M.

Table 3.2: Assumed metrological parameter for the project

Metrological parameter (June)	**Value**	**Reference**
Ambient Temperature (Average high)	33 ^{o} C	Timeanddate.com, 2020
Ambient Temperature (Average low)	29 ^{o} C	Timeanddate.com, 2020
Average Wind speed	11 km/h	Timeanddate.com, 2020
Solar Radiation Intensity (Annual average)	12.08 $MJ/m^2/day$	Mohammad et al., 2020

3.4 Theoretical analysis

In this section, the theoretical research methodology is discussed, due to the unpredicted increase in Covid-19 cases during June 2021, in the time where the experiment was planned to be conducted, Malaysia government announced Full Movement Control Order (FMCO) throughout the national. Therefore, the experimental materials were unable to be obtained, travelling to UTAR to conduct the experiment was also discouraged due to the pandemic. Hence, the experimental based analysis method is replaced with theoretical analysis.

Hence, the theoretical analysis is carried out with the experimental data extracted from various researches, conducted at different locations, the temperature data of the saline water and condenser at different stages are used to calculate the theoretical yield of the multistage solar distiller. With the analysis of distillate output from these theoretical calculations, it is compared to find out the optimal number of stages for solar distiller for thermal performance. After that, cost analysis would be carried out to identify the solar distiller that would produce distillate with minimal cost.

3.5 Mathematical Modelling

As the experimental data extracted from research done include temperature of condenser and saline water. The imperative relationship between temperature of various water and condensers of various stages could be identified. Then, theoretical distillate output could be obtained without calculating radiative heat transfer and energy input from solar irradiation.

To calculate the theoretical heat transfer and distillate output, several assumptions are made as listed below:

1. There is no temperature gradient along the saline water and condenser plate.
2. The insulation system is well controlled and there is no heat lost to the surrounding except on the top condenser where the heat is meant to be released.
3. The solar distiller is properly seal and there is no leakage of fluid.
4. The water level is always constant, and the mass reduction due to evaporation is negligible.

5. The inclination angle of the condenser is small and is limited to 15 ^{o}.
6. The area of condenser surface is identical in size to the water surface area.
7. The heat capacity of the condensers and insulation material are negligible.
8. The saline water has a salinity of 35000 ppm.

The equations used to calculate the theoretical distillate output are as listed below:

Convective heat transfer from saline water to condenser surface could be calculated with the equation 3.3 below (Shukla and Sorayan, 2005; Velmurugan et al., 2009; Zurigat and Abu-Arabi, 2004).

$$Q_{conv,w-c(n)} = h_{conv,w-c(n)}(T_{wn} - T_{cn}) \tag{3.1}$$

$$h_{conv,w-c(n)} = 0.884 \left[(T_{wn} - T_{cn}) + \frac{p_{swn} - p_{cn}}{268.9 \times 10^3 - p_{wn}} T_{wn} \right]^{\frac{1}{3}} \tag{3.2}$$

Substituting equation 3.2 into equation 3.1 yields

$$Q_{conv,w-c(n)} = 0.884 \left[(T_{wn} - T_{cn}) + \frac{p_{swn} - p_{cn}}{268.9 \times 10^3 - p_{swn}} T_{wn} \right]^{\frac{1}{3}} (T_{wn} - T_{cn}) \tag{3.3}$$

Evaporative heat transfer from saline water to condenser surface could be calculated with the equation.

$$Q_{evap,w-c(n)} = h_{evap,w-c(n)}(T_{wn} - T_{cn}) \tag{3.4}$$

$$h_{evap,w-c(n)} = (16.276 \times 10^{-3}) \frac{p_{swn} - p_{cn}}{T_{wn} - T_{cn}} h_{conv,w-c(n)} \tag{3.5}$$

Substituting equation 3.5 and equation 3.1 into equation 3.4 yields

$$Q_{evap,w-c(n)} = (16.276 \times 10^{-3}) \frac{p_{swn} - p_{cn}}{T_{wn} - T_{cn}} Q_{conv,w-c(n)} \tag{3.6}$$

According to Alduchov and Eskridge (1996), the water saturation pressure differs as the temperature changes. The water saturation pressure at different temperatures is approximated using equation 3.7 with 0.384% maximum relative error for water saturation temperature below the condenser.

$$p_{cn} = 610.94 e^{\frac{17.625 T_{cn}}{T_{cn} + 243.04}} \tag{3.7}$$

For saline water surface with moist air above, the following equation is used.

$$p_{wn} = (1.00071 e^{0.0000045 p}) p_{cn} \tag{3.8}$$

Subsituting p = 1000 hpa

$$p_{wn} = 614.13 e^{\frac{17.625 T_{wn}}{T_{wn} + 243.04}} \tag{3.9}$$

To increase the accuracy of analysis, the variation of vapor pressure of saline water is obtained with equation stated by Nayar et al. (2016), assuming calcium-free saline water.

$$In\left(\frac{p_{sw}}{p_w}\right) = -4.58180 \times 10^{-4} S - 2.04430 \times 10^{-6} S^2 \tag{3.10}$$

The enthalpy of vaporization of water and saline water could be approximated with the equations below (Henderson-Sellers, 1984; Sharqawy, Lienhard V and Zubair, 2010).

$$h_{fg,w} = 2500 - 2.386 T \tag{3.11}$$

$$h_{fg,sw} = h_{fg,w} \times (1 - \frac{S}{1000}) \tag{3.12}$$

Substituting equation 3.12 into equation 3.11 yields

$$h_{fg,sw} = (2500 - 2.386T) \times (1 - \frac{S}{1000}) \quad (3.13\ )$$

Equation 3.14 shows the distillate output per hour per m^2 water surface area of each stage (Shukla and Sorayan, 2005)

$$m_{yield(n)} = \frac{Q_{e,w-g(n)} \times A_w \times \Delta t}{h_{fg,sw}} \quad (3.14)$$

Equations 3.15 and 3.16 show the calculation for solar irradiation energy and efficiency of the solar distiller, respectively.

$$E = I(t) \times \Delta t \times A_{total} \quad (3.15)$$

$$Efficiency = \frac{\sum m_{yield} \times h_{fg,sw}}{\sum E} \quad (3.16)$$

3.6 Summary

In this chapter, initially, experiment-based research was planned. However, due to unforeseen circumstances, another route with theoretical analysis was carried out. This research utilizes mathematical modelling to approximate the distillate output and thermal performance of multistage solar distiller to select an optimal number of stage for solar distillers. Equation 3.1 to equation 3.16 would be used to theoretically analyse the performance of the solar distiller. Experimental data from 7 previous research that were reviewed in section 2.7 would be referred and analysed in Chapter 4 in order to identify the imperative relationship between temperature of various components and stages in solar distillers.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this chapter, first section works to identify the imperative relationship between condenser and water. Then, the second section identifies the imperative relationship between water of various stages. With these two relationships, the temperature could be found and used to approximate the thermal performance. Lastly, cost analysis is performed to find the optimal multistage solar distiller with the least cost to produce fresh water.

4.2 Estimation of relationship between condenser and water

From the 6 researches studied, 3 of them provided experimental data of both water temperature and condenser temperature, hence, the temperatures are compared to obtain the difference and ratio between them, then the imperative relationship would be used to estimate the temperatures of condensers. Primarily, the temperature of lower condenser and upper water are compared, e.g. comparing temperature of condenser at stage 1 and water temperature at stage 2, where condenser at stage 1 works as basin for water in stage 2 that they are physically in contact.

Table 4.1, 4.2, 4.3 and 4.4 list and compare the experimental data extracted from Figure 2.21 and calculated with equations 2.1 to 2.4 from the experiment conducted by Shatat and Mahkamov (2010).

Table 4.1: Comparison of condenser temperature stage 1 and water temperature stage 2 from data extracted from Figure 2.21.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{W2}}{T_{C1}}$)**
	T_{C1}	T_{W2}	**Difference (T_{W2} - T_{C1})**	
0 minute	10.22	12.2	-1.98	1.19
100 minute	32.81	34.8	-1.99	1.06
200 minute	69.48	71.5	-2.02	1.03
300 minute	89.85	91.9	-2.05	1.02
400 minute	92.44	94.4	-1.96	1.02
500 minute	89.48	91.5	-2.02	1.02
600 minute	77.26	79.3	-2.04	1.03
700 minute	63.56	65.6	-2.04	1.03
800 minute	53.19	55.2	-2.01	1.04
900 minute	46.89	48.9	-2.01	1.04
1000 minute	42.07	44.1	-2.03	1.05
1100 minute	38.00	40.0	-2.00	1.05
1200 minute	34.67	36.7	-2.03	1.06
1300 minute	31.70	33.7	-2.00	1.06
1400 minute	29.48	31.5	-2.02	1.07
Average			-2.01	1.05
Minimum			-2.05	1.02
Maximum			-1.96	1.19

Table 4.2: Comparison of condenser temperature stage 2 and water temperature stage 3 from data extracted from Figure 2.21.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{W3}}{T_{C2}}$)**
	T_{C2}	T_{W3}	**Difference (T_{W3} - T_{C2})**	
0 minute	9.52	12.2	-2.68	1.28
100 minute	13.97	16.7	-2.73	1.20
200 minute	49.52	52.2	-2.68	1.05
300 minute	79.15	81.9	-2.75	1.03
400 minute	85.82	88.5	-2.68	1.03
500 minute	80.26	83.0	-2.74	1.03
600 minute	69.15	71.9	-2.75	1.04
700 minute	55.82	58.5	-2.68	1.05
800 minute	46.19	48.9	-2.71	1.06
900 minute	39.89	42.6	-2.71	1.07
1000 minute	35.82	38.5	-2.68	1.07
1100 minute	32.11	34.8	-2.69	1.08
1200 minute	29.15	31.9	-2.75	1.09
1300 minute	26.56	29.3	-2.74	1.10
1400 minute	24.71	27.4	-2.69	1.11
Average			-2.71	1.09
Minimum			-2.75	1.03
Maximum			-2.68	1.28

Table 4.3: Comparison of condenser temperature stage 3 and water temperature stage 4 from data extracted from Figure 2.21.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{W4}}{T_{C3}}$)**
	T_{C3}	T_{W4}	**Difference (T_{W4} - T_{C3})**	
0 minute	11.11	12.2	-1.09	1.10
100 minute	11.85	13.0	-1.15	1.10
200 minute	30.37	31.5	-1.13	1.04
300 minute	65.56	66.7	-1.14	1.02
400 minute	74.08	75.2	-1.12	1.02
500 minute	68.89	70.0	-1.11	1.02
600 minute	60.74	61.9	-1.16	1.02
700 minute	48.89	50.0	-1.11	1.02
800 minute	40.37	41.5	-1.13	1.03
900 minute	34.82	35.9	-1.08	1.03
1000 minute	31.85	33.0	-1.15	1.04
1100 minute	28.52	29.6	-1.08	1.04
1200 minute	25.93	27.0	-1.07	1.04
1300 minute	24.45	25.6	-1.15	1.05
1400 minute	22.96	24.1	-1.14	1.05
Average			-1.12	1.04
Minimum			-1.16	1.02
Maximum			-1.07	1.10

Table 4.4: Comparison of condenser temperature stage 4 and water temperature stage 4 from data extracted from Figure 2.21.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{C4}}{T_{W4}}$)**
	T_{W4}	T_{C4}	**Difference (T_{C4} - T_{W4})**	
0 minute	12.2	12.73	-0.53	1.04
100 minute	13.0	13.00	0.00	1.00
200 minute	31.5	23.75	7.75	0.75
300 minute	66.7	57.83	8.87	0.87
400 minute	75.2	67.15	8.05	0.89
500 minute	70.0	61.47	8.53	0.88
600 minute	61.9	52.61	9.29	0.85
700 minute	50.0	40.26	9.74	0.81
800 minute	41.5	32.12	9.38	0.77
900 minute	35.9	27.29	8.61	0.76
1000 minute	33.0	24.90	8.10	0.75
1100 minute	29.6	22.37	7.23	0.76
1200 minute	27.0	20.55	6.45	0.76
1300 minute	25.6	19.56	6.04	0.76
1400 minute	24.1	18.61	5.49	0.77
Average			6.87	0.83
Minimum			-0.53	0.75
Maximum			9.74	1.04

Table 4.5, 4.6 and 4.7 list and compare the experimental data extracted from Figure 2.23 and 2.24 from the experiment conducted by Abed, Kassim and Rahi (2017).

