Experimental Study on Inclined Double Solar Water Distillation System

Foad Irani

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the Degree of

Master of Science
in
Mechanical Engineering

Eastern Mediterranean University
January 2014
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Elvan Yılmaz
Director

I certify that this thesis satisfies the requirements as a thesis for the degree of Master of Science in Mechanical engineering.

Prof. Dr. Ugur Atikol
Chair, Department of Mechanical Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Mechanical Engineering.

Prof. Dr. Hikmet Ş. Aybar
Supervisor

Examining Committee

1. Prof. Dr. Fuat Egelioğlu ______________________
2. Prof. Dr. Hikmet Ş. Aybar ______________________
3. Prof. Dr. Ugur Atikol ______________________

ABSTRACT

The aim of this project is to design and test the double inclined solar water distillation system and compare it with a single inclined solar water distillation system under the climate conditions of North Cyprus. In an inclined solar water distillation system, the feeding water falls down on the bare plate through the distribution pipe. The double inclined solar water distillation system has two sections. In the lower section the feeding water falls down on the bare plate, through distribution pipe. In upper section of the double inclined solar water distillation system, the feeding water falls down on the glass, through distribution pipe. Inclined solar water distillation (ISWD) and double inclined solar water distillation (DISWD) systems have the ability to produce both fresh water and hot water at the same time. These systems were tested by two variants: bare plate and black-fleece wick. It was observed that both systems showed better performance with higher production rate of fresh water when the black-fleece wick was used. Also, the hot water produced by both an inclined solar water distillation and double inclined solar water distillation systems was hot enough for domestic appliances. In comparison of these two systems with each other, the amount of condensate water and hot water produced by a double inclined solar water distillation system is more than that of an inclined solar water distillation system.

Keywords: Solar distillation, solar hot water, wick.

ÖZ

Bu tezin amacı, çift eğimli güneş su damıtma sistemini tasarlamak, test etmek ve Kuzey Kıbrıs iklim koşullarında tek eğimli güneş su damıtma sistemi ile karşılaştırmaktır. Tek eğimli ğüneş su arıtma sisteminde, besleme suyu dağıtım borusundan çıplak plakaya düşmektedir. Çift eğimli ğüneş su arıtma sistemi iki kısımdan oluşmaktadır. Alt kısımda besleme suyu dağıtım borusundan çıplak plakaya düşmektedir. Üst kısımda dağıtım borusundaki su cama düşmektedır. Bu tür sistemlerin aynı anda içilebilir ve sıcak su üretme olanaği vardır. Önerilen bu sistemler iki şekilde test edildi, çıplak plaka ve siyah polar fitil. Tek ve çift eğimli güneş enerjili su damıtma sistemlerinde siyah polar fitil kullanıldığında tatlı su üretimi çıplak plakadaki üretimden daha çoktur. Ayrıca tek eğimli ve çift eğimli güneş enerjili su damıtma sistemleri tarafından üretilen sıcak su, ev aletleri için uygun sıcaklıktadır. Bu iki sistem birbiri ile karşılaştırıldığında, çift eğimli güneş enerjili su damıtma sistemi tarafından üretilen tatlı su ve sıcak su miktarının, tek eğimli güneş enerjili su damıtma sistemi tarafından üretilen tatlı su ve sıcak su miktarından daha fazla olmaktadır.

Anahtar Kelimeler: Güneşle damıtma, Güneşle sıcak su, tapa

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATION

ISWD	Inclined Solar Water Distillation System
DISWD	Double Inclined Solar Water Distillation System

Chapter 1

INTRODUCTION

1.1 Background

Energy and water are two significant issues from the environmental point of view; both of them play vital role in the improvement of the economy over the entire world. Potable water is a basic human need, and pollutants made by human beings have adversely affected it. Most water exists in the form of seawater, and only limited sources of fresh water can be found in the surface of the earth or deep in the earth or as natural aqueducts. Most water resources contain salt, bacteria and pollutants. To obtain fresh and potable water, is a need to distill and process water. These conditions necessitate the application of purification in order to obtain pure water from brackish or salty water. In many places, the fresh and portable water is not enough and demand exceeds the supply. To produce potable water by employing thermal method heat energy is required. The cost of utilizing solar energy to produce fresh water is reasonable and also there is no remained pollutant from the process. Although, there are many different types of distillation processes for desalting water systems using renewable energy such as solar energy has some benefits in the remote areas, where there is no access to electricity or difficult to reach fossil fuels.

1.2 Renewable Energy and Purification Plants

The availability of high quality water is essential and important, so as a solution, desalination of dirty or seawater should be considered where there is lack of fresh water. A positive point of desalination systems is that, they can be installed in the regions where there is no electricity grid. Renewable energy sources, such as solar or wind energy have the potential to be used in order to run the desalination systems. High initial capital cost is an impediment for using renewable energy technologies, but they have several benefits and advantages such as less or no pollutions. In the areas where there is high solar radiation, brackish water can be desalinated by utilizing solar energy to obtain potable water. In many countries people are suffering from lack of potable water, and desalination systems are used to provide potable and fresh water, so running desalination systems by utilizing renewable energy such as solar energy is one of the best solutions for this kind of crisis.

1.3 Solar Desalination Systems

The solar desalination systems provide potable or fresh water for drinking and cooking. There are different classifications for solar desalination systems. In term of energy supply, solar desalination systems fall into two categories: passive and active solar stills. The passive solar still systems are those using solar energy as the only source of thermal energy. In the active solar stills extra thermal energy is given to the passive solar still for faster evaporation.

It can also be classified according to different used techniques, phase change or thermal processes and membrane or single-phase processes. In the phase change process the distillation of sea water is achieved by utilizing a thermal energy source. The thermal energy may be obtained from a conventional fossil-fuel source, nuclear energy or from a non-conventional solar energy source. In the membrane process, electricity is used either for driving high pressure pumps or for ionization of salts contained in the sea water. In term of structure, solar desalination systems fall into two main categories, direct systems and indirect systems. The former one refer to those systems which all parts are integrated into one system which means it uses solar energy directly to produce distillate mainly on the backside of the glass cover of solar collector, while the later one refer to those which two sub-systems are employed separately, one for solar energy collection and one for desalination which means distillate mainly produce in a separate condenser. In the direct solar desalination systems, there are different kinds of solar stills like simple or conventional solar stills, double basin or regenerative solar stills, triple basin solar stills, pyramid shape solar stills, capillary film distiller stills, multi effect solar stills and etc. For the in-direct systems, there are different kinds of humidification-dehumidification systems, solar stills with outside condenser, solar stills with forced condensation and etc.

1.4 Objectives

The main purpose of this project is to design, construct and test a single inclined and double inclined solar water distillation systems. One of the aims is to find and compare the fresh water and hot water production of these systems under North Cyprus climate conditions. The effect of covering plate by fleece on the fresh water and hot water production is also studied.

Review of the literature in distillation demonstrates numerous studies conducted about producing fresh and hot water by using solar energy. There are many studies and experiments that have been done on the inclined solar water distillation system and double inclined solar water distillation system. However, none of them has considered and compared the amount of fresh and hot water produced by inclined solar water distillation system to double inclined solar water distillation system. This work is classified into five Chapters. Chapter 1 introduces the background of solar desalination. Chapter 2 is the literature review and the historical background.

Chapter 3 presents the system description and experimental setup. Chapter 4 presents the results found out in this work. Chapter 5 is the conclusion.

Chapter 2

LITERATURE REVIEW ON SOLAR STILLS

2.1 Background

The use of water desalination technologies accelerated simultaneously as the need for fresh water was increased. During the past years, the cost of distillation plants has decreased because of introduction of new and more efficient technologies.

2.2 Water Distillation

Distillation technologies were used for some years to provide fresh and potable water for labors in small industrial society in the past. After 1945, the demand for potable water was increased; this caused the increase in using distillation systems. Within recent years, the progress that have been made and also the modifications and improvements in efficiency brought down the cost of distillation systems. Separating impure water from dissolved substance is possible by evaporating and then again condensing it. Evaporation procedure requires an external thermal sources which can be provided by different sources such as solar energy [1-5], nuclear energy [6-8] and other sources [9-12]. Solar energy is a renewable energy and the devices which are used to collect solar energy are most expensive and the large number of space are needed in order to storage the solar energy [13].

2.3 Solar Still

Solar still distillation is one of the different processes that can be applied to remove the impurities from water. Solar irradiation is the source of heat energy needed for this kind of work. In this process, the sun radiation provides heat to evaporate water and to separate the vapor from impurities that exist in the water, after that condense it as portable water under the glazing. Distillation processes simulate water evaporation and raining cycle on the earth. The sun's radiation or solar radiation heats the water in the oceans, seas and rivers. It evaporates and condenses and forms clouds, which fall on the earth as rainwater. Solar still can be classified basically in two types; active and passive solar still systems [14].

2.4 Development of Solar Still

A conventional solar still is often used to distill brackish or salty water in order to obtain fresh and drinkable water. However, the efficiency of a conventional solar still is low and made this system not so much popular. Numerous scientists have been working on the conventional solar still by modifying it in order to increase the efficiency of this kind of system. The efficiency of a conventional solar still's efficiency depends on solar irradiation, ambient temperature, weather conditions, heat loss and glazing material [15].

Different designs have been made to make progress in performance of solar stills, some of them are; multi-basin [16], double-basin [17], wick basin [18] and multi-use environmental type [19]. The efficiency of different solar stills depend on many parameters [20]. Also, the water height in the basin affect the yield [21]. The yield increased by using black sand and black rubber in solar stills [22].

2.5 Relative Historical Review

In order to improve fresh water yield various tests and experiments were conducted. Some of these experiments are briefly explained in the following section, which are related to this work.

In 2006 Mathematical modeling of an inclined solar water distillation system was proposed by Aybar, H.S,[23]. An inclined solar water distillation system, which generates distilled water (i.e., condensate) and hot water at the same time, was modeled and simulated. In the parametric studies, the effects of feed water mass flow rate and solar intensity on the system parameters were investigated. Finally, the system was simulated using actual deviations of solar intensity and ambient temperature during a typical summer day in North Cyprus. The system could generate 3.5–5.4 kg (per m^2 absorber plate area) of distilled water during a day (i.e., between 7 am and 7 pm). The temperature of the produced hot water was reached as high as 60˚C, and the average water temperature was about 40˚C, which is good enough for domestic use. The simulation results were in agreement with the experimental results.

In 2005, an experimental study on an inclined solar water distillation system was conducted by Aybar, et al. [24]. This experiment was carried out under Famagusta weather conditions. The feed water flows on the bare plate and solar radiation evaporates water, then the water vapors condenses under the glass, cover used as glazing. Condensate water was collected in a separate reservoir where hot water is directed to another reservoir. This experiment was carried out with three variants; bare plate, black cloth and black fleece. Using the wick caused the even distribution of water on the absorber plate, which improved the yield compared to the flowing water on a bare plate. The potable water production increased when black wick was used. In this work, the test was carried out for 7 hr. In this experiment, 2 ºC and 4 ºC were the temperature difference was between the hot water and air temperature inside the box. The feed water that comes from the main reservoir tank is 4060-brackish feed water (i.e., 4060 ppm). With the bare plate the hardness of fresh water obtained was about 42 ppm. With the black-cloth wick and the black-fleece, the hardness of the fresh water was measured as 79 ppm and 140 ppm, respectively. Using wicks increased the potable water production two to three times.

In 2008, a study was performed by Assefi [25], which was about reviewing an analysis of solar desalination systems under this scope. This study was carried out on modeling and analyzing a single slope solar still in order to investigate the effect of water depth and inclination angle of the glass cover on the productivity of the system. Among the published experimental data, it was found that the highest productivity rate is obtained with solar humidification-dehumidification systems while that the lowest is obtained by using conventional solar stills with bare plate.

Akash, et al [26], proposed a study about performance investigation of a single basin solar still. This system had different absorber materials; they did an experiment with three variants; black absorber rubber mat, black ink and black dye. The results showed that water production was increased by 60% and 45% for black dye and black ink respectively.

The total productivity rate of the proposed system under the climate condition of North Cyprus on 21st of March was obtained which were about 5.3 kg/m^2.day. The total obtained productivity rates are compared with previous experimental studies and it was discovered that there is a difference of ±3.37 on average.

Chapter 3

SYSTEM DESCRIPTION AND EXPERIMENTAL SETUP

3.1 Apparatus

Both the inclined and double inclined solar water distillation systems were designed and constructed in the Department of Mechanical Engineering. They were tested and compared with each other. The experiments were carried out by two different variants: bare plate and black-fleece. Both systems are explained briefly in the following sub-sections.

3.1.1 Inclined Solar Water Distillation System

An inclined solar water distillation system consists of a cavity made of galvanized steel and painted mate black to increase its absorptivity. The length of the cavity is 100 cm, the width of the cavity is 50 cm and the depth of the cavity is 20 cm and an ordinary transparent glass with 4 mm thickness cover the cavity. A distribution pipe having length of 50 cm was placed at the top inside of the box (see Fig.3.1). There are several holes on the pipe to let the feed water drops on the bare plate. On the other side of the box, there is a channel located under the glass, to collect the running condensed water under the glazing. There is a hole in the middle bottom of the box to allow the remaining hot water get collected in separate collector. Theoretically, it is being said that the best angle for a surface to get the most solar radiation is approximately equal to the latitude of the location. North Cyprus is located at 35˚N and 33˚E. The optimum angle for a tilted surface to get the most solar radiation is approximately the same as the latitude of the place, i.e., 35˚ with the horizontal facing south for Famagusta. Figure 3.1 shows a schematic diagram of the ISWD system.

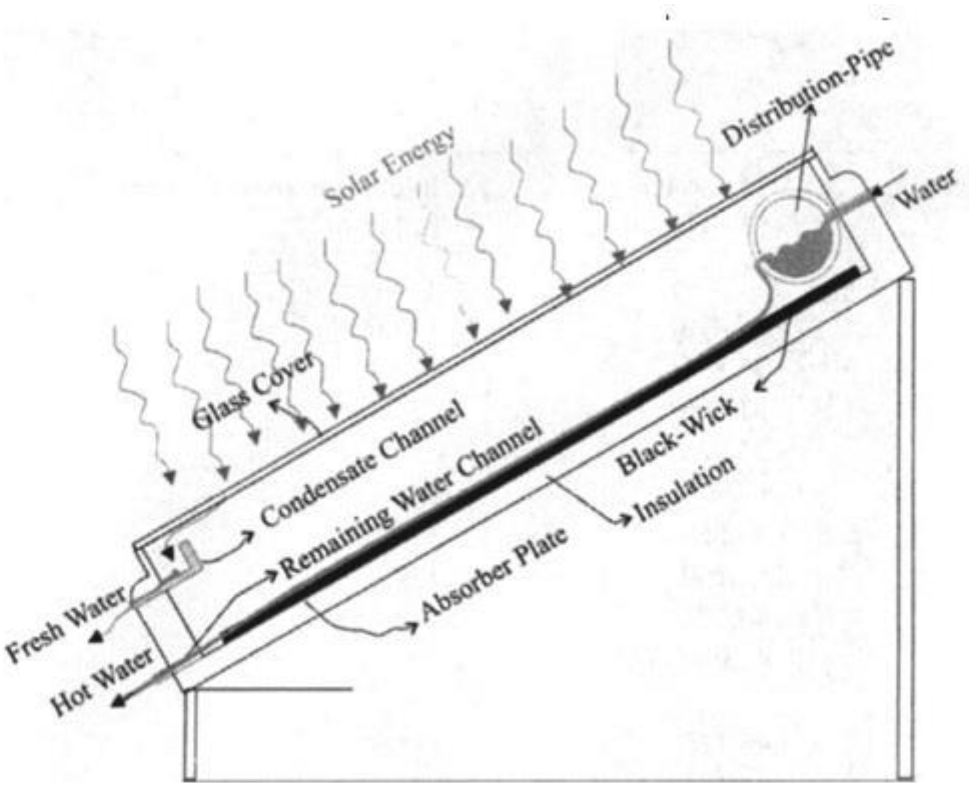

Figure 3.1: Schematic diagram of ISWD [24]

3.1.2 Double Inclined Solar Water Distillation System

Three sides of the double inclined solar water distillation system, i.e., bottom, left and right inner sides are made of galvanized steel, painted to matte black to increase the absorptivity. The middle and the top of the system are covered with transparent glass having thickness of 4 mm. As it is shown in Fig. 3.2, DISWD is divided into two sections; lower and upper section. The lower section has a rectangular shape; the bottom and two sides are made of the galvanized steel, the top and left and right inner sides covered by glass. The upper section of DISWD has two sides made by galvanized steel, the left and right inner sides and the bottom and top are covered with 4mm thick transparent glass. In both lower and upper sections there are pipes that have small holes on them to distribute feeding water on the plate and the glass. The channels collect and allow the condensate water vapor get collected in reservoirs. There are pipes connected to the holes to guide the remaining hot water get collected into separate tanks.

