Experimental Investigation of A Glass Partitioned Solar Still

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ABSTRACT

The population of the world increases rapidly and this causes an increase in the demand for potable water accordingly. It is possible to desalinate brackish and seawater by using solar energy. In North Cyprus, solar radiation is high. Therefore desalination techniques would be a reliable option in order to extract fresh water from brackish water.

In this study, a single slope improved conventional solar still distillation system and simple single slope solar still are studied and compared theoretically and experimentally in Mechanical Engineering Department at EMU Campus area.

The modified solar still consists of five different sizes of glasses and the inside of the still was painted in black colour. The solar stills were constructed $0.98m \times 0.98m$ base area. Solar irradiance, inlet and outlet air temperatures and water temperatures of 2 different types of solar stills, 5 different sizes of glasses' temperatures and the potable water production was measured between 09:00 a.m to 16:00 p.m hourly.

Experimental results showed that, the maximum amount of water produced by the improved solar still system was 3.51 L/day.m^2. The reference system's water production was 2.1 L/day.m^2. The experiment was conducted for a period of three weeks (29 July 2014 – 19 August 2014).

The present study showed that, with the use of 5 different sizes of glass panes in the solar still the amount of water production increased by 67% compared to the conventional still due to the improved air circulation within the modified still.

Keywords: Solar Desalination, Solar Still, Modified Solar Still

ÖZ

Artmakta olan dünya nüfusu ile birlikte kullanılabilir su ihtiyacı da gittikçe artmaktadır. Güneş enerjisi kullanarak deniz suyu veya acı sudan, kullanılabilir su elde edilmesi uygun bir yöntemdir. Güneş radyasyonunun Kuzey Kıbrıs'ta yüksek olması , tuzlu ve acı sudan tatlı su elde etmede güneş enerjisi damıtma tekniklerini güvenilir bir seçenek kılmaktadır.

Bu çalışmada, geliştirilmiş konvansiyonel güneş damıtıcı sistemi ile basit tek eğimli güneş damıtıcı sistemi arasındaki teorik ve deneysel çalışmalar Doğu Akdeniz Üniversitesi kampüsünde Makine Mühendisliği Bölümünde, yapılmıştır.

Geliştirilmiş güneş damıtıcısı sisteminde beş farklı tipte cam kullanıldı. Damıtıcının içerisi siyah boyayla boyanmıştır. Damıtıcı 0.98 m × 0.98 m taban alanı üzerine kurulmuştur. Güneş ışınım değeri, iç ve dış hava sıcaklıkları ve 2 tip damıtıcı içindeki su sıcaklıkları, 5 farklı ölçüdeki cam sıcaklıkları ve kullanılabilir su miktarı saatlik periyodlarla ölçülmüştür.

Yapılan çalışmaya göre, geliştirilmiş güneş damıtıcısının bir günde ürettiği en yüksek su miktarı 3.51 L/gün.m^2 olarak ölçülmüştür. Referans tip damıtıcıda ise 2.1 L/gün.m^2 su üretilmiştir. Bu deney 3 hafta boyunca sürdürülmüştür (29 Temmuz 2014 – 19 Ağustos 2014). Bu çalışmada geliştirilmiş damıtıcı içerisine konan beş adet farklı ölçülerdeki camlar kullanıldığı için hava sirkülasyonu artmış ve damıtılan suyun miktarı konvansiyonel damıtıcıya göre %67 artırılmıştır.

Anahtar Kelimeler: Güneş desalinasyonu, Güneş Enerjili Sera Tipi Damıtma, Geliştirilmiş Güneş Enerjili Sera Tipi Damıtma

To my family

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Chapter 1

INTRODUCTION

1.1 Background

In most of the parts of world people difficult to obtain drinking water and this causes some health problems and even deaths. About 40 % of world's population suffers from lack of drinkable water. Scientists all over the world are currently trying to solve this problem. There are many alternatives to obtain fresh drinkable water, one of which is to discover new fresh water sources. Another method of obtaining drinkable water is to desalinate salty water. Some countries have already employed various techniques to desalinate water. However, in the most of these desalination systems fossil fuels are used for desalination and burning fossil fuels lead to the emission of harmful gases. In some countries there are systems with different capacities which use fossil fuels to obtain edible water. The major water desalination or purification methods can be classified as distillation, reverse osmosis and electrodialysis. It is more economical for bigger systems to use reverse osmosis and electrodialysis however for smaller systems it is more logical and cost effective to use distillation. The countries where you can find examples of these systems are West-Indian Islands, Kuwait, Saudi Arabia, Mexico and Australia.

More than 70% of the world's surface is covered with water. This consists of oceans, seas, lakes, rivers and the underground water. Water can be found in three states as solid, liquid and gas. In the composition of the Earth there are different minerals. The amount of water in the Earth`s crust is more than the amount of any other minerals. According to UNEP (2002) [1] there is 1400 million km^3 of water on Earth. However, apart from 2.5% of this water which is fresh water, 97.5% is salty. This means that 97.5% of the water on earth is unusable for drinking and irrigation purposes.

69% of the freshwater is in the form of ice. This ice is located in the Polar Regions or on high levels with high altitude. 30% of this fresh water is underground water. The amount of water which is found in lakes, rivers, and wells comprises only about 0.3% of the total amount of fresh water.

The amount and presence of fresh water has a direct link with the evaporation level of salty water from the oceans` surface. It is called the water cycle of the earth. This water cycle resembles a huge pump. It takes fresh water from the ocean`s surface up in the atmosphere and transfers it back to land again. The water which evaporates from the earth`s surface accumulates and condenses in the atmosphere and then it returns back to the surface of earth in the form of rain or snow. A certain amount of this water goes back into the atmosphere through evaporation, a certain amount flows into streams, rivers, lakes, and seas. The ground absorbs a certain amount of this water to form ground water.

Distrubition of water on the earth is shown in Fig 1.1[2]

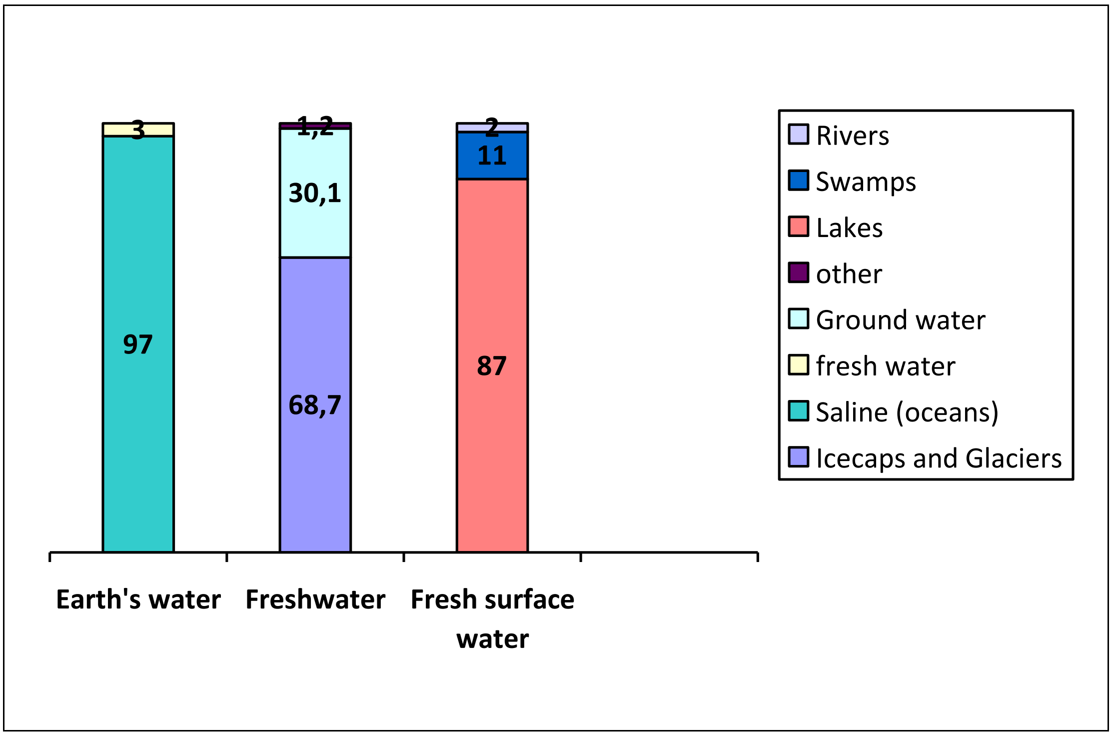

Figure 1.1. Distribution of water on the earth [2].

It is very difficult to estimate how much water is essential to maintain a minimum living standard. An individual needs one or two litres of water daily to survive. Apart from this water is also needed for domestic use, industry and agriculture. United Nations Development Programme (UNDP 1994) estimates that an individual needs approximately 5 litres of water each day for his/her daily biological consumption. Besides this, each individual needs an amount of about 30 litres of water a day for health and hygiene purposes [3].

1.2 Motivation

Shortage of potable water is a noticable problem in the world. If there is a low demand for fresh water and there is suitable space, small production systems such as solar stills can be used with low cost. Solar still is a simple device, easy to built, has no moving parts and it is easy to maintain. Solar stills use low energy and materials and maintenance costs are low. Distilled water from a solar still is ultra – pure water. One of the disadvantages of using conventional solar stills is that their fresh water production per unit area is relatively low (3-4 Lit/day .m^2). Therefore, it can be said that solar stills are expensive due to their low productivities. It is important to improve the efficiency of the conventional still as the yields are low. Therefore modifications are necessary to get better yields.

1.3 Scope and Objectives

The main purpose of the present work is to design, construct and compare two different solar still units and to calculate how much water can be obtained and measure the temperature of the two systems in the summer conditions of North Cyprus.