Table 4.5: Comparison of condenser temperature stage 1 and water temperature stage 2 from data extracted from Figure 2.23 and 2.24.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{C1}}{T_{W2}}$)**
	T_{C1}	T_{W2}	**Difference (T_{W2} - T_{C1})**	
8 AM	12.6	12.6	0.00	1.00
9 AM	14.4	13.6	0.80	0.94
10 AM	27.6	23.3	4.30	0.84
11 AM	50.4	46.7	3.70	0.93
12 PM	74.6	69.9	4.70	0.94
1 PM	90.3	86.5	3.80	0.96
2 PM	96.8	93.9	2.90	0.97
3 PM	94.3	90.6	3.70	0.96
4 PM	92.3	90.1	2.20	0.98
5 PM	91.3	89.1	2.20	0.98
Average			2.83	0.95
Minimum			0.00	0.84
Maximum			4.70	1.00

Table 4.6: Comparison of condenser temperature stage 2 and water temperature stage 3 from data extracted from Figure 2.23 and 2.24.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{C2}}{T_{W3}}$)**
	T_{C2}	T_{W3}	**Difference (T_{W3} - T_{C2})**	
8 AM	12.8	12.8	0.00	1.00
9 AM	12.8	12.8	0.00	1.00
10 AM	15.7	14.6	1.10	0.93
11 AM	28.8	25.8	3.00	0.90
12 PM	52.2	49.5	2.70	0.95
1 PM	72.4	69.9	2.50	0.97
2 PM	81.0	78.6	2.40	0.97
3 PM	77.8	75.1	2.70	0.97
4 PM	77.0	74.3	2.70	0.96
5 PM	76.0	74.0	2.00	0.97
Average			1.91	0.96
Minimum			0.00	0.90
Maximum			3.00	1.00

Table 4.7: Comparison of condenser temperature stage 3 and water temperature stage 3 from data extracted from Figure 2.23 and 2.24.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{C3}}{T_{W3}}$)**
	T_{W3}	T_{C3}	**Difference (T_{C3} - T_{W3})**	
8 AM	12.8	13.2	-0.40	1.03
9 AM	12.8	12.8	0.00	1.00
10 AM	14.6	13.2	1.40	0.90
11 AM	25.8	17.7	8.10	0.69
12 PM	49.5	31.6	17.90	0.64
1 PM	69.9	46.7	23.20	0.67
2 PM	78.6	58.8	19.80	0.75
3 PM	75.1	57.2	17.90	0.76
4 PM	74.3	54.4	19.90	0.73
5 PM	74.0	53.8	20.20	0.73
Average			12.80	0.79
Minimum			-0.40	0.64
Maximum			23.20	1.03

Table 4.8 and 4.9 list and compare the experimental data extracted from Figure 2.25 and 2.26 from the experiment conducted by Kalbasi, Alemrajabi and Afrand (2018).

Table 4.8: Comparison of condenser temperature stage 1 and water temperature stage 2 from data extracted from Figure 2.25.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{W3}}{T_{C3}}$)**
	T_{C1}	T_{W2}	**Difference (T_{W2} - T_{C1})**	
10 AM	17.5	16.6	0.90	0.95
11 AM	23.5	21.5	2.00	0.91
12 PM	34.2	32.2	2.00	0.94
1 PM	47.0	43.1	3.90	0.92
2 PM	55.5	50.7	4.80	0.91
3 PM	60.0	55.1	4.90	0.92
4 PM	62.5	57.0	5.50	0.91
5 PM	60.5	56.2	4.30	0.93
6 PM	55.9	52.2	3.70	0.93
7 PM	49.3	47.0	2.30	0.95
8 PM	41.1	39.7	1.40	0.97
9 PM	33.5	33.1	0.40	0.99
10 PM	28.9	29.1	-0.20	1.01
11 PM	26.2	26.1	0.10	1.00
12 AM	23.8	23.9	-0.10	1.00
1 AM	21.8	22.3	-0.50	1.02
2 AM	21.1	21.2	-0.10	1.00
Average			2.08	0.96
Minimum			-0.50	0.91
Maximum			5.50	1.02

Table 4.9: Comparison of condenser temperature stage 2 and water temperature stage 2 from data extracted from Figure 2.26.

Time	**Temperature (°C)**			**Ratio ($\frac{T_{C2}}{T_{W2}}$)**
	T_{W2}	T_{C2}	**Difference (T_{C2} - T_{W2})**	
10 AM	16.6	15.0	1.60	0.90
11 AM	21.5	16.6	4.90	0.77
12 PM	32.2	20.7	11.50	0.64
1 PM	43.1	26.5	16.60	0.61
2 PM	50.7	32.5	18.20	0.64
3 PM	55.1	35.8	19.30	0.65
4 PM	57.0	37.7	19.30	0.66
5 PM	56.2	36.9	19.30	0.66
6 PM	52.2	33.4	18.80	0.64
7 PM	47.0	29.3	17.70	0.62
8 PM	39.7	24.7	15.00	0.62
9 PM	33.1	21.2	11.90	0.64
10 PM	29.1	19.0	10.10	0.65
11 PM	26.1	17.9	8.20	0.69
12 AM	23.9	17.4	6.50	0.73
1 AM	22.3	17.1	5.20	0.77
2 AM	21.2	16.6	4.60	0.78
Average			12.28	0.69
Minimum			1.60	0.61
Maximum			19.30	0.90

Table 4.10 lists and compares the experimental data extracted from Figure 2.20 from the experiment conducted by Chen et al. (2017).

Table 4.10: Comparison of condenser temperature stage 3 and water temperature stage 3 from data extracted from Figure 2.20.

Time	**Temperature (ºC)**			**Ratio ($\frac{T_4}{T_3}$)**
	T₃	***T₄***	**Difference (*T₃* - *T₄*)**	
8:30 AM	35.289	27.851	7.44	0.79
9:30 AM	39.380	34.917	4.46	0.89
10:30 AM	50.165	43.099	7.07	0.86
11:30 AM	62.438	55.000	7.44	0.88
12:30 PM	73.223	63.926	9.30	0.87
1:30 PM	81.405	74.339	7.07	0.91
2:30 PM	83.636	78.058	5.58	0.93
3:30 PM	82.149	78.430	3.72	0.95
4:30 PM	79.545	72.107	7.44	0.91
5:30 PM	69.132	62.066	7.07	0.90
6:30 PM	60.207	51.281	8.93	0.85
Average			6.86	0.89
Minimum			3.72	0.79
Maximum			9.30	0.95

Table 4.11 lists and compares the experimental data extracted from Figure 2.22 from the experiment conducted by Suneja and Tiwari (1998).

Table 4.11: Comparison of condenser temperature stage 7 and water temperature stage 7 from data extracted from Figure 2.22.

Time	**Temperature (°C)**			**Ratio ($\frac{T_g}{T_7}$)**
	T_7	T_g	**Difference (T_g - T_7)**	
8 AM	16.7	16.4	-0.30	0.98
9 AM	15.7	16.1	0.40	1.03
10 AM	16.8	18.7	1.90	1.11
11 AM	19.1	21.7	2.60	1.14
12 PM	23.4	26.4	3.00	1.13
1 PM	29.4	32.4	3.00	1.10
2 PM	37.0	36.7	-0.30	0.99
3 PM	44.6	40.3	-4.30	0.90
4 PM	49.6	41.0	-8.60	0.83
5 PM	50.3	39.4	-10.90	0.78
6 PM	47.7	34.8	-12.90	0.73
7 PM	42.7	30.5	-12.20	0.71
8 PM	38.2	25.9	-12.30	0.68
Average			-3.92	0.93
Minimum			-12.90	0.68
Maximum			3.00	1.14

Table 4.12 lists and compares the experimental data extracted from Figure 2.27 from the experiment conducted by Adhikari and Kumar (1993).

Table 4.12: Comparison of condenser temperature stage 3 and water temperature stage 3 from data extracted from Figure 2.27.

Time	**Temperature (ºC)**			**Ratio ($\frac{T_g}{T_3}$)**
	T_3	T_g	**Difference (T_g - T_3)**	
40 minute	24.3	22.1	2.20	0.91
80 minute	25.7	22.7	3.00	0.88
120 minute	28.0	23.3	4.70	0.83
160 minute	31.1	24.2	6.90	0.78
200 minute	34.7	24.8	9.90	0.71
240 minute	38.3	27.1	11.20	0.71
280 minute	41.9	28.8	13.10	0.69
320 minute	45.2	30.8	14.40	0.68
360 minute	48.0	32.2	15.80	0.67
Average			9.02	0.76
Minimum			2.20	0.67
Maximum			15.80	0.91

With the comparison data obtained from Table 4.1 to Table 4.12, the average data obtained from them are compared in Table 4.13 and Table 4.14 below.

Table 4.13: Comparison of temperature of condenser in nth stage and water in (n+1)th stage (Where condenser works as basin for the water) from Table 4.1 to Table 4.9

Data From Table	**Average difference in temperature (°C)**	**Average Temperature Ratio**
Table 4.1	-2.01	1.05
Table 4.2	-2.71	1.09
Table 4.3	-1.12	1.04
Table 4.5	2.83	0.95
Table 4.6	1.91	0.96
Table 4.8	2.08	0.96
Grand Average	0.16	1.01
Minimum	-2.71	0.95
Maximum	2.83	1.09

From the data in Table 4.13 that analyse the temperature between nth stage and water in (n+1)th stage, it shows that the grand average difference in temperature is 0.16 °C with temperature difference value of minimum -2.71 °C and maximum value of 2.83 °C, whereby the grand average temperature ratio 1.01 with temperature ratio of minimum 0.95 and maximum value of 1.09.