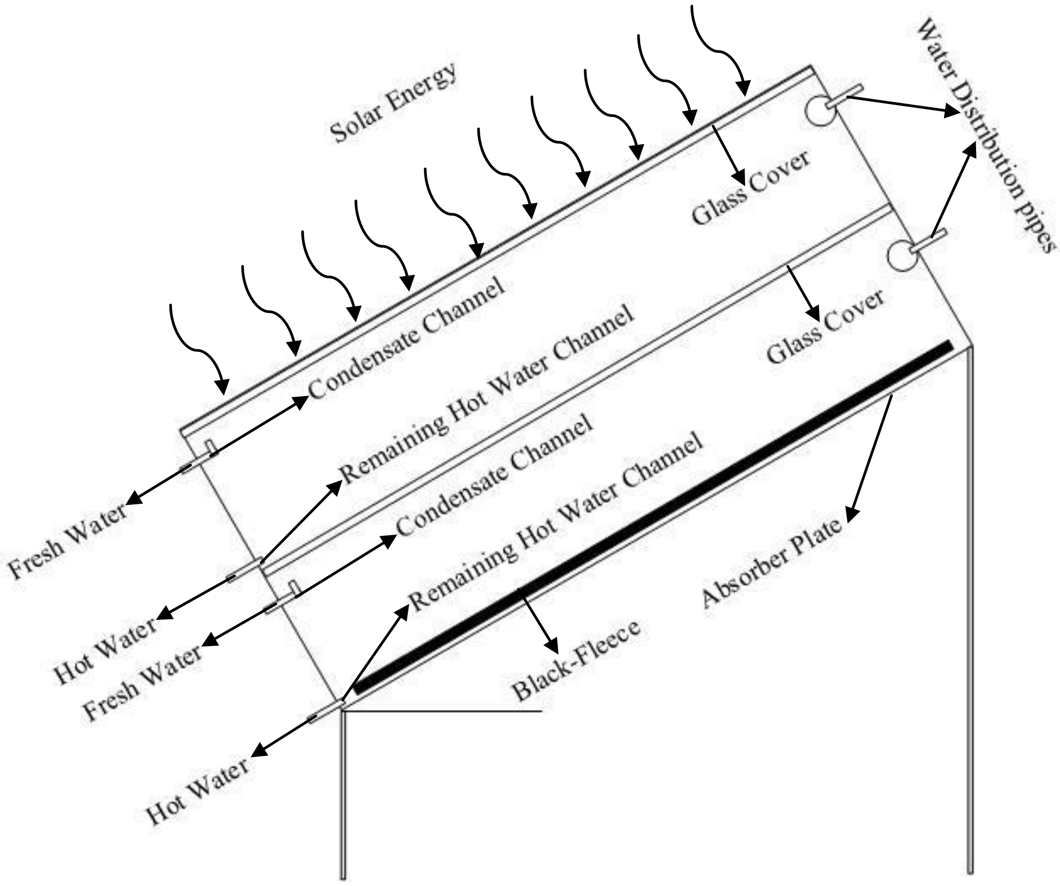

Figure 3.2: Schematic diagram of DISWD system

3.1.3 Water Reservoir and Black-Fleece

The volume of the container of the feeding water in this study is 200 Litter. From the water reservoir, the feeding water through the pipes was distributed in the inclined solar water distillation system and double inclined solar water distillation system. Black-fleece is preferred in this work, due to the fact that by applying black fleece, thicker layer of evenly distributed water was made whereas the distribution on the bare plate was uneven. Figure 3.3and Fig.3.4 shows the ISWD and DISWD systems and the experimental setup of DISWD system.

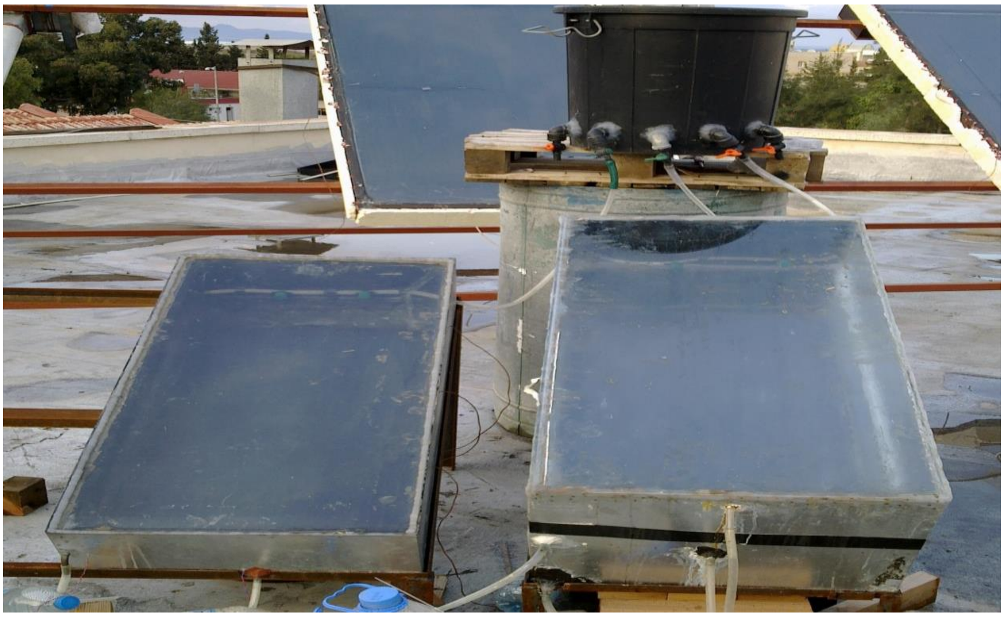

Figure 3.3: ISWD and DISWD systems

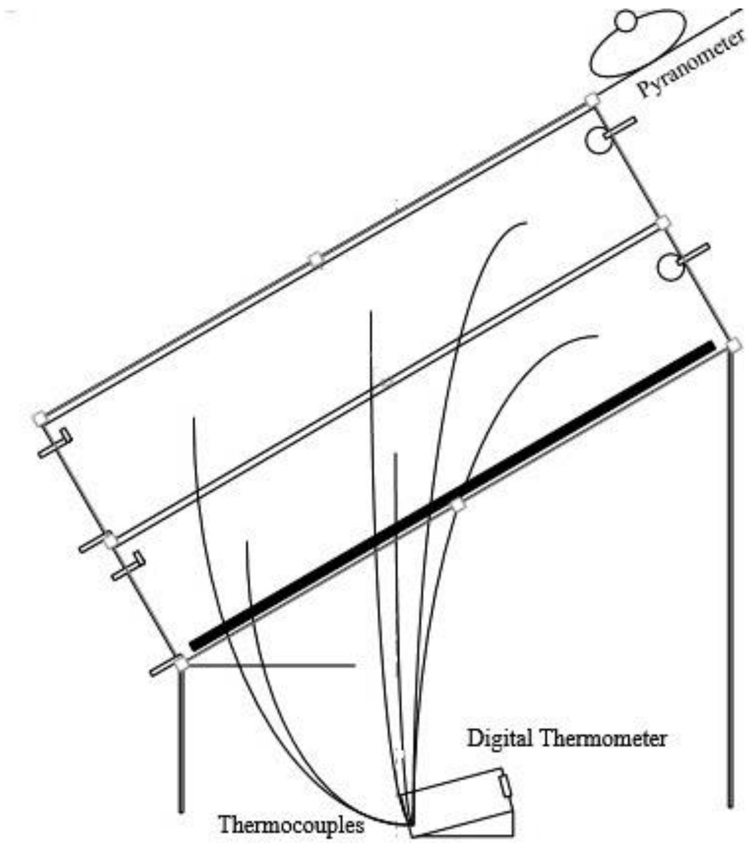

Figure 3.4: Experimental setup of DISWD system

3.2 Theoretical Formulae

3.2.1 Energy Equation of the Absorber Plate

Figure 3.4 shows the thermal process of the inclined solar water distillation system.

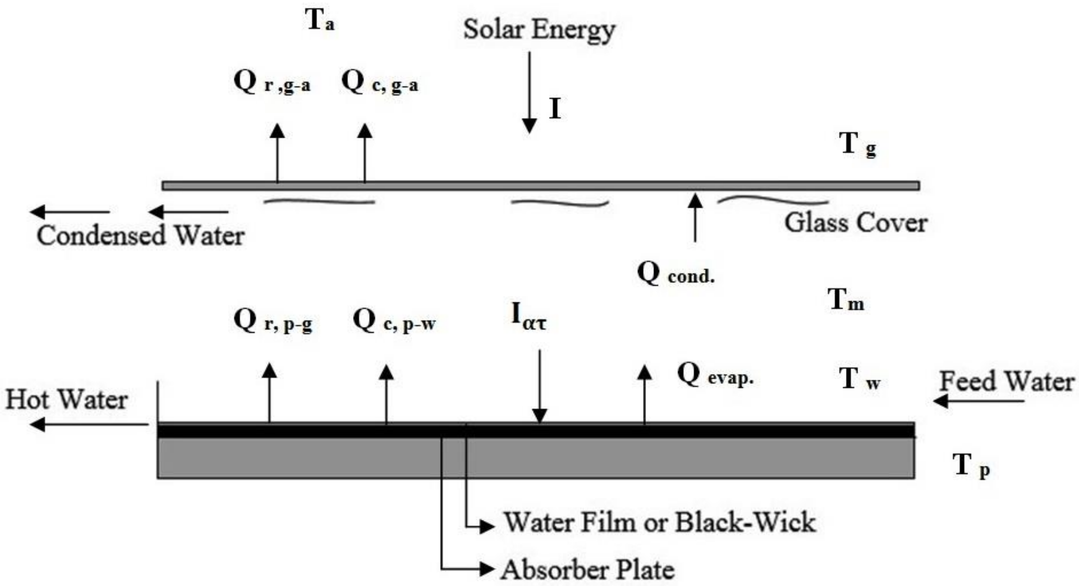

Figure 3.5: Thermal processes of the system

The energy equation for the absorber plate can be written as

$$M_p C_p \frac{\mathrm{d}T_p}{\mathrm{d}_t} = I\tau\alpha - Q_{r,p-g} - Q_{c,p-w} \tag{3.1}$$

Where, T_p is the temperature of the absorber, M_p is the mass of absorber plate per square meter, and C_p is the specific heat of absorber plate material. $I, \tau,$ And α are solar intensity, the transmissivity of the glass cover, and the absorptivity of the plate, respectively. The heat flux terms, $Q_{r,p-g}$ and $Q_{c,p-w}$ represent the radiation heat transfer from the plate to glass cover, and the convection heat transfer from the plate to water.

3.2.2 Humidity

There are three main measurements of humidity: absolute, relative and specific. Absolute humidity is the water content of air. Relative humidity, expressed as a percent, measures the current absolute humidity relative to the maximum for that temperature. Specific humidity is a ratio of the water vapor content of the mixture to the total air content on a mass basis.

If the relative humidity of the moist air and the water vapor density and density of the air are known, the specific humidity can be expressed as:

$$X = 0.622\varphi \frac{\rho_{ws}}{(\rho-\rho_{ws})100}\% \tag{3.2}$$

Where:

X: Specific humidity of air vapor mixture (kg/kg)

φ: Relative humidity (%)

ρ_{ws} : Density of water vapor (kg/m^3)

3.3 The Need for Economic Analysis

Initial investment in desalination system utilizing solar energy is high. Therefore, an economic system evaluation is essential in decision making. Like many other systems the basis of design decisions is economics. Designing a technical system is a part of the designer's task. Equally important is the requirement that the system be economical and show an adequate return on investment. Therefore, the economic objective of this study is to design a system that has high yield i.e., low production cost. The cost of desalting water can be segregated into two principal components:

- Capital cost
- Operating and maintenance costs

The system capital cost includes inclined solar water distillation system and double inclined solar water distillation system and their equipments. Operating and the maintenance costs include energy consumed by the desalination unit, cleaning of the system and the cost of brackish or saline water.

3.3.1 System Capital Cost

The units cost of producing fresh water can be estimated by dividing output to total cost. The total capital cost of the inclined solar water distillation system and double inclined solar water distillation system are estimated to be 200 TL and 360 TL respectively.

3.4 Measurement and Calibration of the Instruments

3.4.1 Pyranometer

To measure the global solar irradiation on the surface on objects, a pyranometer is used. This device has the ability of 180 degrees of view. Thermopile sensor has a black coating, which absorbs the solar radiation. The radiation is observed as heat. This kind of sensors creates a voltage signal proportional to the solar irradiance. The pyranometer was located over a glass surface an inclined solar water distillation system and the double inclined solar water distillation system. An Eppley Pyranometer, coupled with a solar radiation meter model HHM1A digital with resolution of ±0.5% from 0 to 2800 W/m^2. The radiation was recorded hourly. Figure 3.4 shows the pyranometer.

Figure 3.6: Pyranometer

3.4.2 Temperature Measurement

The temperature recorded hourly by using a digital thermometer (Omega MDssi8 SERIES) with accuracy of ± 1.0 (˚C). Figure 3.5 shows the thermometer.

Figure 3.7: Digital Omega Thermometer

3.4.3 Measuring Cylinder

Measuring or graduated cylinder is a piece of the equipment's that is used in the laboratory, and also used to measure the volume of the liquids. Measuring cylinders are generally more accurate and precise than beakers and laboratory flasks. However, they are less accurate and precise than volumetric glassware, such as a volumetric pipette or volumetric flask. Usually the largest measuring cylinders are made of polypropylene for its excellent chemical resistance for its transparency, making them lighter and less fragile than glass. The typical graduated cylinders capacities are between 5 ml and 2000 ml; they have the scale along the length and easily can be read by eye to read the volume of the liquid. The graduated cylinder used in this work, with accuracy of ± 5 ml, had a capacity of maximum 1000 ml, and used to measure the volumes of the fresh water and hot water obtained from the inclined and double inclined solar water distillation systems.

3.5 Experimental Procedure

Inclined solar water distillation system and double inclined solar water distillation system are promising techniques to produce potable water and hot water for domestic applications. This experiment has been done under Northern Cyprus climate and weather condition of Famagusta. Famagusta city is located at 35 ºN and 33 ºE longitude. The absorber of solar collector was tilted by 35º angle with horizontal. The experiment conducted from 21/10/2013 to 25/10/2013 and 27/10/2013 to 31/10/2013 from 09:00 AM to 04:00 PM.

The water from the reservoir tank through the pipes distributed in to the ISWD and into the double solar water distillation system in both lower and upper sections simultaneously with different mass flow rate. The feeding water drops from the holes that are made along the pipes into the cavity and gradually flows on the bare plate on the ISWD, the bare plate of the DISWD and on the glass surface of the upper section on the DISWD unit. Sun radiates on the both systems and the water was heated and water vapors condense on the inner glass which runs down to channels that were provided to collect fresh water. The remaining water that did not become vapor gets heated and collected in a separate tank as hot water. This work has been tested by two variants, as explained the first test was with bare plate, and the second test was carried out by using black-fleece covering the surface of the plates. In inclined solar water distillation system, in the second test, some black-fleece has put over the surface of the bare plate on the bottom of the box. The black-fleece makes a thicker film of water and distribution of water became evenly. So by using black-fleece, the water kept longer time in the system and these produce in more fresh water.

In the second test of DISWD the bare plate in the lower section was covered with black-fleece wick. Same procedure, which was used in ISWD, was conducted in the DISWD and changes were made for the upper section in the DISWD system.

Every hour the amount of fresh water and hot water produced by the inclined solar water distillation system were measured. Also the solar intensity, air temperature within the cavity, and the temperatures of the fresh and hot water and the ambient temperature were measured. The same measurements were done for both the lower and upper sections of double inclined solar water distillation system.

Chapter 4

RESULT AND DISCUSSION

In this chapter, the results are presented by using graphs. As it mentioned earlier the experiments were conducted under Famagusta climate condition in Northern Cyprus in the EMU at the Mechanical Engineering Department roof.

The first experiment was carried out from 21^{st} to 25^{th} of October 2013 from 09:00 AM to 04:00 PM with using bare plate for ISWD and DISWD in the lower section and glass surface for the upper section. The second test was conducted from 27^{th} to 31^{st} of October 2013 from 09:00 AM to 04:00 PM, with using black-fleece wick for ISWD and DISWD lower section and glass surface for upper section of DISWD. The main aim of these tests is to compare the performance of the inclined solar water distillation system with the double inclined solar water distillation system. The systems performances were evaluated by the amount of produced fresh water, hot water and the temperature of the hot water and air cavity.

4.1 Effect of Solar Radiation and Ambient Air Temperature

Different parameters are affecting the amount of water production in solar stills. These parameters include solar radiation and ambient air temperature. Of course, there are some other parameters, which affect the solar still production, but in this study the solar radiation and the ambient air temperature are measured. The maximum solar radiation occurs at noon time and the solar radiation intensity plays a vital role in the output of these systems.

The ambient temperatures and the solar radiation were measured for the both inclined and double inclined solar water distillation system. Figure 4.1 and Fig.4.2 show the average of ambient temperatures and solar intensity hourly.

