Solar Desalination System by Humidification Dehumidification Method

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ABSTRACT

A humidification/dehumidification (HDH) solar desalination unit having combined solar water/air heater was designed constructed and experimentally investigated. The main components of the desalination system are the combined solar air/water heater collector with double glazing, humidifier (evaporator), dehumidifier (condenser), circulating pump, fan and a storage tank. Both air and saline (or brackish water) were heated in a single combined solar water/air heater.

The effect of air mass flow rate and the temperature difference of the brackish water between the solar collector and humidifier exits on the performance were investigated. The result showed that the temperature difference has no effect on the system productivity however; the change in the air mass flow rate has a direct effect on fresh water productivity.

The maximum productivity was achieved on 7th of July 7.2L/m^{2}day at air mass flow rate of 0.0261 kg/s. Furthermore, economic study was provided and it is found that the cost of fresh water per liter was calculated as 0.041TL and the payback period was estimated to be 770 days.

Keywords: Solar desalination, Humidification, Dehumidification

ÖZ

Kombine güneş su/hava ısıtıclı bir nemlendirme/nem alma (HDH) desalinasyon ünitesi tasarlanmış, yapılmış ve deneysel olarak incelenmiştir Desalinasyon sisteminin ana bileşenleri kombine çift cam güneş hava/su ısıtıcı kolektörü, nemlendirici (evaporatör), nem alıcı (kondenser), pompa, fan ve bir su tankıdır. Hava ve tuzlu su (veya acı su) kombine güneş su/hava ısıtıcısında ısıtılmıştır. Hava kütle akış hızının, güneş kolektörü ve nemlendirici çıkışındaki tuzlu su sıcaklıklarının sistem üretkenliğine etkileri incelenmiştir. Sonuç olarak, tuzlu sudaki sıcaklık farkının sistem verimliliği üzerinde hemen hemen hiçbir etkisinin olmadığını ancak; hava kütle akış oranındaki değişimin tatlı su verimliliği üzerinde doğrudan bir etkiye sahip olduğu gözlemlenmiştir. Maksimum verimlilik 0,0261 kg/s hava debisi ile 7 Temmuzda 7.2L/m^{2}gün olarak elde edildi. Ayrıca, ekonomik çalışma sağlandı ve elde edilen tatlı su maliyetinin litre fiyatı 0.041TL olarak tesbit edildi sistemin kendisini geri ödeme süresi ise 770 gün olarak tahmin edilmiştir.

Anahtar Kelimeler: Güneş desalinasyonu, Nemlendirme, Nem alma.

To my family

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

HDH	Humidification Dehumidification
MSF	Multi-stage flash
MEE	Multiple-effect evaporation
RO	Reverse Osmosis
MVC	Mechanical Vapor- compression
ϕ_a	Ambient relative humidity
ϕ_{eo}	The evaporator outlet relative humidity
ϕ_{ei}	The evaporator inlet relative humidity
T_{eo}	The evaporator temperature outlet
T_a	Ambient temperature
T_{ei}	The evaporator temperature inlet
$\dot{m}_a$	The air mass flow rate
C_{pa}	Specific heat of air
$T_{a\ out}$	The air outlet temperature
$T_{a\ in}$	The air inlet temperature
A_c	The combined collector area
$\dot{m}_w$	The water mass flow rate
C_{pw}	Specific heat of water
$T_{w\ out}$	The water outlet temperature
$T_{w\ in}$	The water inlet temperature
I	Solar irradiation

ω	The uncertainty
η	Efficiency of the solar collector

Chapter 1

INTRODUCTION

1.1 Background

The water and energy are the most important topics of the international environment and development agenda, both of them are playing acute role in the overall economic improvement of any place in the world. At present the water reduction is a real problem in many countries of the world. In several regions in the world the pollution of the seas, oceans, lakes, rivers and groundwater has extremely decreased the accessibility of clean fresh water. The potable water for drinking and cooking must be treated well for safety purposes. This situation leads to apply the cleaning principle that used to purify the salty water. In many places around the world the authorities are trying to supply drinking water for their citizen. But in many places the water demand around the world exceeds its supply [1]. The production of potable water from utilizing the sun requires large amounts of solar energy. The cost of water treatment depends on the availability and the country's ability of providing the suitable prices for purifying the salty water. This is the biggest challenges that face the production of fresh water. By the rapid growth of population the water resources are decreasing dramatically. In desert areas and semi-desert areas of the Middle East countries the future water scarcity is always on their agenda because it is a real issue of growing importance in the countries that suffering from the conflict of the water resources [2]. Desalination method is increasingly considered as the best solution to meet the increasing water demands in the countries that suffering from the scarcity of potable water. The cost of desalinated water by using the solar energy is more efficient than using other purification sources [3]. The distribution of water resources on the earth as fresh and salty water is 3% and 97% respectively. The potable water quantity resources during the years is roughly constant and the water utilization significantly increased by the increase in the population, heavy minerals and industrial water and bad management of water is weary the fresh water sources. The increase of the world population, the addition to the unbalanced diffusion of water sources and climate change have lead reduction of fresh water around the world, These parameters make another way of providing appropriate sources of fresh water an issue worth to be considered. Purification principles are deemed by many regions around the globe as the most applicable and economical way for producing drinking water [4].

1.2 Renewable Energy and Purification plants

The renewable energies and purification systems are two different technologies that can be utilized in many ways. The purification systems are operated by using the renewable energy sources; it can be installed in any place especially in the regions that have no electricity grid, renewable energy like wind and solar energy that can be used to operate the purification plants. The drawback of using the renewable energy is the initial cost and the requirement of large areas renewable energy technologies has many advantages. The arid or semi-arid regions that have abundant renewable energy sources and have no conventional energy supply that can utilize the renewable energy for the desalination . Using the solar energy for water desalination is a promising technique for supplying the potable water. In some cases the increase of freshwater demand occurs by the tourism and other reasons, which are normally, happen in some countries. During summer when the availability of solar radiation is high, using the renewable energy (i.e., solar radiation) for purifying the water and the desalination systems refer to self sufficiency. Desalination plants utilizing renewable energy easily in any place compared to conventional energy systems and it can be compiled and supported by local resources. In developing countries that are suffering from the water deduction issues the purification by utilizing the renewable energy sources are being the best solution to decrease the human demand of the energy supply [5].

1.3 Solar Desalination

The main purpose of using the solar desalination units is to purify and extract the salt from water by using the solar energy. The solar desalination categorization mainly based on the techniques and the supply of energy. Solar desalination systems that can produce the water for drinking and cooking from the salty water is the best solution for covering the human demand by using the renewable energy in the purification method. The solar purification plants can be classified according to technically and the design of the system. They can be also classified to direct and indirect collection systems. In the direct collection systems all parts are integrated into one system while the indirect systems sub-systems. Some solar purification systems coupled with the conventional purification units were installed in different regions in the Middle East and other places many of these systems are either experimental or demonstration scales. These systems have high initial and maintenance costs. In some Arab countries which are suffering a potable water detection and almost 95% from their demand is covered by sea water purification and they have a lot of oil. However, they should try to run their plants by using the renewable energy like solar energy and they also have high solar insulation during a year [6]. The present work based on the indirect type of solar purification unit.

1.4 Scope and objectives

The main purpose of the present work is to design, construct and test humidification dehumidification (HDH) solar desalination unit to find out the maximum productivity of the water purification system in summer conditions for North Cyprus. The effect of the weather change on the unit productivity was studied.

The literature review on solar desalination shows that there are widespread works on the humidification dehumidification units. There are many studies close to the HDH desalination systems. However, none have considered combining the air and water in the same solar collector. Thus there is no experimental work available in the literature in combining the solar collectors in the HDH units. The whole work is classified into five (5) chapters as follows.

Chapters 1, introduce the backgrounds of solar desalination, water shortage in the world and the relation between the renewable energy and desalination units.

Chapter 2 presented the literature review of the solar HDH purification systems as related to the thesis topic.

Chapter 3 discusses the configuration, and the experimental procedure of HDH purification principle under the study is introduced.

Chapter 4 presents in detail the results that obtained from the test.

Chapter 5 is the Conclusions and the future work recommendations.

Chapter 2

BACKGROUND

2.1. Desalination

The desalination process is used to remove the salts and other dissolved solids of the brackish or the sea water. Desalination requires energy. Using conventional energy resources (i.e., fossil fuels) will cause environmental pollution. The purification process based on energy used can be classified as thermal, mechanical, electrical or chemical energy. The thermal desalination includes Multi-stage flash(MSF),Multiple-effect evaporation (MEE),Humidification dehumidification (HDH),Solar distillation and freezing. Mechanical desalination methods include Reverse Osmosis (RO) and Mechanical Vapor-compression (MVC).In electrodialysis desalination method electrical energy is used and chemical energy is used in the ion exchange desalination method.

2.2. Solar stills

Solar stills simulate the natural cycle of water. It is simple to build and operate and provides the need of potable water for small scale that can be applied to cover a family demand. These types of systems get the benefits from the solar radiation that incident on the solar collector surface from the sun to evaporate the water inside the chamber. Then the condensation takes place on the glass cover and collected as potable water. The solar stills can be classified basically in two types; active and passive solar still systems [11].

2.3 Historical review

Many researchers worked on a humidification dehumidification principle from different aspects. E. Hassan et al [14] investigated numerically the performance of a HDH unit. The HDH has the following components; solar air heater, humidifier, dehumidifier and the air circulation. The study covers the effect of different parameters like environmental, design, and operational criteria on the desalination system productivity. Environmental parameters include the solar incident radiation, ambient temperature and wind velocity. Design parameters include the solar air heater, humidifier and the dehumidifier effectiveness. Operational parameters include air circulation flow rate, and the temperature of feed water. The result showed that the productivity of the system is increased by increase in the solar intensity, ambient temperature and decreasing wind velocity, the increment of air flow rate to 0.7 kg/s increased the system productivity, temperature and the feed water flow rate had no effect on the unit's productivity.

M. Adel et al [15] carried out an experimental and numerical study. The objective of their study was to demonstrate the performance of a solar purification system based on the multiple condensation–evaporation cycle. The system consisted of flat-plate collector, humidifier, and dehumidifier. The air circulation is maintained by natural convection in the unit. They indicated that high inlet temperature has a negative effect on the collector performance. The solar collector only used to preheat the hot return water and an auxiliary heater used to acquire the required temperature. The difference between the outlet temperatures of the heat exchanger nearly was same to the outlet temperature of the collector. The system productivity in summer reached about 24 l/day.