Table 4.14: Comparison of temperature of condenser in n^{th} stage and water in n^{th} stage (Where condenser does not work as basin for the water) from Table 4.1 to Table 4.12

Data From Table	**Average difference in temperature (°C)**	**Average Temperature Ratio**
Table 4.4	6.87	0.83
Table 4.7	12.80	0.79
Table 4.9	12.28	0.69
Table 4.10	6.86	0.89
Table 4.11	-3.92	0.93
Table 4.12	9.02	0.76
Grand Average	7.32	0.82
Minimum	-3.92	0.69
Maximum	12.80	0.93

From the data in Table 4.14 that analyses the temperature between n^{th} stage and water in n th stage, it shows that the grand average difference in temperature is 7.32 °C with temperature difference value of minimum -3.92 °C and maximum value of 12.80 °C, whereby the grand average temperature ratio 0.82 with temperature ratio of minimum 0.69 and maximum value of 0.93.

As the difference in temperature has relatively larger range as compared to temperature ratio, hence, the grand average temperature ratios are used for the analysis in the further section as summarized in Table 4.15

Table 4.15: Summarized imperative relationship between temperature of condenser and water.

Relationship between condenser and water	**Grand average temperature ratio used**
For temperature of condenser in n^{th} stage and water in $(n+1)^{th}$ stage stage (Where condenser works as basin for the water)	1.01
For temperature of condenser in n^{th} stage and water in n^{th} stage (Where condenser does not work as basin for the water)	0.82

4.3 Estimation of relationship between water temperature of various stages.

Table 4.16 lists and compares the experimental data extracted from Figure 2.20 from the experiment conducted by Chen et al. (2017).

Table 4.16: Temperature ratio between various stages for data extracted from Figure 2.20.

Time	**Temperature Ratio**	
	Between Stage 1 and 2 $(\frac{T_2}{T_1})$	**Between Stage 2 and 3** $(\frac{T_3}{T_2})$
8.30 AM	0.74	-
9:30 AM	0.71	-
10:30 AM	0.85	0.88
11:30 AM	0.89	0.90
12:30 PM	0.89	0.92
1:30 PM	0.92	0.94
2:30 PM	0.93	0.94
3:30 PM	0.93	0.94
4:30 PM	0.95	0.93
5:30 PM	0.94	0.91
6:30 PM	0.90	0.89
Average	0.88	0.92

For data in Figure 2.20, the temperature between stage 2 and 3 in 8.30 AM and 9.30 AM is not included in calculation as there were problem with the temperature of input water during that time.

Table 4.17 lists and compares the experimental data extracted from Figure 2.21 and calculated with equations 2.1 to 2.4 from the experiment conducted by Shatat and Mahkamov (2010).

Table 4.17: Temperature ratio between various stage for data extracted from Figure 2.21.

Time	**Temperature Ratio**		
	Between Stage 1 and 2 ($\frac{T_2}{T_1}$)	**Between Stage 2 and 3 ($\frac{T_3}{T_2}$)**	**Between Stage 3 and 4 ($\frac{T_4}{T_3}$)**
0 minute	1.00	1.00	1.00
100 minute	0.68	0.48	0.78
200 minute	0.89	0.73	0.60
300 minute	0.96	0.89	0.81
400 minute	0.98	0.94	0.85
500 minute	0.97	0.91	0.84
600 minute	0.96	0.91	0.86
700 minute	0.95	0.89	0.85
800 minute	0.95	0.89	0.85
900 minute	0.95	0.87	0.84
1000 minute	0.95	0.87	0.86
1100 minute	0.95	0.87	0.85
1200 minute	0.95	0.87	0.85
1300 minute	0.95	0.87	0.87
1400 minute	0.95	0.87	0.88
Average	0.93	0.85	0.83

Table 4.18 lists and compares the experimental data extracted from Figure 2.22 from the experiment conducted by Suneja and Tiwari (1998).

Table 4.18: Temperature ratio between various stages for data extracted from Figure 2.22.

Time	**Temperature Ratio Between T_n and T_{n-1} stage**					
	$\frac{T_2}{T_1}$	$\frac{T_3}{T_2}$	$\frac{T_4}{T_3}$	$\frac{T_5}{T_4}$	$\frac{T_6}{T_5}$	$\frac{T_7}{T_6}$
8 AM	0.93	0.94	0.92	0.91	0.90	0.85
9 AM	0.84	0.88	0.89	0.91	0.86	0.83
10 AM	0.81	0.82	0.83	0.85	0.85	0.88
11 AM	0.83	0.81	0.80	0.81	0.85	0.86
12 PM	0.86	0.84	0.81	0.79	0.84	0.86
1 PM	0.89	0.87	0.83	0.82	0.82	0.85
2 PM	0.91	0.90	0.87	0.85	0.84	0.82
3 PM	0.94	0.92	0.90	0.87	0.86	0.83
4 PM	0.94	0.94	0.92	0.90	0.88	0.83
5 PM	0.95	0.95	0.94	0.91	0.89	0.84
6 PM	0.97	0.97	0.94	0.92	0.89	0.85
7 PM	0.97	0.96	0.95	0.92	0.89	0.84
8 PM	0.97	0.97	0.95	0.91	0.90	0.84
Average	0.91	0.90	0.89	0.87	0.87	0.85

Table 4.19 lists and compares the experimental data extracted from Figure 2.23 and 2.24 from the experiment conducted by Abed, Kassim and Rahi (2017).

Table 4.19: Temperature ratio between various stages for data extracted from Figure 2.23 and 2.24.

Time	**Temperature Ratio**	
	Between Stage 1 and 2 $(\frac{T_2}{T_1})$	**Between Stage 2 and 3** $(\frac{T_3}{T_2})$
8 AM	1.00	1.02
9 AM	0.66	0.94
10 AM	0.52	0.63
11 AM	0.69	0.55
12 PM	0.81	0.71
1 PM	0.90	0.81
2 PM	0.95	0.84
3 PM	0.92	0.83
4 PM	0.92	0.82
5 PM	0.92	0.83
Average	0.83	0.80

Table 4.20 lists and compare the experimental data extracted from Figure 2.25 and 2.26 from the experiment conducted by Kalbasi, Alemrajabi and Afrand (2018).

Table 4.20: Temperature ratio between stage 1 and 2 for data extracted from Figure 2.25 and 2.26.

Time	**Temperature Ratio**
	Between Stage 1 and 2 $(\frac{T_2}{T_1})$
10 AM	0.86
11 AM	0.74
12 PM	0.72
1 PM	0.80
2 PM	0.82
3 PM	0.84
4 PM	0.85
5 PM	0.85
6 PM	0.85
7 PM	0.83
8 PM	0.84
9 PM	0.83
10 PM	0.85
11 PM	0.85
12 AM	0.86
1 AM	0.85
2 AM	0.88
Average	0.83

Table 4.21 lists and compares the experimental data extracted from Figure 2.27 from the experiment conducted by Adhikari and Kumar (1993).

Table 4.21: Temperature ratio between various stages for data extracted from Figure 2.27.

Time	**Temperature Ratio**	
	Between Stage 1 and 2 ($\frac{T_2}{T_1}$)	**Between Stage 2 and 3** ($\frac{T_3}{T_2}$)
40 minute	0.95	0.85
80 minute	0.88	0.74
120 minute	0.88	0.69
160 minute	0.89	0.67
200 minute	0.91	0.67
240 minute	0.91	0.69
280 minute	0.93	0.71
320 minute	0.94	0.74
360 minute	0.96	0.75
Average	0.92	0.72

Table 4.22 to Table 4.24 summarize the average temperature ratio of the extracted temperature ratio from experimental data of Table 4.16 to 4.21.

Table 4.22: Comparison of temperature of water between stage 1 and stage 2 from Table 4.16 to Table 4.21

Data From Table	**Average Temperature Ratio**
Table 4.16	0.88
Table 4.17	0.93
Table 4.18	0.91
Table 4.19	0.83
Table 4.20	0.83
Table 4.21	0.92
Grand Average	0.88
Minimum	0.83
Maximum	0.93

Table 4.23: Comparison of temperature of water between stage 2 and stage 3 from Table 4.16 to Table 4.21

Data From Table	**Average Temperature Ratio**
Table 4.16	0.92
Table 4.17	0.85
Table 4.18	0.90
Table 4.19	0.80
Table 4.21	0.72
Grand Average	0.84
Minimum	0.72
Maximum	0.92

Table 4.24: Comparison of temperature of water between stage 3 and stage 4 from Table 4.16 to Table 4.21

Data From Table	**Average Temperature Ratio**
Table 4.17	0.83
Table 4.18	0.89
Grand Average	0.86
Minimum	0.83
Maximum	0.89

Table 4.25: Comparison of temperature of water between various stages from Table 4.18

Between Stage	**Average Temperature Ratio**
Stage 4 and 5	0.87
Stage 5 and 6	0.87
Stage 6 and 7	0.84

From the analysis of Table 4.22 to Table 4.25, the average temperature ratio of water between n^{th} stage and $(n+1)^{th}$ stage is 0.86. Hence, the ratio of 0.86 would be used to perform analysis in the further sections

4.4 Thermal analysis

Using the data recorded in Table 2.1, imperative relationship for temperature as stated in Table 4.15 and section 4.2. Analysis is carried out on 1,2,3,4,5,6 and 7-stages solar distiller, the water temperature, condenser temperature, distillate output and thermal analysis are calculated and listed in Appendix A. As the atmospheric water temperature in Malaysia is 29.3 ^{o}C on average, any temperature obtained with analysis that goes below 29.3 ^{o}C will be replaced with 29.3 ^{o}C. For simplicity, the area of condensation and total area (A_{total}) for solar irradiation are assumed to both be 1 m^2. The summarized distillate output and efficiency from calculation listed in Appendix A are tabulated in Table 4.26.

Table 4.26: Distillate Output and Efficiency of various solar distillers

Solar distiller with number of stage	Total distillate output (ml)	Increase in distillate output compared to 1-stage solar distiller	Efficiency
1 Stage	6638.86	-	42.82 %
2 Stage	8204.06	23.58%	53.17 %
3 Stage	9116.60	37.32%	59.24 %
4 Stage	9657.27	45.47%	62.86 %
5 Stage	9989.97	50.48%	65.09 %
6 Stage	10193.74	53.55%	66.47 %
7 Stage	10307.65	55.26%	67.24 %

The results obtained as tabulated in Table 4.26 are visually displayed using graphs with Figure 4.1 and Figure 4.2.