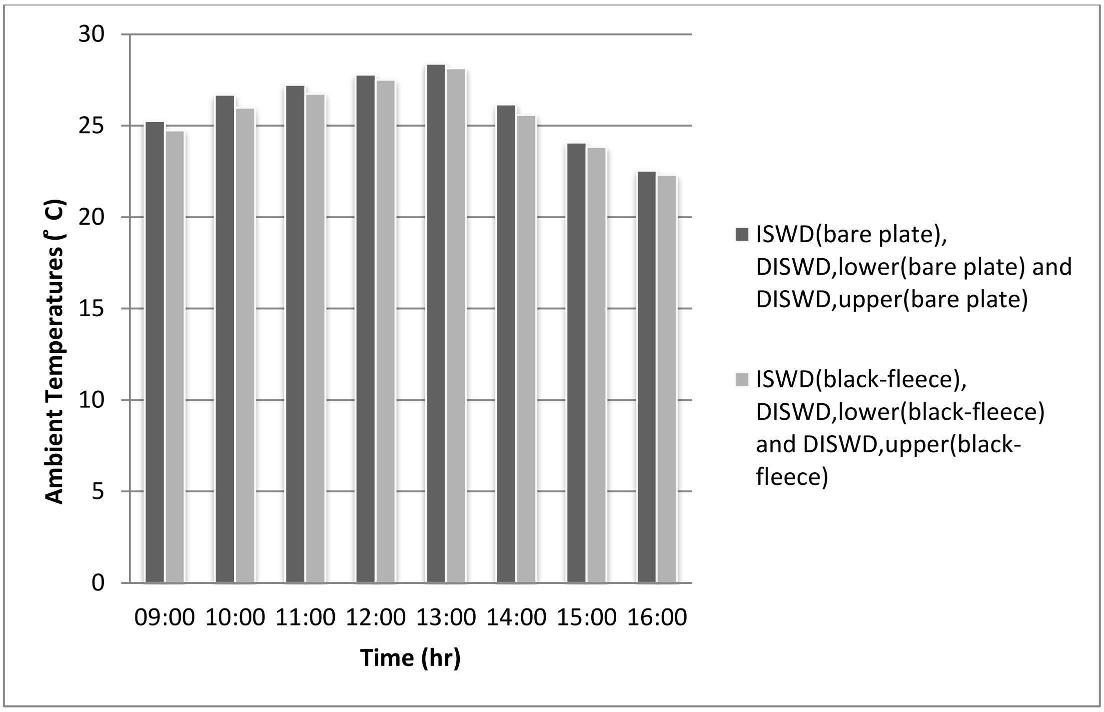

Figure 4.1: Hourly average of ambient temperatures of Test#1 and Test#2

Figure 4.1 shows the hourly average ambient temperatures. The left side bar shows the average ambient temperatures for ISWD (bare plate), DISWD with lower section with bare plate and DISWD with upper part with glass surface of double inclined solar water distillation system. The right side bar shows the average ambient temperatures for ISWD (black-fleece), DISWD with lower section with black-fleece and DISWD with upper part which is glass surface of double inclined solar water distillation system.

The ambient temperatures vary hourly as expected. Figure 4.1 shows that the maximum ambient temperature occurs at 01:00 PM for both systems in the first and second tests.

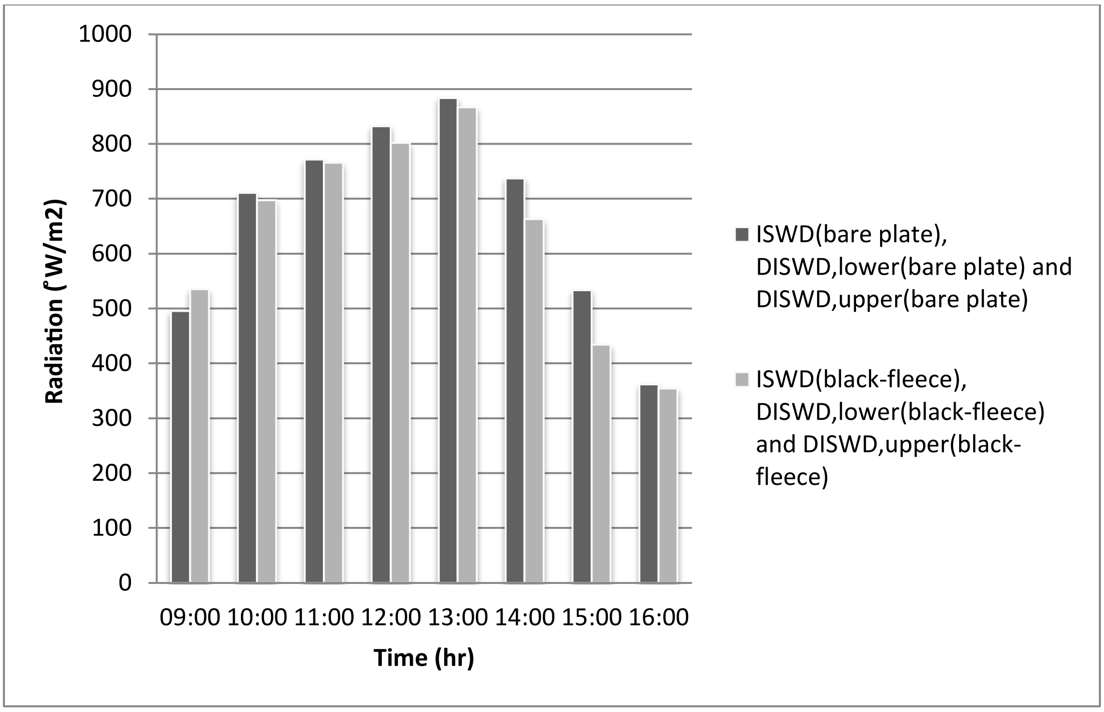

Figure 4.2: Hourly average of radiation of Test#1 and Test#2

Figure 4.2 represents the hourly average solar radiation. The left side bar shows the average solar radiation for ISWD (bare plate), DISWD with lower part with bare plate and DISWD for an upper part with glass surface of double inclined solar water distillation system. The right side bar shows the average solar radiation for ISWD (black-fleece), DISWD with lower part with black-fleece and DISWD with upper part which is glass surface of double inclined solar water distillation system.

The rate of ambient temperatures varies due to the duration of the experiment. Figure 4.2 shows that the maximum solar radiation occurs at 01:00 PM for both systems in first and second tests.

4.2 Results

The fresh water produced by ISWD (bare plate), DISWD $_{lower}$ section with bare plate and DISWD $_{upper}$ section with glass surface of the first test, were measured and the hourly average of fresh water production plotted in Fig.4.3.

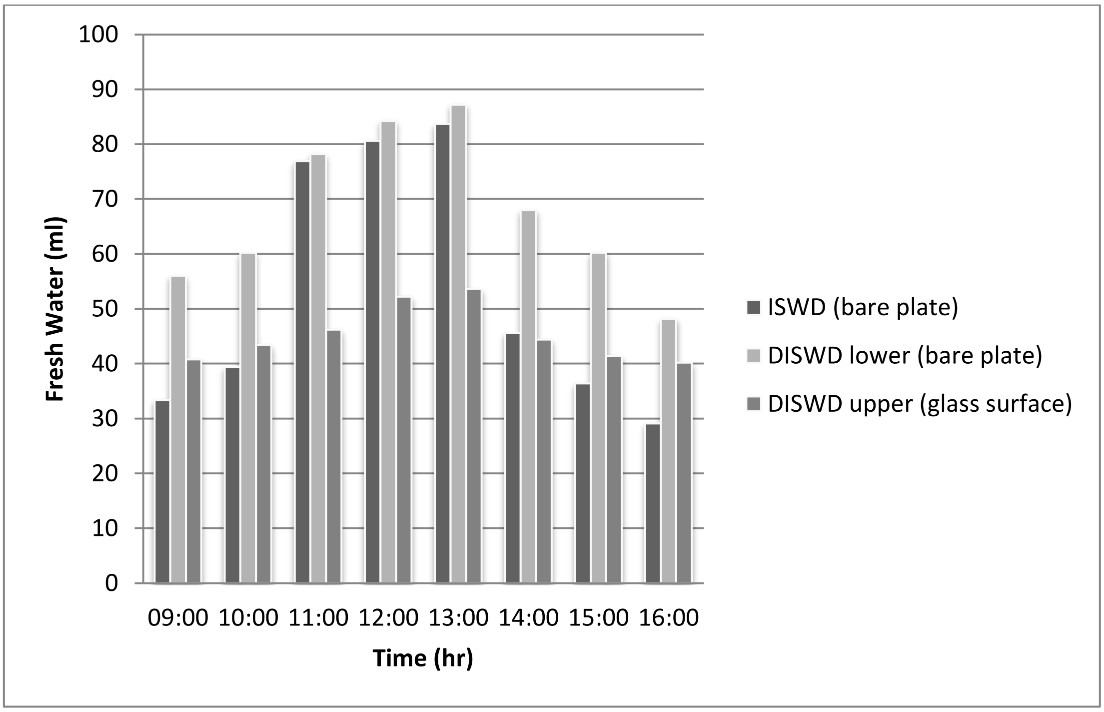

Figure 4.3: Hourly average of fresh water produced with bare plate (Test#1)

As it can be seen in this diagram, the amount of fresh water produced by DISWD $_{Lower}$ section is more than that of ISWD (bare plate) and DISWD $_{upper}$ part (glass surface) in the first test. The averages of the highest amount of fresh water produced by ISWD (bare plate), DISWD $_{lower}$ (bare plate) and DISWD $_{upper}$ (glass surface) in the first test were 83.7 ml/hr, 87.2 ml/hr and 53.6 ml/hr respectively.

The fresh water produced by ISWD (black-fleece) , DISWD $_{lower}$ section with black-fleece and DISWD $_{upper}$ section with glass surface of the second test, were measured and the hourly average of fresh water production were plotted in Fig.4.4.

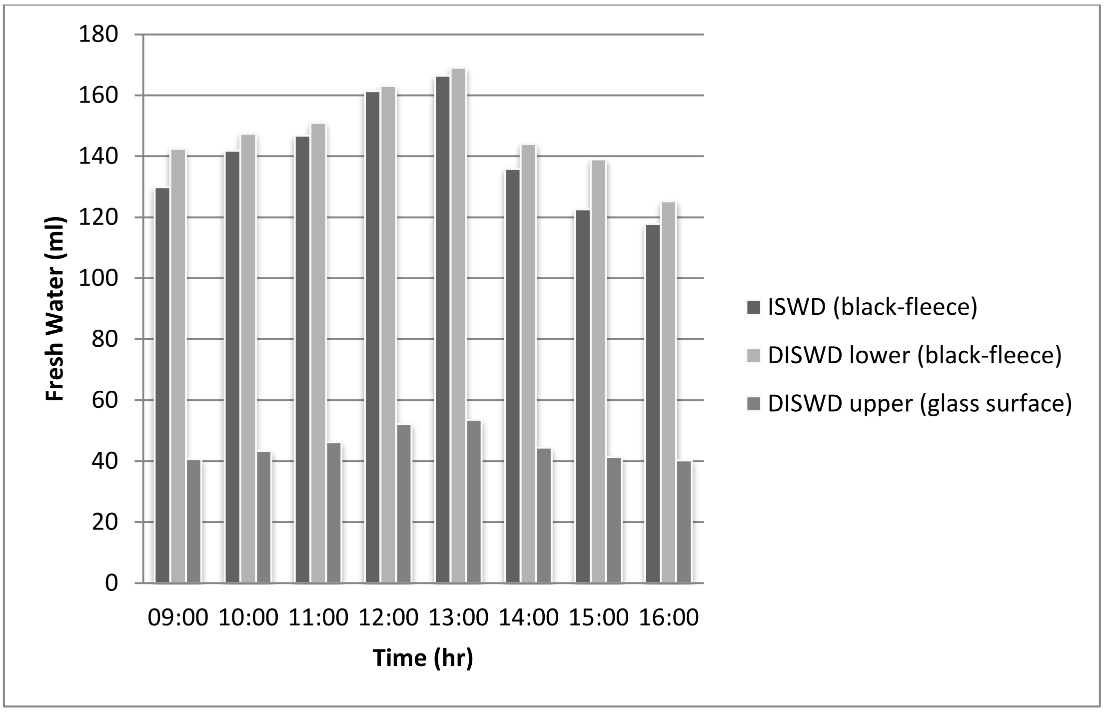

Figure 4.4: Hourly average of fresh water produced with black-fleece (Test#2)

As it can be seen in this diagram the amount of fresh water produced by DISWD $_{lower}$ section is more than the amount of fresh water produced by ISWD (bare plate) and DISWD $_{upper}$ part (glass surface). The average of the highest amount of fresh water produced by ISWD (black-fleece), DISWD $_{lower}$ (black-fleece) and DISWD $_{upper}$ (glass surface) in the second test were 166.4 ml/hr., 169 ml/hr and 53.18 ml/hr respectively. In this test it can be observed that by using the black-fleece wick were increased the rate of fresh water production.

By using thermocouples the temperature of hot water and air cavity were measured. Figure 4.5 shows the hourly average variation of the hot water temperatures of ISWD and DISWD systems in test 1 and 2 as follow.

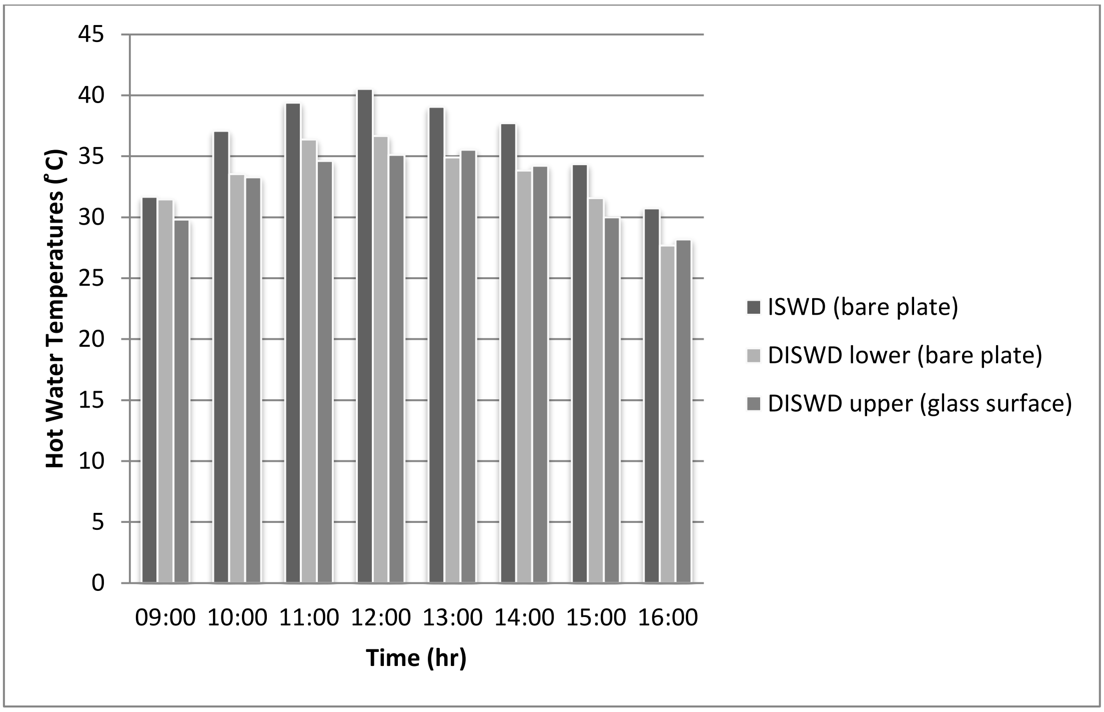

Figure 4.5: Hourly average of hot water temperature in (Test#1)

This diagram shows the hourly average of hot water temperature for ISWD (bare plate), DISWD $_{lower}$ (bare plate) and DISWD $_{upper}$ (glass surface) in Test#1. The highest amount of hourly average of hot water temperatures of ISWD (bare plate), DISWD $_{lower}$ (bare plate) and DISWD $_{upper}$ (glass surface) were 40.52 ºC, 36.66 ºC and 35.54 ºC respectively.

Figure 4.6 shows the hourly average variation of the hot water temperatures of ISWD and DISWD systems in Test#2 as follow.

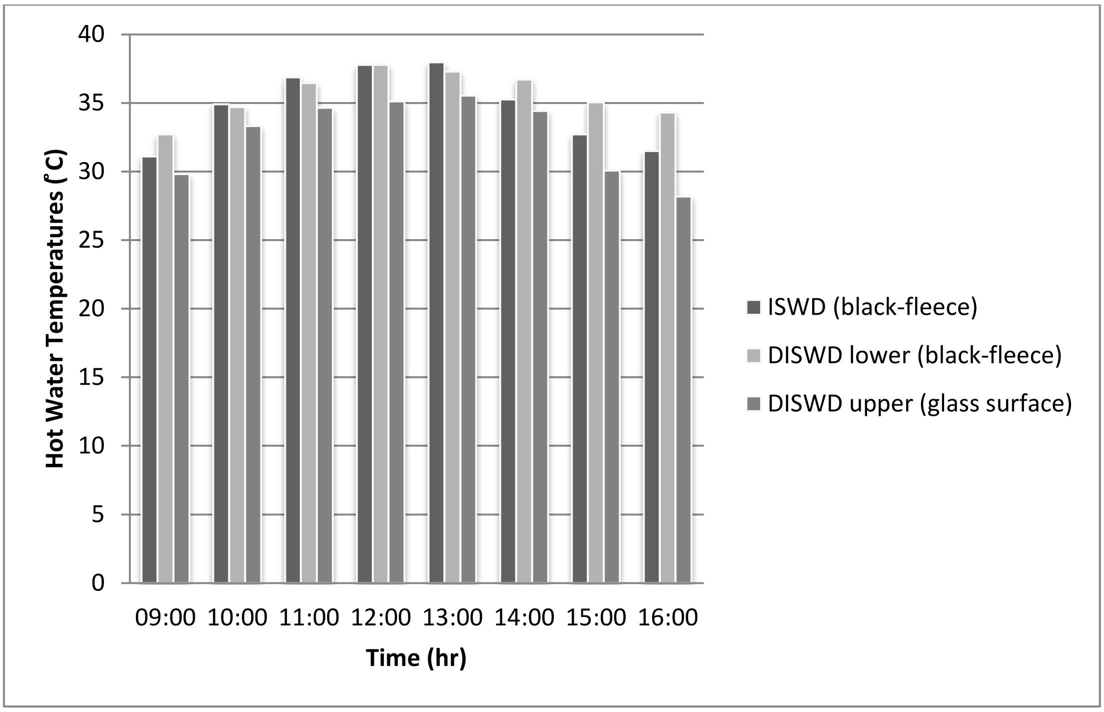

Figure 4.6: Hourly average of hot water temperature of (Test#2)

This diagram shows the hourly average of hot water temperature for ISWD (black-fleece), DISWD $_{lower}$ (black-fleece) and DISWD $_{upper}$ (glass surface) of Test#2. The highest amount of hourly average of hot water temperatures of ISWD (black-fleece), DISWD $_{lower}$ (black-fleece) and DISWD $_{upper}$ (glass surface) are 37.96 ºC, 37.76 ºC and 35.24 ºC respectively.