This productivity is comparatively low compared with the published data in the literature. However, it is greater than the basin solar still.

Shaobo H, et al [16], worked on solar humidification dehumidification systems by using pinch technology. The study aimed to determine the performance optimization of the HDH method by using pinch technology. The unit under their study was consisting of flat plate solar collector, humidifier and a dehumidifier. The thermal energy recovery rate increases whereas the temperature differences at a pinch point shrinks. The result showed that when the pinches' temperature difference 1^0C, the recovery rate of energy could reach 0.836.

C. Yamal, and I. Solmus [17] studied in HDH desalination unit consisting of double-pass flat plate solar air heater with two glass covers, humidifying tower, condensation chamber and water storage tank. The unit is closed water and open air cycles. The unit productivity is affected by increasing the inlet water and air mass flow rates for the humidifier. Also, increasing and decreasing the cooling water mass flow rate temperature leads to definite increment in the system productivity the energy balance equations were solved numerically.

The authors indicated that the productivity of the unit improved up to 8% by using the double -pass solar air heater compared with a single pass solar air heater, under the same operating conditions. Its productivity decreased approximately 30% without double-pass solar air heater.

Orfi.N,et al [18], studied a HDH desalination unit in Tunisia. The system was consisted of two solar collectors; one for heating the air and the other for heating the water, humidifier and dehumidifier chambers, the study aimed to express the maximum production of potable water with permanently adjusting the ratio between the air mass flow rate and the saline water. The air and water were heated in the collectors, and they contacted with each other in the humidifier. The theoretical results show that there was an optimum mass flow rate ratio to a corresponding maximum potable water product.

S. Houa [19] carried out plotted pinch analysis purification process of two-stage solar multi-effect humidification dehumidification. The unit consisted of two closed loops for the air circulation. One was the highest level, high-circulation, temperature, and the other one was the lower stage, the lower temperature circulation. The author reported that, by using two stages the energy recovers rate is higher compared to one have one stage. The recovery rate of the minimum temperature could reach 0.836 when differences at pinches are 1°C.The energy recovery rate by using multistage would be the highest, and that leads to a higher grain output ratio.

C. Yamal, and I, Solmus [20] carried out an experimental study on HDH unit to certify the mathematical model of the unit developed in “2007."Their system consisted of a double -pass flat plate solar air heater with two glass covers, evaporator, condenser and water storage tank. The experimental setup concept was based on closed water and open-air cycles. There were many parameters that effect on the unit productivity such as the mass flow rate of the feed water, solar incident radiation, wind velocity, relative humidity, water initial temperature and the water quantity in the storage tank. The authors indicate that the unit productivity decreases about 15% without using a double-pass solar air heater.

K. Zhani, and H. Ben Bacha [21] carried out an experimental study. Their study was aimed to investigate the feasibility of a solar purification prototype using the humidification dehumidification method. Their unit was consisted of five main components; two flat plate solar collectors one for heating the air and the other one for heating the water, humidifier, an evaporation tower and a condensation tower. Based on the authors report the system was very efficient but economically was not an effective due to the cost of water production was very high. The experimental results show that the maximum potable water productions were in July, which increased with the solar radiation. The direction of the outlet and the inlet temperatures at various component levels were same as solar radiation also the results show that the ambient air temperature has an insignificant influence on thermal performance of the unit.

Z. Wang, et al [22] carried out an experimental study to investigate the feasibility of a purification unit by using humidification–dehumidification method to produce 1000 L/day. The unit under their study was consisting of 100 m^2 solar air heater field, 12 m^2 solar water collector, humidifier dehumidifier, treatment unit and other subsystems. The water temperature in the solar water collector was kept below 50 °C to prevent the corrosion of tubes with hot and salty seawater. The result shows that the parallel outlet solar collector temperature can rise to 118 °C when the solar radiation reaches 760 W/m^2 and the outlet air temperature of the humidifier ranges between 40 to 55 °C, with 80% to 90% relative humidity. The performance of the system is affected by the solar radiation. The economic analysis results show that the price of the produced water is about 19.2 $Yuan/m^3$ which equal to 6.58$/ m^3. The solar air heater is the key for reducing the production water cost in developing a low-cost and high performance unit.

S. Farsad and A. Behzadmehr [23], studied the solar humidification dehumidification system. Their HDH system consisted of two collectors one for heating the water and the other one for the air, humidifier and a dehumidifier. Solar energy is used as a source of heating in the system. The energy and mass balance equations were solved numerically to analyze the cycle parameters and the quantity of fresh water production.

A. Kr Tiwari, and T. Sachdev [24] carried out theoretical study on a humidification dehumidification unit by using a solar air heater. The system includes a double -pass flat plate solar air heater with two glass covers, evaporator, dehumidifier and water storage tank. The mathematical programming was based on the energy balance equations to investigate the effect of design and operating parameters. The authors indicated that by using a double-pass solar air heater the system productivity increased up to 10% instead compared to using the single-pass flat plate solar air heater. By increasing the air mass flow rate up to the unit the productivity increased. The maximum production was achieved at mass flow rate of 0.03 kg/s. Wind velocity and bottom heat loss of the solar heater and the storage tank has a negligible effect on the system's productivity.

M. Zamena, et al [25] carried out an experimental study to investigate the effect of using two stages on solar humidification-dehumidification units. Their unit was consisting of 80m^2 solar collector area, humidifier, and dehumidifier. The main purpose of their study was to improve the efficiency of the HDH method and to promote the energy consumption per unit of potable water production.

They were solved the governing equations mathematically of each stage that based on heat and mass balance. Based on the authors' report; by increasing the number of the stages energy consumption was reduced by more than 35%. By using a two-stage unit the daily production per solar collector area will increase more than 40% while decreasing in using 3 and 4 stages by 4% and 1% respectively also the authors report mentioned that the main enhancement for the energy consumption per kg of potable water and the system productivity occurs from one to two-stage process.

By using two stages would reduce 20% of the required solar collector area compared with the single one which also reduces the investment cost. The maximum productivity of the purification system reached to about 500 l/day.

Chapter 3

EXPERIMENTAL PROCEDURE

3.1 Apparatus

A HDH system experimental setup was designed and constructed at the workshop in the Mechanical Engineering Department at EMU in order to get data for the investigation. Fig 3.1 shows a schematic diagram of the HDH unit. The system includes combined solar air/water collector, evaporator, condenser, pump, fan, duct and pipes. The parts of the system are explained briefly in the following sub-sections

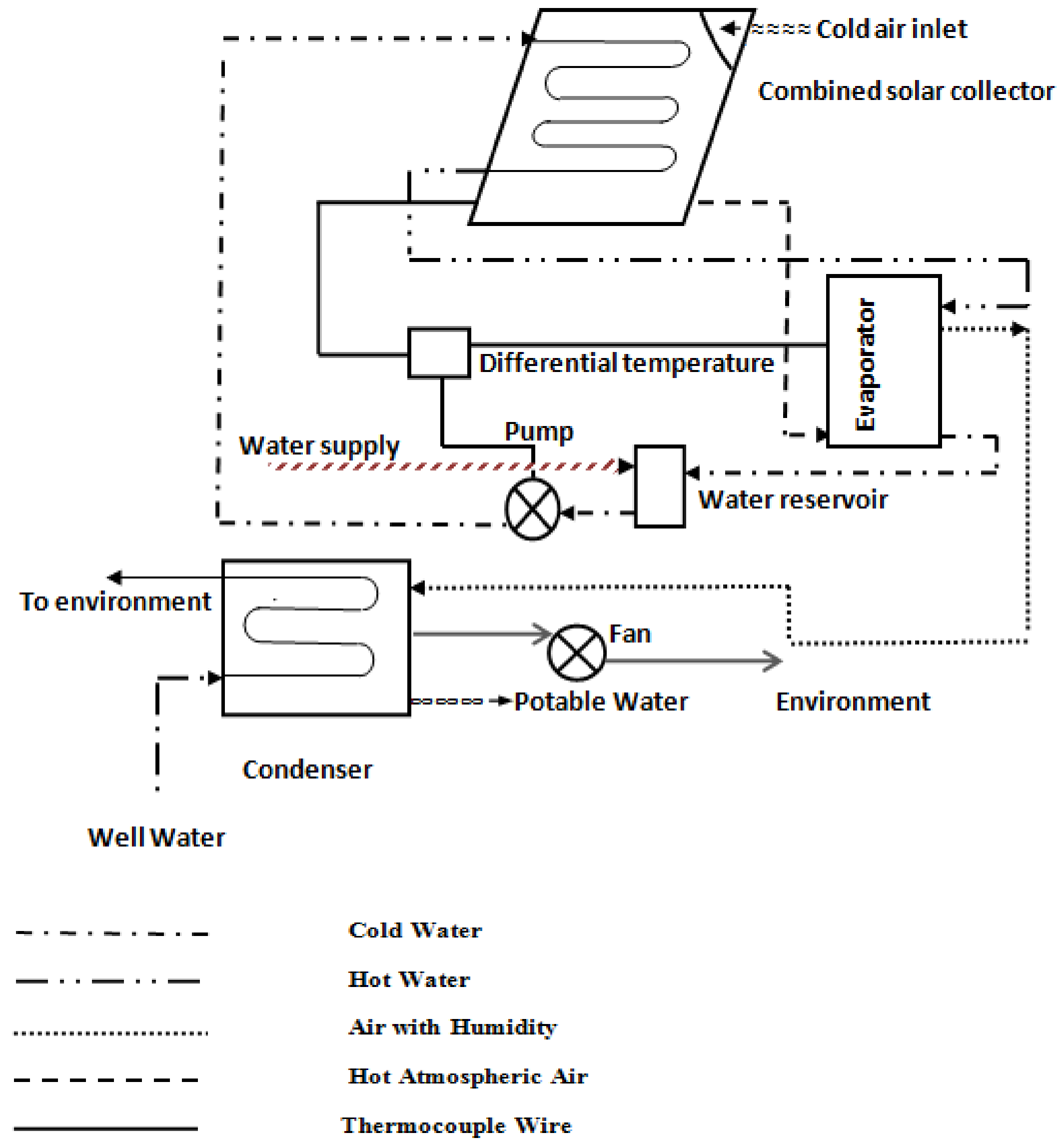
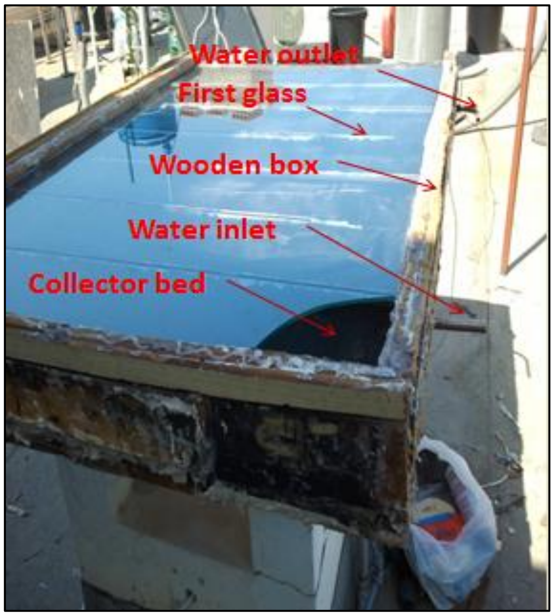