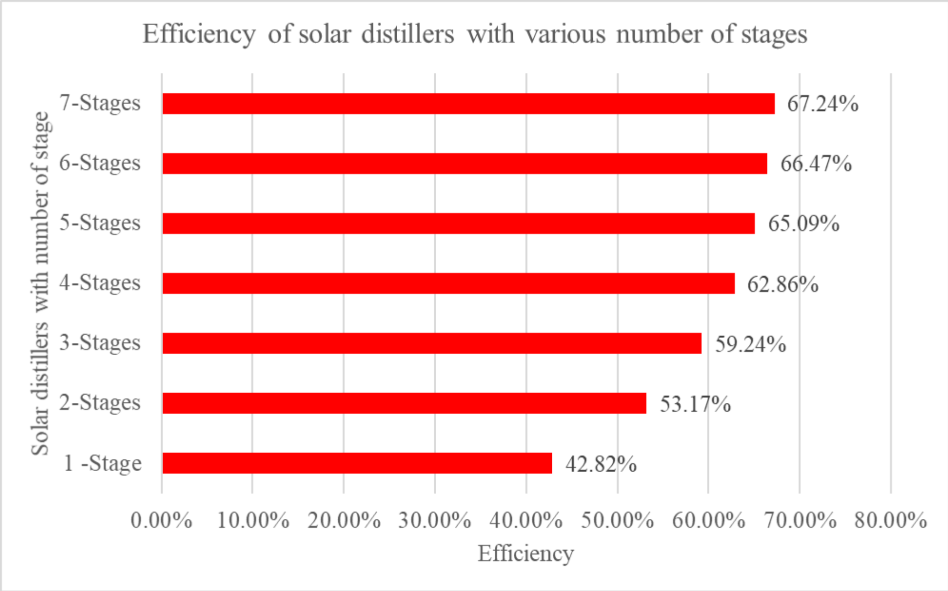

Figure 4.1: Efficiency of solar distiller with various number of stages

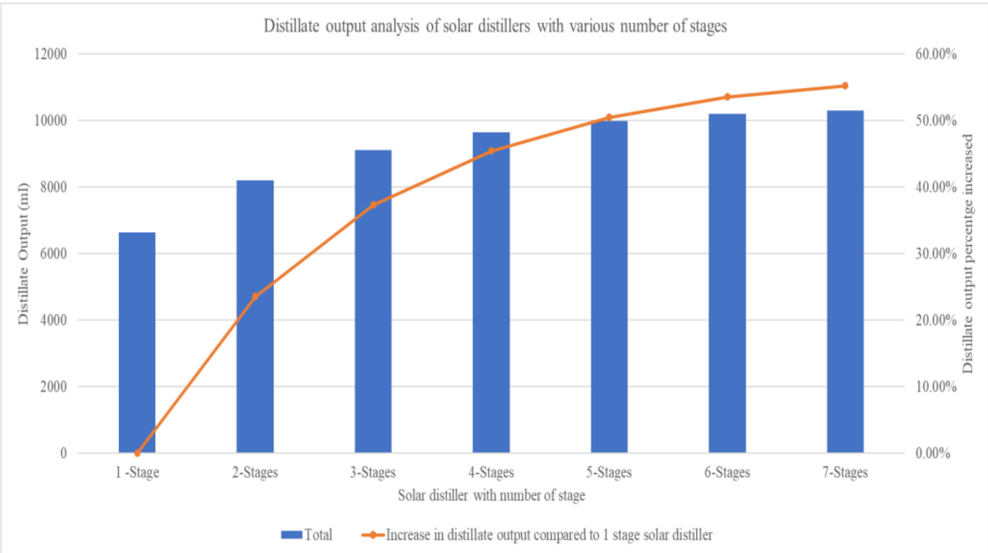

Figure 4.2: Distillate output analysis of solar distillers with various number of stages

Based on Figure 4.1, it is observed that the solar distiller has a steady increase in efficiency as the number of stages increases from 1-stage to 7-stages. From the thermal analysis, the optimal number of stages is found to be 5-stages solar distiller, because any further increment in the number of stage will lead to efficiency increment of less than 1.5 %. In terms of distillate output, the increment of number of stage would only bring less than 3.07 % after 5-stages.

4.5 Cost analysis

The economic feasibility of solar distillers is analysed based on the study made by Ho (2021) and Shafii et al. (2016) to obtain the cost of solar distiller construction and distillate. Table 4.27 shows the cost analysis listed by Ho (2021), of a conventional double-slope single-stage solar distiller.

Table 4.27: Cost analysis of a conventional double-slope single-stage solar distiller. (Ho, 2021)

Parameter	Unit	Double-slope single-stage
Principal Cost (P)	RM	96.61
Salvage cost (S, 10 % of P)	RM	9.661
Life (n)	Years	15
Interets Rate (i)	%	-
Capital recovery factor (CRF)	0.117	0.117
Sink Fund Factor (SFF)	0.017	0.017
Annual First Cost (CRF x P)	RM	11.30
Annual Salvage Value (SSF x S)	RM	0.16
Annual Maintenance Cost (0.15 x Annual First Cost)	RM	1.70
Annual Cost (Annual First Cost + Annual Maintenance Cost – Annual Salvage value)	RM	12.83
Average Daily Yield (kg/m^2)	kg/m^2	0.88
Annual Yield of the Still (Average Daily Yield x 365)	kg/m^2	321.20
Cost per Litre per unit area of still (CPL = Annual cost / Annual Yield of Still)	$RM/kg/m^2$	0.04
Average Daily Yield (L)	L	0.220
Annual Yield of the Still (Average Daily Yield x 365)	L	80.3
Cost per Litre per unit area of still (CPL = Annual cost / Annual Yield of Still)	RM/L	0.1598

As Ho (2021)'s solar distiller has an area of 0.22 m^2, and the theoretical calculation in this research is based on solar distiller with area of 1 m^2, hence, the principal cost would be approximated to RM 439.10 by dividing RM 96.61 with 0.22, any increment of the number of stage would have increase in principle cost of RM 351.28, an approximation based on 80 % of the original principal cost. Other than that, the rental cost of RM 720 per year per m^2 in Petaling Jaya (Malaysia Investment Development Authority, 2020) is added into calculation, several amendments would also be made and the analysis is listed in Table 4.28.

Table 4.28: Cost analysis of a conventional double slope single stage solar distiller.

Parameter	Solar distiller with number of stage						
	1-stage	2-stages	3-stages	4-stages	5-stages	6-stages	7-stages
Principal Cost (P)	RM 439.10	RM 790.38	RM 1,141.66	RM 1,492.94	RM 1,844.22	RM 2,195.50	RM 2,546.78
Salvage cost (S, 10 % of P)	RM 43.91	RM 79.04	RM 114.17	RM 149.29	RM 184.42	RM 219.55	RM 254.68
Annual First Cost (0.117 x P)	RM 51.37	RM 92.47	RM 133.57	RM 174.67	RM 215.77	RM 256.87	RM 297.97
Annual Salvage Value (0.017 x S)	RM 0.75	RM 1.34	RM 1.94	RM 2.54	RM 3.14	RM 3.73	RM 4.33
Annual Maintenance Cost (0.15 x Annual First Cost)	RM 7.71	RM 13.87	RM 20.04	RM 26.20	RM 32.37	RM 38.53	RM 44.70
Annual Rental Cost	RM 720.00	RM 720.00	RM 720.00	RM 720.00	RM 720.00	RM 720.00	RM 720.00
Annual Cost (Annual First Cost + Annual Maintenance + Annual Rental Cost – Annual Salvage value)	RM 778.33	RM 825.00	RM 871.67	RM 918.34	RM 965.00	RM 1,011.67	RM 1,058.34
Average Daily Yield	6.639 L	8.204 L	9.117 L	9.657 L	9.990 L	10.194 L	10.308 L
Annual Yield of the Still	2423 L	2994 L	3328 L	3525 L	3646 L	3721 L	3762 L
Cost per Litre (CPL = Annual cost / Annual Yield of Still)	RM 0.321/L	RM 0.276/L	RM 0.262/L	RM 0.261/L	RM 0.265/L	RM 0.272/L	RM 0.281/L

With analysis done in Table 4.28, it is observed that the principal cost and annual cost of the solar distiller increases as the number of stage increases. However, as all the distillate output increases from 1-stage solar distiller to 7-stages solar distillers, 4-stages solar distiller is the optimal design in economical context, with the cost of RM 0.261 per litre of distillate output. Figure 4.3 below shows the annual cost of running the solar distillers and cost per litre distillate each solar distiller produces.

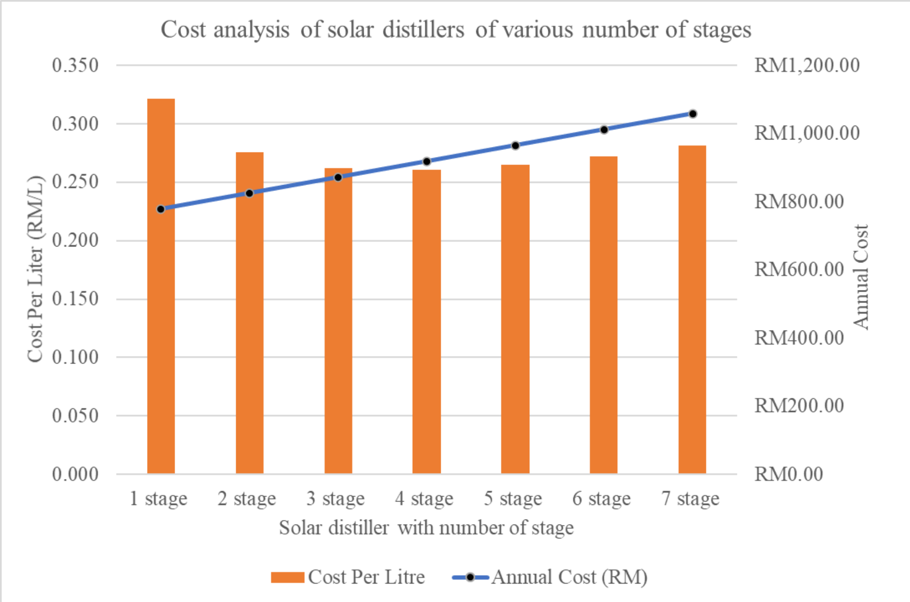

Figure 4.3: Cost analysis of solar distillers of various number of stages

4.6 Summary

In this chapter, it is discovered that the temperature of condenser in n^{th} stage and water in $(n+1)^{th}$ stage stage, where condenser works as basin for the water has a temperature ratio of 1.01, while the temperature of condenser in n^{th} stage and water in n^{th} stage has the temperature ratio of 0.82. Then, by analysing experimental data from other researchers, the average temperature ratio of water between n^{th} stage and $(n+1)^{th}$ stage is 0.86. Using these 3 imperative temperature relationships to estimate temperatures of various stages, it is found that the efficiency of solar distiller increases as the number of stage increases and 5-stages solar distiller is found to be optimal as any increment in number of stage after the 5^{th} stage has an insignificant effect on efficiency. From the view of cost analysis, 4-stages solar distiller is the optimal as it has the lowest cost per litre distillate output of RM 0.261/L.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

In conclusion, there are various factors that would affect the productivity of solar distiller including metrological parameters such as solar radiation intensity, ambient temperature and wind velocity that are uncontrollable, the modifiable design parameter includes temperature difference between water and cover plate, inclination angle of the condenser, insulation of the solar distiller, depth of the saline water and multistage design to reuse enthalpy of vaporization. In this study, experimental data from 7 research are referred to draw the imperative relationship between temperature of various components and stages in solar distiller, then, using mathematical modelling, the performance of the solar distiller are approximated. By analysing the thermal performance of multistage solar distiller, it is found that the efficiency and distillate output of solar distiller increases as number of stage increases, 5-stages solar distiller is identified to be the optimal as any improvement in efficiency after the 5th stage is insignificant. As a comparison, 5-stages solar distiller performs 50.48 % and 65.09 % better than 1-stage solar distiller in distillate output and efficiency, respectively. Yet, cost analysis shows that 4-stages solar distiller is the optimal as it has the lowest cost per litre distillate output of RM 0.261/L.