Figure 4.7 shows the hourly average variation of the air temperatures inside the cavity of ISWD and DISWD systems of Test#1 as follow.

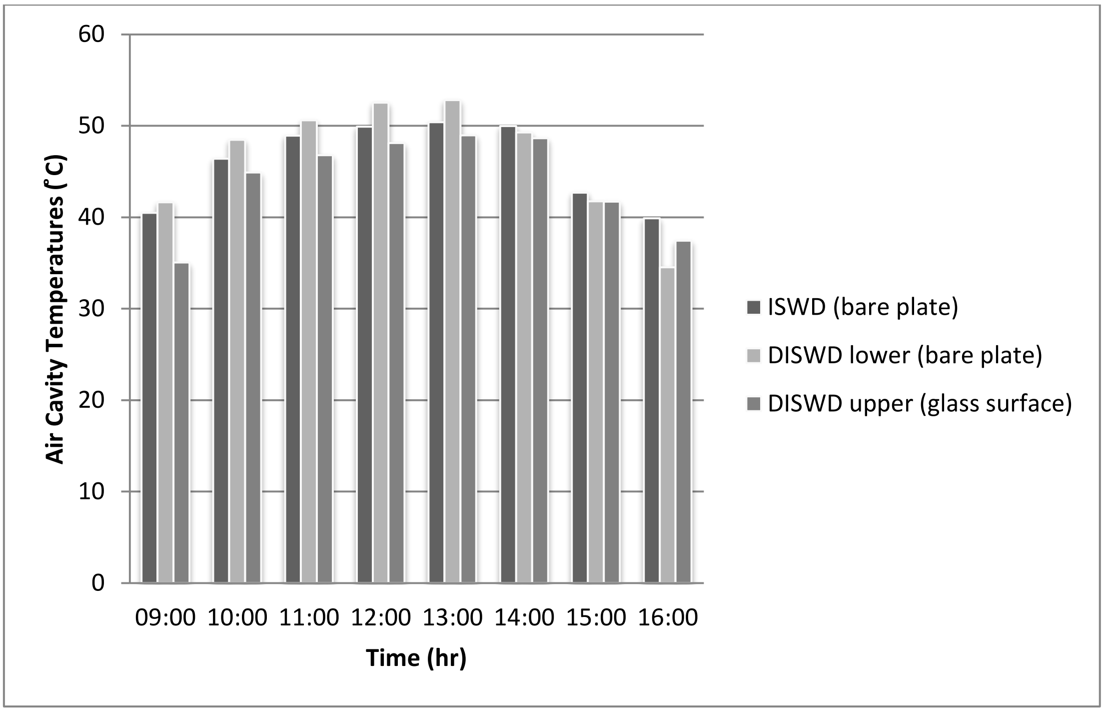

Figure 4.7: Hourly average of air cavity temperatures of (Test#1)

This diagram shows the hourly average of air temperature inside the cavity for ISWD (bare plate), DISWD $_{lower}$ (bare plate) and DISWD $_{upper}$ (glass surface) in Test#1. The highest amount of hourly average of air temperatures inside the cavity of ISWD (bare plate), DISWD $_{lower}$ (bare plate) and DISWD $_{upper}$ (glass surface) are 50.38 ºC, 52.8 ºC and 48.96 ºC respectively.

Figure 4.8 shows the hourly average variation of the air temperatures inside the cavity of ISWD and DISWD systems of Test#2 as follow.

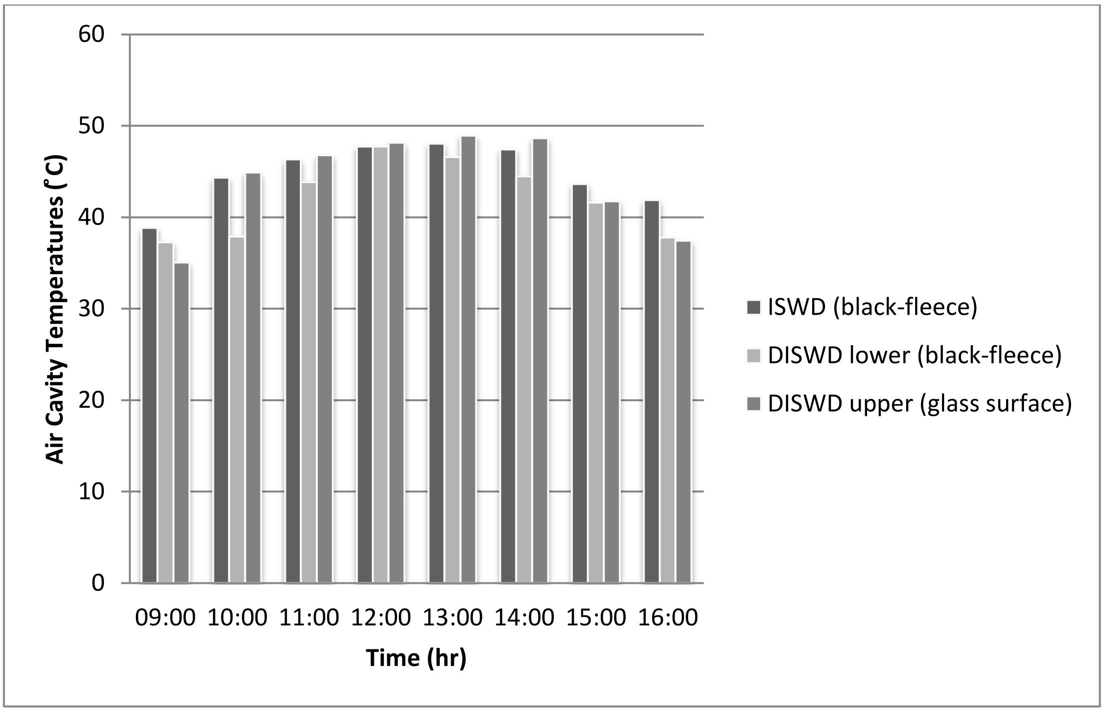

Figure 4.8: Hourly average of air cavity temperatures of (Test#2)

This diagram shows the hourly average of air temperature inside the cavity for ISWD (black-fleece), DISWD lower (black-fleece) and DISWD upper (glass surface) in Test#2. The highest amount of hourly average of air temperatures inside the cavity of ISWD (black-fleece), DISWD $_{lower}$ (black-fleece) and DISWD $_{upper}$ (glass surface) are 48.04 º C, 47.74 ºC and 48.1 ºC respectively.

4.3 Experimental Efficiency

The efficiency of the system can be calculated using the following equation.

$$\eta = \frac{\dot{m}_f \times h_{fg}}{Radiation\left(\frac{W}{m^2}\right) \times Area(m^2)} \tag{4.1}$$

Where:

$\dot{m}_f$: Mas flow rate of fresh water

h_{fg}: Latent heat of evaporation

Table 4.1 shows the hourly average of efficiency of inclined and double inclined solar water distillation systems in first and second tests.

Table 4.1.Hourly average of efficiency of ISWD and DISWD of Test#1 and Test#2

ISWD (bare plate) Test#1	DISWD (bare plate) Test#1	ISWD (black-fleece) Test#2	DISWD (black-fleece) Test#2
9.48%	19.97%	29.44%	38.54%
9.73%	20.32%	26.35%	35.90%
10.40%	22.16%	25.26%	36.50%
10.11%	21.72%	28.62%	38.91%
10.16%	22.07%	27.92%	39.07%

Figure 4.9 and 4.10 shows the hourly average of efficiency of ISWD and DISWD of Test#1 and Test#2.

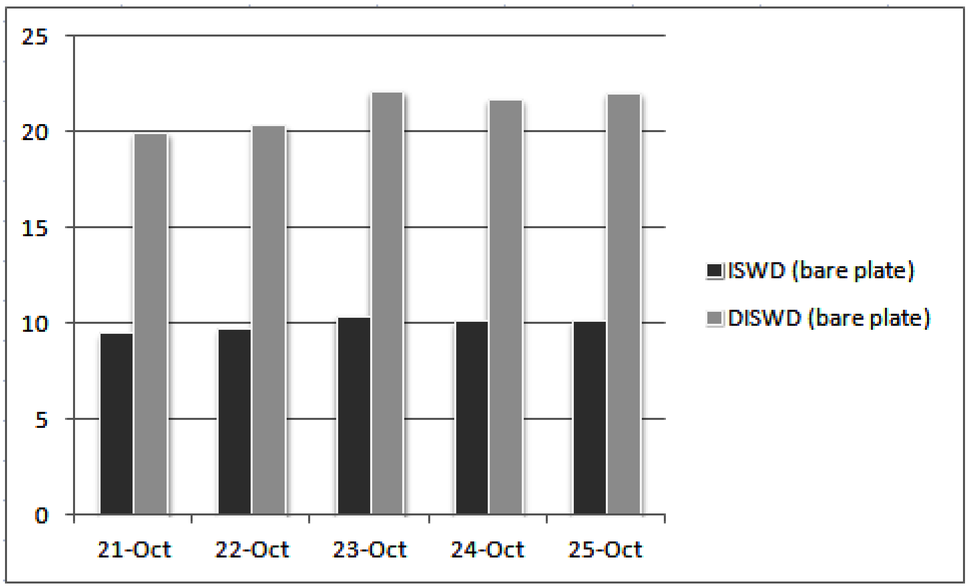

Figure 4.9: Hourly average efficiency of ISWD and DISWD of (Test#1)

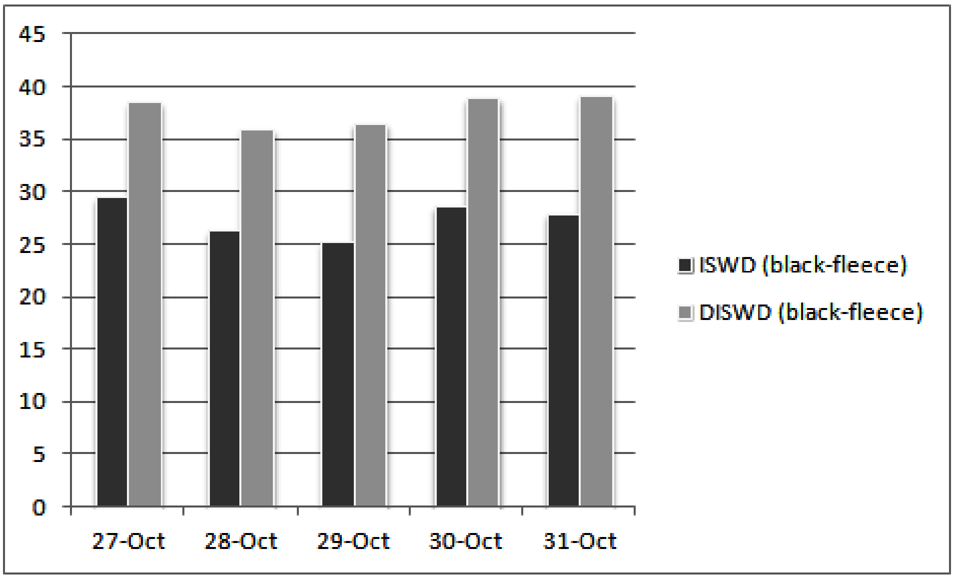

Figure 4.10: Hourly average efficiency of ISWD and DISWD of (Test#2)

4.4 Economic analysis

4.4.1 Simple Payback Period (SPP)

The Simple Payback Period is employed to find out for how long the distillation systems will pay back the money invested. The average of fresh water productivity of the inclined solar water distillation system with black-fleece during the summer season it is about 1.8 L/day and for the winter season is 1.16 L/day. The average of fresh water productivity of the double inclined solar water distillation system with black-fleece during the summer season it is about 2.3 L/day and for the winter season is 1.5 L/day. The average of fresh water productivity for the whole year for the inclined solar water distillation system is about 1.48 L/day. The average of fresh water productivity for the whole year for the double inclined solar water distillation system is about 1.9 L/day. The sale price of a 20 liters water bottle is 5.0 TL. The SPP is calculated as follows.

For ISWD:

Daily (saving) = litters produced × price/litter

Therefore, the daily savings is 0.37 TL

Net savings/day = Daily savings - Running cost

The net savings are estimated to be 0.37 TL

For DISWD:

Daily (saving) = litters produced × price/litter

Therefore, the daily savings is 0.475 TL

Net savings/day = Daily savings - Running cost

The net savings are estimated to be 0.475 TL

The investment cost of the systems are 560 TL this includes all the equipment and other parts in the distillation systems.

The Simple Payback Period is calculated for ISWD and DISWD by the following equation.

$$SPP = \frac{Investment\ cost}{Income\ per\ day} \tag{4.2}$$

The Simple Payback Period for ISWD is calculated to be 1514 days (i.e., 4.15 years) and the Simple payback period for DISWD is calculated to be 1179 days (i.e., 3.2 years). The Simple Payback Period is not acceptable for time span greater than 10 years. As the Payback Period is less than 10 years for both ISWD and DISWD, the method is acceptable.

Chapter 5

CONCLUSION

5.1 Conclusion

The present work proposes an experimental study to distill the brackish water by using ISWD and DISWD systems with two different variants (bare plate and black-fleece). The study was carried out under the climate conditions of Famagusta; Northern Cyprus, from 21st of October to 25th of October 2013 and from 27th of October to 31st of October 2013.

One of the most important factors that affect the productivity of an inclined solar water distillation system and double inclined solar water distillation system is solar radiation. As the solar radiation increased the productivity of fresh water also increases.

According to the results obtained from the first test, the average of the highest amount of fresh water produced by ISWD and DISWD were measured as 83.7 ml/h and 140.8 ml/h respectively. In the first test, the highest hourly average efficiency for ISWD and DISWD systems were evaluated as 10.40% and 22.16% respectively. Since, the fresh water production rate and the efficiency of DISWD system were greater than ISWD system, DISWD was the preferred system. According to the results obtained from the second test, the average of the highest amount of fresh water produced by ISWD and DISWD were measured as 166.4 ml/h and 222.18 ml/h respectively. In the second test, the highest hourly average of efficiency for ISWD and DISWD systems were evaluated as 29.44% and 39.07% respectively. Since, the fresh water production rate and the efficiency of DISWD system were greater than ISWD system, DISWD was the preferred system.

5.2 Suggestions for Future Work

Some of the future suggestions for performance improvement are listed below:

- Testing the effect of glass cover thickness and using low iron content glass.
- Using selective pain to absorb the solar radiations more effectively.
- Study the water film thickness.
- Using mirrors to boost evaporation.
- Circulating the outlet hot water as feeding water to increase evaporation.

REFRENCES

[1] "history.wisc.edu/undergraduate/whystudyhistory.htm#study_history."

[2] R. González-Acuña, F. Malpica, and P. Pieretti, "Solar collector exergetic optimization for a multi effect humidification desalination prototype," *International Journal of Multiphysics*, vol. 7, no. 4, pp. 287-300, 2013.

[3] R. Kannan, C. Selvaganesan, M. Vignesh *et al.*, "Solar still with vapor adsorption basin: Performance analysis," *Renewable Energy*, vol. 62, pp. 258-264, 2014.

[4] G. Y. Liu, H. Yang, G. Q. Shen *et al.*, "A controlled thermal solar desalination system," *Applied Mechanics and Materials*, pp. 1529-1532, 2014.

[5] M. Shatat, M. Worall, and S. Riffat, "Opportunities for solar water desalination worldwide: Review,"*Journal of Sustainable Cities and Society*, vol. 9, pp. 67-80, 2013.

[6] I. Khamis, and K. C. Kavvadias, "Nuclear desalination: Practical measures to prevent pathways of contamination," *Desalination*, vol. 321, pp. 55-59, 2013.

[7] J. Li, C. F. Li, Y. X. Zhang *et al.*, "Study on the large-scale water/electricity cogeneration system in nuclear power plants," *Journal of Energy and Buildings*, pp. 1912-1915, 2014.

[8] R. Soto, and J. Vergara, “Thermal power plant efficiency enhancement with Ocean Thermal Energy Conversion,” *Applied Thermal Engineering,* vol. 62, no. 1, pp. 105-112, 2014.

[9] R. Gomri, “Energy and exergy analyses of seawater desalination system integrated in a solar heat transformer,” *Desalination,* vol. 249, no. 1, pp. 188-196, 2009.

[10] R. Gomri, “Thermal seawater desalination: Possibilities of using single effect and double effect absorption heat transformer systems,” *Desalination,* vol. 253, no. 1-3, pp. 112-118, 2010.

[11] A. Huicochea, R. J. Romero, W. Rivera *et al.*, “A novel cogeneration system: A proton exchange membrane fuel cell coupled to a heat transformer,” *Applied Thermal Engineering,* vol. 50, no. 2, pp. 1530-1535, 2013.