There are many studies related with Solar Still desalination systems. However, none of them has glass panes inside the system which divides the water basin in several smaller containers. These glass panes increase the air circulation inside the basin and thus evaporation and condensation leading an increase in production.

1.4 Organization of the thesis

This work consists of six (6) chapters.

Chapter 1, introduces the background of solar still desalination, water shortage and the link between the renewable energy and solar still units.

Chapter 2, presents a literature review

Chapter 3, gives information about solar stills and measuring equipment, mathematical modelling and working principle of solar stills.

In Chapter 4, results, calculations of axial velocity of improved solar desalination system and comments are provided.

In Chapter 5, life cycle cost(LCC) and error analysis are provided.

Chapter 6, conclusion and future work are presented.

Chapter 2

LITERATURE REVIEW

Many researchers worked on solar still desalination systems from different aspects. In order to investigate the performance of a single basin solar still G.n. Tiwari and B. Rao [5] used flowing water. The water was flowing over the glass cover. This study is based on a simple theory of a single basin solar still. You can double the amount of distilled water you obtain by lowering the temperature of the glass cover. Flowing water is used to lower the temperature. Various studies have been made in order to increase the efficiency of the system.

H. Al-Hinai et al [6] carried out experimental and mathematical study. In their paper they reported that in Oman they used a mathematical model to calculate the output of a simple solar still under different climatic, design and operational variants. The optimum design parameters needed for this solar still are

- A shallow water tank, 23° cover tilt angle,
- An insulation with a thickness of 100 mm and
- An asphalt coating

The annual productivity rate of this solar still is 4.15 kg/m^2 day. They carried out a cost analysis to calculate the cost of installing simple solar stills for the production of drinking water in remote areas. After making detailed analysis and calculations they claimed that when such a series of solar stills are used the unit cost for distilled water is \$7.4 m/s^2.

H. Aburideh et al [7] introduced an experimental study of a solar still. This study is interested in the internal parameters on a double slope solar still. They carried out these experiments under different conditions. They have studied the variation of the different operating parameters of the solar still. They have found out that there is a direct link between the production of distilled water and the temperature of the water and glass. The distilled water production rate increases when the temperature of water and glass cover temperature incereases. Wind and climatic changes also affect the amount of water produced. Wind and climatic changes decrease the amount of diffuse solar energy which is received by the dirty water. The average amount of distilled water was measured as 4 L/m^2 day.

F.Banat et al [8] studied the technical feasibility of producing drinking water from seawater by using a membrane distillation module with a solar still. They used the relatively hot brine in the solar still to feed the membrane module. They measured the synergistic action of the solar still and the membrane module during this fresh water production. They carried out two types of experiments as indoor and outdoor experiments. They investigated the sensitivity of the solar flux to the salty water temperature, flow rate, salt concentration and solar irradiation. It was found that the flux of water from the solar still was lower than 20% of the solar flux. The temperature of the salty water significantly affected by the flux of both the membrane module and the solar still. Meanwhile the effect of salt concentration was marginal.

A.A.Badran et al [9] in a different study combined solar still and conventional flat plate collector. In order to study the effect of accumulation on the still under local conditions they connected a single-stage, basin-type solar still and a conventional flat-plate collector. They connected the still inlet to a locally made fin-tube collector. The outlet of the fin-tube was fed to the still basin instead of the common storage tank. They carefully measured and noted down various temperatures, solar intensities and the amount of distilled water for several days under various conditions. They studied different modes of operation such as; a) still connected to collector for a 24-h period; b) still connected only from 8 am to 5 pm, (during sunlight hours) and; c) still operating alone for a 24-h period. Tap water and saline water were used in these tests. At the end of the study they found that, when tap water used as a feed, there was an increase of 231% in the amount of distilled water production and there was an increase of 52% in the case of salty water used as a feed.

A. E. Kabeel et al [10] used a wick concave evaporation surface to analyze the performance of solar still. In this study the amount of distilled water obtained from the solar still depends on different factors. The most important and effective factors are the evaporative surface area and glass cover temperature. You can increase the amount of distilled water by increasing the surface area or decreasing the cover temperature. In their experiment they used a wick concave type solar still with four glass cover surfaces. The purpose of using four glass cover surfaces is to increase the amount of solar radiation which falls on the evaporative surface. During the day time conditions there is a temperature difference between the four still glass sides and the evaporative surface and this allows more vapor to condensate on the lower glass cover surface. They found out that the average distillate productivity during the day time is approximately 4 L/m^2 with a system efficiency of 0.38 at noon. It is proved that the amount of distilled water is higher than the amount of distilled water obtained when conventional type solar still used.

K. Vinothkumar et al [11] experimentally studied on various solar still designs . In this paper, the fabrication of seven solar still designs such as spherical solar still, pyramid solar still, hemispherical solar still, double basin glass solar still, concentrator coupled single slope solar still, tubular solar still and tubular solar still coupled with pyramid solar still and their performance evaluation in converting brackish water into fresh water for drinking are presented. The experiment was constructed and tested during January to May 2011. All the solar stills were operated in the same climatic conditions to analyze the influence of the modifications on the productivity. From the observations, the compound parabolic concentrator-assisted tubular solar still shows the maximum yield.

H. N. Panchal and P. K. Shah [12] carried out an experiment to compare performance of solar still which has different plates. Using free energy supply from the sun is a method to obtain clean water from brakish and sea water. In their experiment they used three identical solar stills which are shown in Figure 2.1. In the first two solar stills they used plates made of Aluminum and Galvanized Iron. They employed a conventional solar still as the third one. They tested, recorded and compared the findings of three solar stills under same climate conditions. Authors found out that the solar still which has aluminum plate increases distillate output by 45% and galvanized iron sheet by 15% when compared with conventional solar still.

Figure 2.1. Experimental Set up of Solar still [12].

Garcia Rodriguez L et all. [13] studied renewable energy effect on solar stills. The performance of solar stills are significantly affected by wind velocity, solar radiation, temperature and ambient temperature. Approximately 10–15% effect in overall daily water production because of climatic changes and operational parameters within the expected range is observed. It is proposed by various scientists that in order to obtain beter performance results from a conventional solar still some modifications should be made. These are:

- Reducing bottom loss coefficient

- Reducing water depth in basin
- Using internal and external condensers
- Use of dye
- Use of energy storage element
- Condensing cover cooling
- Inclined solar still
- Increasing evaporative area.

Millions of people around the world have no or little access to a secure source of fresh water. However desalianting saewater is an alternative because most of these areas which have water shortage problems are in coastal areas. Although it is a logical alternative, a lot of energy is needed to desalinate seawater. Therefore, the energy supply in underdeveloped countries or remote areas can create problems, especially in the case of electricity requirement. As a geographical benefit solar energy is in abundance in arid areas. It can be used to desalinate seawater.

Cecilie Kolstad et all, [14] carried out an experiment in Afghanistan to obtain fresh water from salinated groundwater by solar stills. Afghanistan has long been having problems of obtaining clean drinking water as most of its underground water sources are polluted. In other words the salinity level of underground water sources in Afghanistan is very high.

In order to overcome this problem and to find sustainable and feasible solutions, they designed and built low cost solar stills in the city of Kabul. In order to produce distilled water four different types of sloar stills were proposed for this project. All of these solar stills use evaporation and condensation to produce distilled water. They have decided to use six units of three different designs ranging from 0.1 to 1m^2 in size. Plywood, stainless steel, iron, silicone, paint, insulation were used to built these solar stills and these were placed with different inclination on the glass cover. The experiment was carried out in the year 2014 from 17th May to 27th May. All the variables like the level of radiation, potable water and temperatures were registered on an hourly basis from 07:00 am to 18:00 pm, and wind- and weather conditions were also taken into consideration. Within the research period some other individual experiments such as glass cooling, coal application and increased salt concentration were carried out. The Plywood single sloped solar still was found out to have the highest efficiency (57%). The Plywood single-sloped solar still had the average efficiency of 43% whereas the Wick solar still had an average efficiency of 31%. The two smallest size solar stills, Sink double sloped and Plastic single sloped solar still, obtained the lowest efficiency, with 12% and 8% respectively. They have found out that the estimated cost showed a diversion of 7 to 70 USD, in that the most expensive still was the one which produces the highest amount of potable water.

Arunkumar T. et al [15] carried out a study to investigate whether the efficiency of the solar still is affected by air flow on tubular solar still. After this study they reported that there was an increase in the amount of distilled water for a compound parabolic concentrator-concentric tubular solar still (CPC-CTSS). There was a dramatic increase in the heating of saline water when CPC used. In order to produce larger amounts of distilled water they have put forward a new idea work on the characteristic properties of compound parabolic concentrator for desalination. A rectangular water tank made of copper with the dimension of 2 m × 0.025 m × 0.02 m was prepared and this rectangular tank was installed at the focus of the CPC. They used two glass tubes in the shape of cylinder of whose lengths were 2 m but with two different diameters of 0.02 m and 0.03 m to cover the water tank. They used two different modes for this experiment; One mode is with air and one without air flow between inner and outer tubes. Throughout the experiment the air flow rate was kept at 4,5 kg/s. When the results of the experiment were analysed, they came to a conclusion that the rate of water collection was 2020 ml/day with flow of air and 1445 ml/day without the flow of air and the efficiency of both systems were 18.9% and 16.2%, respectively. Fig 2.2 shows the schematic view of CPC-CTSS.