5.2 Problem encountered

On the path of conducting this research, undesired obstacles emerged that had hindered and changed the route of this research, initially planned experimental based research was forced to be converted into theoretical based analysis due to sudden surge of Covid-19 case that ultimately led to the government announcing the implementation of Full Movement Control Order (FMCO) that cause situation unfavourable to conduct the experiment.

5.3 Recommendation for future work

The experimental data that this research refers to include experiments conducted in various locations, including Algeria, Iraq, Malaysia, India, China, Iran and United Kingdom, hence, the imperative relationship of temperature between various components would be different than analysing merely experimental data from Malaysia, this is because the metrological parameter such as ambient temperature, geographical location, humidity and etcetera are dissimilar at different locations. Therefore, it is recommended to identify the connection between temperature and metrological parameters to adjust the temperature relationship among various components in solar distillers so that the accuracy of the theoretical analysis could be improved.

REFERENCES

Abdallah, S. and Nijmeh, S., 2004. Two axes sun tracking system with PLC control. *Energy Conversion and Management*, 45(11–12), pp.1931–1939.

Abdelal, N. and Taamneh, Y., 2017. Enhancement of pyramid solar still productivity using absorber plates made of carbon fiber/CNT-modified epoxy composites. *Desalination*, [online] 419(June), pp.117–124. Available at: <http://dx.doi.org/10.1016/j.desal.2017.06.012>.

Abed, F.M., Kassim, M.S. and Rahi, M.R., 2017. Performance improvement of a passive solar still in a water desalination. *International Journal of Environmental Science and Technology*, 14(6), pp.1277–1284.

Abujazar, M.S.S., Fatihah, S. and Kabeel, A.E., 2017. Seawater desalination using inclined stepped solar still with copper trays in a wet tropical climate. *Desalination*, [online] 423(March), pp.141–148. Available at: <http://dx.doi.org/10.1016/j.desal.2017.09.020>.

Abujazar, M.S.S., Fatihah, S., Lotfy, E.R., Kabeel, A.E. and Sharil, S., 2018. Performance evaluation of inclined copper-stepped solar still in a wet tropical climate. *Desalination*, [online] 425(August 2017), pp.94–103. Available at: <http://dx.doi.org/10.1016/j.desal.2017.10.022>.

Adhikari, R.S. and Kumar, A., 1993. Transient simulation studies on a multi-stage stacked tray solar still. *Desalination*, 91(1), pp.1–20.

Ahsan, A., Imteaz, M., Rahman, A., Yusuf, B. and Fukuhara, T., 2012. Design, fabrication and performance analysis of an improved solar still. *Desalination*, [online] 292, pp.105–112. Available at: <http://dx.doi.org/10.1016/j.desal.2012.02.013>.

Akash, B.A., Mohsen, M.S. and Nayfeh, W., 2000. 00/01458 Experimental study of the basin type solar still under local climate conditions. *Fuel and Energy Abstracts*, 41(3), p.163.

Al-Hinai, H., Al-Nassri, M.S. and Jubran, B.A., 2002. Parametric investigation of a double-effect solar still in comparison with a single-effect solar still. *Desalination*, 150(1), pp.75–83.

Al-Hussaini, H. and Smith, I.K., 1995. Enhancing of solar still productivity using vacuum technology. *Energy Conversion and Management*, 36(11), pp.1047–1051.

Al-Karaghouli, A.A. and Alnaser, W.E., 2004. Performances of single and double basin solar-stills. *Applied Energy*, 78(3), pp.347–354.

Alduchov, O.A. and Eskridge, R.E., 1996. *Improved Magnus form approximation of saturation vapor pressure*. *Journal of Applied Meteorology*, .

Ali, M.T., Fath, H.E.S. and Armstrong, P.R., 2011. A comprehensive techno-economical review of indirect solar desalination. *Renewable and Sustainable Energy Reviews*, [online] 15(8), pp.4187–4199. Available at: <http://dx.doi.org/10.1016/j.rser.2011.05.012>.

Arunkumar, T., Jayaprakash, R., Denkenberger, D., Ahsan, A., Okundamiya, M.S., kumar, S., Tanaka, H. and Aybar, H.Ş., 2012. An experimental study on a hemispherical solar still. *Desalination*, [online] 286, pp.342–348. Available at: <http://dx.doi.org/10.1016/j.desal.2011.11.047>.

Arunkumar, T., Kabeel, A.E., Raj, K., Denkenberger, D., Sathyamurthy, R., Ragupathy, P. and Velraj, R., 2018. Productivity enhancement of solar still by using porous absorber with bubble-wrap insulation. *Journal of Cleaner Production*, [online] 195, pp.1149–1161. Available at: <https://doi.org/10.1016/j.jclepro.2018.05.199>.

Badran, O.O. and Abu-Khader, M.M., 2007. Evaluating thermal performance of a single slope solar still. *Heat and Mass Transfer/Waerme- und Stoffuebertragung*, 43(10), pp.985–995.

Begum, H.A., Yousuf, M.A. and Rabbani, K.S. e, 2018. Effect of top cover material on productivity of solar distillation unit. *Bangladesh Journal of Medical Physics*, 9(1), pp.11–16.

Boukar, M. and Harmim, A., 2004. Parametric study of a vertical solar still under desert climatic conditions. *Desalination*, 168(1–3), pp.21–28.

Chen, Z., Peng, J., Chen, G., Hou, L., Yu, T., Yao, Y. and Zheng, H., 2017. Analysis of heat and mass transferring mechanism of multi-stage stacked-tray solar seawater desalination still and experimental research on its performance. *Solar Energy*, [online] 142, pp.278–287. Available at: <http://dx.doi.org/10.1016/j.solener.2016.12.028>.

Delyannis, E., 2003. Historic background of desalination and renewable energies. 75, pp.357–366.

Dev, R. and Tiwari, G.N., 2009. Characteristic equation of a passive solar still. *Desalination*, [online] 245(1–3), pp.246–265. Available at: <http://dx.doi.org/10.1016/j.desal.2008.07.011>.

El-Sebaii, A.A., 2000. Effect of wind speed on some designs of solar stills. *Energy Conversion and Management*, 41(6), pp.523–538.

El-Sebaii, A.A., 2004. Effect of wind speed on active and passive solar stills. *Energy Conversion and Management*, 45(7–8), pp.1187–1204.

El-Sebaii, A.A., 2005. Thermal performance of a triple-basin solar still. *Desalination*, 174(1), pp.23–37.

El-Sebaii, A.A. and El-Bialy, E., 2015. Advanced designs of solar desalination systems: A review. *Renewable and Sustainable Energy Reviews*, [online] 49, pp.1198–1212. Available at: <http://dx.doi.org/10.1016/j.rser.2015.04.161>.

Ghoneyem, A. and Ileri, A., 1997. Software to analyze solar stills and an experimental study on the effects of the cover. *Desalination*, 114(1), pp.37–44.

Gioda, A., 1999. A short history of water. *Nature and Resources,* 35(1), pp.42–48.

Gude, V.G., Nirmalakhandan, N. and Deng, S., 2010. Renewable and sustainable approaches for desalination. *Renewable and Sustainable Energy Reviews*, [online] 14(9), pp.2641–2654. Available at: <http://dx.doi.org/10.1016/j.rser.2010.06.008>.

Hamdan, M.A., Musa, A.M. and Jubran, B.A., 1999. Performance of solar still under Jordanian climate. *Energy Conversion and Management*, 40(5), pp.495–503.

Henderson-Sellers, B., 1984. A new formula for latent heat of vaporization of water as a function of temperature. *Quarterly Journal of the Royal Meteorological Society*, 110(466), pp.1186–1190.

Ho, Z.Y., 2021. Development and performance evaluation of fresnel lens and phase change material assisted portable solar desalination system for fresh water production. (June), p.156.

Ismail, B.I., 2009. Design and performance of a transportable hemispherical solar still. *Renewable Energy*, 34(1), pp.145–150.

Jubran, B.A., 2003. Effect of climatic, design and operational parameters on the yield of a simple solar still. *Fuel and Energy Abstracts*, 44(2), p.87.

Kalbasi, R., Alemrajabi, A.A. and Afrand, M., 2018. Thermal modeling and analysis of single and double effect solar stills: An experimental validation. *Applied Thermal Engineering*, [online] 129, pp.1455–1465. Available at: <https://doi.org/10.1016/j.applthermaleng.2017.10.012>.

Kumar, S., Tiwari, G.N. and Singh, H.N., 2000. Annual performance of an active solar distillation system. *Desalination*, 127(1), pp.79–88.

Malaysia Investment Development Authority, 2020. Market Rate of Business Space [online] Available at: < https://www.mida.gov.my/setting-up-content/space/> [Accessed 29 August 2021]

Mink, G., Horváth, L., Evseev, E.G. and Kudish, A.I., 1998. Design parameters, performance testing and analysis of a double-glazed, air-blown solar still with thermal energy recycle. *Solar Energy*, 64(4–6), pp.265–277.

Mohammad, S.T., Al-Kayiem, H.H., Aurybi, M.A. and Khlief, A.K., 2020. Measurement of global and direct normal solar energy radiation in Seri Iskandar and comparison with other cities of Malaysia. *Case Studies in Thermal Engineering*, [online] 18(October 2019), p.100591. Available at: <https://doi.org/10.1016/j.csite.2020.100591>.

Muftah, A.F., Alghoul, M.A., Fudholi, A., Abdul-Majeed, M.M. and Sopian, K., 2014. Factors affecting basin type solar still productivity: A detailed review. *Renewable and Sustainable Energy Reviews*, [online] 32, pp.430–447. Available at: <http://dx.doi.org/10.1016/j.rser.2013.12.052>.

Muthu Manokar, A., Kalidasa Murugavel, K. and Esakkimuthu, G., 2014. Different parameters affecting the rate of evaporation and condensation on passive solar still - A review. *Renewable and Sustainable Energy Reviews*, [online] 38, pp.309–322. Available at: <http://dx.doi.org/10.1016/j.rser.2014.05.092>.

Naim, M.M. and Abd El Kawi, M.A., 2003. Non-conventional solar stills. Part 2. Non-conventional solar stills with energy storage element. *Desalination*, 153(1–3), pp.71–80.

Nayar, K.G., Sharqawy, M.H., Banchik, L.D. and Lienhard, J.H., 2016. Thermophysical properties of seawater: A review and new correlations that include pressure dependence. *Desalination*, [online] 390, pp.1–24. Available at: <http://dx.doi.org/10.1016/j.desal.2016.02.024>.

Prakash, E.S., 2012. INTERNATIONAL JOURNAL OF ENERGY AND ENVIRONMENT An investigation on the performance characteristics of solar flat plate collector with different selective surface coatings. *Journal homepage: www.IJEE.IEEFoundation.org ISSN*, [online] 3(1), pp.2076–2909. Available at: <www.IJEE.IEEFoundation.org>.

Rajaseenivasan, T., Elango, T. and Kalidasa Murugavel, K., 2013. Comparative study of double basin and single basin solar stills. *Desalination*, [online] 309, pp.27–31. Available at: <http://dx.doi.org/10.1016/j.desal.2012.09.014>.