[12] G. Srinivas, S. Sekar, R. Saravanan *et al.*, “Studies on a water-based absorption heat transformer for desalination using MED,” *Desalination and Water Treatment,* vol. 1, no. 1-3, pp. 75-81, 2009.

[13] A. E. Kabeel, and S. A. El-Agouz, “Review of researches and developments on solar stills,” *Desalination,* vol. 276, no. 1-3, pp. 1-12, 2011.

[14] C. Yamali, and I. Solmuş, “Theoretical investigation of a humidification-dehumidification desalination system configured by a double-pass flat plate solar air heater,” *Desalination,* vol. 205, no. 1-3, pp. 163-177, 2007.

[15] G. N. Tiwari, J. M. Thomas, and E. Khan, "Optimisation of glass cover inclination for maximum yield in a solar still," *Heat Recovery Systems and CHP*, vol. 14, no. 4, pp. 447-455, 1994.

[16] G. N. Tiwari, S. K. Singh, and V. P. Bhatnagar, "Analytical thermal modelling of multi-basin solar still," *Energy Conversion and Management,* vol. 34, no. 12, pp. 1261-1266, 1993.

[17] A. A. Al-Karaghouli, and W. E. Alnaser, "Experimental comparative study of the performances of single and double basin solar-stills," *Applied Energy,* vol. 77, no. 3, pp. 317-325, 2004.

[18] A. N. Minasian, and A. A. Al-Karaghouli, "An improved solar still: The wick-basin type," *Energy Conversion and Management,* vol. 36, no. 3, pp. 213-217, 1995.

[19] E. Mathioulakis, and V. Belessiotis, "Integration of solar still in a multi-source, multi-use environment," *Solar Energy,* vol. 75, no. 5, pp. 403-411, 2003.

[20] D. W. Lee, and A. Sharma, "Thermal performances of the active and passive water heating systems based on annual operation," *Solar Energy,* vol. 81, no. 2, pp. 207-215, 2007.

[21] G. N. Tiwari, and N. K. Dhiman, “Performance study of a high temperature distillation system,” *Energy Conversion and Management,* vol. 32, no. 3, pp. 283-291, 1991.

[22] A. S. Nafey, M. Abdelkader, A. Abdelmotalip *et al.*, “Enhancement of solar still productivity using floating perforated black plate,” *Energy Conversion and Management,* vol. 43, no. 7, pp. 937-946, 2002.

[23] H. Ş. Aybar, “Mathematical modeling of an inclined solar water distillation system,” *Desalination,* vol. 190, no. 1-3, pp. 63-70, 2006.

[24] H. Ş. Aybar, F. Egelioğlu, and U. Atikol, “An experimental study on an inclined solar water distillation system,” *Desalination,* vol. 180, no. 1-3, pp. 285-289, 2005.

[25] H. Assefi, “Review and analysis of solar desalination system,” M.S Thesis, Department of Mechanical Engineering, Eastern Mediteranean University, Famagusta, Northern Cyprus, 2005.

[26] B. A. Akash, M. S. Mohsen, O. Osta *et al.*, “Experimental evaluation of a single-basin solar still using different absorbing materials,” *Renewable Energy*, vol. 14, no. 1-4, pp. 307-310, 1998.

APPENDICES

Appendix A: Row Data

The following tables show row data for both ISWD and DISWD with bare plate and black-fleece from 21^{st} to 25^{th} October 2013 and 27^{th} to 31^{st} October 2013 respectively.

Table A.1. Measured values of ISWD (bare plate) 21 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.1	485.71	23.8	27	2565	30.9	38.6	3000
10:00	07.3	695.24	25.2	33	2556	37.4	44.5	3000
11:00	07.9	752.38	25.7	70.5	2540	38.9	50.1	3000
12:00	08.4	800	26.3	74	2538	39.2	51.9	3000
13:00	08.6	819.05	26.9	77.5	2535	38.2	49.6	3000
14:00	06.9	657.14	24.9	39	2577	37.1	50.1	3000
15:00	04.1	390.48	22.6	30	2583	32.7	41.2	3000
16:00	03.1	295.24	20.8	22.5	2577	29.6	39.2	3000

Table A.2. Measured values of ISWD (bare plate) 22 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.2	495.24	24.8	31	2554	31.0	42.1	3000
10:00	07.3	696.24	26.2	37	2546	37.4	44.5	3000
11:00	07.9	752.38	26.8	75	2531	38.1	45.3	3000
12:00	08.9	847.62	27.3	79	2527	39.6	46.5	3000
13:00	09.1	866.67	27.9	82	2524	38.4	49.5	3000
14:00	07.4	704.76	25.7	44	2566	36.3	49.3	3000
15:00	05.3	504.76	23.6	34	2573	32.5	42.8	3000
16:00	04.2	400	22.1	27	2566	30.9	40.8	3000

Table A.3. Measured values of ISWD (bare plate) 23 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.5	523.81	26.3	39	2543	32.2	40.3	3000
10:00	07.9	752.38	27.7	45	2533	36.4	47.5	3000
11:00	08.4	800	28.3	82	2518	38.9	48.7	3000
12:00	09.1	866.67	28.8	86	2516	39.9	51.9	3000
13:00	09.7	923.81	29.4	89	2512	38.3	49.6	3000
14:00	08.3	790.48	27.2	51	2554	36.9	50.1	3000
15:00	06.4	609.52	25.1	42	2560	35.5	41.2	3000
16:00	04.1	390.48	23.6	35	2554	30.5	39.2	3000

Table A.4. Measured values of ISWD (bare plate) 24 October 2013

TIME	Radition (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	04.9	466.67	25.7	34	2551	33.0	42	3000
10:00	07.3	695.24	27.1	40	2542	38.9	48.7	3000
11:00	08.1	771.43	27.7	78	2527	41.3	51.9	3000
12:00	08.5	809.52	28.2	81	2524	43.6	50.8	3000
13:00	09.4	895.24	28.8	84	2521	42.1	53.6	3000
14:00	08.0	761.90	26.6	46	2563	41.1	50.2	3000
15:00	06.1	580.95	24.5	37	2575	38.3	47.1	3000
16:00	03.7	352.38	23	30	2563	31.7	41.0	3000

Table A.5. Measured values of ISWD (bare plate) 25 October 2013

TIME	Radition (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.3	504.76	25.6	36	2547	31.2	39.4	3000
10:00	07.5	714.28	27.2	42	2538	35.3	46.7	3000
11:00	08.2	780.95	27.6	79	2523	39.8	48.6	3000
12:00	08.8	838.10	28.3	83	2520	40.3	48.4	3000
13:00	09.6	914.29	28.9	86	2517	38.2	49.6	3000
14:00	08.1	771.43	26.4	48	2559	37.1	50.1	3000
15:00	06.1	580.95	24.6	39	2565	32.7	41.2	3000
16:00	03.9	371.43	23.2	31	2559	30.9	39.2	3000

Table A.6. Measured values of $DISWD_{lower}$ (bare plate) 21 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.1	485.71	23.8	48	2607	33.2	38.7	3000
10:00	07.3	695.24	25.2	52	2583	36.3	49.6	3000
11:00	07.9	752.38	25.7	70	2541	38.9	52.7	3000
12:00	08.4	800	26.3	76	2574	37.2	55.1	3000
13:00	08.6	819.05	26.9	79	2556	36.4	54.2	3000
14:00	06.9	657.14	24.9	60	2592	35.3	51.6	3000
15:00	04.1	390.48	22.6	52	2601	32.4	42.5	3000
16:00	03.1	295.24	20.8	40	2619	28.1	37.8	3000

Table A.7. Measured values of DISWD $_{lower}$ (bare plate) 22 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.2	495.24	24.8	52	2602	30.8	44.1	3000
10:00	07.3	696.24	26.2	57	2578	32.2	48.2	3000
11:00	07.9	752.38	26.8	75	2536	35.3	49.7	3000
12:00	08.9	847.62	27.3	81	2569	36.8	51.3	3000
13:00	09.1	866.67	27.9	84	2551	34.4	52.3	3000
14:00	07.4	704.76	25.7	64	2587	33.4	48.2	3000
15:00	05.3	504.76	23.6	57	2596	31.5	41.7	3000
16:00	04.2	400	22.1	45	2614	27.9	32.9	3000

Table A.8. Measured values of DISWD $_{lower}$ (bare plate) 23 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.5	523.81	26.3	63	2580	32.3	37.8	3000
10:00	07.9	752.38	27.7	67	2556	35.4	48.7	3000
11:00	08.4	800	28.3	85	2514	37.9	51.8	3000
12:00	09.1	866.67	28.8	91	2547	36.3	54.2	3000
13:00	09.7	923.81	29.4	94	2529	35.5	53.3	3000
14:00	08.3	790.48	27.2	75	2565	34.4	50.7	3000
15:00	06.4	609.52	25.1	67	2574	31.5	41.6	3000
16:00	04.1	390.48	23.6	55	2592	27.2	36.9	3000

Table A.9. Measured values of DISWD $_{lower}$ (bare plate) 24 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	04.9	466.67	25.7	57	2598	29.9	43.2	3000
10:00	07.3	695.24	27.1	61	2574	31.3	47.3	3000
11:00	08.1	771.43	27.7	79	2532	34.3	48.8	3000
12:00	08.5	809.52	28.2	85	2565	35.9	50.4	3000
13:00	09.4	895.24	28.8	88	2547	33.5	51.4	3000
14:00	08.0	761.90	26.6	69	2583	32.4	47.3	3000
15:00	06.1	580.95	24.5	61	2592	30.6	40.8	3000
16:00	03.7	352.38	23	49	2610	27.0	31.9	3000

Table A.10. Measured values of DISWD $_{lower}$ (bare plate) 25 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.3	504.76	25.6	60	2589	31.1	44.4	3000
10:00	07.5	714.28	27.2	64	2565	32.5	48.5	3000
11:00	08.2	780.95	27.6	82	2523	35.5	50.0	3000
12:00	08.8	838.10	28.3	88	2556	37.1	51.6	3000
13:00	09.6	914.29	28.9	91	2538	34.7	52.8	3000
14:00	08.1	771.43	26.4	72	2574	33.6	48.5	3000
15:00	06.1	580.95	24.6	64	2583	31.8	42.0	3000
16:00	03.9	371.43	23.2	52	2601	28.2	33.1	3000

Table A.11. Measured values of DISWD $_{upper}$ (glass surface) 21 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.1	485.71	23.8	34	2659	30.1	37.2	3000
10:00	07.3	695.24	25.2	37	2641	33.2	46.9	3000
11:00	07.9	752.38	25.7	39	2623	34.8	49.6	3000
12:00	08.4	800	26.3	45	2611	35.9	51.2	3000
13:00	08.6	819.05	26.9	46	2605	35.0	49.4	3000
14:00	06.9	657.14	24.9	36	2671	34.3	50.7	3000
15:00	04.1	390.48	22.6	33	2656	28.6	40.2	3000
16:00	03.1	295.24	20.8	33	2665	27.1	34.3	3000

Table A.12. Measured values of DISWD $_{upper}$ (glass surface) 22 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.2	495.24	24.8	38	2652	30.1	34.1	3000
10:00	07.3	696.24	26.2	40	2667	33.9	44.2	3000
11:00	07.9	752.38	26.8	43	2619	35.0	45.4	3000
12:00	08.9	847.62	27.3	49	2607	35.2	46.6	3000
13:00	09.1	866.67	27.9	51	2601	36.4	49.2	3000
14:00	07.4	704.76	25.7	42	2637	34.7	47.8	3000
15:00	05.3	504.76	23.6	39	2655	31.5	43.2	3000
16:00	04.2	400	22.1	37	2661	29.4	40.1	3000

Table A.13. Measured values of DISWD $_{upper}$ (glass surface) 23 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.5	523.81	26.3	46	2644	29.2	36.3	3000
10:00	07.9	752.38	27.7	48	2659	32.2	45.7	3000
11:00	08.4	800	28.3	51	2611	33.8	48.7	3000
12:00	09.1	866.67	28.8	57	2599	34.8	50.2	3000
13:00	09.7	923.81	29.4	59	2593	34.1	48.4	3000
14:00	08.3	790.48	27.2	50	2629	33.3	49.7	3000
15:00	06.4	609.52	25.1	47	2647	27.7	39.3	3000
16:00	04.1	390.48	23.6	45	2653	26.2	33.2	3000

Table A.14. Measured values of DISWD $_{upper}$ (glass surface) 24 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	04.9	466.67	25.7	42	2647	29.2	33.2	3000
10:00	07.3	695.24	27.1	45	2662	32.9	43.2	3000
11:00	08.1	771.43	27.7	48	2614	34.1	44.5	3000
12:00	08.5	809.52	28.2	54	2602	34.2	45.7	3000
13:00	09.4	895.24	28.8	55	2596	35.5	48.3	3000
14:00	08.0	761.90	26.6	46	2632	33.8	46.9	3000
15:00	06.1	580.95	24.5	43	2650	30.5	42.3	3000
16:00	03.7	352.38	23	42	2656	28.5	39.2	3000

Table A.15. Measured values of DISWD $_{upper}$ (glass surface) 25 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.3	504.76	25.6	44	2646	30.4	34.4	3000
10:00	07.5	714.28	27.2	47	2661	34.1	44.4	3000
11:00	08.2	780.95	27.6	50	2613	35.3	45.7	3000
12:00	08.8	838.10	28.3	56	2601	35.4	46.9	3000
13:00	09.6	914.29	28.9	57	2595	36.7	49.5	3000
14:00	08.1	771.43	26.4	48	2631	35.0	48.1	3000
15:00	06.1	580.95	24.6	45	2649	31.7	43.5	3000
16:00	03.9	371.43	23.2	44	2655	29.7	40.4	3000

Table A.16. Measured values of ISWD (black-fleece) 27 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.3	504.76	24.4	132	2473	30.2	37.4	3000
10:00	06.9	657.14	25.3	144	2482	35.3	43.7	3000
11:00	07.7	733.33	26.3	149	2476	36.3	47.3	3000
12:00	08.2	780.95	27.1	167	2459	37.0	48.7	3000
13:00	08.9	847.62	27.9	169	2454	37.4	47.1	3000
14:00	06.6	628.57	25.1	138	2487	34.9	46.0	3000
15:00	04.2	400	23.3	126	2478	30.7	42.1	3000
16:00	03.4	323.81	21.6	120	2469	30.5	40.4	3000

Table A.17. Measured values of ISWD (black-fleece) 28 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.6	533.33	24.3	123	2485	30.3	40.3	3000
10:00	07.3	695.24	25.5	135	2584	34.5	42.6	3000
11:00	08.1	771.43	26.2	140	2488	35.9	43.2	3000
12:00	08.4	800	26.9	158	2471	36.7	44.2	3000
13:00	08.9	847.62	27.4	160	2466	36.9	47.6	3000
14:00	07.1	676.19	25.3	129	2499	33.5	45.9	3000
15:00	04.6	438.10	23.5	117	2490	31.2	42.8	3000
16:00	03.6	342.86	22.4	111	2481	30.9	41.7	3000

Table A.18. Measured values of ISWD (black-fleece) 29 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.6	533.33	24.2	117	2491	31.4	39.2	3000
10:00	07.2	685.71	25.6	129	2500	34.5	45.4	3000
11:00	08.0	761.90	26.3	134	2494	36.2	46.1	3000
12:00	08.3	790.48	26.9	152	2477	37.1	49.2	3000
13:00	09.1	866.67	27.4	154	2472	37.6	48.0	3000
14:00	06.9	657.14	25.4	123	2505	34.2	47.3	3000
15:00	04.5	428.57	23.3	105	2496	33.3	43.2	3000
16:00	03.7	352.38	21.9	105	2487	31.8	41.3	3000

Table A.19. Measured values of ISWD (black-fleece) 30 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.7	542.86	25.1	137	2464	32.8	41.1	3000
10:00	07.4	704.76	26.6	149	2473	36.6	45.4	3000
11:00	08.1	771.43	27.3	154	2467	39.2	48.6	3000
12:00	08.5	809.52	28.2	172	2450	40.1	49.2	3000
13:00	09.2	876.19	28.7	174	2445	39.6	50.1	3000
14:00	07.0	666.67	25.7	143	2478	38.9	49.5	3000
15:00	04.7	447.62	24.3	131	2467	36.5	45.4	3000
16:00	03.9	371.43	22.5	125	2460	33.1	42.8	3000

Table A.20. Measured values of ISWD (black-fleece) 31 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.9	561.90	25.7	140	2460	30.8	36.2	3000
10:00	07.8	742.86	26.9	152	2468	33.6	44.6	3000
11:00	08.3	790.48	27.6	157	2463	36.7	46.5	3000
12:00	08.7	828.57	28.4	158	2440	37.9	47.3	3000
13:00	09.4	895.24	29.3	175	2445	38.3	47.4	3000
14:00	07.2	685.71	26.4	146	2473	34.8	48.4	3000
15:00	04.8	457.14	24.7	134	2464	31.8	44.6	3000
16:00	04.0	380.95	23.1	128	2455	31.1	43.1	3000

Table A.21. Measured values of DISWD $_{lower}$ (black-fleece) 27 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.3	504.76	24.4	144	2484	32.9	36.9	3000
10:00	06.9	657.14	25.3	149	2472	34.8	37.5	3000
11:00	07.7	733.33	26.3	153	2478	36.6	43.5	3000
12:00	08.2	780.95	27.1	165	2459	38.0	47.4	3000
13:00	08.9	847.62	27.9	171	2451	37.4	46.2	3000
14:00	06.6	628.57	25.1	146	2470	36.9	44.1	3000
15:00	04.2	400	23.3	141	2470	35.2	41.2	3000
16:00	03.4	323.81	21.6	127	2466	34.5	37.4	3000