Figure 3.1 : Schematic Diagram of HDH Unit

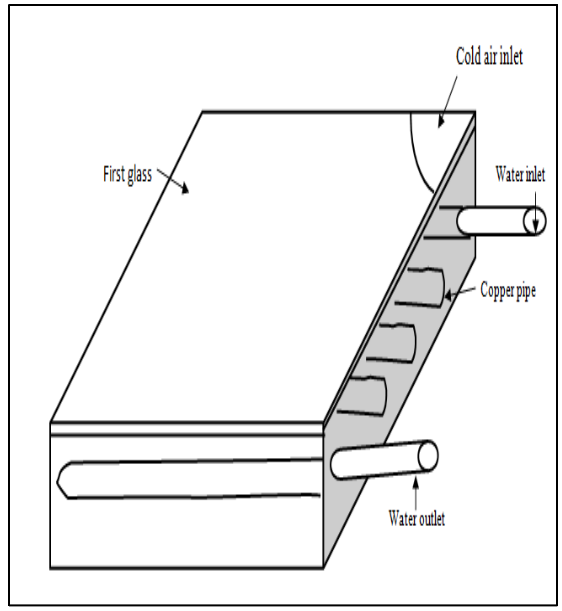
3.1.1 Double pass solar air and water heater collector

The double pass solar air and water heater collector wooden box are 150 cm long and 100 cm wide and 10 cm high. The inside of the collector box was painted with black color in order to increase the absorptivity. The collector bottom was externally insulated with 2 cm thick Styrofoam. Two normal window glasses with 0.4 cm thickness each were used to glaze the collector and to form a second channel pass within the collector.

The distance between the upper and the lower glass was fixed to be 3 cm. In the lower glass a quarter circle having a radius of 15 cm hole was made to allow the air flow between the first glass and the bottom of the collector see Figure 3.2.



A1



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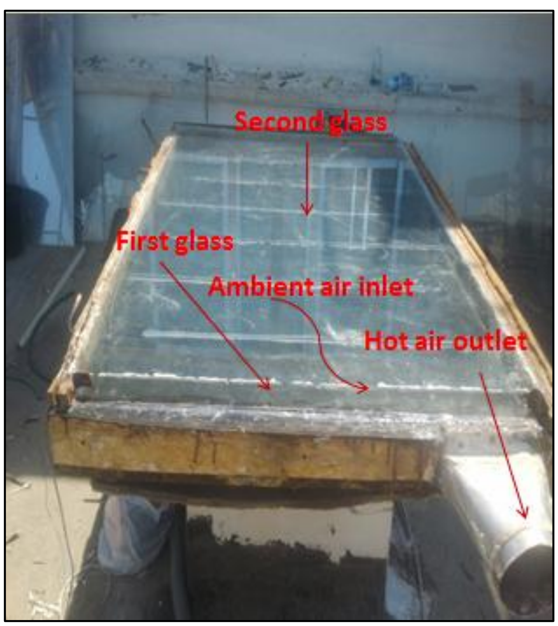

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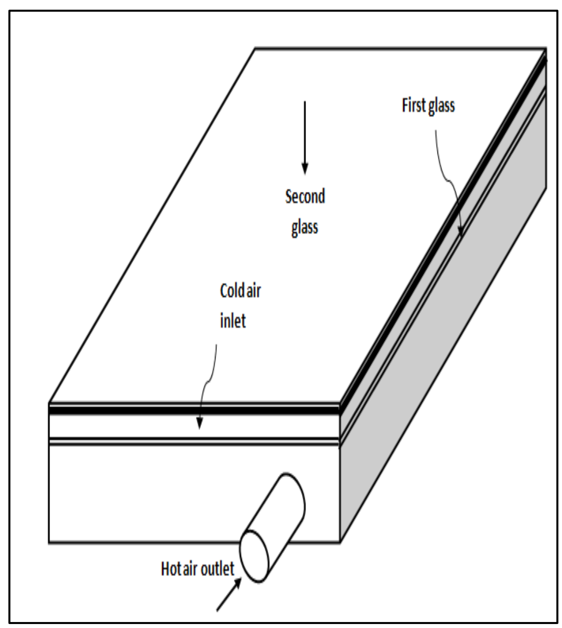


B2

Figure 3.2: (A1) and (B1) Pictorial View and (A2) and (B2) diagram of solar collector

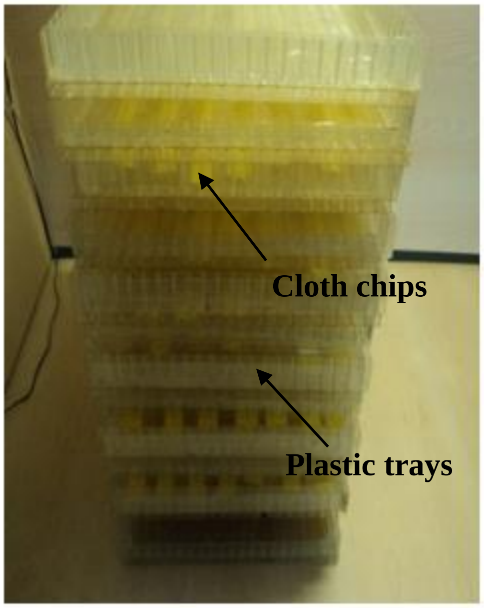
20 meter copper tube having 10 mm diameter was used in the collector to heat the incoming water. The copper pipe was bended in a U shape and run from the bottom to the top of the collector. The pipe was placed 2.5 cm below the first glass. Outside air sucked into the collector through the opening between tpper and the lower classes. Then air enters into the second passage through the quarter circle and contacts with the copper pipes conveying water.

3.1.2 Evaporator

The humidification part of the present experiment is a cascading evaporator; the humidifier was consisting of metal box made of 2 mm galvanized steel sheet metal of dimensions 30 cm long, 30 cm wide and 45 cm high.

Twelve trays were mounted parallel in the metal box; each one of them from the back side has at least sixteen small cloth chips to boost the evaporation. Thermocouples were installed in the middle of the trays to measure the temperature.

A liquid distributor at the top of the metal box feed the trays by the hot water coming from the combined solar air/water heater collector; water drained from the box is directed back to the collector. The air enters to the humidifier and contact with water in the parallel trays which have cloth chips to improve the heat and mass exchange, hence the water flows downward, while the air passes in the cross flow direction through the trays. The air is humidified with the wetted surface of the trays. The aim is to boost the amount of water vapor in the air. Thus higher air and water temperatures are desirable. Figures 3-3 shows the humidifier.



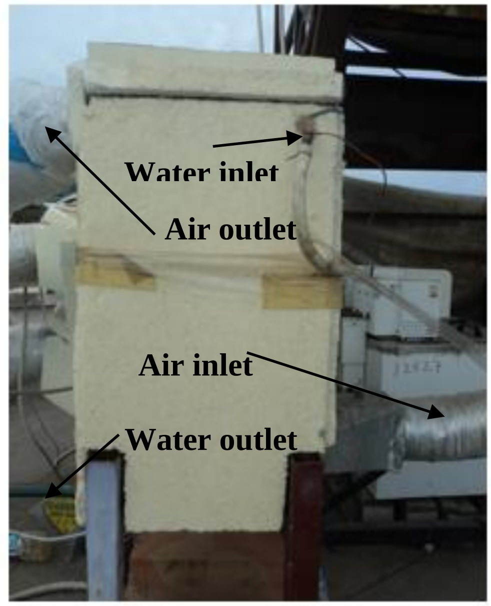


Figure 3.3 (a): Pictorial View of the Humidifier Trays   Figure 3.3 (b): Pictorial View of the Humidifier box