Reddy, K.S. and Sharon, H., 2016. Active multi-effect vertical solar still: Mathematical modeling, performance investigation and enviro-economic analyses. *Desalination*, [online] 395, pp.99–120. Available at:

<http://dx.doi.org/10.1016/j.desal.2016.05.027>.

Selvaraj, K. and Natarajan, A., 2018. Factors influencing the performance and productivity of solar stills - A review. *Desalination*, [online] 435(October 2017), pp.181–187. Available at: <https://doi.org/10.1016/j.desal.2017.09.031>.

Shafii, M.B., Shahmohamadi, M., Faegh, M. and Sadrhosseini, H., 2016. Examination of a novel solar still equipped with evacuated tube collectors and thermoelectric modules. *Desalination*, 382, pp.21–27.

Sharqawy, M.H., Lienhard V, J.H. and Zubair, S.M., 2010. Thermophysical properties of seawater: A review of existing correlations and data. *Desalination and Water Treatment*, 16(1–3), pp.354–380.

Sharshir, S.W., Yang, N., Peng, G. and Kabeel, A.E., 2016. Factors affecting solar stills productivity and improvement techniques: A detailed review. *Applied Thermal Engineering*, [online] 100, pp.267–284. Available at: <http://dx.doi.org/10.1016/j.applthermaleng.2015.11.041>.

Shatat, M. and Riffat, S.B., 2014. Water desalination technologies utilizing conventional and renewable energy sources. *International Journal of Low-Carbon Technologies*, 9(1), pp.1–19.

Shatat, M.I.M. and Mahkamov, K., 2010. Determination of rational design parameters of a multi-stage solar water desalination still using transient mathematical modelling. *Renewable Energy*, [online] 35(1), pp.52–61. Available at: <http://dx.doi.org/10.1016/j.renene.2009.06.022>.

Shukla, S.K. and Sorayan, V.P.S., 2005. Thermal modeling of solar stills: An experimental validation. *Renewable Energy*, 30(5), pp.683–699.

Singh, H.N. and Tiwari, G.N., 2004. Monthly performance of passive and active solar stills for different Indian climatic conditions. *Desalination*, 168(1–3), pp.145–150.

Suneja, S. and Tiwari, G.N., 1998. Optimization of number of effects for higher yield from an inverted absorber solar still using the Runge-Kutta method. *Desalination*, 120(3), pp.197–209.

Taamneh, Y. and Taamneh, M.M., 2012. Performance of pyramid-shaped solar still: Experimental study. *Desalination*, [online] 291, pp.65–68. Available at: <http://dx.doi.org/10.1016/j.desal.2012.01.026>.

Tanaka, H. and Nakatake, Y., 2006. Theoretical analysis of a basin type solar still with internal and external reflectors. *Desalination*, 197(1–3), pp.205–216.

Velmurugan, V., Gopalakrishnan, M., Raghu, R. and Srithar, K., 2008. Single basin solar still with fin for enhancing productivity. *Energy Conversion and Management*, 49(10), pp.2602–2608.

Velmurugan, V., Naveen Kumar, K.J., Noorul Haq, T. and Srithar, K., 2009. Performance analysis in stepped solar still for effluent desalination. *Energy*, [online] 34(9), pp.1179–1186. Available at: <http://dx.doi.org/10.1016/j.energy.2009.04.029>.

Velmurugan, V. and Srithar, K., 2011. Performance analysis of solar stills based on various factors affecting the productivity - A review. *Renewable and Sustainable Energy Reviews*, [online] 15(2), pp.1294–1304. Available at: <http://dx.doi.org/10.1016/j.rser.2010.10.012>.

Younas, O., Banat, F. and Islam, D., 2016. Seasonal behavior and techno economical analysis of a multi-stage solar still coupled with a point-focus Fresnel lens. *Desalination and Water Treatment*, [online] 57(11), pp.4796–4809. Available at: <http://dx.doi.org/10.1080/19443994.2014.1001443>.

World Health Organization, 2019. Drinking-Water [online] Available at: < https://www.who.int/news-room/fact-sheets/detail/drinking-water> [Accessed 29 March 2021]

Zarasvand Asadi, R., Suja, F., Ruslan, M.H. and Jalil, N.A., 2013. The application of a solar still in domestic and industrial wastewater treatment. *Solar Energy*, [online] 93, pp.63–71. Available at: <http://dx.doi.org/10.1016/j.solener.2013.03.024>.

Zurigat, Y.H. and Abu-Arabi, M.K., 2004. Modelling and performance analysis of a regenerative solar desalination unit. *Applied Thermal Engineering*, 24(7), pp.1061–1072.

APPENDICES

Appendix A: Theoretical calculated result

Sample calculation for distillate output

With assumption of water salinity of 35000 ppm, S = 0.035

Water temperature at stage 1, T_{W1} = 74.45 °C

Condenser temperature at stage 1, T_{C1} = 61.05 °C

Area of condensation = 1 m^2

Time of calculating distillate output = 1800 seconds

Using equation 3.8 and 3.9, the saturation pressure of saline water and condenser can be calculated.

Where water saturation pressure is

$$p_{wn} = 614.13e^{\frac{17.625T_{wn}}{T_{wn}+243.04}}$$

$$p_{wn} = 614.13e^{\frac{17.625(74.45)}{74.45+243.04}}$$

$$p_{wn} = 38299.46 \text{ Pa}$$

Condenser water saturation pressure.

$$p_{cn} = 610.94e^{\frac{17.625T_{cn}}{T_{cn}+243.04}}$$

$$p_{cn} = 610.94e^{\frac{17.625(61.05)}{61.05+243.04}}$$

$$p_{cn} = 21023.56 \text{ Pa}$$

Using equation 3.10, saturation pressure of water with salinity of 35000 ppm could be approximated.

$$In\left(\frac{p_{sw}}{p_w}\right) = -4.58180 \times 10^{-4}S - 2.04430 \times 10^{-6}S^2$$

$$In\left(\frac{p_{sw}}{38299.46}\right) = -4.58180 \times 10^{-4}(0.035) - 2.04430 \times 10^{-6}(0.035)^2$$

$$p_{sw} = 38299.46e^{(-4.58180\times10^{-4}(0.035)-2.04430\times10^{-6}(0.035)^2)}$$

$$p_{sw} = 38298.84 \text{ Pa}$$

Using equation 3.3, the convective heat transfer could be approximated

$$Q_{conv,w-c} = 0.884\left[(T_w - T_c) + \frac{p_{sw} - p_g}{268.9\times10^3 - p_{sw}}T_w\right]^{\frac{1}{3}}(T_w - T_c)$$

$$Q_{conv,w-c} = 0.884\left[(74.45 - 61.05) + \frac{38298.84 - 21023.56}{268.9\times10^3 - 38298.84}74.45\right]^{\frac{1}{3}}(74.45 - 61.05)$$

$$Q_{conv,w-c} = 31.599 \text{ W/m}^2$$

Using equation 3.6, the convective heat transfer could be approximated

$$Q_{evap,w-c} = (16.276\times10^{-3})\frac{p_{sw} - p_c}{T_w - T_c}Q_{conv,w-c}$$

$$Q_{evap,w-c} = (16.276\times10^{-3})\frac{38298.84 - 21023.56}{74.45 - 61.05}31.599 \text{ W/m}^2$$

$$Q_{evap,w-c} = 662.99\ \frac{\text{W}}{\text{m}^2}$$

Using equation 3.13, the enthalpy of vaporization of saline water could be approximated

$$h_{fg,sw} = (2500 - 2.386T)\times\left(1 - \frac{S}{1000}\right)$$

$$h_{fg,sw} = (2500 - 2.386(74.45))\times(1 - \frac{0.035}{1000})$$

$$h_{fg,sw} = 2322.28\ \frac{\text{kJ}}{\text{kg}}$$

Using equation 3.14 and above calculated value, the distillate output could be calculated.

$$m_{yield} = \frac{Q_{evap,w-c} \times A_w \times \Delta t}{h_{fg,sw}}$$

$$m_{yield} = \frac{662.99\ \frac{\mathrm{W}}{\mathrm{m}^2} \times 1\ \mathrm{m}^2 \times 1800\ s}{2322.28\ \frac{\mathrm{kJ}}{\mathrm{kg}}}$$

$$m_{yield} = 513.88\ \mathrm{g}$$

$$m_{yield} = 513.88\ \mathrm{ml}$$

Using equation 3.14, the solar irradiation energy could be calculated. In this case, total area of 1 m^2, solar irradiation of 1301.8 W/m^2 and time of 1800 seconds are used

$$E = I(t) \times \Delta t \times A_{total}$$

$$E = 1301.8\ \frac{\mathrm{W}}{\mathrm{m}^2} \times 1800\ \mathrm{s} \times 1\ \mathrm{m}^2$$

$$E = 2343240\ \mathrm{J}$$

With value of distillate output, enthalpy of vaporization and solar irradiation energy, the efficiency of the solar distiller could be approximated with equation 3.15

$$Efficiency = \frac{\sum m_{yield} \times h_{fg,sw}}{\sum E} \times 100\ \%$$

$$Efficiency = \frac{513.88\ \mathrm{g} \times 2322.28\ \frac{\mathrm{kJ}}{\mathrm{kg}}}{2343240\ \mathrm{J}} \times 100\%$$

$$Efficiency = 50.93\%$$

Table A-1: Theoretical temperature of water at 1-stage solar distiller.

Time	**Temperature of water at n^th^ stage (°C) at T_{wn}**						
	T_{W1}	T_{W2}	T_{W3}	T_{W4}	T_{W5}	T_{W6}	T_{W7}
9:00 AM	29.30	-	-	-	-	-	-
9:30 AM	30.85	-	-	-	-	-	-
10:00 AM	38.35	-	-	-	-	-	-
10:30 AM	39.85	-	-	-	-	-	-
11:00 AM	50.55	-	-	-	-	-	-
11:30 AM	54.05	-	-	-	-	-	-
12:00 PM	64.15	-	-	-	-	-	-
12:30 PM	67.75	-	-	-	-	-	-
1:00 PM	74.45	-	-	-	-	-	-
1:30 PM	75.05	-	-	-	-	-	-
2:00 PM	79.05	-	-	-	-	-	-
2:30 PM	79.65	-	-	-	-	-	-
3:00 PM	80.75	-	-	-	-	-	-
3:30 PM	83.65	-	-	-	-	-	-
4:00 PM	79.95	-	-	-	-	-	-
4:30 PM	76.25	-	-	-	-	-	-
5:00 PM	66.15	-	-	-	-	-	-

Table A-2: Theoretical temperature of condenser at 1-stage solar distiller.