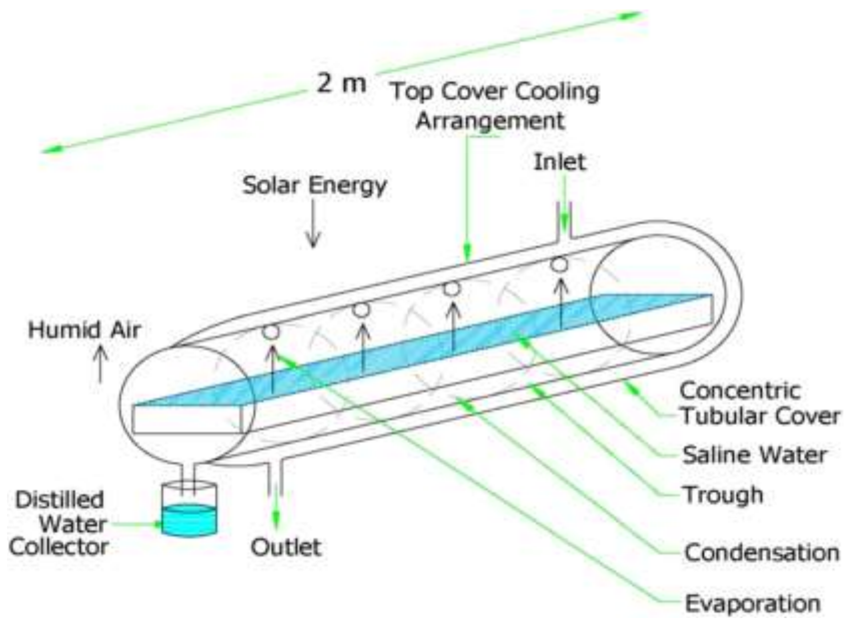

Figure 2.2. Schematic view of CPC-CTSS [15].

Chapter 3

DISTILLATION TECHNOLOGIES

3.1 Desalination Technologies

There are mainly two desalination techniques that are used in today`s world. These techniques are known as Thermal Distillation and Membrane Distillation.

Thermal distillation technologies are very well-known and widely used in the Middle East countries like Saudi Arabia, Qatar, Bahreyn e.t.c. due to low energy costs because of the abundance of oil reserves of the region. There are mainly three types of thermal distillation techniques which are as multistage flash distillation, multi-effect distillation and vapor compression distillation. These are large-scale thermal processes. For smaller scale productions there is another thermal method called solar distillation. This type of distillation technique is mainly used for very small production rates.

Membrane distillation technologies are very popular in the USA. In this technique fresh water is obtained by treating the brakish water with some membranes. Brakish water is forcefed through the membranes by a pressure gradient. The three most known membrane processes are reverse osmosis, electrodialysis and electrodialysis reversal.

3.2 The Development of Desalting

One of the essential parts of the water cycle is desalting and it is a natural and continual process. When precipitation occurs the resulting water travels on the surface of the earth and reaches the sea. During this journey water is used by people. As water flows on the crust of earth, it gathers minerals and becomes salty. During the process of travelling a certain amount of water evaporates due to temperature and concentration difference. When the water evaporates, the salt remains on earth. During and after the process of evaporation the water vapour accumulates and condenses to form clouds which produce rain, and thus forms a natural water cycle as shown in figure 3.1.

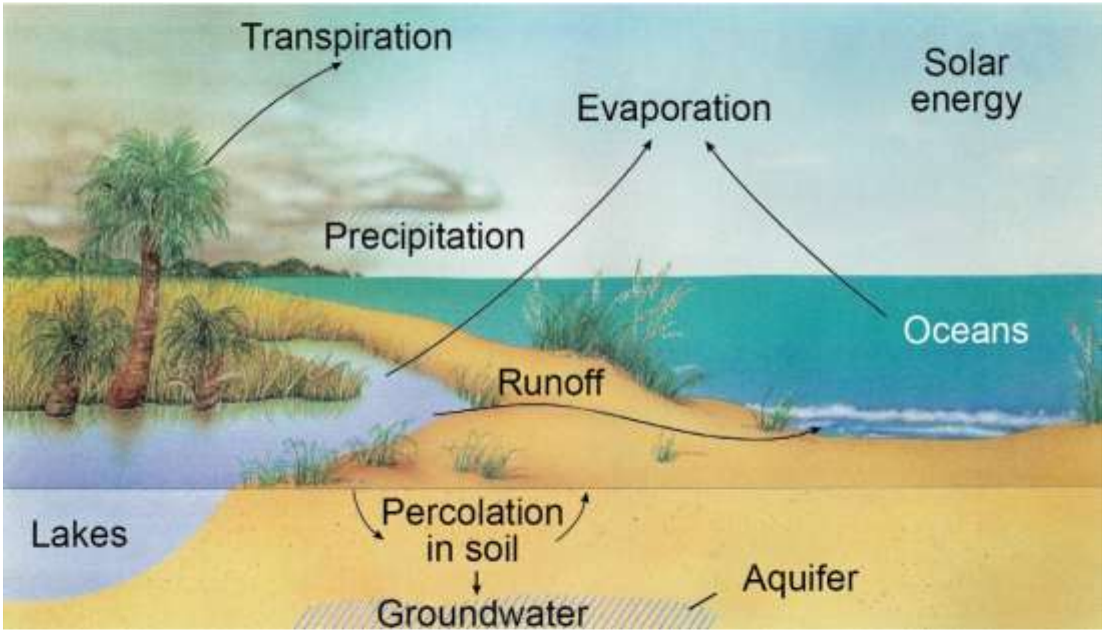

Figure 3.1. Natural Water Cycle. [4]

3.3 Solar Still Distillation System

The aim of successful still design is to maximize distillate yield for a given set of environmental and operating factors. This can be achieved by developing and applying a well-structured design methodology. Still design factors can broadly be classified into optical, heat transfer and heat loss characteristics. Optical characteristics are absorption, reflection and transmission of solar radiation. Moreover, solar radiation is the most influential environmental factor in solar energy systems. Once the radiation is absorbed by the still, it is converted to heat which is transferred from the absorber to other components of the still and the environment.

It is known that the oldest method of desalinating water is solar still. The system on which solar stills are based creates greenhouse effect. The heat from the sun rays is used to evaporate water which is stored in a box-shaped apparatus covered with glass. The temperature inside the glass covered apparatus is higher than the temperature outside. It is more convenient to use solar stills when compared with other methods because it is easier to build a solar still using available materials. Operation and maintenance are not costly. Besides, it is environmentally friendly. In countries where there is a lot of sunshine it is very reliable and efficient to use solar stills. Water demand is very high in Cyprus during the summer and in the meantime we have a lot of sunshine. Therefore it is very logical and beneficial to use this solar energy to desalinate water by using solar stills.

There are two important advantages of using solar stills. First of all the energy used is renewable and free, and it is environmentally friendly. When it comes to their disadvantages we can say that the amount of distilled water obtained is lower than when other desalination methods used.

The operation system of solar stills is very simple. The basin is partially filled with water to be distilled. Solar energy passes through the glass cover and heats the water. The reason why we use a black material on the base of the solar still is to absorb the solar energy. As the water heats up evaporation occurs and the water vapour gathers between the water surface and the glass cover. When the amount of water vapour increases it condenses on the inside of the glass cover. During this process, salts and micro-organisms in the brakish water are left behind. Condensed water vapour which is collected on the inside surface of the glass cover slowly flows down through the inclined glass cover into a collection canal and stored in a storage bottle. A simple basin type solar still is shown in Fig. 3.2.

Figure 3.2. A simple conventional solar still.

In order to build a good solar still you have to meet certain requirements. A good solar still

- Should be easily built
- Should be able to be constructed with available materials,
- Be light weight in order to handle and transport easily,
- Have an effective life span of 10 to 20 years,
- Should not require any other power source except solar energy,
- Should be strong enough to withstand prevailing wind conditions,
- Should not contaminate the collected fresh water with the materials used to built the still,
- Should meet the civil and structural engineering standards, and,
- Should be affordable.

Chapter 4

EXPERIMENTAL PROCEDURE

4.1 Working Principle of Solar Still Desalination System

At any given time and place, data about the position of the sun is required for calculation of the beam component of the solar radiation incident on a tilted surface, and for determination of the angular-dependent optical properties of transparent materials.

Solar Still's principle of operation is the greenhouse effect; the heat from the sun heats and evaporates the water inside a single glass covered apparatus as the inside temperature gets higher than the outside temperature. Solar still works on the principle of solar distillation. While desalinating water, a solar still uses two processes i.e: evaporation and condensation. Saline water is filled in the black painted absorber plate of the solar still. The mechanizm of the still is enclosed in a completely air tight surface. The system works just like an ocean. The water from the oceans evaporates, rises, cools and condenses. It forms the rain clouds and then returns to earth as rain. During the evaporation process all the bacteria remains in the oceans. The tecnique which is used in the solar stills is based on the same process.

The selection of the material for the cover should be made properly as this is the most important component of the solar still. There is a tendency to prefer glass covers; however, plastic covers have the advantage of being cheaper.

Firstly, solar radiation passes through the glass cover. This solar energy is absorbed by the black ground surface of the basin. The system works as follows. The solar energy heats the seawater and the basin. With the help of the black surface the heat is conducted into the seawater and as a result an increase occurs in the temperature of the seawater. Five different size glasses, increases the water temperature and the circulation of heated air. The heated water vapor evaporates, rises and condenses on the glass cover and other five glasses.

During this process, the salts and micro-organisms in the brakish are left behind. Through a channel the condensed water is stored into a storage bottle. Figure 4.1. shows evaporation and condensation process of the improved conventional solar still.

Figure 4.1. Condensation and evaporation process of (CSS) desalination system.

4.2 Factors Affecting the Efficiency of a Solar Still

The productivity of a solar still is affected by:

*Ambient conditions,

*Operating conditions

*Design conditions.

Ambient conditions include the temperature, the insulation, and the velocity of the wind.

Operating conditions consist of the depth of the water, the orientation of the still and the inlet temperature of the water.

Design conditions include the material selection for the still and cover, slope of the cover, gap distance and the numbers of covers used.