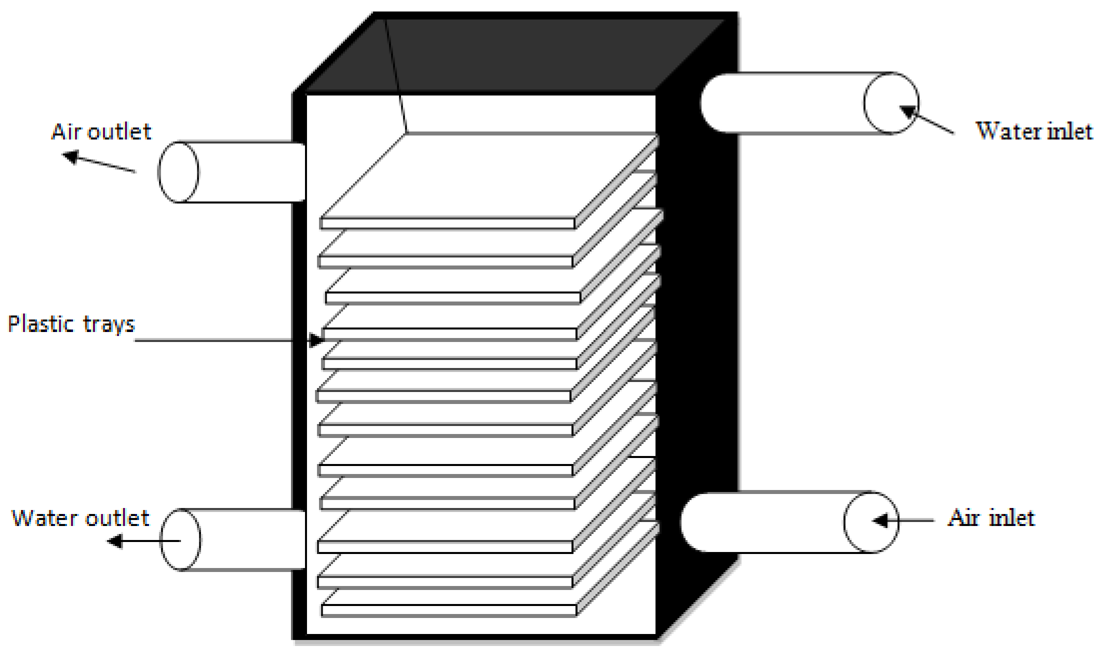


Figure 3.3 (c): Schematic Diagram of the evaporator

3.1.3 Condenser

Four air conditioning condensers were used as a distiller in the insulated dehumidifier part, each one of the four air conditioning have pipes, consequently each have an inlet and an outlet for water circulation. Dimensions of the dehumidifier metal box are 45 cm long, 50 cm wide and 50 cm high. The box was constructed from 2mm thick galvanized steel. When the cooling water circulates through the dehumidifier tubes, potable water condensed outside the evaporator drains to a tube connected to condensate collection. The cooling water temperature in the condenser was between 18^{0}C and 24 ^{0}C which are not constant. The system productivity strongly depends on the condenser efficiency and cooling water temperature. Condenser and an inside view of the dehumidifier are presented in Fig. 3.4 (a), (b) and (c).

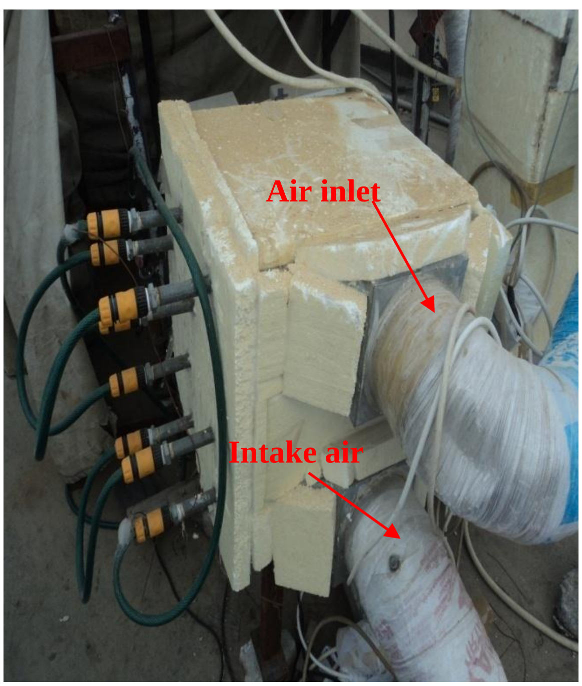


Figure 3.4 (a): Pictorial View of the Condenser

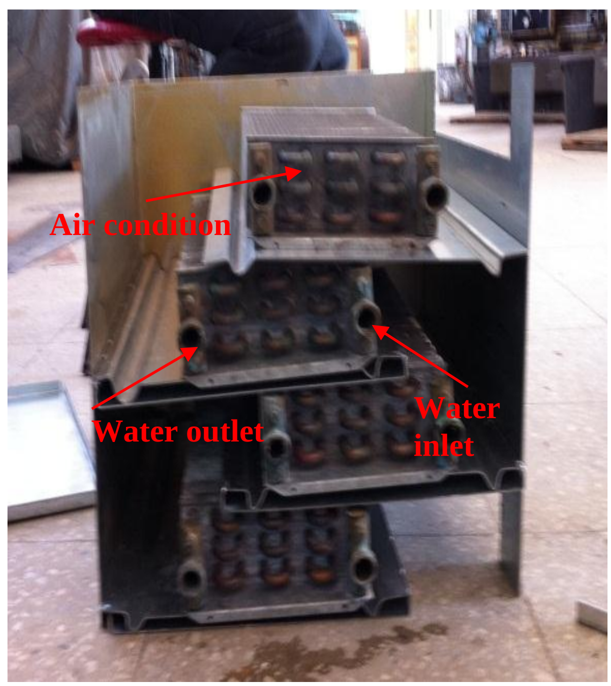


Figure 3.4 (b): Inside view of the Dehumidifier

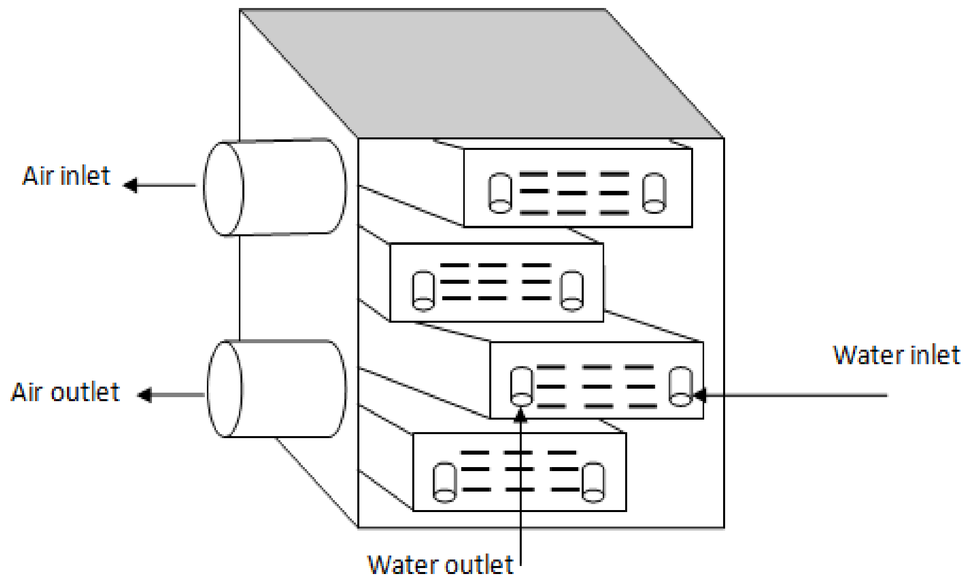


Figure 3.4 (c): Schematic Diagram of the condenser

3.1.4 Water reservoir

The water reservoir that used in the present work was made of plastic and it has a capacity of five liters.

There is a hole at the bottom of the humidifier, this hole connected directly to the water reservoir and the reservoir bottle connected to the water pump, for pumping the water to the combined solar collector. There is a water source for supplying the water reservoir from time to time.

3.1.5 Water pump

The pump is used to circulate the water through the double pass solar collector to the humidification chamber. The pump stops if the temperatures of the combined collector and the evaporator become equal.

3.1.6 Differential temperature

The differential temperature is used to control the temperature of the water between the double pass solar collector and the evaporator by connecting a thermocouple in the sixth tray of the humidifier and the other one in the water exit of the combined collector these thermocouples linked to the differential temperature and controls the pump.

3.1.7 Fan

The aim of using the fan is to intake the air from the condensation chamber to increase the humidified air flow rate (i.e., to increase the production by increasing the air flow rate).

3.2 Measurement and Calibration of the Instrument

3.2.1 Solar Flux

The incident solar irradiation on the inclined surface in the global was measured by using Eppley Radiometer Pyranometer. A pyranometer is an instrument used to measure the total (beam and diffuse) radiation. Its sensor is designed to assess the solar radiation flux density. The DC voltage is measured by a voltmeter connected to the pyranometer. The pyranometer was placed on the glazing of the combined solar air/water heater to obtain the irradiance onto the tilted collector.

Figure3.5: Pictorial View of the Pyranometer

3.2.2 Temperature and humidity Measurement

Thermohygrometer Digital Remote Sensing accurately reads the humidity and temperature, for the humidity measurement ranges from 2 to 98% RH, accuracy 3% @ 25°C, between 20 and 90% of range 5% @ 25°C, below 20 % or above 90% and the response time 30seconds for a 30 to 80 % step change and the accuracy of the temperature measurement is 0.5°C/1°F and the response time 30seconds for 63% step change. This device storage of high and low readings for both temperature and humidity; user reset to clear stored values at any time.

Figure 3.6: Pictorial View of the Thermohygrometer

3.2.3 Anemometer

Hot Wire Anemometer is a device for measuring the air flow rate especially in low velocity measurement. The data were collected by inserting the probe of the instrument in the tube between the collector exit and the evaporator inlet the: cross sectional area of the tube was 10 cm. It has a dual LCD to display the air velocity with temperature and the second display to update; the device can read from 0.2 to 20 m/s. Figure 3.8 shows the pictorial view of the hot wire anemometer.

Figure 3.7: Pictorial View of the Anemometer

3.2 Experimental procedure

Solar desalination systems which are driven by using humidification dehumidification is the promising technique for producing potable water at small scale (few m^3/d) [25]. The experiments of this work were carried out on the roof of the Mechanical Engineering Department at the Eastern Mediterranean University. The experiments were done under the weather condition of Famagusta, North Cyprus during summer months from 21.6.2012 until 13.7.2012.Famagusta city located at 35.3^0 N and 33.9^0 E longitude. In order to optimize the production the collector was facing to the south and had a tilt angle of 35^0.The experiments were carried from 9:00 AM to 6:00 PM. Figure 3.d shows the HDH Desalination system.

Figure 3.8: HDH Desalination system

The air enters to the double pass combined solar air/water heater collector between the two glasses, the air moves upward the inclined collector and directed to the bottom channel. The warm air within the collector was sucked by the fan. Warm air enters into the humidifier where it contacts with warm water from the combined collector. The humidified air then moves to the condenser and condensed water and dehumidified air leaves the condenser.

The water in the copper tubes within the collector was circulated by a small pump and directed to the humidifier. The pump was controlled by a differential temperature such that when the temperature difference between the warm air and warm water reached to a specified value (for example, when $\Delta T = 8\ ^0C$) the pump is turned on and water was circulated within the collector. When $\Delta T = 0^0C$ the pump stops automatically.

Hence the condensate potable water produced drains to a tube connected to condensate collection and there are 8 holes in the condenser box with 5 cm little pipes collect the produced fresh water.