Time	Temperature of condenser at n^{th} stage (°C) at T_{cn}						
	T_{C1}	T_{C2}	T_{C3}	T_{C4}	T_{C5}	T_{C6}	T_{C7}
9:00 AM	24.03	-	-	-	-	-	-
9:30 AM	25.30	-	-	-	-	-	-
10:00 AM	31.45	-	-	-	-	-	-
10:30 AM	32.68	-	-	-	-	-	-
11:00 AM	41.45	-	-	-	-	-	-
11:30 AM	44.32	-	-	-	-	-	-
12:00 PM	52.60	-	-	-	-	-	-
12:30 PM	55.56	-	-	-	-	-	-
1:00 PM	61.05	-	-	-	-	-	-
1:30 PM	61.54	-	-	-	-	-	-
2:00 PM	64.82	-	-	-	-	-	-
2:30 PM	65.31	-	-	-	-	-	-
3:00 PM	66.22	-	-	-	-	-	-
3:30 PM	68.59	-	-	-	-	-	-
4:00 PM	65.56	-	-	-	-	-	-
4:30 PM	62.53	-	-	-	-	-	-
5:00 PM	54.24	-	-	-	-	-	-

Table A-3: Thermal Analysis of 1-stage solar distiller

Stage	Thermal energy of the distillate output (J)	Total Distillate Output from 9 AM to 5 PM (ml)
1	15403137.4	6638.9
2	0.0	0.0
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0
7	0.0	0.0
Total	15403137.4	6638.9

Total Solar Energy = 35967960 J, Efficiency = 42.82 %

Table A-4: Theoretical temperature of water at 2-stages solar distiller.

Time	**Temperature of water at n^th^ stage (ºC) at T_{wn}**						
	T_{W1}	T_{W2}	T_{W3}	T_{W4}	T_{W5}	T_{W6}	T_{W7}
9:00 AM	29.30	29.30	-	-	-	-	-
9:30 AM	30.85	29.30	-	-	-	-	-
10:00 AM	38.35	32.98	-	-	-	-	-
10:30 AM	39.85	34.27	-	-	-	-	-
11:00 AM	50.55	43.47	-	-	-	-	-
11:30 AM	54.05	46.48	-	-	-	-	-
12:00 PM	64.15	55.17	-	-	-	-	-
12:30 PM	67.75	58.27	-	-	-	-	-
1:00 PM	74.45	64.03	-	-	-	-	-
1:30 PM	75.05	64.54	-	-	-	-	-
2:00 PM	79.05	67.98	-	-	-	-	-
2:30 PM	79.65	68.50	-	-	-	-	-
3:00 PM	80.75	69.45	-	-	-	-	-
3:30 PM	83.65	71.94	-	-	-	-	-
4:00 PM	79.95	68.76	-	-	-	-	-
4:30 PM	76.25	65.58	-	-	-	-	-
5:00 PM	66.15	56.89	-	-	-	-	-

Table A-5: Theoretical temperature of condensers at 2-stages solar distiller.

Time	**Temperature of condenser at n^{th} stage (^{o}C) at T_{cn}**						
	T_{C1}	T_{C2}	T_{C3}	T_{C4}	T_{C5}	T_{C6}	T_{C7}
9:00 AM	29.59	24.03	-	-	-	-	-
9:30 AM	29.59	24.03	-	-	-	-	-
10:00 AM	33.31	27.04	-	-	-	-	-
10:30 AM	34.61	28.10	-	-	-	-	-
11:00 AM	43.91	35.65	-	-	-	-	-
11:30 AM	46.95	38.12	-	-	-	-	-
12:00 PM	55.72	45.24	-	-	-	-	-
12:30 PM	58.85	47.78	-	-	-	-	-
1:00 PM	64.67	52.50	-	-	-	-	-
1:30 PM	65.19	52.93	-	-	-	-	-
2:00 PM	68.66	55.75	-	-	-	-	-
2:30 PM	69.18	56.17	-	-	-	-	-
3:00 PM	70.14	56.94	-	-	-	-	-
3:30 PM	72.66	58.99	-	-	-	-	-
4:00 PM	69.44	56.38	-	-	-	-	-
4:30 PM	66.23	53.77	-	-	-	-	-
5:00 PM	57.46	46.65	-	-	-	-	-

Table A- 6: Thermal Analysis of 2-stages solar distiller.

Stage	Thermal energy of the distillate output (J)	Total Distillate Output from 9 AM to 5 PM (ml)
1	10844335.5	4675.5
2	8279595.0	3528.6
3	0.0	0.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0
7	0.0	0.0
Total	19123930.6	8204.1

Total Solar Energy = 35967960 J, Efficiency = 53.17 %

Table A-7: Theoretical temperature of water at 3-stages solar distiller.

Time	**Temperature of water at nth stage (°C) at T_{wn}**						
	T_{W1}	T_{W2}	T_{W3}	T_{W4}	T_{W5}	T_{W6}	T_{W7}
9:00 AM	29.30	29.30	29.30	-	-	-	-
9:30 AM	30.85	29.30	29.30	-	-	-	-
10:00 AM	38.35	32.98	29.30	-	-	-	-
10:30 AM	39.85	34.27	29.47	-	-	-	-
11:00 AM	50.55	43.47	37.39	-	-	-	-
11:30 AM	54.05	46.48	39.98	-	-	-	-
12:00 PM	64.15	55.17	47.45	-	-	-	-
12:30 PM	67.75	58.27	50.11	-	-	-	-
1:00 PM	74.45	64.03	55.06	-	-	-	-
1:30 PM	75.05	64.54	55.51	-	-	-	-
2:00 PM	79.05	67.98	58.47	-	-	-	-
2:30 PM	79.65	68.50	58.91	-	-	-	-
3:00 PM	80.75	69.45	59.72	-	-	-	-
3:30 PM	83.65	71.94	61.87	-	-	-	-
4:00 PM	79.95	68.76	59.13	-	-	-	-
4:30 PM	76.25	65.58	56.39	-	-	-	-
5:00 PM	66.15	56.89	48.92	-	-	-	-

Table A-8: Theoretical temperature of condensers at 3-stages solar distiller.

Time	**Temperature of condenser at n^th^ stage (°C) at T_{cn}**						
	T_{C1}	T_{C2}	T_{C3}	T_{C4}	T_{C5}	T_{C6}	T_{C7}
9:00 AM	29.59	29.59	24.03	-	-	-	-
9:30 AM	29.59	29.59	24.03	-	-	-	-
10:00 AM	33.31	29.59	24.03	-	-	-	-
10:30 AM	34.61	29.77	24.17	-	-	-	-
11:00 AM	43.91	37.76	30.66	-	-	-	-
11:30 AM	46.95	40.38	32.78	-	-	-	-
12:00 PM	55.72	47.92	38.91	-	-	-	-
12:30 PM	58.85	50.61	41.09	-	-	-	-
1:00 PM	64.67	55.61	45.15	-	-	-	-
1:30 PM	65.19	56.06	45.52	-	-	-	-
2:00 PM	68.66	59.05	47.94	-	-	-	-
2:30 PM	69.18	59.50	48.31	-	-	-	-
3:00 PM	70.14	60.32	48.97	-	-	-	-
3:30 PM	72.66	62.49	50.73	-	-	-	-
4:00 PM	69.44	59.72	48.49	-	-	-	-
4:30 PM	66.23	56.96	46.24	-	-	-	-
5:00 PM	57.46	49.41	40.12	-	-	-	-

Table A-9: Thermal Analysis of 3-stages solar distiller

Stage	Thermal energy of the distillate output (J)	Total Distillate Output from 9 AM to 5 PM (ml)
1	10844335.5	4675.5
2	5739033.0	2447.1
3	4723769.0	1994.0
4	0.0	0.0
5	0.0	0.0
6	0.0	0.0
7	0.0	0.0
Total	21307137.6	9116.6

Total Solar Energy = 35967960 J, Efficiency = 59.24 %

Table A-10: Theoretical temperature of water at 4-stages solar distiller.

Time	Temperature of water at nth stage (^oC) at T_{wn}						
	T_{W1}	T_{W2}	T_{W3}	T_{W4}	T_{W5}	T_{W6}	T_{W7}
9:00 AM	29.30	29.30	29.30	29.30	-	-	-
9:30 AM	30.85	29.30	29.30	29.30	-	-	-
10:00 AM	38.35	32.98	29.30	29.30	-	-	-
10:30 AM	39.85	34.27	29.47	29.30	-	-	-
11:00 AM	50.55	43.47	37.39	32.15	-	-	-
11:30 AM	54.05	46.48	39.98	34.38	-	-	-
12:00 PM	64.15	55.17	47.45	40.80	-	-	-
12:30 PM	67.75	58.27	50.11	43.09	-	-	-
1:00 PM	74.45	64.03	55.06	47.35	-	-	-
1:30 PM	75.05	64.54	55.51	47.74	-	-	-
2:00 PM	79.05	67.98	58.47	50.28	-	-	-
2:30 PM	79.65	68.50	58.91	50.66	-	-	-
3:00 PM	80.75	69.45	59.72	51.36	-	-	-
3:30 PM	83.65	71.94	61.87	53.21	-	-	-
4:00 PM	79.95	68.76	59.13	50.85	-	-	-
4:30 PM	76.25	65.58	56.39	48.50	-	-	-
5:00 PM	66.15	56.89	48.92	42.08	-	-	-

Table A-11: Theoretical temperature of condensers at 4-stages solar distiller.

Time	**Temperature of condenser at n^th stage (°C) at T_{cn}**						
	T_{C1}	T_{C2}	T_{C3}	T_{C4}	T_{C5}	T_{C6}	T_{C7}
9:00 AM	29.59	29.59	29.59	24.03	-	-	-
9:30 AM	29.59	29.59	29.59	24.03	-	-	-
10:00 AM	33.31	29.59	29.59	24.03	-	-	-
10:30 AM	34.61	29.77	29.59	24.03	-	-	-
11:00 AM	43.91	37.76	32.47	26.37	-	-	-
11:30 AM	46.95	40.38	34.72	28.19	-	-	-
12:00 PM	55.72	47.92	41.21	33.46	-	-	-
12:30 PM	58.85	50.61	43.52	35.34	-	-	-
1:00 PM	64.67	55.61	47.83	38.83	-	-	-
1:30 PM	65.19	56.06	48.21	39.14	-	-	-
2:00 PM	68.66	59.05	50.78	41.23	-	-	-
2:30 PM	69.18	59.50	51.17	41.54	-	-	-
3:00 PM	70.14	60.32	51.88	42.12	-	-	-
3:30 PM	72.66	62.49	53.74	43.63	-	-	-
4:00 PM	69.44	59.72	51.36	41.70	-	-	-
4:30 PM	66.23	56.96	48.98	39.77	-	-	-
5:00 PM	57.46	49.41	42.50	34.50	-	-	-

Table A-12: Thermal Analysis of 4-stages solar distiller

Stage	Thermal energy of the distillate output (J)	Total Distillate Output from 9 AM to 5 PM (ml)
1	10844335.5	4675.5
2	5739033.0	2447.1
3	3162270.3	1336.3
4	2862113.8	1198.3
5	0.0	0.0
6	0.0	0.0
7	0.0	0.0
Total	22607752.6	9657.3

Total Solar Energy = 35967960 J, Efficiency = 62.86 %

Table A-13: Theoretical temperature of water at 5-stages solar distiller.