4.2.1 Wind Velocity

There is little effect of wind velocity on productivity, however it is observed that even in the event of low wind there is an increase in the production rates as compared to zero wind conditions. It is observed that high wind velocity causes an increase in the heat loss by convection from the cover to the ambient.

4.2.2 Water Depth

The performance of a still is consirebaly affected by the depth of the water in the still. When the level of the water in the still is low, it has a lower thermal capacity and this increases rate of increase of the water temperature which directly results in higher outputs. Therefore the lower the water level the higher the output. When there is low solar energy available in the earlier times of the day, water depth becomes important as you need to heat water quickly to produce fresh water.

4.3.3 Gap Distance

You can increase the performance of the still by reducing the gap distance between the evaporating surface and the condensing cover.

4.3 Solar Still and Modified Solar Still

Two solar stills were designed and constructed in the Mechanical Engineering Department at EMU and experimentaly investigated. One of the stills was a conventional one and the other was is a modified still. The modified and reference solar stills employed in this study are shown in Fig 4.2 and Fig 4.3 respectively. 3D CAD model of the modified solar still is shown in figure 4.4.The system includes black absorbing basin, wooden box, glass cover, 5 different sized glass panes, plastic pure water pipe and metal water collection channel. The components of the system are dealt in brief in the following sections.

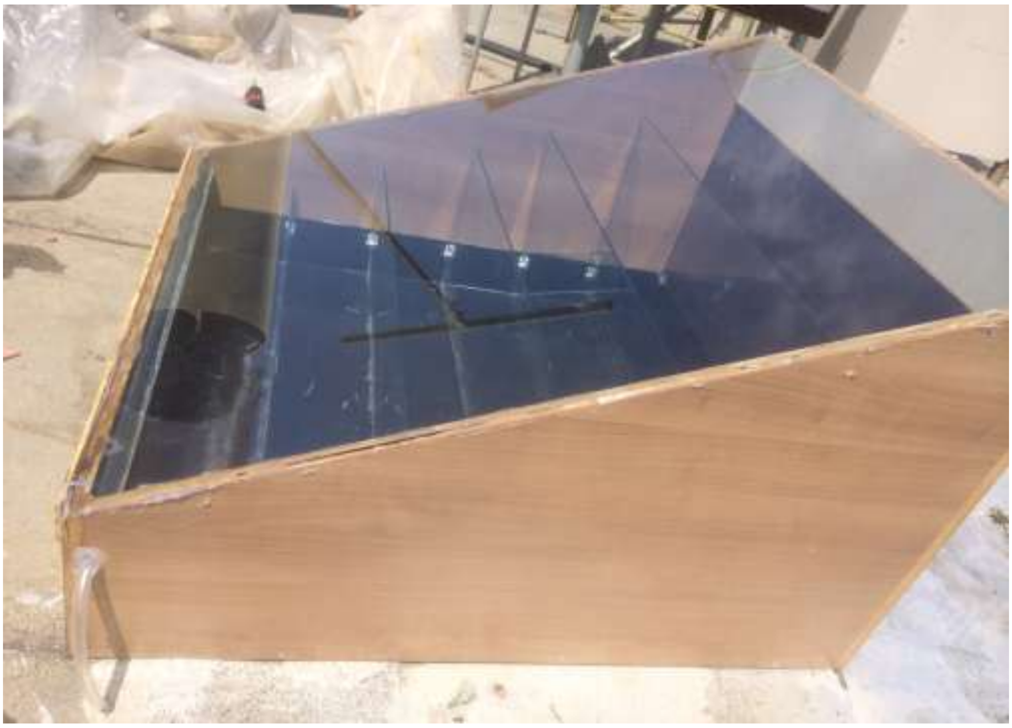

Figure 4.2. Modified Solar still.

Figure 4.3. Reference solar still.

Figure 4.4. CAD model of Modified Solar Still

4.3.1 Wooden Box

The stills basin is a wooden box with dimensions 1m long, 1 m width with a board thickness of 18 mm. The box is painted with black colour. The frame of the box glued with silicon several times from inside to prevent leakage. The still has a 3 mm thick glass cover fixed on the wooden box.

4.3.2 Black Absorbing Pan

The saline water is put into a black absorbing pan. The pan was made from galvanized steel. This pan is a rectangular shape with an area of $0.98m \times 0.98m$ and the height of the pan is 10 cm. There is a gap of 2 cm between the sides of the pan and the wooden box. In order to absorb more solar radiation the absorbing pan is painted in black colour.

4.3.3 Channel

The condensed water is collected with the help of a galvanized channel which is installed underneath the lower side of the glass. This galvanized channel is securely attached on the wooden box. It is used to collect the fresh water into the channel. In order to collect the fresh water this channel is connected to an external storage bottle with a plastic pipe.

4.3.4 5 Different Sizes Glasses

In this project there are 5 different sized glasses in a black aluminium pan. The glasses are placed into the pan in descending order from the biggest one to the smallest one. The glasses' heights are 16, 23, 30 , 37 and 45 cm . The aim of these glasses is to increase the circulation of heated air inside the wooden box. The glasses are fixed in a secured position to the aluminium pan with special connectors. The placement of glasses are presented in Fig. 4.5.

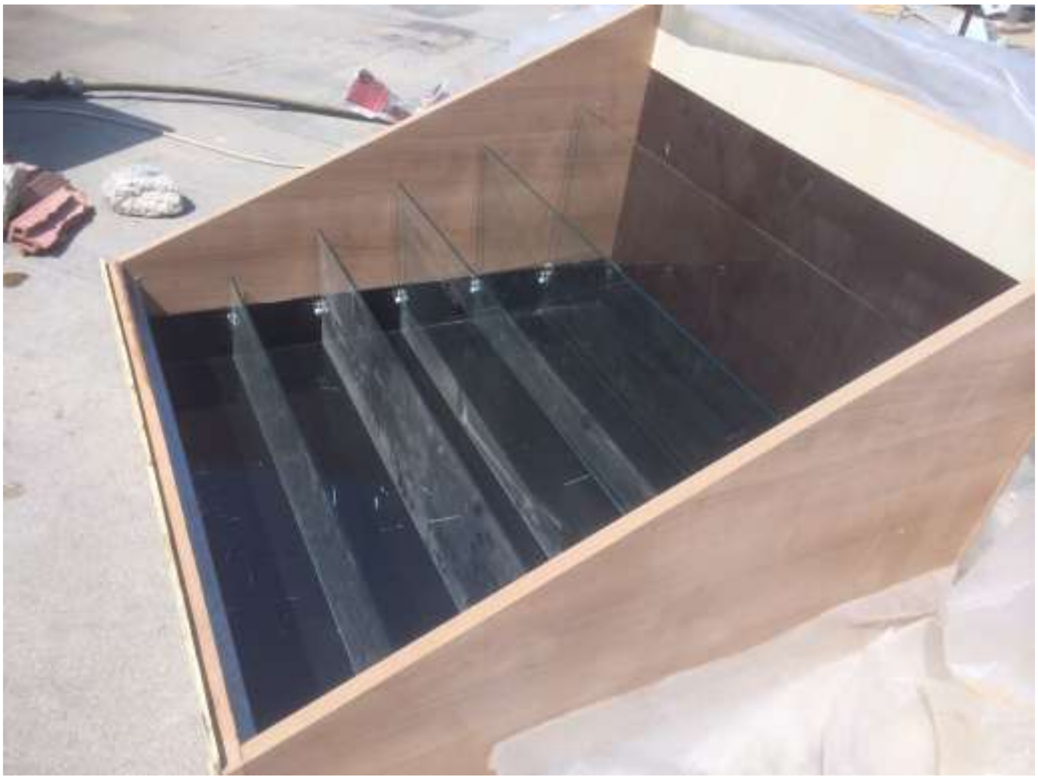

Figure 4.5. Placement of glass panes.

Vertical glass panes were inserted in the solar still as shown in Fig 4.5 above. The laminar free convection with a uniform glass pane temperature was assumed.

4.4 Measuring Equipment

4.4.1 Solar Flux

A pyranometer is a type of actinometer that can measure solar irradiance in the desired location and the flux density of the solar radiation. The solar transmission of pyranometer is from 300 nm or less to about 3000 nm. A voltmeter which is connected to the pyranometer is used to measure the DC voltage. Then the solar irradiance is evaluated by using Equation 4.1. The accuracy of a digital voltmeter may be stated in a two-term form, such as "±0.25% of reading +2 counts", reflecting the different sources of error in the instrument. The pyranometer is installed on the glass surface to obtain the amount of the irradiance of solar still system. Fig4.6 shows a picture of pyranometer and voltmeter.

$$G = \frac{V * 1000}{10.5} \tag{4.1}$$

Where G is the solar irradiance and V is the voltage measured from the multimeter.

Figure 4.6. Pyranometer and DC voltmeter.

4.4.2 Digital Thermometer and Thermocouples

Digital Thermometer temperature range is -50.0 to +200.0 °C and the accuracy is $\mp$0.5 °C. Digital Thermometer measures the temperatures of 5 different sized glasses, air inside the wooden box, ambient temperature, inlet water temperature and also glass cover temperature. There are 10 screw terminals at the back to the digital thermometer and 10 thermocouples sensors can be connected to these terminals. Thermocouples are suitable for measuring over a large temperature range, from −270 up to 3000 °C. All the temperatures are measured in °C. The digital thermometer and thermocouples are presented in Fig.4.7.

Figure 4.7. View of the connection of digital thermometer and thermocouples.