3.4 Uncertainty analysis

The previous section defined the accuracy of the devices that uses in the experimental part .The efficiency of the solar collector η, represent the ratio of the energy gained from the incident solar radiation on the collector plate.(This is a combined solar air/water heater so where is the heat gain of water)

$$\eta = \frac{\dot{m}_a C_{pa}(T_{a\,out} - T_{a\,in}) + \dot{m}_w C_{pw}(T_{w\,out} - T_{w\,in})}{I A_c} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.1)$$

Where η efficiency of the solar collector, $\dot{m}_a$ is the mass flow rate of air, Cpa is the specific heat of air, Ta out is the outlet of air, $T_{a\,in}$ is the inlet of air, Ac the area of the combined collector, $\dot{m}_w$ is the mass flow rate of water, C_{pw} is the specific heat of water, $T_{w\,out}$ is the outlet of water, $T_{w\,in}$ is the inlet of water and I is the solar radiation

The uncertainty analysis of the efficiency of Eq3.1 is

$$\omega_\eta = \left[\left(\frac{\partial\eta}{\partial\dot{m}_a}\omega_{\dot{m}_a}\right)^2 + \left(\frac{\partial\eta}{\partial\Delta T_a}\omega_{\Delta T_a}\right)^2 + \left(\frac{\partial\eta}{\partial\dot{m}_\omega}\omega_{\dot{m}_\omega}\right)^2 + \left(\frac{\partial\eta}{\partial\Delta T_\omega}\omega_{\Delta T_\omega}\right)^2 + \left(\left(\frac{\partial\eta}{\partial I}\right)\omega_I\right)^2\right]^{1/2} \quad ..(3.2)$$

Chapter 4

RESULTS AND DISCUSSONS

This chapter presents the results that obtained from the experimental study. The experimental data were collected from 21.6.2012 until 13.7.2012 under Famagusta (35.12^0 N latitude and 33.95^0E longitude) prevailing weather conditions. Seven different air mass flow rates and three differential temperatures (for controlling the pump) were used in this study. The mass flow rates used were 0.00276 kg/s, 0.01032 kg/s, 0.01404 kg/s, 0.01884 kg/s, 0.0216 kg/s 0.02352 kg/s and 0.03012 kg/s. The temperature differentials used were 8^0C, 10^0C and 15^0C.

The experiments were carried out from 9.00 AM to 6:00 PM. The data mainly were based on two parameters first one is the temperature difference of the collector exit air temperature and the water/air temperature at the humidifier exit. The second parameter was the air mass flow rate. The results showed that the first parameter has negligible effect on the system productivity but the effect of mass flow rate on the unit productivity was significant. The system performance was evaluated by the amount of produced potable water.

4.1 Experiment Results

In this study the solar irradiance, ambient temperature, ambient relative humidity, inlet and outlet air and water temperatures of the humidifier, inlet and outlet relative humidity of the humidifier and the potable water production were presented. As expected it can be seen clearly that the solar irradiance was increasing from the morning to peak value at noon and then start decreasing until the sunset. The solar intensity has a direct effect on the fresh water production. Parameters like ambient air temperature, cooling water temperature are also affecting fresh water production. In this study the work was mainly focused on the humidifying section. The impact of air mass flow rate on the water production was extensively studied.

The fresh water production was measured to be 4085 ml/m^{2}day, for the air mass flow rate of 0.00276 kg/s and the differential temperature was 10^{0}C. The experiments were repeated by changing the mass flow rate of the air. The fresh water production increased with increasing mass flow rate from 0.00276 kg/s to 0.0216 kg/s and further increase in the mass flow rate adversely affected the production. The maximum production was 7210 ml/m^{2}day. The production was decreased to 6880 ml/m^{2}day as the mass flow rate was increased to 0.02352 kg/s. The variation of solar irradiance, ambient temperature (T) and relative humidity, inlet and outlet of the humidifier temperature and its relative humidity (ϕ) and the fresh water production with air mass flow rate of 0.00276 kg/s indicated in the Fig 4.1, Fig 4.2, Fig 4.3 and Fig 4.4 respectively.