Table A.22. Measured values of DISWD $_{lower}$ (black-fleece) 28 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.6	533.33	24.3	135	2496	31.9	35.7	3000
10:00	07.3	695.24	25.5	140	2484	33.9	36.4	3000
11:00	08.1	771.43	26.2	144	2490	35.7	42.4	3000
12:00	08.4	800	26.9	156	2471	37.0	46.3	3000
13:00	08.9	847.62	27.4	162	2463	36.5	45.1	3000
14:00	07.1	676.19	25.3	137	2482	35.9	43.1	3000
15:00	04.6	438.10	23.5	132	2482	34.3	40.1	3000
16:00	03.6	342.86	22.4	118	2478	33.5	36.3	3000

Table A.23. Measured values of DISWD $_{lower}$ (black-fleece) 29 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.6	533.33	24.2	131	2502	33.1	38.1	3000
10:00	07.2	685.71	25.6	136	2490	35.1	38.7	3000
11:00	08.0	761.90	26.3	139	2496	36.9	44.7	3000
12:00	08.3	790.48	26.9	151	2477	38.2	48.6	3000
13:00	09.1	866.67	27.4	157	2496	37.7	47.4	3000
14:00	06.9	657.14	25.4	132	2488	37.1	45.3	3000
15:00	04.5	428.57	23.3	127	2488	35.5	42.4	3000
16:00	03.7	352.38	21.9	114	2484	34.7	38.6	3000

Table A.24. Measured values of DISWD $_{lower}$ (black-fleece) 30 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.7	542.86	25.1	149	2475	32.2	37.2	3000
10:00	07.4	704.76	26.6	154	2463	34.2	37.8	3000
11:00	08.1	771.43	27.3	158	2469	35.9	43.7	3000
12:00	08.5	809.52	28.2	170	2450	37.2	47.6	3000
13:00	09.2	876.19	28.7	176	2442	36.8	46.5	3000
14:00	07.0	666.67	25.7	151	2461	36.2	44.3	3000
15:00	04.7	447.62	24.3	146	2461	34.5	41.5	3000
16:00	03.9	371.43	22.5	132	2457	33.8	37.7	3000

Table A.25. Measured values of DISWD $_{lower}$ (black-fleece) 31 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.9	561.90	25.7	153	2470	33.4	38.4	3000
10:00	07.8	742.86	26.9	158	2458	35.4	39.0	3000
11:00	08.3	790.48	27.6	161	2464	37.1	44.9	3000
12:00	08.7	828.57	28.4	173	2445	38.4	48.8	3000
13:00	09.4	895.24	29.3	179	2437	38.0	47.7	3000
14:00	07.2	685.71	26.4	154	2457	37.4	45.5	3000
15:00	04.8	457.14	24.7	149	2457	35.7	42.7	3000
16:00	04.0	380.95	23.1	135	2452	35.0	38.9	3000

Table A.26. Measured values of DISWD $_{upper}$ (glass surface) 27 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.3	504.76	24.4	34	2659	30.1	37.2	3000
10:00	06.9	657.14	25.3	37	2641	33.2	46.5	3000
11:00	07.7	733.33	26.3	39	2623	34.7	49.6	3000
12:00	08.2	780.95	27.1	45	2611	35.9	51.2	3000
13:00	08.9	847.62	27.9	46	2605	35.0	49.4	3000
14:00	06.6	628.57	25.1	36	2671	34.6	50.7	3000
15:00	04.2	400	23.3	33	2657	28.6	40.2	3000
16:00	03.4	323.81	21.6	33	2665	27.1	34.3	3000

Table A.27. Measured values of DISWD $_{upper}$ (glass surface) 28 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.6	533.33	24.3	37	2655	30.1	34.1	3000
10:00	07.3	695.24	25.5	40	2667	33.9	44.2	3000
11:00	08.1	771.43	26.2	43	2619	35.0	45.4	3000
12:00	08.4	800	26.9	49	2607	35.2	46.6	3000
13:00	08.9	847.62	27.4	50.4	2601	35.7	49.2	3000
14:00	07.1	676.19	25.3	42	2637	34.7	47.8	3000
15:00	04.6	438.10	23.5	39	2655	31.5	43.2	3000
16:00	03.6	342.86	22.4	37	2661	29.4	40.1	3000

Table A.28. Measured values of DISWD $_{upper}$ (glass surface) 29 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (ºC)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (ºC)	$T_{air\ cavity}$ (ºC)	Feeding water (ml)
09:00	05.6	533.33	24.2	44	2646	30.4	34.4	3000
10:00	07.2	685.71	25.6	47	2661	34.1	44.6	3000
11:00	08.0	761.90	26.3	50	2613	35.3	45.7	3000
12:00	08.3	790.48	26.9	56	2602	35.4	46.9	3000
13:00	09.1	866.67	27.4	56.5	2595	36.5	49.5	3000
14:00	06.9	657.14	25.4	48	2631	35.0	48.1	3000
15:00	04.5	428.57	23.3	45	2649	31.8	43.6	3000
16:00	03.7	352.38	21.9	44	2665	29.7	40.3	3000

Table A.29. Measured values of DISWD $_{upper}$ (glass surface) 30 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.7	542.86	25.1	42	2647	29.2	33.2	3000
10:00	07.4	704.76	26.6	45	2663	32.9	43.5	3000
11:00	08.1	771.43	27.3	48	2614	34.4	44.5	3000
12:00	08.5	809.52	28.2	54	2602	34.2	45.9	3000
13:00	09.2	876.19	28.7	55	2596	35	48.3	3000
14:00	07.0	666.67	25.7	46	2633	33.8	46.9	3000
15:00	04.7	447.62	24.3	43	2650	30.7	42.3	3000
16:00	03.9	371.43	22.5	42	2656	28.5	39.2	3000

Table A.30. Measured values of DISWD $_{upper}$ (glass surface) 31 October 2013

TIME	Radiation (mv)	Radiation (W/m^2)	$T_{Ambient}$ (°C)	Fresh water(ml)	Hot water (ml)	$T_{hot\ water}$ (°C)	$T_{air\ cavity}$ (°C)	Feeding water (ml)
09:00	05.9	n	25.7	46	2646	29.2	36.3	3000
10:00	07.8	742.86	26.9	48	2659	32.5	45.7	3000
11:00	08.3	790.48	27.6	51	2611	33.8	48.7	3000
12:00	08.7	828.57	28.4	57	2599	34.8	50.2	3000
13:00	09.4	895.24	29.3	58	2593	34	48.1	3000
14:00	07.2	685.71	26.4	50	2639	33.9	49.7	3000
15:00	04.8	457.14	24.7	47	2647	27.7	39.3	3000
16:00	04.0	380.95	23.1	45	2654	26.2	33.2	3000

Appendix B: Figures

The following figures show row data for both ISWD and DISWD with bare plate and black-fleece from 21st to 25th October 2013 and 27th to 31st October 2013 respectively.

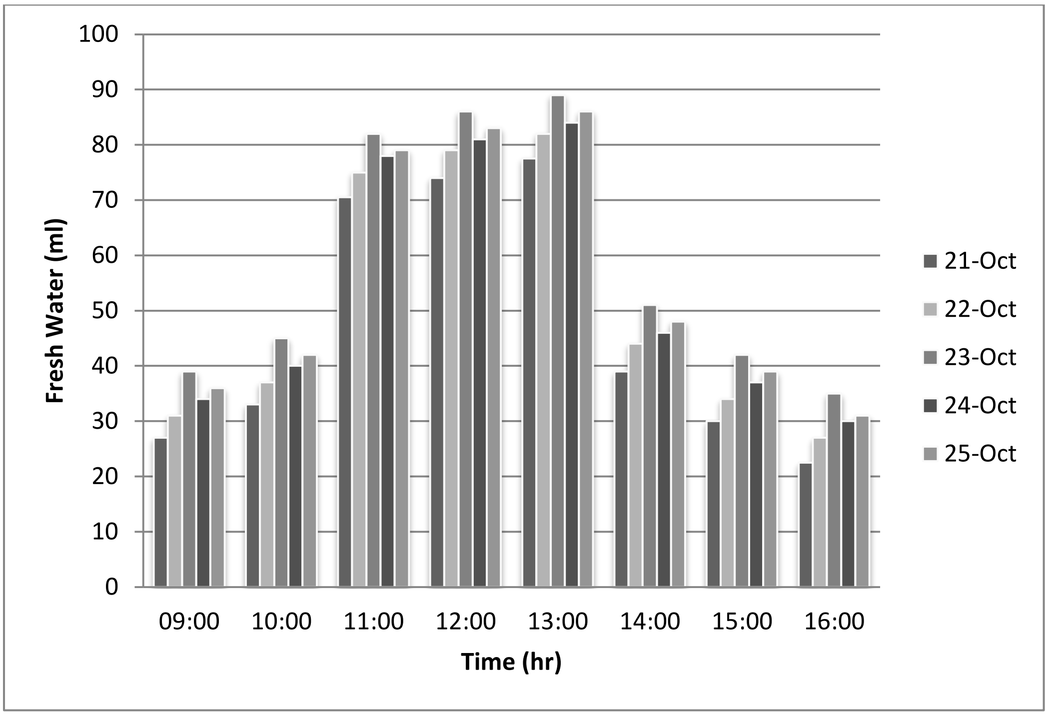

Figure B.1: Fresh water for ISWD (bare plate) from 21st to 25th October 2013

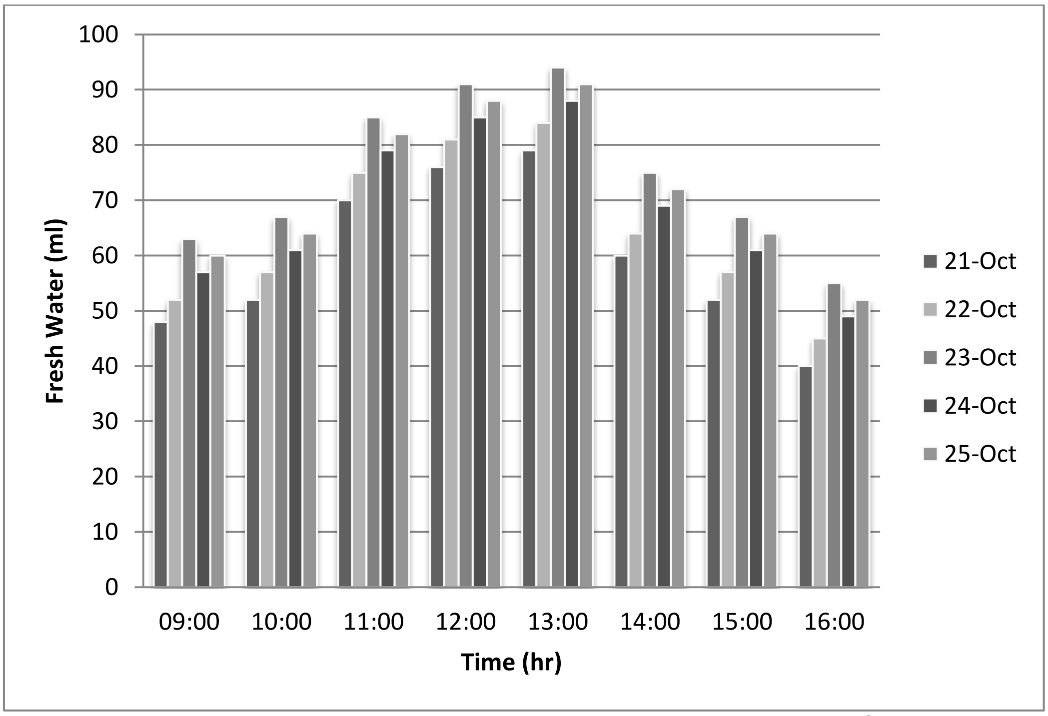

Figure B.2: Fresh water for DISWD $_{lower}$ (bare plate) from 21st to 25th October 2013

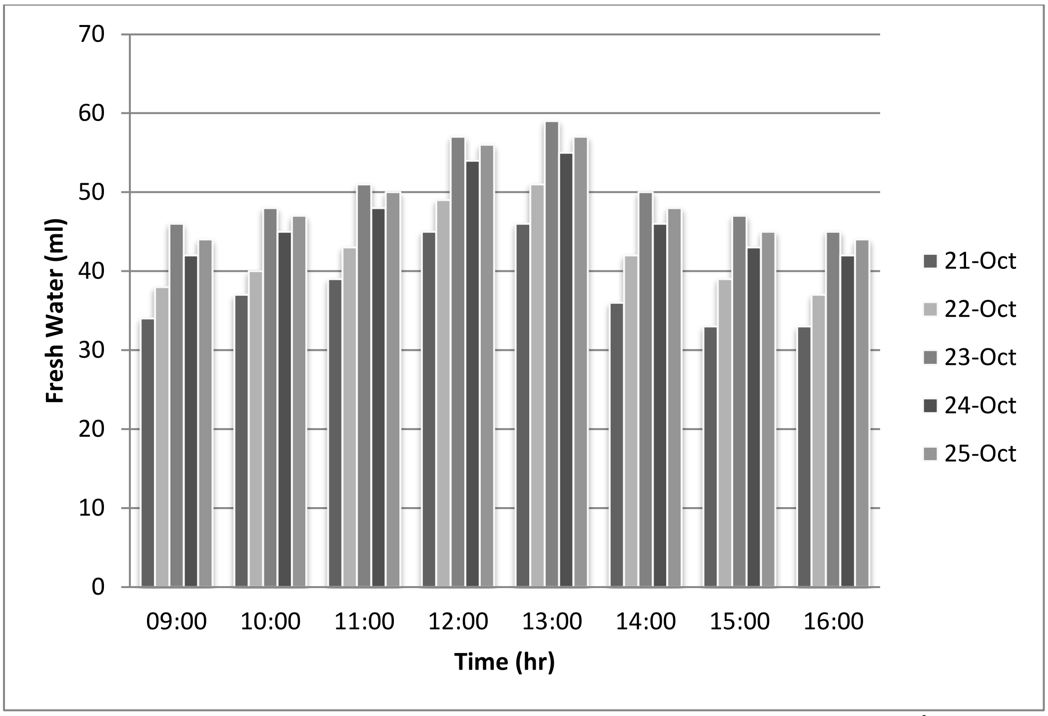

Figure B.3: Fresh water for DISWD $_{upper}$ (glass surface) from 21st to 25th October 2013

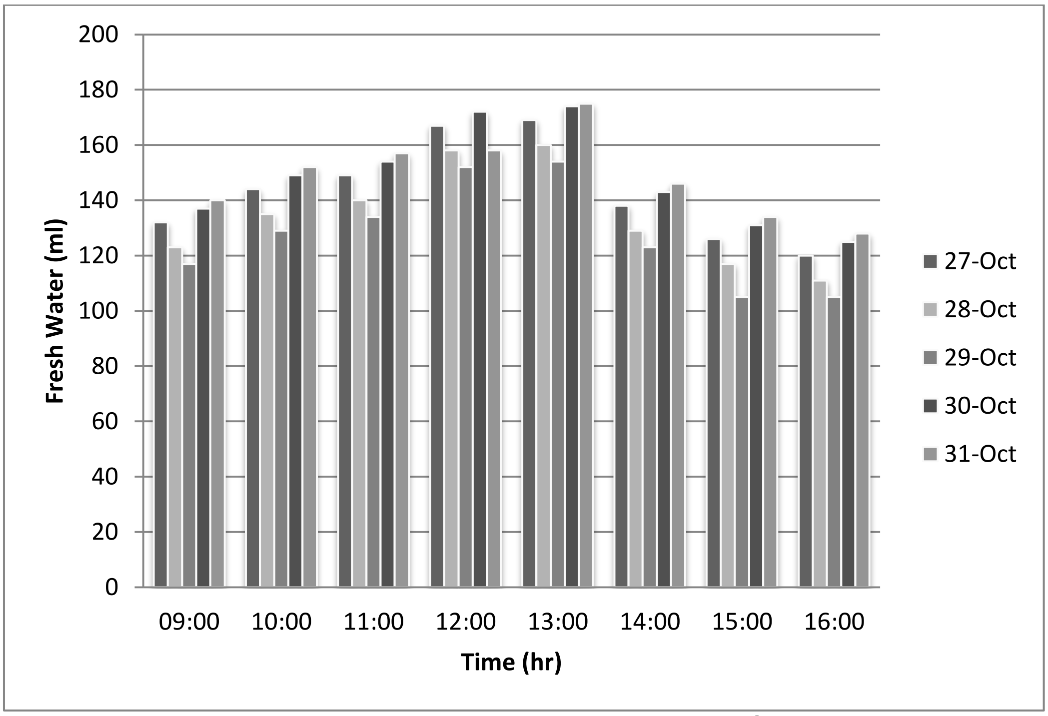

Figure B.4: Fresh water for ISWD (black-fleece) from 27th to 31st October 2013

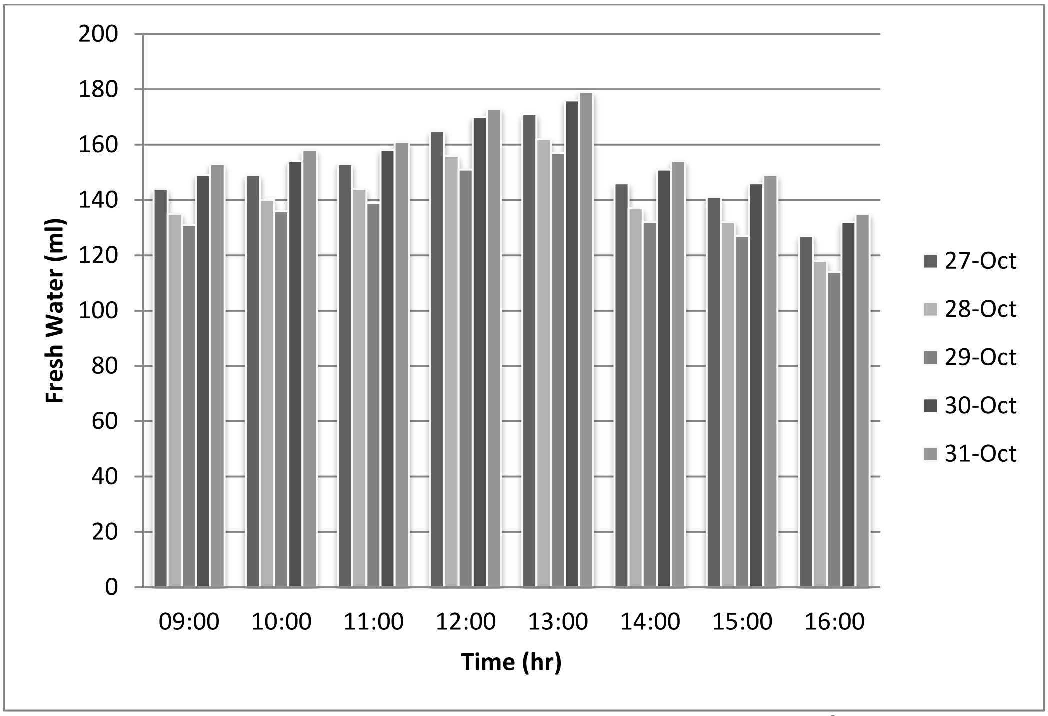

Figure B.5: Fresh water for DISWD $_{lower}$ (black-fleece) from 27th to 31st October 2013