4.5 Mathematical Modelling of Solar Still

4.5.1 Heat loss

Heat is lost in this solar still system through the upper part, the lower part and the sides. Heat loss through the top window is desirable because it helps to keep the transparent cover temperature low, thereby increasing the rate of condensation and distillate production. Top heat loss occurs through convection and radiation. Convective heat loss from the top is influenced by the speed of wind over the transparent cover while radiative heat loss from the top depends on the temperature and emittance of the transparent cover, and ambient temperature. In solar distilation systems, heat transfer can be clasiffied, as internal heat transfer and external heat transfer. External heat transfer is due to conduction, convection and radiation proceses which are independent of each others. The heat transfer which takes place in the solar stil is called internal heat transfer due to convection, radiation and evaporation. Performance of a solar still is directly depent on the internal heat transfer and fresh water production rate. Density difference of humid air due to temperature difference inside the solar still is the major reason for convective heat transfer. The evaporative heat transfer rate from water surface to glass cover a solar still is given by ; [16]

$$q_{ew} = 0{,}0163 h_{cw} \left(P_w - P_g\right) \text{ (W/m}^2\text{)} \tag{4.2}$$

Where, h_{cw} is the convective heat transfer coefficient, P_w is the partial vapour pressure at water temperature, P_g is partial vapour pressure at glass temperature. The convective heat transfer coefficient (h_{cw}) can be obtained from:

$$Nu = \frac{h_{cw} d}{k} = C(Gr\,\mathrm{Pr})^n \tag{4.3}$$

Where, Nu is the Nusselt Number, Gr is Grashof number, C is a constant number, Pr is the Prandtl number, ,

The dimensionless quantities are given by;

$$Gr = \frac{g\beta\rho^2(\Delta T)L^3}{\mu^2} \tag{4.4}$$

Where, g is the acceleration, β is the volumetric thermal expansion coefficient, ρ is fluid density, μ is the fluid viscosity and L is significant length.

$$\mathrm{Pr} = \frac{c_p \mu}{k} \tag{4.5}$$

Where, k is the thermal conductivity, c_p is the specific heat

$$h_{cw} = 0{,}884\left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268{,}9 * 10^3 - P_w}\right]^{\frac{1}{3}} \tag{4.6}$$

Where, T_w is average water temperature, T_g is average glass temperature.

$$P_w = \exp\left(25{,}317 - \frac{5144}{T_w + 273}\right) \tag{4.7}$$

$$P_g = \exp\left(25{,}317 - \frac{5144}{T_g + 273}\right) \tag{4.8}$$

Due to solar radiation water get heated and evaporated. The evaporative heat transfer (h_{ew}) from water to glass is given by:

$$h_{ew} = 16{,}27 * 10^{-3} * h_{cw} * \frac{(P_w - P_g)}{(T_w - T_g)} \qquad (4.9)$$

The convective heat transfer coefficient h_{cw} is also calculated using the following Wattmuf et al, [17] correlation (Wattmuf, at al 1977);

h_{cw} =2.8 +3V; for V≤5 m/s;
(4.10)

h_{cw} = 6.15V $^{0.8}$; for V > 5 m/s (4.11)

The radiation heat ransfer coeficient (h_{rw}) from water to glass is given by: [18]

$$h_{rw} = \varepsilon_{effect}\sigma\left((T_w + 273)^2 + (T_g + 273)^2 (T_w + T_g + 546)\right) \qquad (4.12)$$

where, $\sigma = 5{,}669 * 10^{-8} W / m^2 K^4$ is the Stefan Boltzmann constant

$$\varepsilon_{effective} = \left(\frac{1}{\varepsilon_g} + \frac{1}{\varepsilon_w} - 1\right)^{-1} \qquad (4.13)$$

$$\varepsilon_g = \varepsilon_w = 0{,}9 \qquad (4.14)$$

Total heat transfer coeficient (h_{total}) from water to glass is given by:

$$h_{total} = h_{cw} + h_{ew} + h_{rw} \qquad (4.15)$$

Hourly yield of solar stil is given by;

$$m_w = \frac{q_{ew} A_w}{L} * 3600 \text{ kg/m}^2\text{h} \qquad (4.16)$$

For calculating the axial velocity of u is given by; [19]

$$Ra_L = \frac{\beta g (Ts - T\infty) L}{\nu\alpha} \qquad (4.17)$$

Where, g is gravitational acceleration, L is the plate length, Ra_L is the Rayleigh number at the trailing end x=L, Ts is surface temperature, T∞ is ambient temperature, α is the Thermal diffusivity, β is coefficient of thermal expansion and v is the kinematic viscosity.

$$T_f = \frac{Ts + T\infty}{2} \text{ to find Pr, k and v} \quad (4.18)$$

$$\alpha = \frac{v}{\Pr} \quad (4.19)$$

$$u = 2v \frac{\sqrt{Gr_x}}{x} \frac{d\xi}{d\eta} \quad (4.20)$$

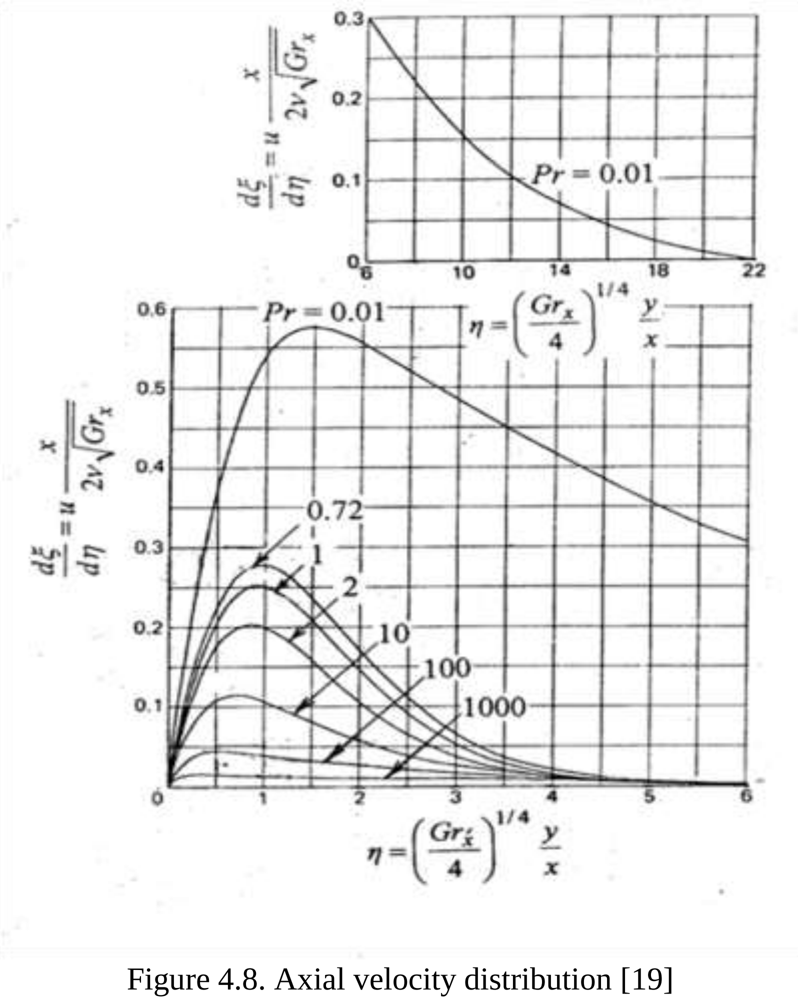

Figure 4.8. Axial velocity distribution [19]

$$\eta = \left(\frac{Gr_x}{4} \right)^{1/4} \frac{y}{x} \tag{4.21}$$

By using Fig 4.7 η and Pr can be found.

$$\frac{d\xi}{d\eta} = u \frac{x}{2v\sqrt{Gr_x}} \tag{4.22}$$

Chapter 5

EXPERIMENTAL RESULTS AND DISCUSSIONS

In this chapter, results obtained from the experimental study and diccussions are presented. The data is gathered from 29.07.2014 to 19.08.2014 under the local weather conditions of Famagusta (35.12°N latitude and 33.95°E longitude) .

The time span of the experiment was from 9.00 AM to 4.00 PM. Temperatures of 5 different sized glasses, inside air, ambient temperature, inside water and the glass cover are measured and solar radiation and potable water are compared with reference solar still.

The results showed that the amount of water produced by the improved solar still (solar still with glasses) is aproximately two folds of the reference solar still. The modified solar still experienced a 5-10 °C rise in the temperature of inside air and the temperature of the inside water when compared with the reference solar still.

5.1 Experimental Results

Solar irradiance, inside air, ambient air, inside water temperatures of 2 different types of solar stills and 5 different sized glasses temperatures for modified solar still are measured and the potable water production is evaluated. It is seen in table 5.1 that solar irradiance starts to increase in the morning, reaching its peak value in the afternoon, and then it starts to decrease after 2.00 PM. Table 5.1 also shows ambient temperature, inside air temperature, inside water temperature, radiation, 5 glasses temparatures and potable water production in each hour.

The maximum fresh water production from modified solar still was evaluated to be 3.51 L/m^2 day. Hourly ambient and inside air temperatures, inside water temperatures, potable water production and solar irradiance of the improved solar still system are also indicated in Fig 5.1, Fig 5.2 and Fig 5.3 respectively.