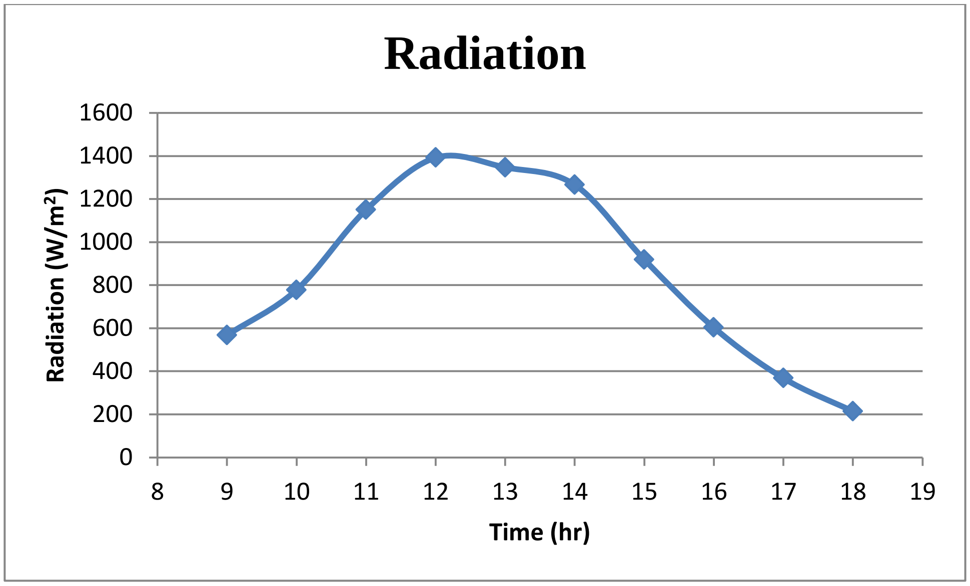


Figure 4.1: The total solar irradiance on 27th of June

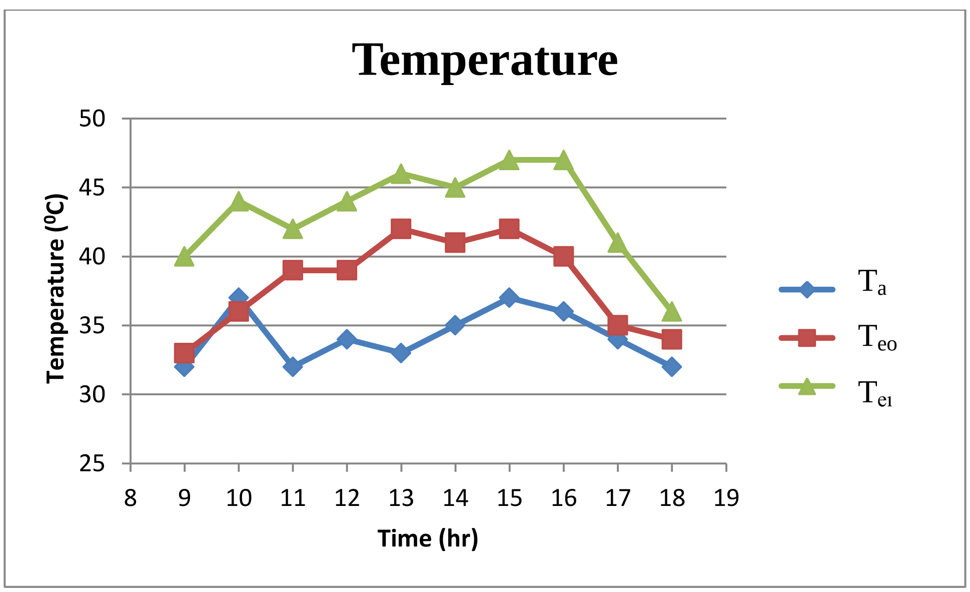


Figure 4.2: The temperature variation on 27th of June

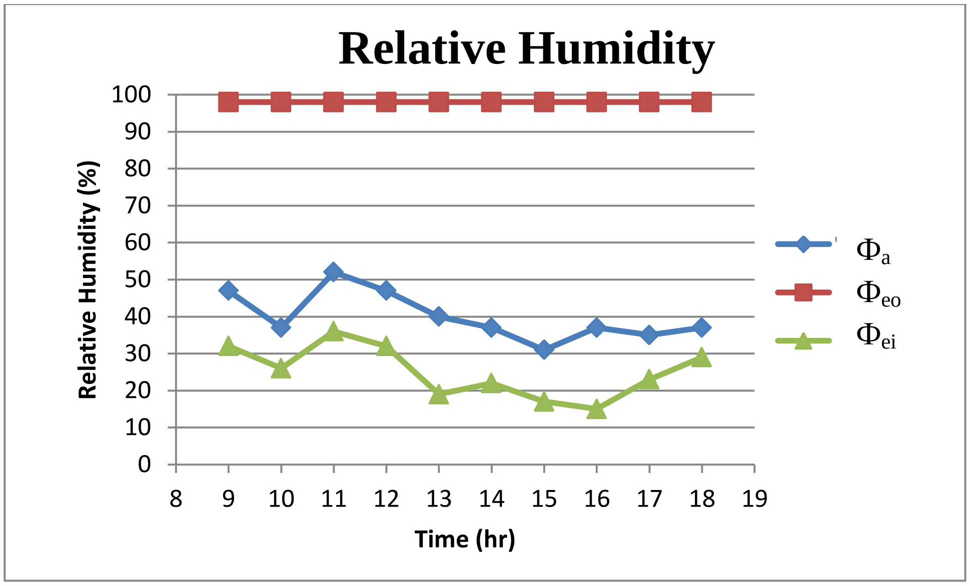


Figure 4.3: The relative humidity variation on 27th of June

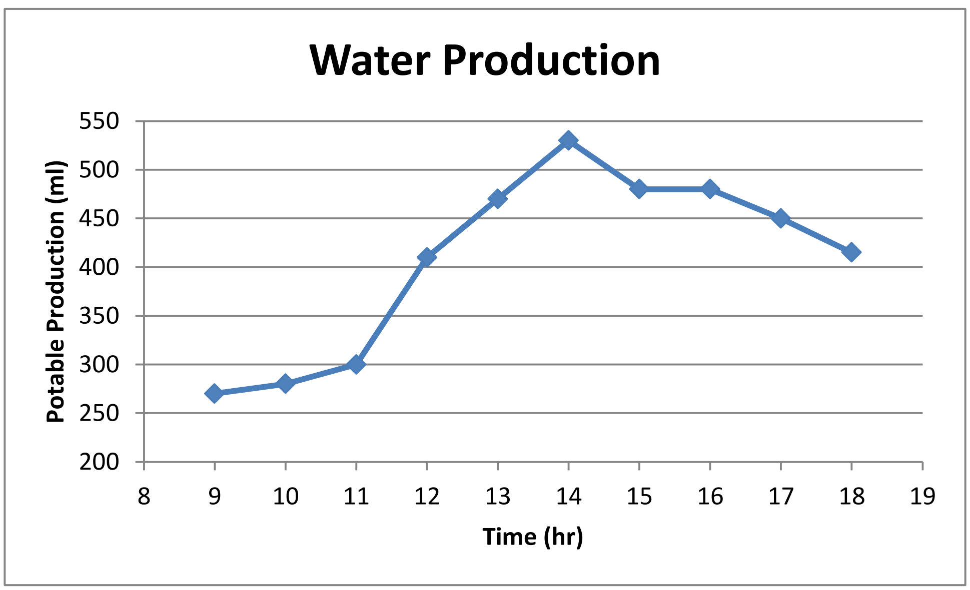


Figure 4.4: The water production on 27th of June

The air mass flow rate was adjusted to be 0.01032 kg/s and the experiment was repeated for the temperature difference of 10^0C between the combined solar collector and the evaporator. The increasing of the mass flow rate improved the system productivity to 4580ml for the day.

The comparison between the obtained results from the previous and the current day experiment showed that by increasing the air mass flow rate the system productivity increased from 4085 ml/m^{2}day to 4580 ml/m^{2}day. As mentioned earlier the insolation is the most important parameter that effects on the fresh water Productivity. Although the average solar intensity in the previous experiment was greater than the second experiment, the system output was higher than the previous study. Therefore, the air mass flow rate plays a key role in increasing the productivity of the system.

Fig 4.5, Fig 4.6, Fig 4.7 and Fig 4.8 shows the variation of solar irradiance, ambient temperature and its relative humidity, inlet and outlet of the humidifier temperature and its humidity and the potable water production for the air mass flow rate of 0.01032 kg/s.

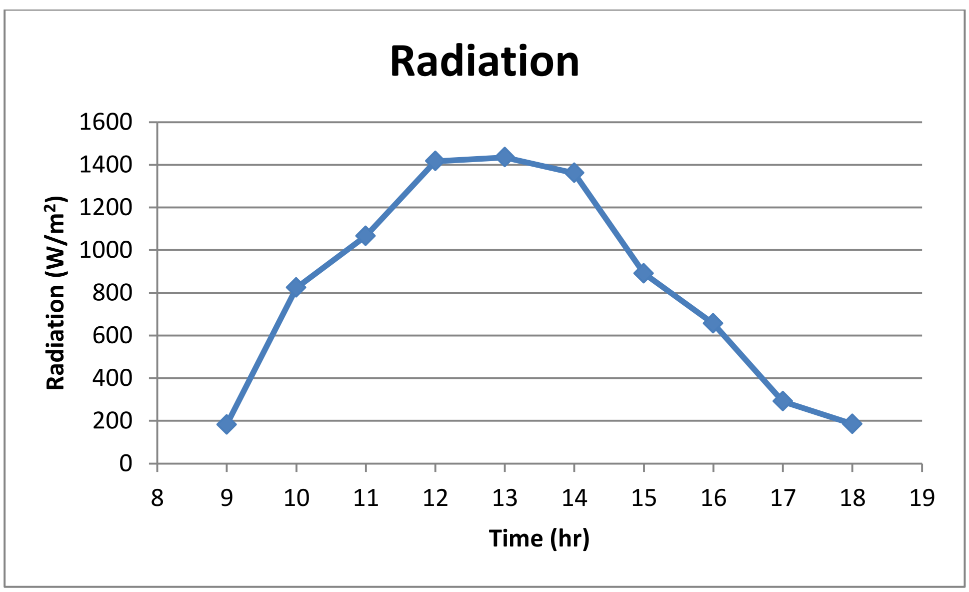


Figure 4.5: Variation of irradiance during 30th of June

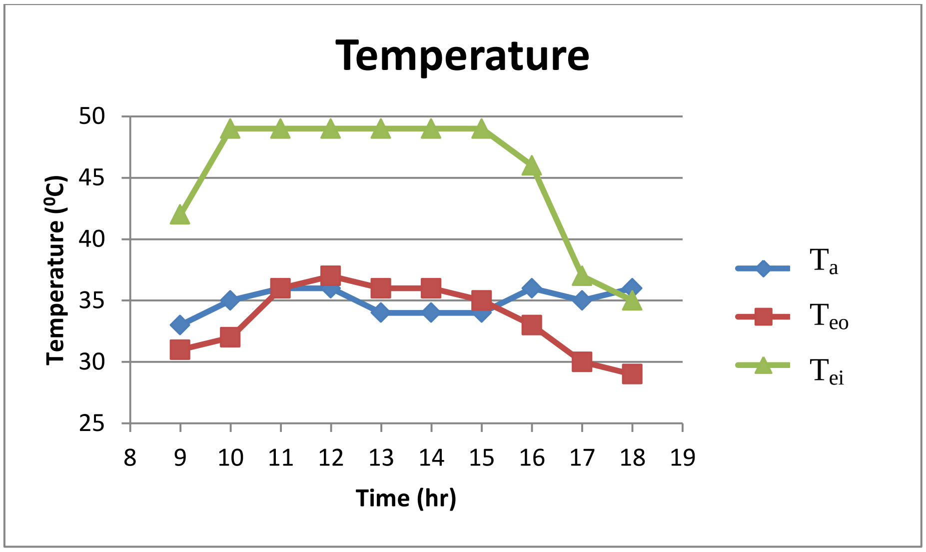


Figure 4.6: The Temperature variation during 30th June

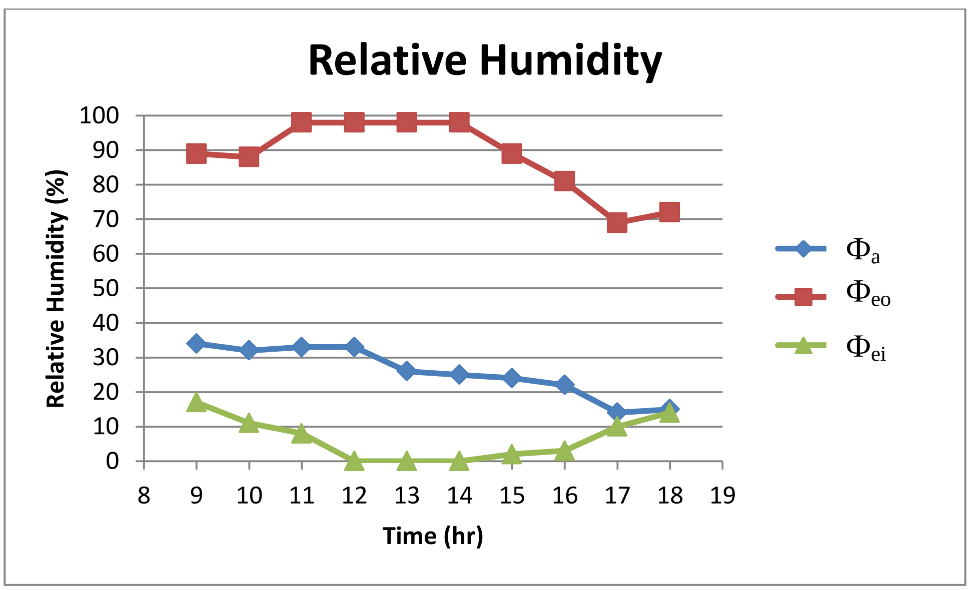


Figure 4.7: The variation of relative humidity on June 30th

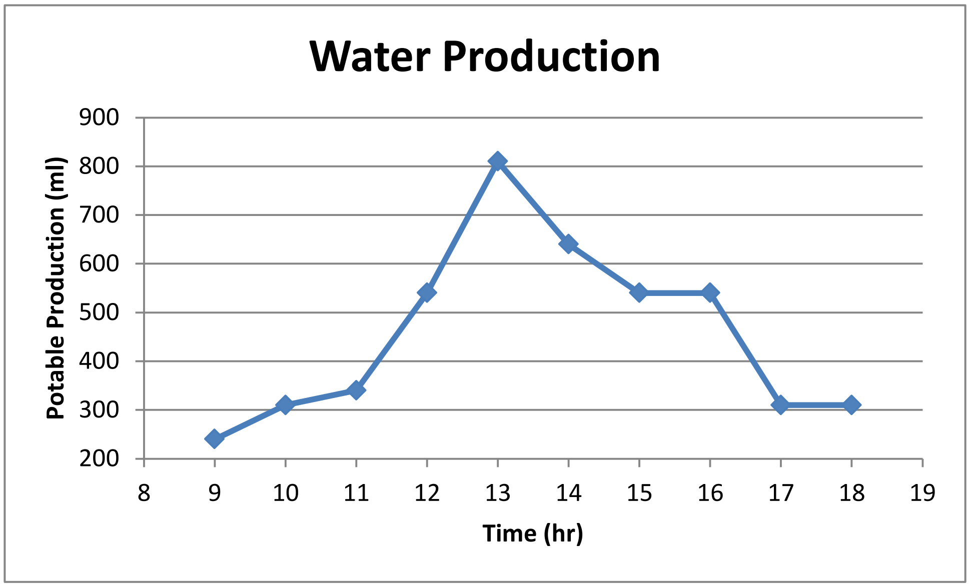


Figure 4.8: Hourly water production during June 30^{th}

By comparing the results that obtained at the mass flow rate of 0.01404 kg/s to lower mass flow rate (i.e., 0.01032kg/s) showed that increasing the air mass flow results in reduction of the average relative humidity at outlet of the evaporator. For the mass flow rate of 0.01404 kg/s and 8^0C temperature differential the production was 5170 ml/m^2day.

The total irradiance variation on the combined collector surface at the mass flow rate of 0.01404 kg/s is illustrated in Fig4.9, the temperature variation on the same day is indicated in Fig4.10, Fig4.11 shows the relative humidity variation and Fig4.12 shows the hourly production of potable water during the same day.