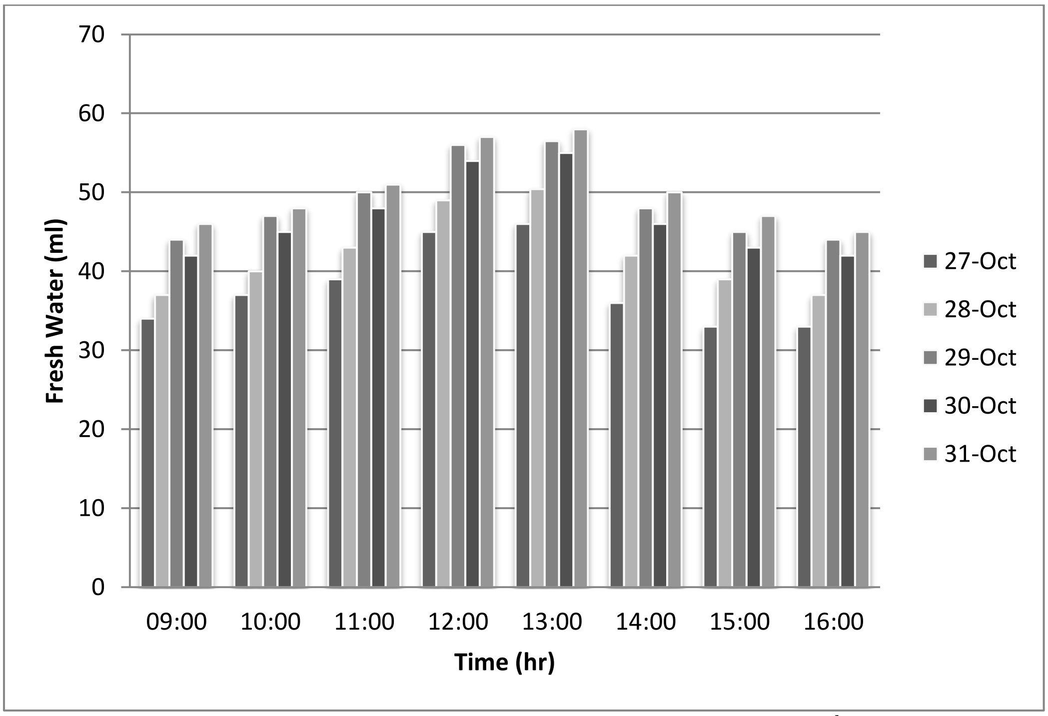

Figure B.6: Fresh water for DISWD $_{upper}$ (glass surface) from 27th to 31st October 2013

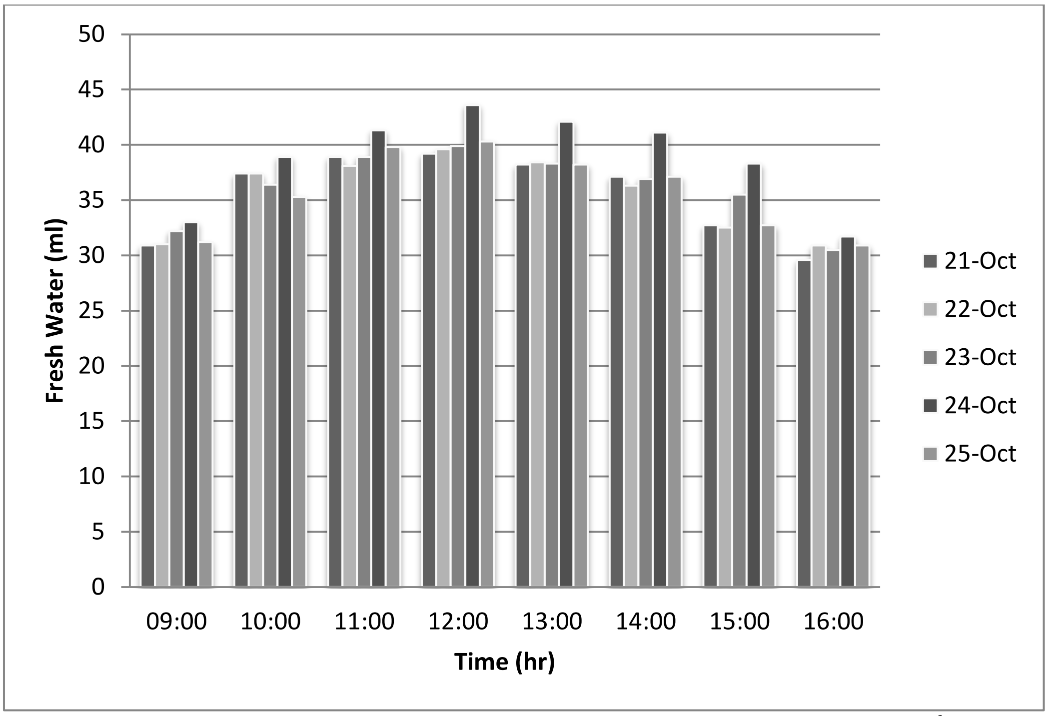

Figure B.7: Hot water temperatures for ISWD (bare plate) from 21st to 25th October 2013

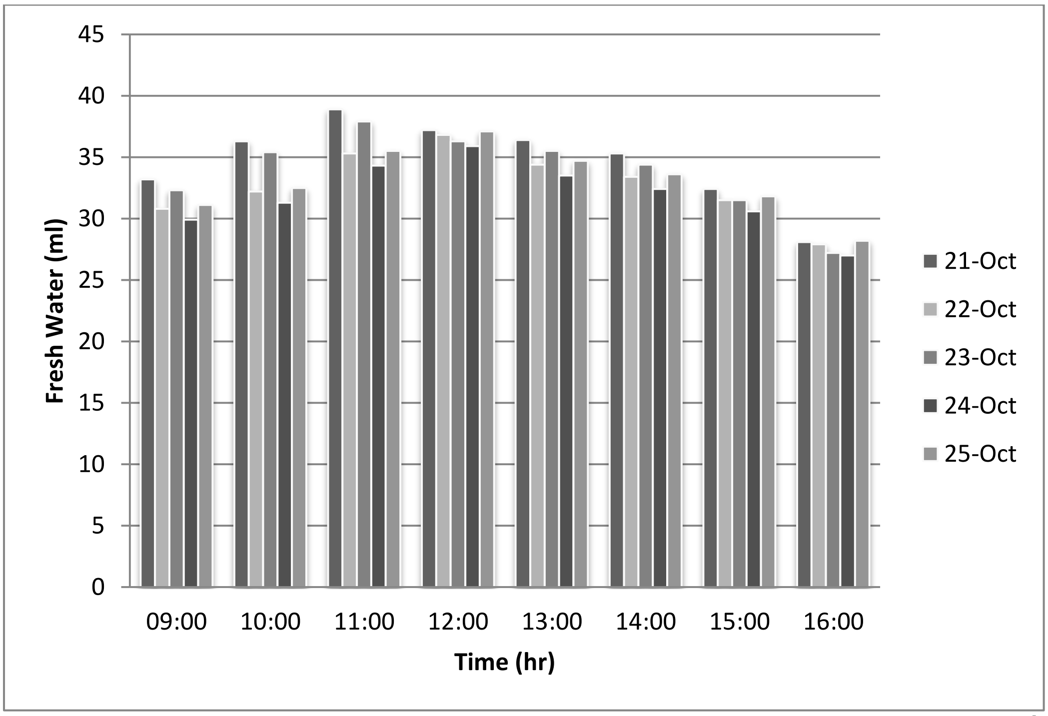

Figure B.8: Hot water temperatures for DISWD $_{lower}$ (bare plate) from 21st to 25th October 2013

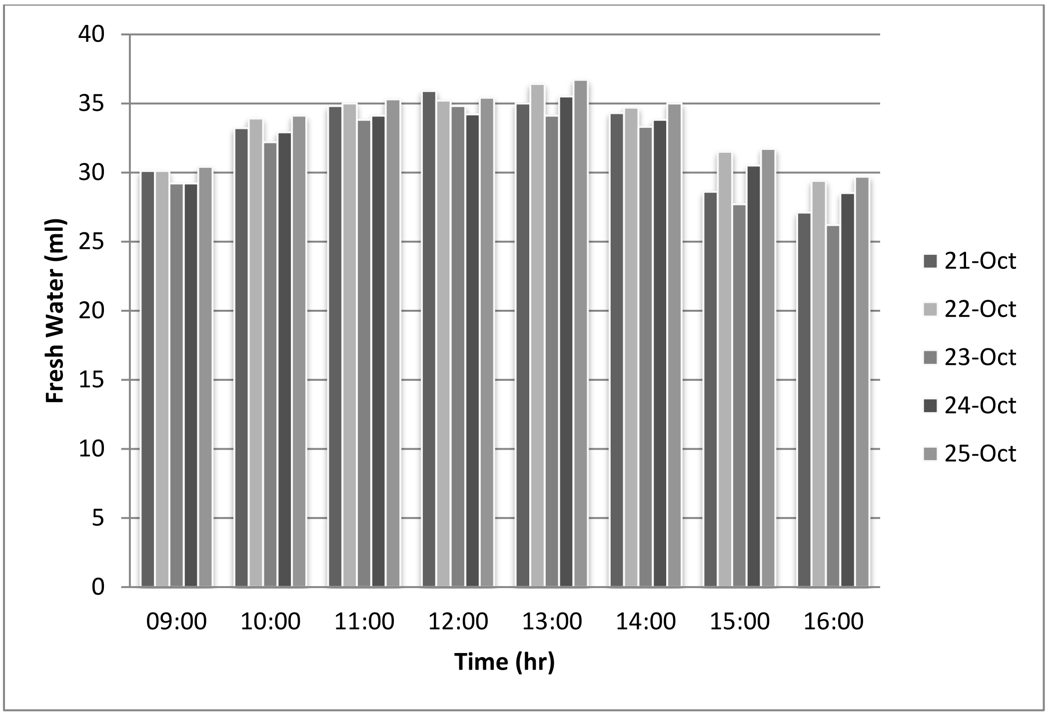

Figure B.9: Hot water temperatures for DISWD $_{upper}$ (glass surface) from 21st to 25th October 2013

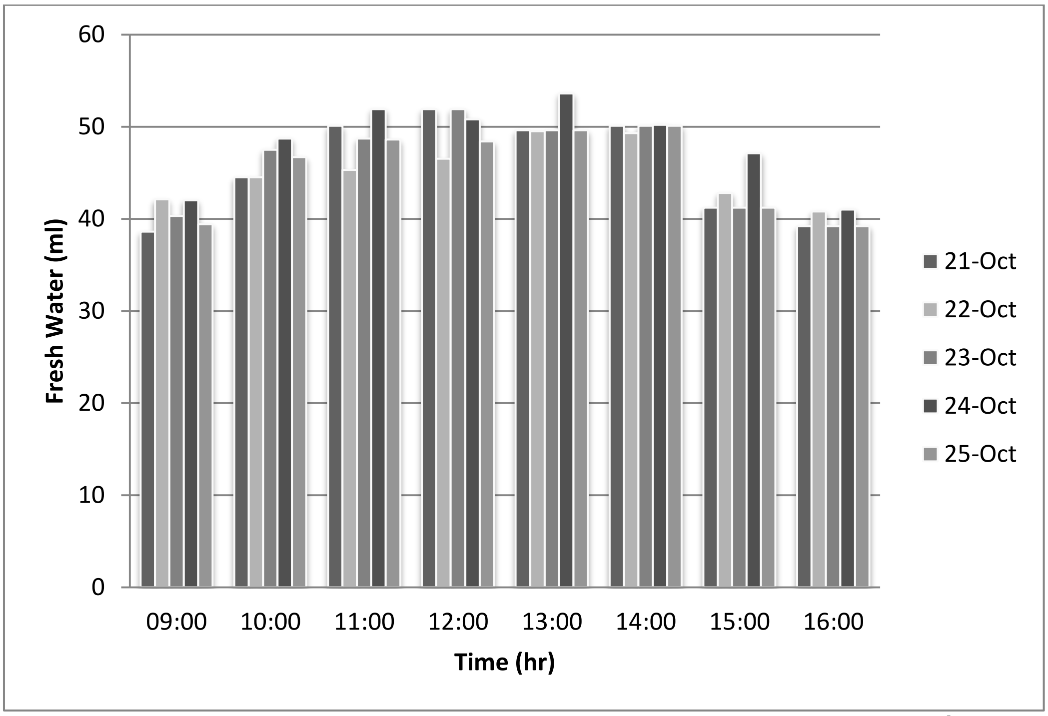

Figure B.10: Air cavity temperatures for ISWD (bare plate) from 21st to 25th October 2013

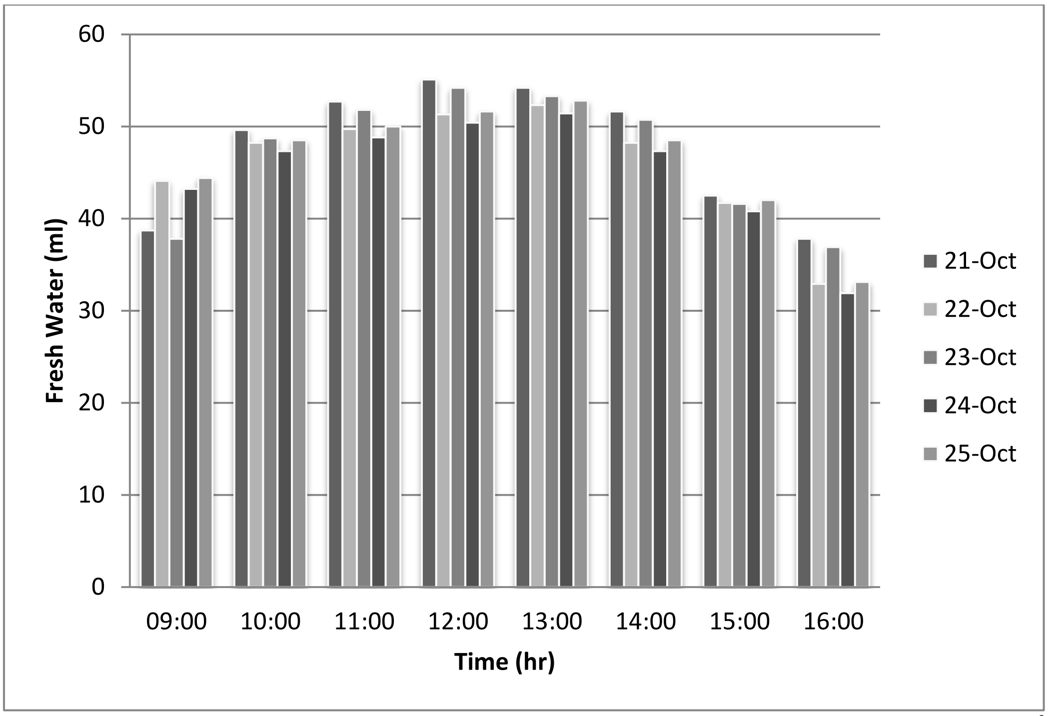

Figure B.11: Air cavity temperatures for DISWD $_{lower}$ (bare plate) from 21st to 25th October 2013