Table 5.1. Experimental Results of Improved Solar Still on 11th of August

Time	Ambient Temp (°C)	Inside air Temp (°C)	Inside Water Temp (°C)	Radiation (W/m^2)	1.Glass Temp (°C)	2.Glass Temp (°C)	3.Glass Temp (°C)	4.Glass Temp (°C)	5.Glass Temp (°C)	Potable Water Production (ml)
9	30,90	40,8	35,2	704,7	42	42,3	42,5	43	43,4	0
10	32,1	47,8	39,5	876,2	49,2	50,2	51,8	52,3	51,5	200
11	34,5	53,1	46,5	1028,5	54,1	55,7	56,3	56,5	56,8	345
12	35,4	56,8	53,4	1104,7	57,3	59,2	59,8	61,1	61,5	495
13	36,1	61,5	59,5	1123,8	62	63,8	63,6	63,7	64,2	580
14	36,2	66,1	63	1009,5	65,7	68,1	67	67,3	67,5	720
15	35,9	66,8	64,4	923,8	68,2	69,8	68,6	68,7	68,6	650
16	34,7	65,9	64,5	761,9	67,5	68,2	67,3	67,7	67,5	515

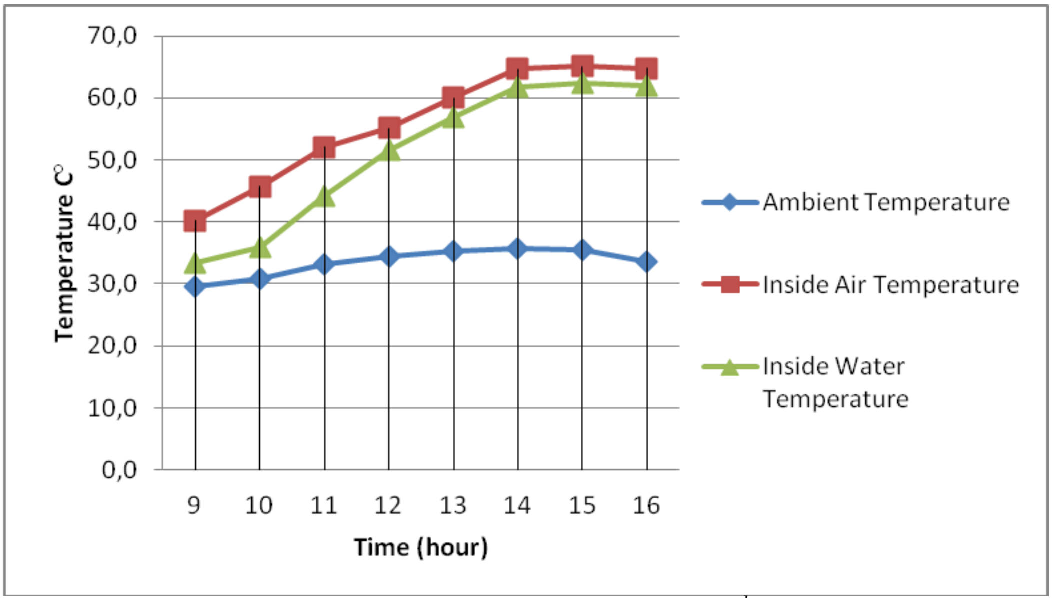

Figure 5.1. Hourly temperature values on 11th of August

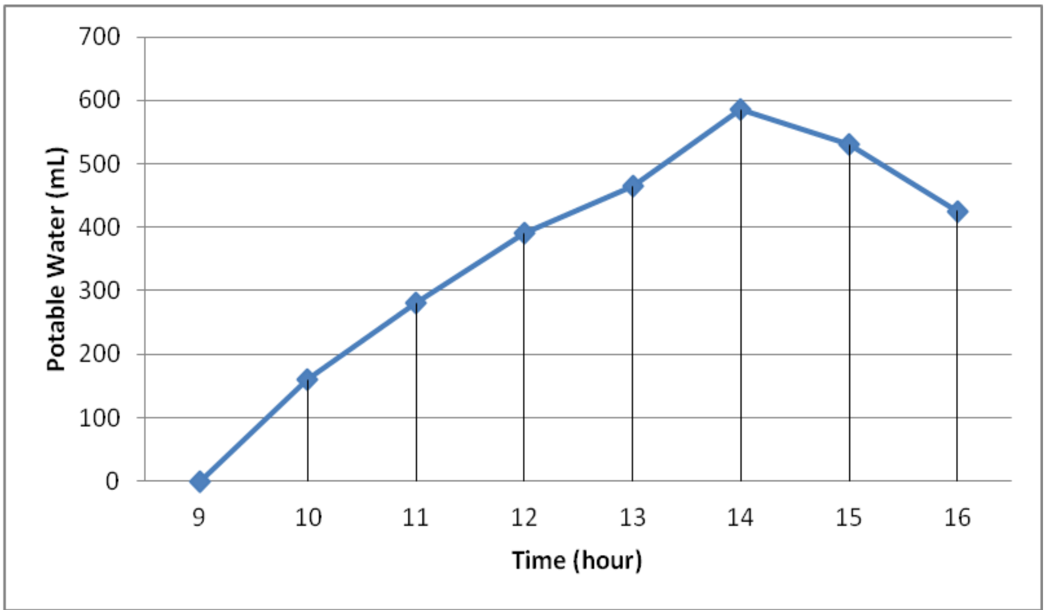

Figure 5.2. Hourly water production on 11th of August

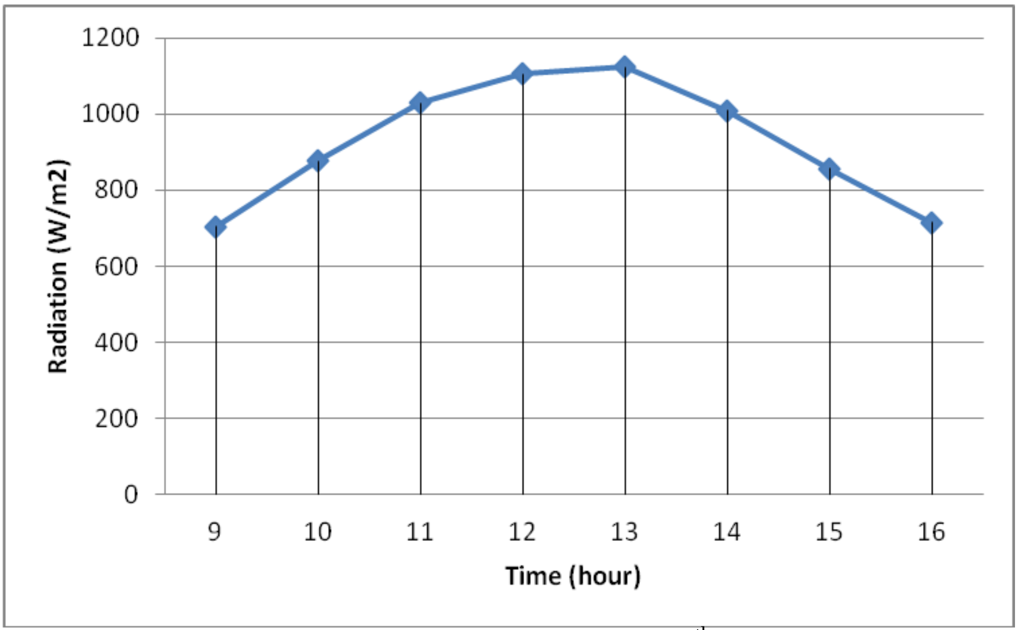

Figure 5.3. Hourly solar irradiance on 11th of August

During the experiment period (29.07.2014 to 19.08.2014), the average outside temperature was 33,6 °C. There were cloudy and rainy days during this period. Fig 5.4 and Fig 5.5 shows outside, ambient and inside water temperatures for modified and reference solar still respectively for a cloudy day (2nd of August). Fig 5.6 shows potable water production for modified and reference solar still for the same cloudy day. Fig 5.7 illustrates the hourly solar irradiance on the modified and reference solar stills on the same cloudy day.