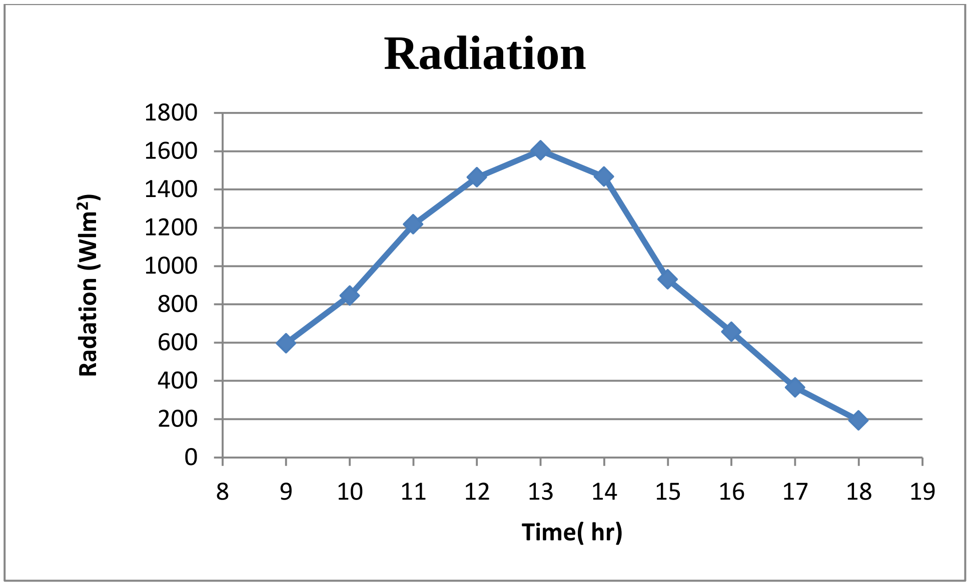


Figure 4.9: The total solar irradiance on 1th of July

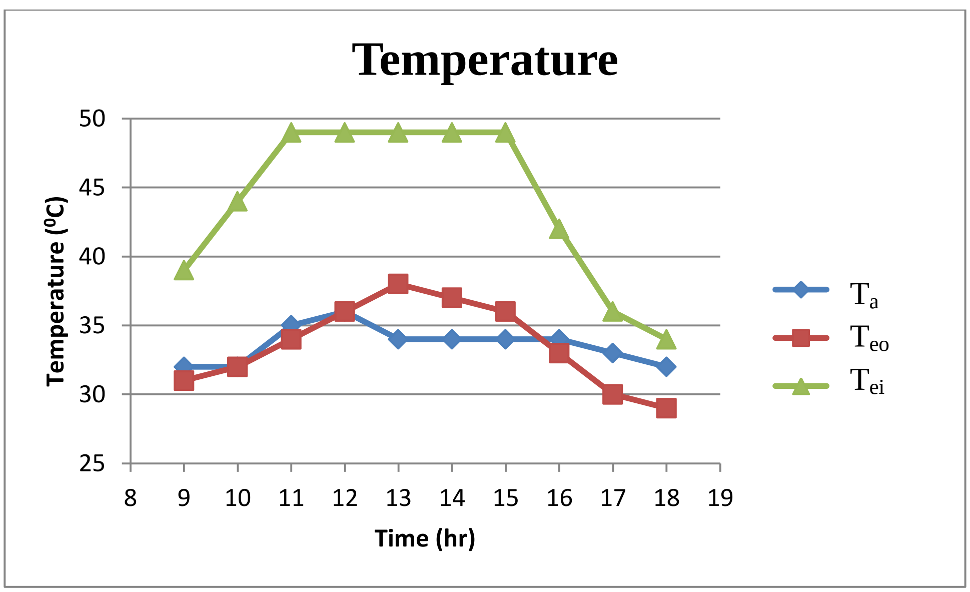


Figure 4.10: The Temperature variation on 1th of July

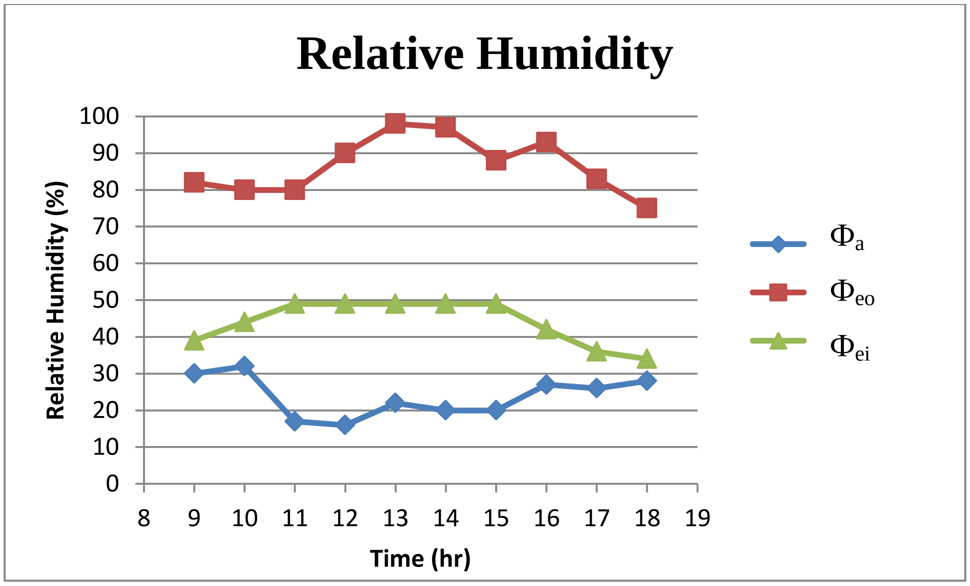


Figure 4.11: The relative humidity variation on 1th of July

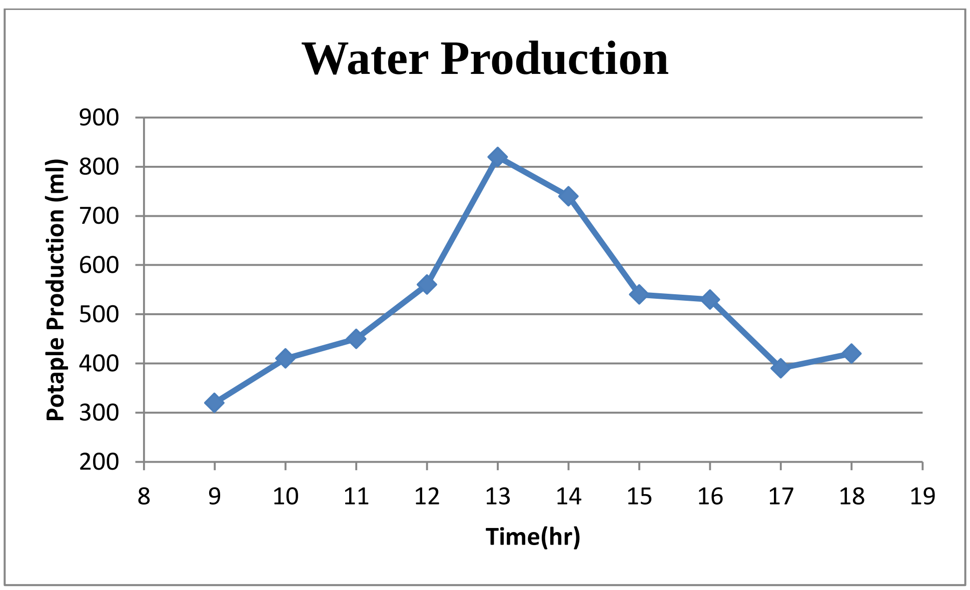


Figure 4.12: The water production on 1th of July

As mentioned earlier increasing the air mass flow rate to a certain value increased the production. Increasing the air mass flow rate from 0.01404kg/s to 0.01884 kg/s the rate of potable water production was increased. The experiments were tested for the same mass flow rate but different temperature differentials between the combined solar collector and evaporator (i.e. 10^0C and 15^0C). The increased differential temperatures almost did not make any change in the system productivity.

Therefore it can be said that temperature differentials had no significant effect on the production. However, the air mass flow rate plays an important role in the system productivity.

Figure 4.13 shows the solar irradiance during the day, temperature variation is shown in Fig. 4.14, Fig. 4.15 shows the relative humidity variation and Fig. 4.16 illustrates the hourly production of potable water during the same day.