Time	**Temperature of water at nth stage (°C) at T_{wn}**						
	T_{W1}	T_{W2}	T_{W3}	T_{W4}	T_{W5}	T_{W6}	T_{W7}
9:00 AM	29.30	29.30	29.30	29.30	29.30	-	-
9:30 AM	30.85	29.30	29.30	29.30	29.30	-	-
10:00 AM	38.35	32.98	29.30	29.30	29.30	-	-
10:30 AM	39.85	34.27	29.47	29.30	29.30	-	-
11:00 AM	50.55	43.47	37.39	32.15	29.30	-	-
11:30 AM	54.05	46.48	39.98	34.38	29.57	-	-
12:00 PM	64.15	55.17	47.45	40.80	35.09	-	-
12:30 PM	67.75	58.27	50.11	43.09	37.06	-	-
1:00 PM	74.45	64.03	55.06	47.35	40.72	-	-
1:30 PM	75.05	64.54	55.51	47.74	41.05	-	-
2:00 PM	79.05	67.98	58.47	50.28	43.24	-	-
2:30 PM	79.65	68.50	58.91	50.66	43.57	-	-
3:00 PM	80.75	69.45	59.72	51.36	44.17	-	-
3:30 PM	83.65	71.94	61.87	53.21	45.76	-	-
4:00 PM	79.95	68.76	59.13	50.85	43.73	-	-
4:30 PM	76.25	65.58	56.39	48.50	41.71	-	-
5:00 PM	66.15	56.89	48.92	42.08	36.18	-	-

Table A-14: Theoretical temperature of condensers at 5-stages solar distiller.

Time	**Temperature of condenser at n^th^ stage (°C) at T_{cn}**						
	T_{C1}	T_{C2}	T_{C3}	T_{C4}	T_{C5}	T_{C6}	T_{C7}
9:00 AM	29.59	29.59	29.59	29.59	24.03	-	-
9:30 AM	29.59	29.59	29.59	29.59	24.03	-	-
10:00 AM	33.31	29.59	29.59	29.59	24.03	-	-
10:30 AM	34.61	29.77	29.59	29.59	24.03	-	-
11:00 AM	43.91	37.76	32.47	29.59	24.03	-	-
11:30 AM	46.95	40.38	34.72	29.86	24.24	-	-
12:00 PM	55.72	47.92	41.21	35.44	28.77	-	-
12:30 PM	58.85	50.61	43.52	37.43	30.39	-	-
1:00 PM	64.67	55.61	47.83	41.13	33.39	-	-
1:30 PM	65.19	56.06	48.21	41.46	33.66	-	-
2:00 PM	68.66	59.05	50.78	43.67	35.46	-	-
2:30 PM	69.18	59.50	51.17	44.00	35.73	-	-
3:00 PM	70.14	60.32	51.88	44.61	36.22	-	-
3:30 PM	72.66	62.49	53.74	46.21	37.52	-	-
4:00 PM	69.44	59.72	51.36	44.17	35.86	-	-
4:30 PM	66.23	56.96	48.98	42.13	34.20	-	-
5:00 PM	57.46	49.41	42.50	36.55	29.67	-	-

Table A-15: Thermal Analysis of 5-stages solar distiller

Stage	Thermal energy of the distillate output (J)	Total Distillate Output from 9 AM to 5 PM (ml)
1	10844335.5	4675.5
2	5739033.0	2447.1
3	3162270.3	1336.3
4	1831889.6	768.1
5	1834653.9	762.9
6	0.0	0.0
7	0.0	0.0
Total	23412182.4	9990.0

Total Solar Energy = 35967960 J, Efficiency = 65.09 %

Table A-16: Theoretical temperature of water at 6-stages solar distiller.

Time	**Temperature of water at n^th^ stage (ºC) at T_{wn}**					
	T_{W1}	T_{W2}	T_{W3}	T_{W4}	T_{W5}	T_{W6}	T_{W7}
9:00 AM	29.30	29.30	29.30	29.30	29.30	29.30	-
9:30 AM	30.85	29.30	29.30	29.30	29.30	29.30	-
10:00 AM	38.35	32.98	29.30	29.30	29.30	29.30	-
10:30 AM	39.85	34.27	29.47	29.30	29.30	29.30	-
11:00 AM	50.55	43.47	37.39	32.15	29.30	29.30	-
11:30 AM	54.05	46.48	39.98	34.38	29.57	29.30	-
12:00 PM	64.15	55.17	47.45	40.80	35.09	30.18	-
12:30 PM	67.75	58.27	50.11	43.09	37.06	31.87	-
1:00 PM	74.45	64.03	55.06	47.35	40.72	35.02	-
1:30 PM	75.05	64.54	55.51	47.74	41.05	35.31	-
2:00 PM	79.05	67.98	58.47	50.28	43.24	37.19	-
2:30 PM	79.65	68.50	58.91	50.66	43.57	37.47	-
3:00 PM	80.75	69.45	59.72	51.36	44.17	37.99	-
3:30 PM	83.65	71.94	61.87	53.21	45.76	39.35	-
4:00 PM	79.95	68.76	59.13	50.85	43.73	37.61	-
4:30 PM	76.25	65.58	56.39	48.50	41.71	35.87	-
5:00 PM	66.15	56.89	48.92	42.08	36.18	31.12	-

Table A-17: Theoretical temperature of condensers at 6-stages solar distiller.

Time	**Temperature of condenser at nth stage (^oC) at T_{cn}**						
	T_{C1}	T_{C2}	T_{C3}	T_{C4}	T_{C5}	T_{C6}	T_{C7}
9:00 AM	29.59	29.59	29.59	29.59	29.59	24.03	-
9:30 AM	29.59	29.59	29.59	29.59	29.59	24.03	-
10:00 AM	33.31	29.59	29.59	29.59	29.59	24.03	-
10:30 AM	34.61	29.77	29.59	29.59	29.59	24.03	-
11:00 AM	43.91	37.76	32.47	29.59	29.59	24.03	-
11:30 AM	46.95	40.38	34.72	29.86	29.59	24.03	-
12:00 PM	55.72	47.92	41.21	35.44	30.48	24.75	-
12:30 PM	58.85	50.61	43.52	37.43	32.19	26.13	-
1:00 PM	64.67	55.61	47.83	41.13	35.37	28.72	-
1:30 PM	65.19	56.06	48.21	41.46	35.66	28.95	-
2:00 PM	68.66	59.05	50.78	43.67	37.56	30.49	-
2:30 PM	69.18	59.50	51.17	44.00	37.84	30.72	-
3:00 PM	70.14	60.32	51.88	44.61	38.37	31.15	-
3:30 PM	72.66	62.49	53.74	46.21	39.74	32.27	-
4:00 PM	69.44	59.72	51.36	44.17	37.99	30.84	-
4:30 PM	66.23	56.96	48.98	42.13	36.23	29.41	-
5:00 PM	57.46	49.41	42.50	36.55	31.43	25.52	-

Table A- 18: Thermal Analysis of 6-stages solar distiller

Stage	Thermal energy of the distillate output (J)	Total Distillate Output from 9 AM to 5 PM (ml)
1	10844335.5	4675.5
2	5739033.0	2447.1
3	3162270.3	1336.3
4	1831889.6	768.1
5	1063723.7	443.2
6	1265615.6	523.5
7	0.0	0.0
Total	23906867.7	10193.7

Total Solar Energy = 35967960 J, Efficiency = 66.47 %

Table A-19: Theoretical temperature of water at 7-stages solar distiller.

Time	**Temperature of water at nth stage (ºC) at T_{wn}**						
	T_{W1}	T_{W2}	T_{W3}	T_{W4}	T_{W5}	T_{W6}	T_{W7}
9:00 AM	29.30	29.30	29.30	29.30	29.30	29.30	29.30
9:30 AM	30.85	29.30	29.30	29.30	29.30	29.30	29.30
10:00 AM	38.35	32.98	29.30	29.30	29.30	29.30	29.30
10:30 AM	39.85	34.27	29.47	29.30	29.30	29.30	29.30
11:00 AM	50.55	43.47	37.39	32.15	29.30	29.30	29.30
11:30 AM	54.05	46.48	39.98	34.38	29.57	29.30	29.30
12:00 PM	64.15	55.17	47.45	40.80	35.09	30.18	29.30
12:30 PM	67.75	58.27	50.11	43.09	37.06	31.87	29.30
1:00 PM	74.45	64.03	55.06	47.35	40.72	35.02	30.12
1:30 PM	75.05	64.54	55.51	47.74	41.05	35.31	30.36
2:00 PM	79.05	67.98	58.47	50.28	43.24	37.19	31.98
2:30 PM	79.65	68.50	58.91	50.66	43.57	37.47	32.22
3:00 PM	80.75	69.45	59.72	51.36	44.17	37.99	32.67
3:30 PM	83.65	71.94	61.87	53.21	45.76	39.35	33.84
4:00 PM	79.95	68.76	59.13	50.85	43.73	37.61	32.35
4:30 PM	76.25	65.58	56.39	48.50	41.71	35.87	30.85
5:00 PM	66.15	56.89	48.92	42.08	36.18	31.12	29.30

Table A-20: Theoretical temperature of condensers at 7-stages solar distiller.

Time	**Temperature of condenser at nth stage (°C) at T_{cn}**						
	T_{C1}	T_{C2}	T_{C3}	T_{C4}	T_{C5}	T_{C6}	T_{C7}
9:00 AM	29.59	29.59	29.59	29.59	29.59	29.59	24.03
9:30 AM	29.59	29.59	29.59	29.59	29.59	29.59	24.03
10:00 AM	33.31	29.59	29.59	29.59	29.59	29.59	24.03
10:30 AM	34.61	29.77	29.59	29.59	29.59	29.59	24.03
11:00 AM	43.91	37.76	32.47	29.59	29.59	29.59	24.03
11:30 AM	46.95	40.38	34.72	29.86	29.59	29.59	24.03
12:00 PM	55.72	47.92	41.21	35.44	30.48	29.59	24.03
12:30 PM	58.85	50.61	43.52	37.43	32.19	29.59	24.03
1:00 PM	64.67	55.61	47.83	41.13	35.37	30.42	24.70
1:30 PM	65.19	56.06	48.21	41.46	35.66	30.67	24.90
2:00 PM	68.66	59.05	50.78	43.67	37.56	32.30	26.22
2:30 PM	69.18	59.50	51.17	44.00	37.84	32.55	26.42
3:00 PM	70.14	60.32	51.88	44.61	38.37	33.00	26.79
3:30 PM	72.66	62.49	53.74	46.21	39.74	34.18	27.75
4:00 PM	69.44	59.72	51.36	44.17	37.99	32.67	26.52
4:30 PM	66.23	56.96	48.98	42.13	36.23	31.16	25.30
5:00 PM	57.46	49.41	42.50	36.55	31.43	29.59	24.03

Table A- 21: Thermal Analysis of 7-stages solar distiller

Stage	Thermal energy of the distillate output (J)	Total Distillate Output from 9 AM to 5 PM (ml)
1	10844335.5	4675.5
2	5739033.0	2447.1
3	3162270.3	1336.3
4	1831889.6	768.1
5	1063723.7	443.2
6	583485.4	241.9
7	959749.1	395.5
Total	24184486.6	10307.6

Total Solar Energy = 35967960 J, Efficiency = 67.24 %