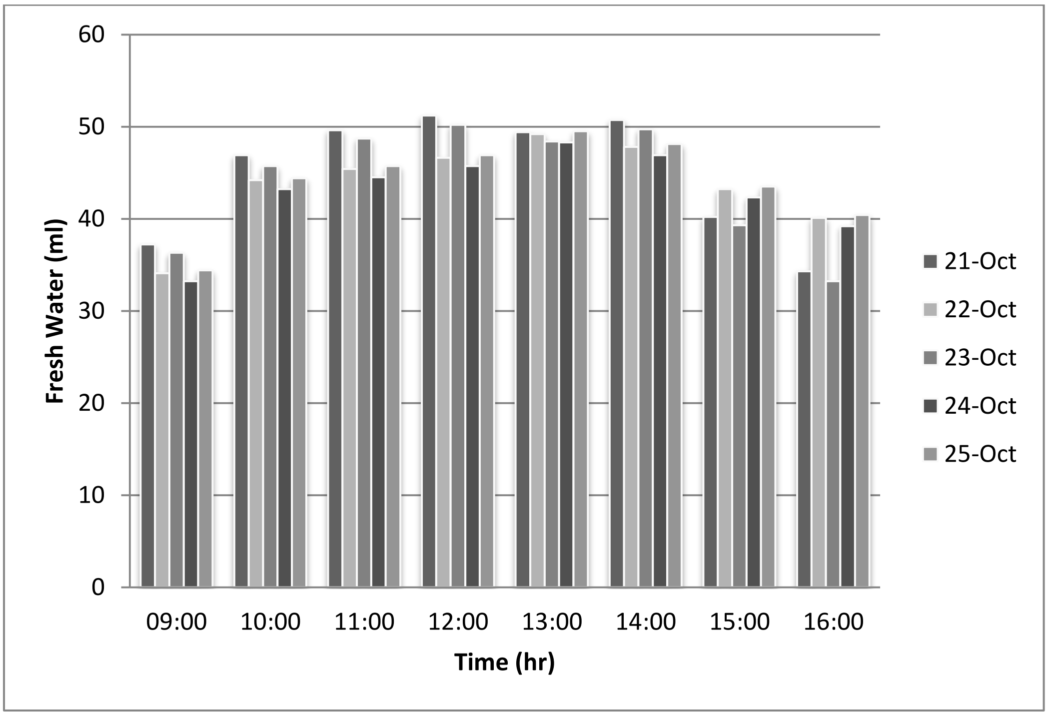

Figure B.12: Air cavity temperatures for DISWD $_{upper}$ (glass surface) from 21st to 25th October 2013

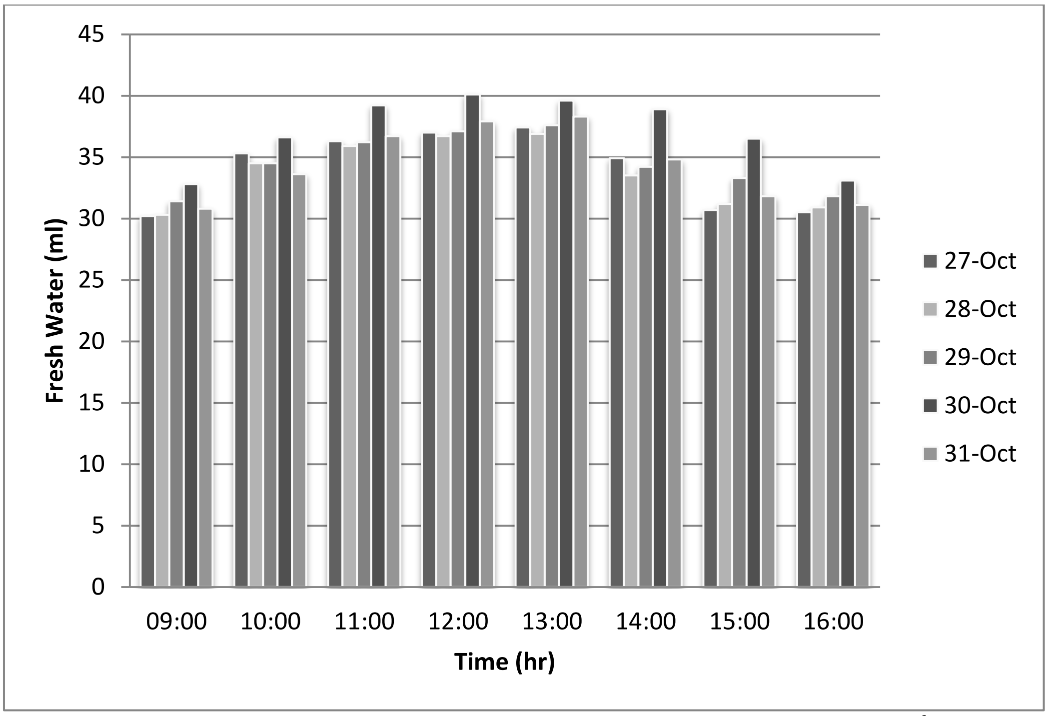

Figure B.13: Hot water temperature for ISWD (black-fleece) from 27th to 31st October 2013

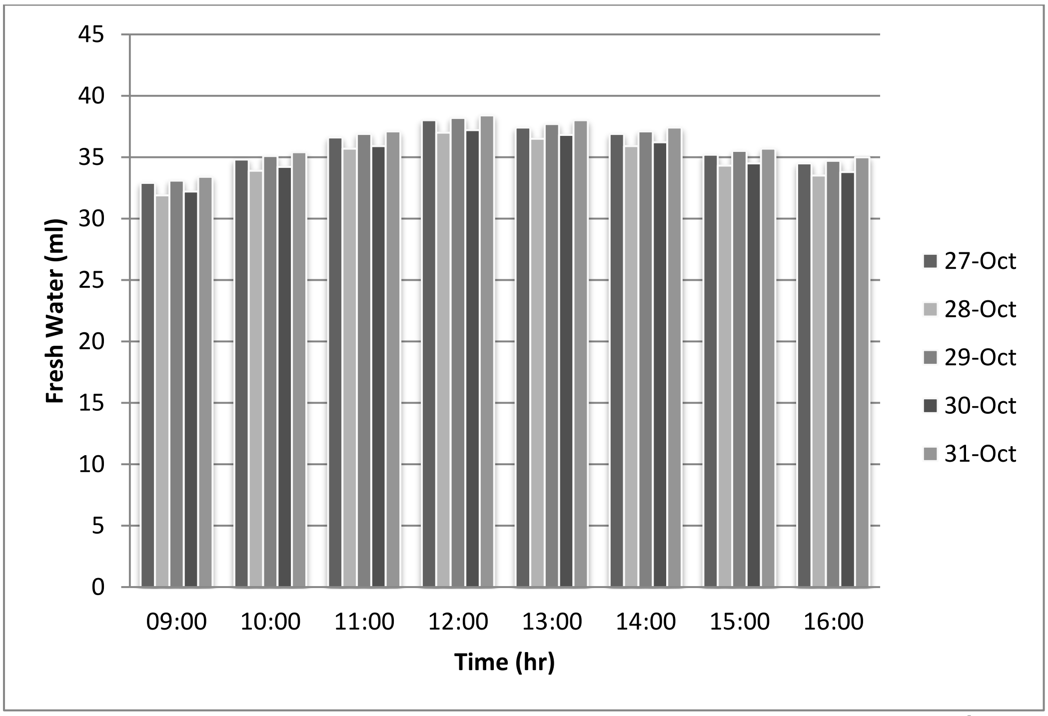

Figure B.14: Hot water Temperature for DISWD $_{lower}$ (black-fleece) from 27th to 31st October 2013

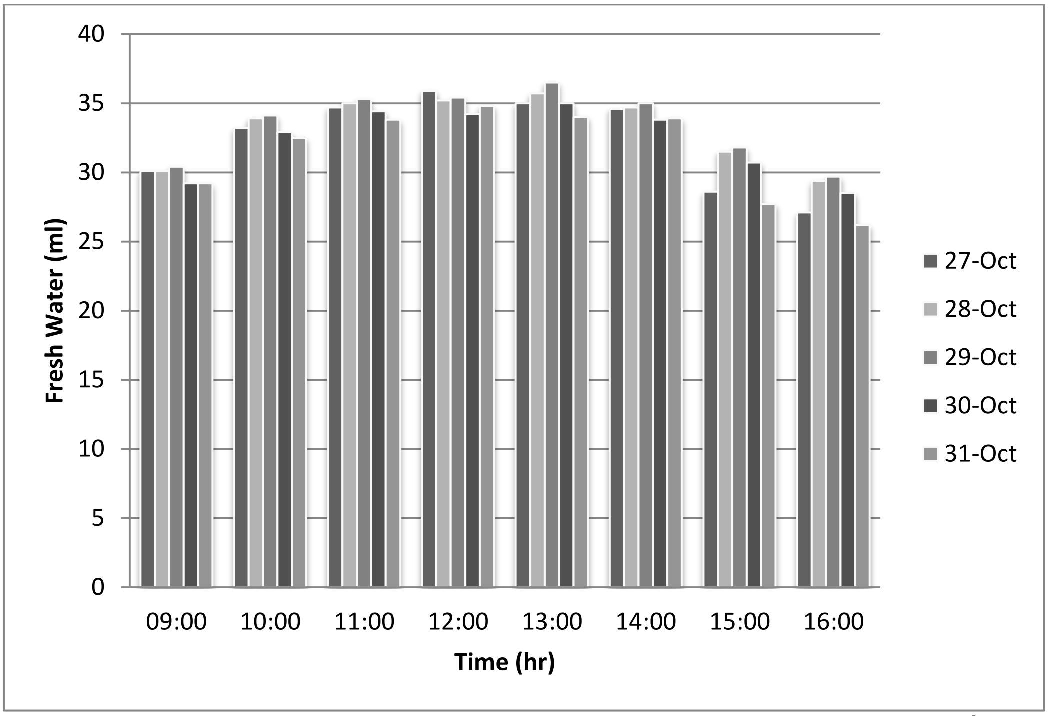

Figure B.15: Hot water Temperature for DISWD $_{upper}$ (glass surface) from 27th to 31st October 2013

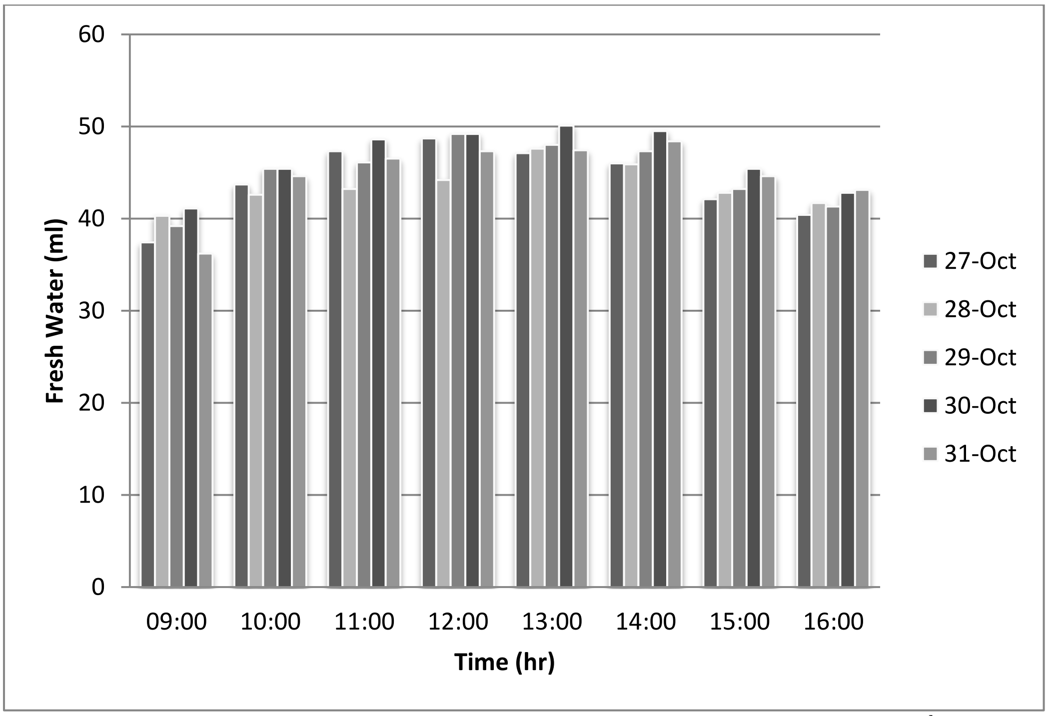

Figure B.16: Air cavity temperatures for ISWD (black-fleece) from 27th to 31st October 2013

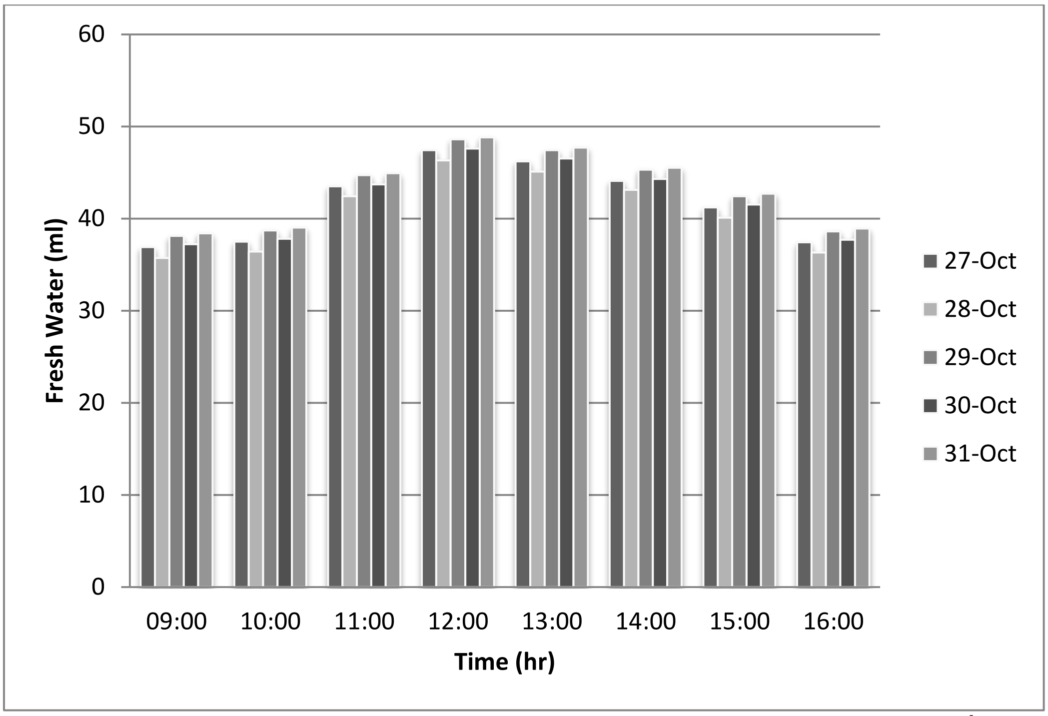

Figure B.17: Air cavity temperatures for DISWD $_{lower}$ (black-fleece) from 27th to 31st

October 2013

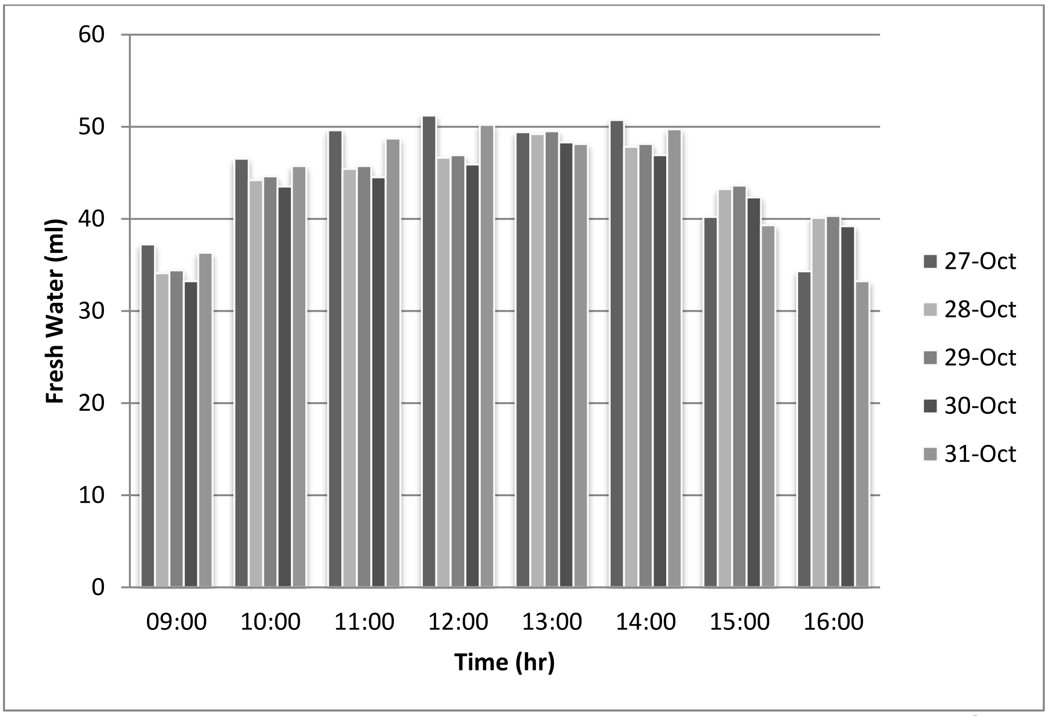

Figure B.18: Air cavity temperatures for DISWD $_{upper}$ (glass surface) from 27th to 31st

October 2013