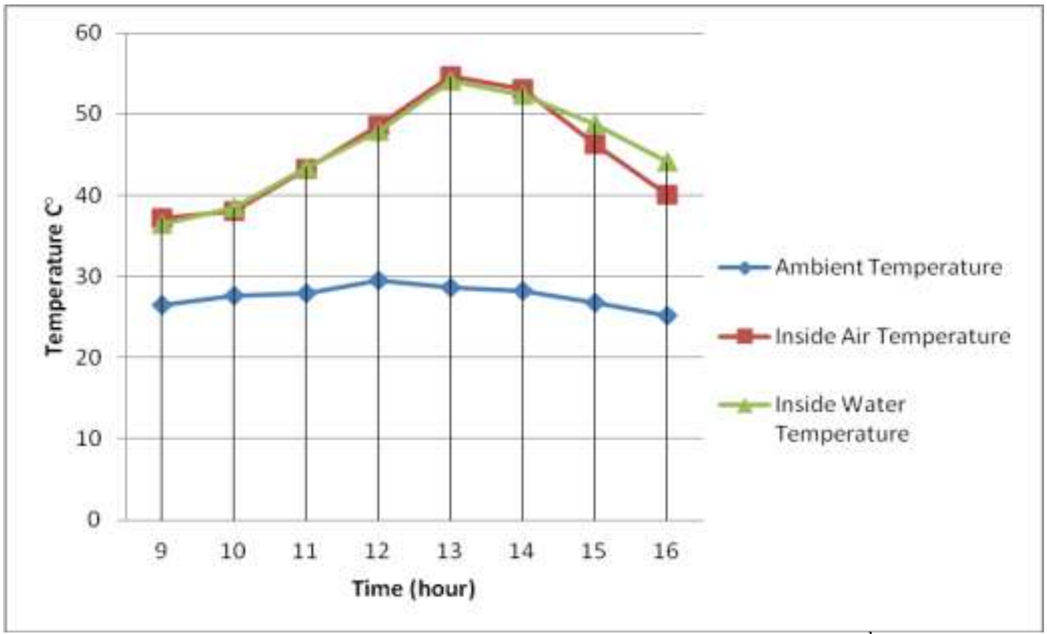

Figure 5.4. The temperature variation of modified solar still on 2th of August

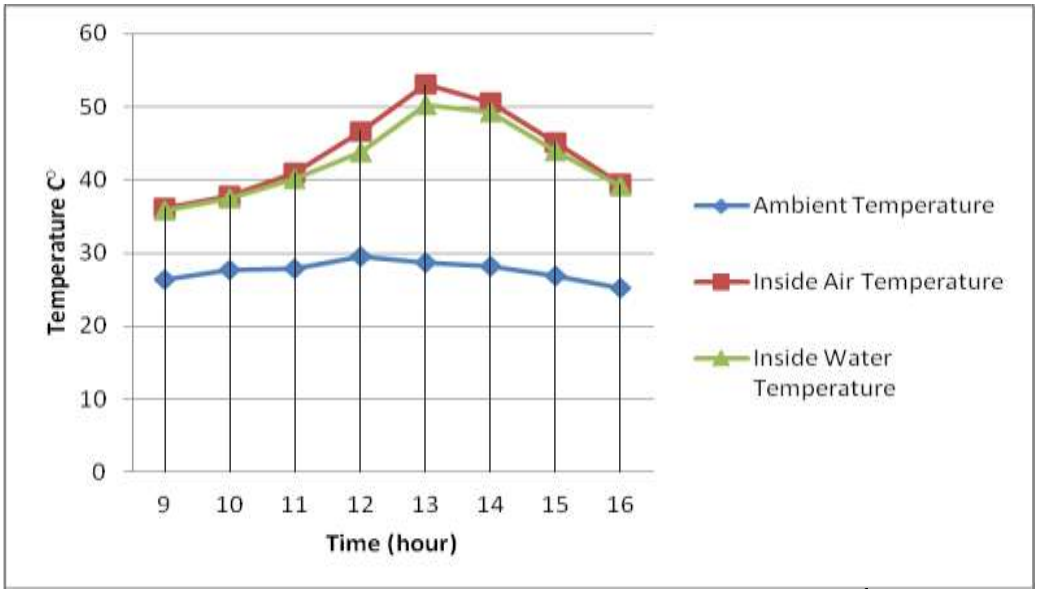

Figure 5.5. The temperature variation of reference solar still on 2th of August

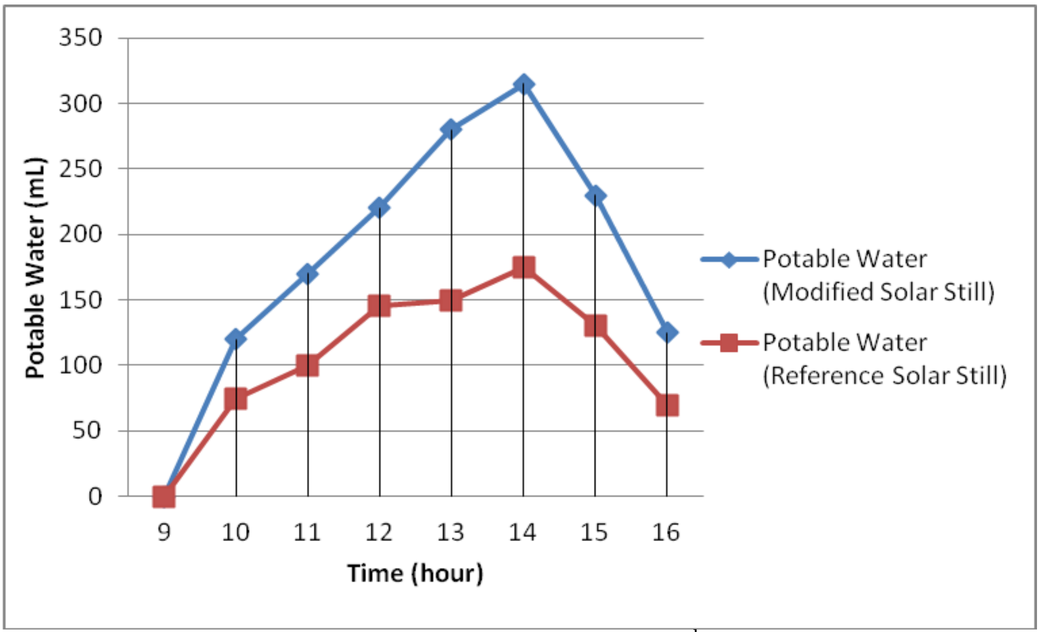

Figure 5.6. The water production on 2th of August

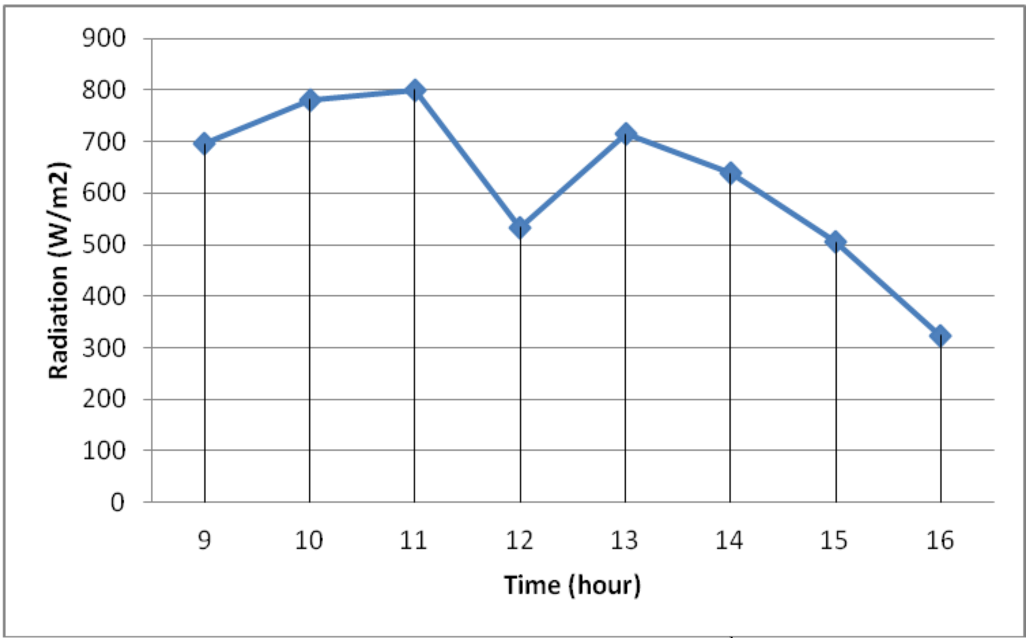

Figure 5.7. Hourly change of irradiance on 2th of August

The averages of all measurements taken in 21 days are calculated. The time period was from 29.07.2014 to 19.08.2014. Table 5.2 and Table 5.3 shows the averages of ambient temperature, inside air temperature, inside water temperature, and the potable water production of the modified solar still and reference solar still respectively. Table 5.2 also involves the averages of temperatures of 5 different sized glasses.

Table 5.2. Averages of measurements for modified solar still during the period 29.07.2014 - 19.08.2014.

Time	Ambient Temp (°C)	Solar Still Inside air Temp (°C)	Inside Water Temp (°C)	Radiation (W/m^2)	1.Glass Temp (°C)	2.Glass Temp (°C)	3.Glass Temp (°C)	4.Glass Temp (°C)	5.Glass Temp (°C)	Potable Water Production (ml)
9	29,5	40,2	33,4	666,6	41,5	41,7	42,0	42,4	42,8	0
10	30,8	45,7	36,0	771,4	47,8	48,2	49,3	50,0	50,7	180
11	33,2	52,1	44,1	933,3	52,5	53,2	54,8	55,1	55,4	300
12	34,4	55,2	51,5	1009,5	55,7	56,8	58,7	59,8	60,2	405
13	35,3	60,0	56,9	1038,1	60	61,5	62,0	62,4	62,7	485
14	35,8	64,8	61,7	980,9	63,8	65,1	65,9	66,3	66,5	590
15	35,6	65,1	62,3	857,1	66,4	66,8	67,5	67,8	68,0	540
16	33,9	64,5	62,1	714,3	66,1	66,7	66,8	67,0	67,1	425

Table 5.3. Averages of measurements for the reference solar still during the period 29.07.2014 - 19.08.2014.

Time	Ambient Temp (°C)	Solar Still Inside air Temp (°C)	Inside Water Temp (°C)	Radiation (W/m^2)	Potable Water Production (ml)
9	29,5	36,2	30,8	666,6	0
10	30,8	42,8	34,5	771,4	110
11	33,2	48,7	40,8	933,3	180
12	34,4	50,5	48,5	1009,5	260
13	35,3	53,9	52,9	1038,1	335
14	35,8	57,7	56,7	980,9	415
15	35,6	59,1	58,4	857,1	350
16	33,9	57,3	57,7	714,3	295

5.2 Error analysis of the device used in the measurements

The measurements were done with devices whose accuracies are given in table 5.4 below and the uncertainties of the readings such as temperature, and solar radiation taken into account.

Table 5.4: Accuracies of the device used

Devices	Accuracy
Digital Thermometer	± 0.5 °C
K type thermocouples	± 1.5 °C
Pyranometer	$8\ \mu V/(W/m^2)$
VICHY VC9805A+ Multimeter	Current: 2%; Voltage: 0.25%

There are two main types of errors associated with experimental works and they are:

- The precision which comes from random error distribution.
- The accuracy is as a result of errors in calibrations and systematic errors.

In this study, the uncertainties are calculated as :

For product functions, the equations 5.1 and 5.2 below is used

$$R = x_1^{a_1} x_2^{a_2} \dots x_n^{a_n} \quad (5.1)$$

$$\frac{W_R}{R} = \left(\sum \left(\frac{a_i w_{xi}}{x_i} \right)^2 \right)^{1/2} \quad (5.2)$$

Where $a_i = \frac{\partial R}{\partial x_i}$

Where R represents the result, and the variables be represented by W_R, W_1,W_2, …,W_n

The maximum irradiance was calculated to be 1123.8 (W/m^2), where the measured voltage was 11.7 mV, so the uncertainty of the irradiance is calculated with the above equations 5.1 and 5.2 as

$G = 1123.8 \pm 2.5\ (W/m^2)$

5.3 Economic Analysis of Modified Solar Still

This study aims to investigate the performance of modified solar still desalination system in terms of daily production, system cost and distilled water production cost and to compare it with reference solar still. The life cycle cost analysis should be done in order to make this comparison. The cost of the modified solar still system materials are shown in Table 5.5 whereas the cost of the reference solar still system materials are shown in Table 5.6.

Table 5.5. Cost of the materials used to build the modified solar still in Turkish Lira (TL).

Material	Cost in TL
Wood	70
All Glasses	45
Heat resistant black paint	28
100% silicon	42
Screws	3
Total Cost	188TL

Table 5.6. Cost of the materials used to build the reference solar still in Turkish Lira (TL).

Material	Cost in TL
Wood	70
All Glasses	27
Heat resistant black paint	28
100% silicon	42
Screws	3
Total Cost	170 TL

- The LCC analysis of the modified solar still was done by using the spreadsheet program which is given in appendix A. The parameters for the Life Cycle Cost analysis (LCC) for modified solar still are given as:

Estimated annual clean water output = average daily output x 365 day

= 2.925litres/day x 365days

= 1067.63 liters

The annual savings = annual output x water price (0.5TL/ litre), which is = 533.81TL

- Total annual savings = 533.81TL
- The initial investment = 188TL
- analysis period =10 years
- Discount rate = 4%

In the analysis, below factors were evaluated:

- The Net Present Value (NPV) shows the sum of the present worth of the cash flows within the considered analysis period, results > 0 validates the project as being economically feasible.
- Savings-to-Investment (SIR) evaluates the ratio of the savings to investment, where result = 1 shows that the initial cost is totally recovered, results > 1 shows that the savings will be more than and results < 1 shows that the cost would be greater than savings over the analysis period.
- Internal rate of return (IRR) is the discount rate that makes the net present value of the initial investment equal to zero.

Table 5.7 shows the result of the LCC analysis fort he modified solar still

Table 5.7. Results of the LCC analysis for modified solar still

Economic Evaluations	**Results**
Net Present Value (NPV)	**4 134 TL**
Savings-to-Investment Ratio (SIR)	**23.0**
Internal Rate of Return (IRR)	**28.3%**
Simple Payback (SP)	**0.4 years**

- The LCC analysis of the reference solar still was done by using the spreadsheet program which is given in appendix B. The parameters for the Life Cycle Cost analysis (LCC) for reference solar still are given as:

Estimated annual clean water output = average daily output x 365 days

= 1.95litres/day x 365days

= 711.75 liters

The annual savings = annual output x water price (0.5TL/ litre), which is = 355.87TL

- Total annual savings = 355.87TL
- The initial investment = 170TL
- analysis period =10 years
- Discount rate = 4%

Table 5.8 shows the results of the LCC analysis for reference solar still

Table 5.8: Results of the LCC analysis for reference solar still.

Economic Evaluations	**Results**
Net Present Value (NPV)	**2716 TL**
Savings-to-Investment Ratio (SIR)	**17.0**
Internal Rate of Return (IRR)	**20,9%**
Simple Payback (SP)	**0.5 years**

Chapter 6

CONCLUSION

In this study, a comparison of performances of modified solar still and simple conventional solar still which is named as reference solar still is presented. The number of days the experimental studies were conducted was 21 days. The experimental set up is constructed onto the roof of the Mechanical Engineering Department of E.M.U building and the tests were done under the weather and climate conditions of North Cyprus. Brackish water was used to fill the basin of two solar still desalination systems.

With the modified solar still, the maximum daily clean water production obtained on 11^{th} August 2014 was 3,51 L/m^2day. The maximum clean water production in reference solar still, was 2.1 L/m^2day at the same day. Also the solar irradiance, inside and ambient air of the solar still and water temperatures of 2 different type of solar stills, 5 different sized of glasses temperatures were measured.

With the average measurements of the modified solar still, the maximum average glasses temperatures were on 5 th glass was 68 °C at 15:00 in the afternoon. We can see that in Table 5.2, solar still inside air temperature was greater than the inside water temperature on the modified solar still. The maximum average radiation was

1.03 W/m^2. The total average clean water production was 2.92 L/m^{2}day. The average clean water production on reference solar still type was 1.95 L/m^{2}day.

When the figures in Table 5.7 and Table 5.8 are investigated, it is seen that modified solar still is more feasable than the reference solar still. All the indicators (NVP, SIR, IRR, SP) are better for modified solar still. This is expected as the clean water production is much higher in the modified solar still than the reference solar still.

The most important factor which affects the productivity of the solar still during the experiment is solar radiation. The more the solar radiation, the more the amount of distilled water produced in both systems but the modified system produced more compared to the reference system.

6.1 Future work

The aim of this project was to produce a modified solar still and test its performance (clean water output). Clean water output from a solar still is dependent on the inside temperature of the solar still. As the inside temperature increases clean water output from the solar still increases. In this work no insulation used for the wooden box of the solar still causing increased heat loss. As a future work insulation could be added to wooden box for the aim of reducing heat losses thus increasing clean water output.

Our solar still is desigend relatively small due to the lack of available space on the roof. However it is known that if the sytem gets bigger clean water output increases. Therefore it should be considered in future to design bigger system to increase clean water output.

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APPENDICES

Appendix A: Life Cycle Cost Analysis for Modified Solar Still

Table 1: Life Cycle Investment Schedule

TABLE1

Life Cycle Investment Schedule, from Steps 1, 2, and 3

Year	New	Old	Net Amount
0	$188		$188
1			$0
2			$0
3			$0
4			$0
5			$0
6			$0
7			$0
8			$0
9			$0
10			$0
11			$0
12			$0
13			$0
14			$0
15			$0
16			$0
17			$0
18			$0
19			$0

TABLE 2

Annual Savings	$533	(from Step 3)
Discount Rate	4%	(from Step 4)
Analysis period (years)	10	(from Step 5)
Residual value	$0	(from Step 6)

Life Cycle Cost Analysis

Calculations

TABLE 3: Savings Calculations Formula: PV Annual Savings = Annual Savings / (1 + Discount Rate)^{year} (from Step 7)

Year	0	1	2	3	4	5	6	7	8	9	10
Annual Savings	$0	$533	$533	$533	$533	$533	$533	$533	$533	$533	$533
PV Annual Savings	$0	$512	$493	$474	$456	$438	$421	$405	$389	$374	$360
Σ PV Annual Savings	$4.322										

TABLE 4: Investments Formula: PV Life Cycle Investment = Life Cycle Investment / (1 + Discount Rate)^{year} (from Step 8)

Year	0	1	2	3	4	5	6	7	8	9	Residual
Net Life Cyle Investments	$188	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
PV Life Cycle Investments	$188	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Σ PV Life Cycle Investments	$188										

Net Cash Flows (for IRR calculation)	($188)	$533	$533	$533	$533	$533	$533	$533	$533	$533	$533

Life Cycle Cost Analysis

Output

TABLE 5: Results	OUTPUTS		Formulas:	
Net Present Value (NPV)	$4 134	(from Step 9)	Life Cycle Net Savings	= Σ PV Annual Savings - Σ PV Life Cycle Investments
Savings-to-Investment Ratio	23,0	(from Step 10)	Savings-to-Investment Ratio	= Σ PV Annual Savings / Σ PV Life Cycle Investments
Internal Rate of Return (IRR)	283%	(from Step 10)	Internal rate of return	= Discount rate, where SIR = 1.0, or NPV = 0
Simple Payback (years)	0,4		Simple payback	= Initial investment / annual savings

Appendix B: Life Cycle Cost Analysis for Reference Solar Still

Table 1: Life Cycle Investment Schedule

TABLE1

Life Cycle Investment Schedule, from Steps 1, 2, and 3

Year	New	Old	Net Amount
0	$170		$170
1			$0
2			$0
3			$0
4			$0
5			$0
6			$0
7			$0
8			$0
9			$0
10			$0
11			$0
12			$0
13			$0
14			$0
15			$0
16			$0
17			$0
18			$0
19			$0

TABLE 2

Annual Savings	$356	(from Step 3)
Discount Rate	4%	(from Step 4)
Analysis period (years)	10	(from Step 5)
Residual value	$0	(from Step 6)

Life Cycle Cost Analysis

Calculations

TABLE 3: Savings Calculations — Formula: PV Annual Savings = Annual Savings / (1 + Discount Rate)^{year} (from Step 7)

Year	0	1	2	3	4	5	6	7	8	9	10
Annual Savings	$0	$356	$356	$356	$356	$356	$356	$356	$356	$356	$356
PV Annual Savings	$0	$342	$329	$316	$304	$292	$281	$270	$260	$250	$240
Σ PV Annual Savings	$2.886										

TABLE 4: Investments — Formula: PV Life Cycle Investment = Life Cycle Investment / (1 + Discount Rate)^{year} (from Step 8)

Year	0	1	2	3	4	5	6	7	8	9	Residual
Net Life Cyle Investments	$170	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
PV Life Cycle Investments	$170	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Σ PV Life Cycle Investments	$170										

Net Cash Flows (for IRR calculation)	($170)	$356	$356	$356	$356	$356	$356	$356	$356	$356	$356

Life Cycle Cost Analysis

Output

TABLE 5: Results	OUTPUTS		Formulas:	
Net Present Value (NPV)	**$2 716**	(from Step 9)	Life Cycle Net Savings	= Σ PV Annual Savings - Σ PV Life Cycle Investments
Savings-to-Investment Ratio	**17,0**	(from Step 10)	Savings-to-Investment Ratio	= Σ PV Annual Savings / Σ PV Life Cycle Investments
Internal Rate of Return (IRR)	**209%**	(from Step 10)	Internal rate of return	= Discount rate, where SIR = 1.0, or NPV = 0
Simple Payback (years)	**0,5**		Simple payback	= Initial investment / annual savings