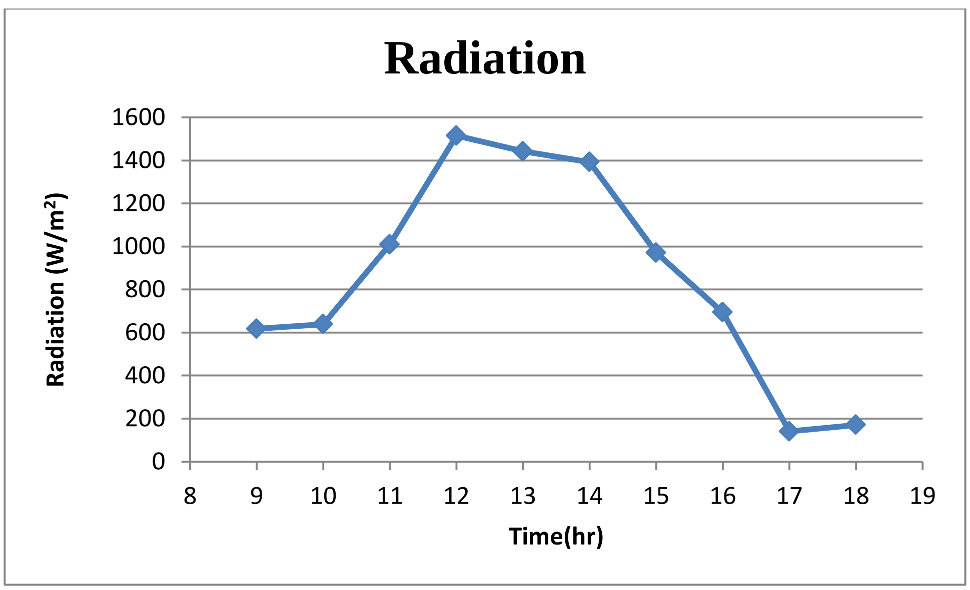


Figure 4-13: Hourly changing of irradiance on July 2^{th}

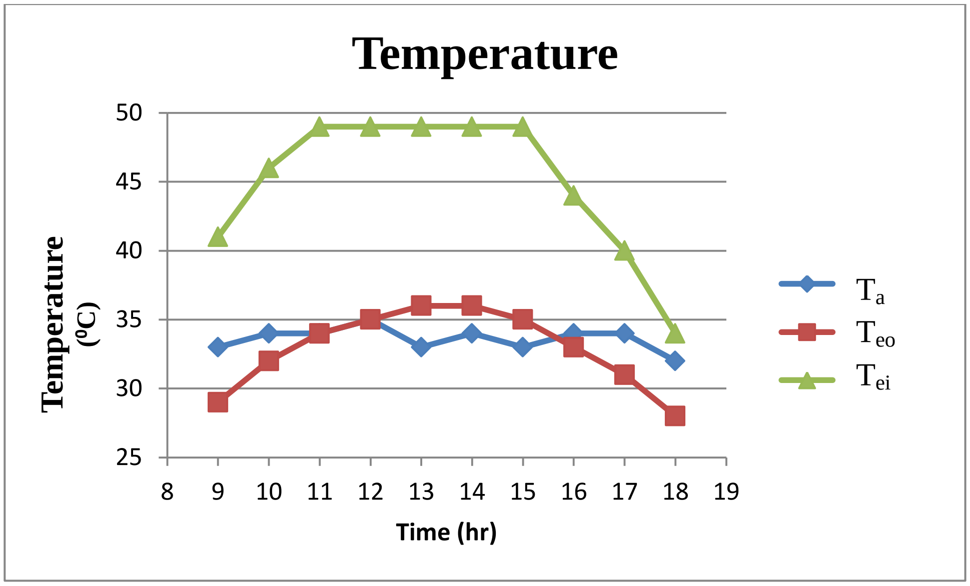


Figure 4.14: The temperature variation on 2th of July

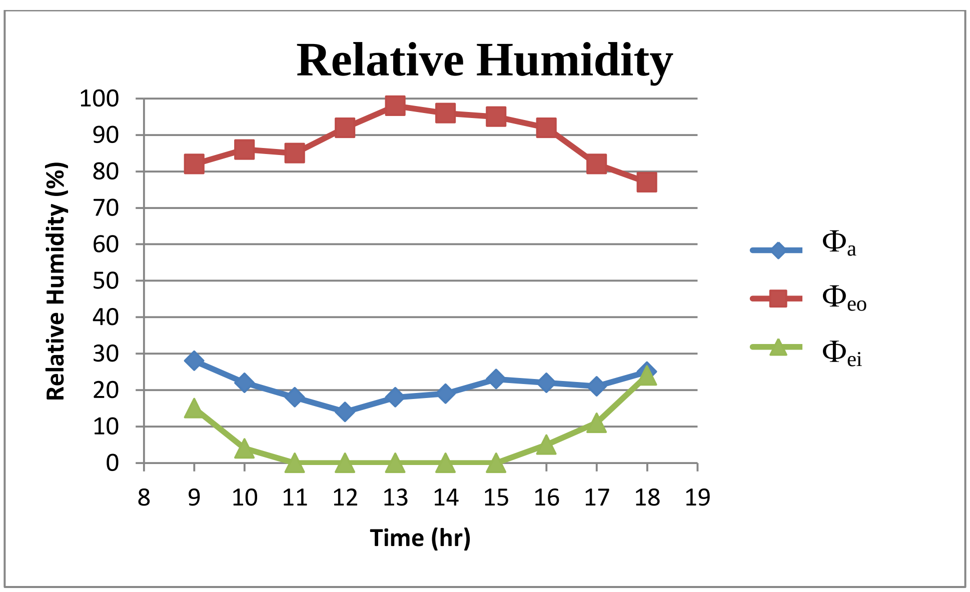


Figure 4.15: Hourly relative humidity variation during July 2th

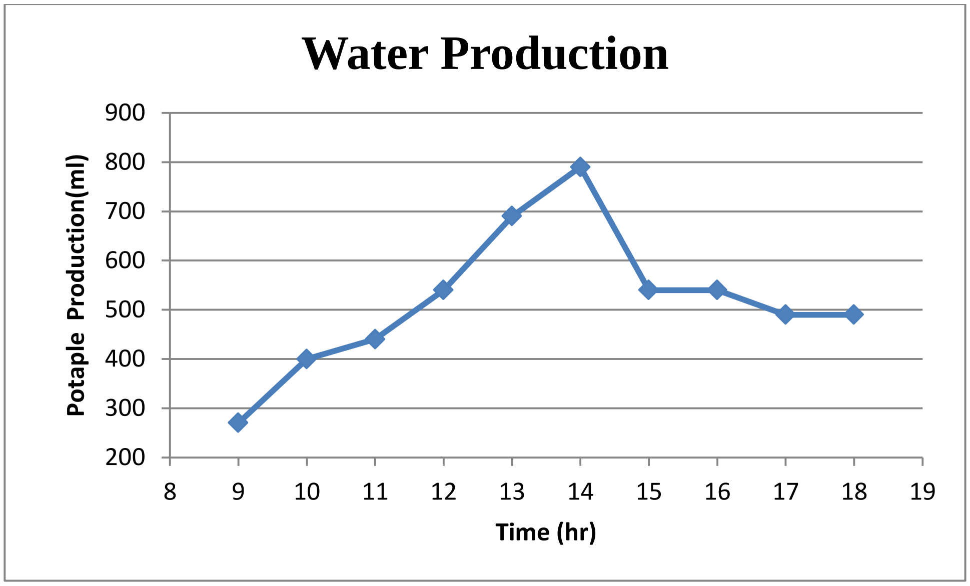


Figure 4.16 Hourly production of water during July 2^{th}

The air mass flow rate was adjusted to be 0.0216 kg/s and the experiment was repeated for the temperature difference of 8^{0}C between the combined solar collector and the evaporator. The increasing of the mass flow rate improved the system productivity to 7210 ml/m^2 day. The productivity was increased by increasing the mass flow rate. The variation of the parameters had a direct effect on the potable water production.

The variation of solar irradiance, ambient temperature, inlet and outlet of the humidifier temperature and its humidity and the fresh water production at an air mass flow rate of 0.01884kg/s are indicated in the Fig 4.17, Fig 4.18, Fig 4.19and Fig 4.20 respectively.

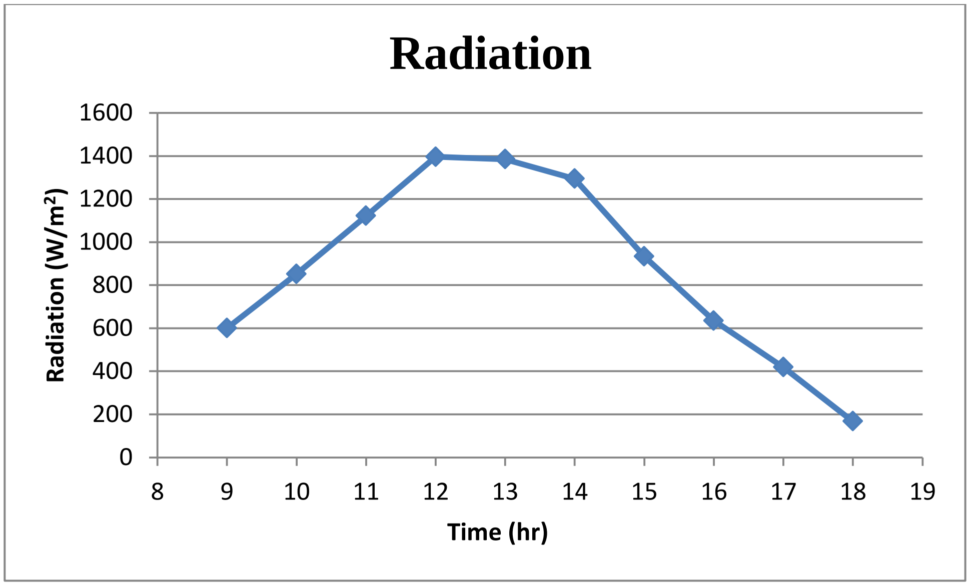


Figure 4.17: Variation of irradiance during 7th of July

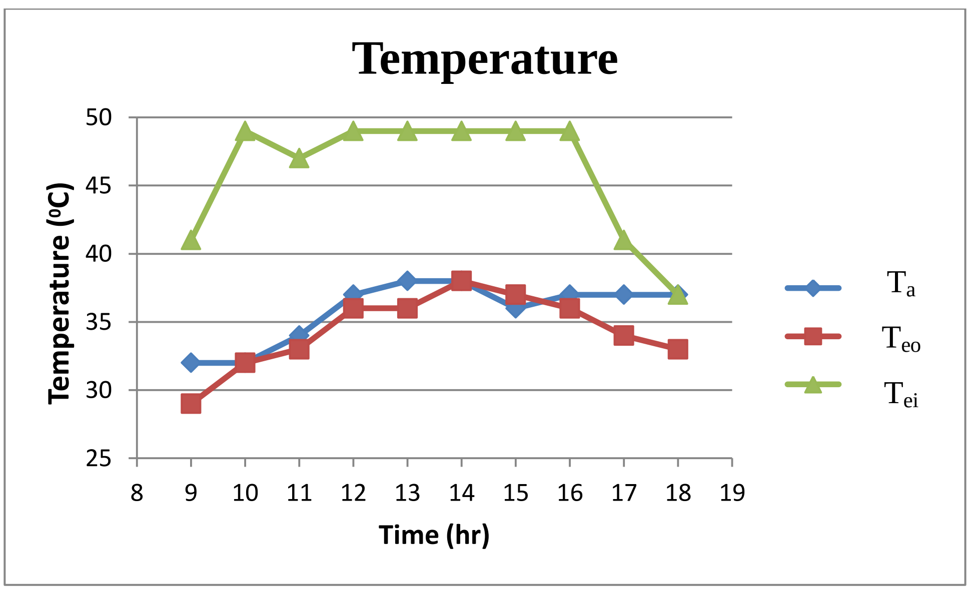


Figure 4.18: The temperature variation during 7th July

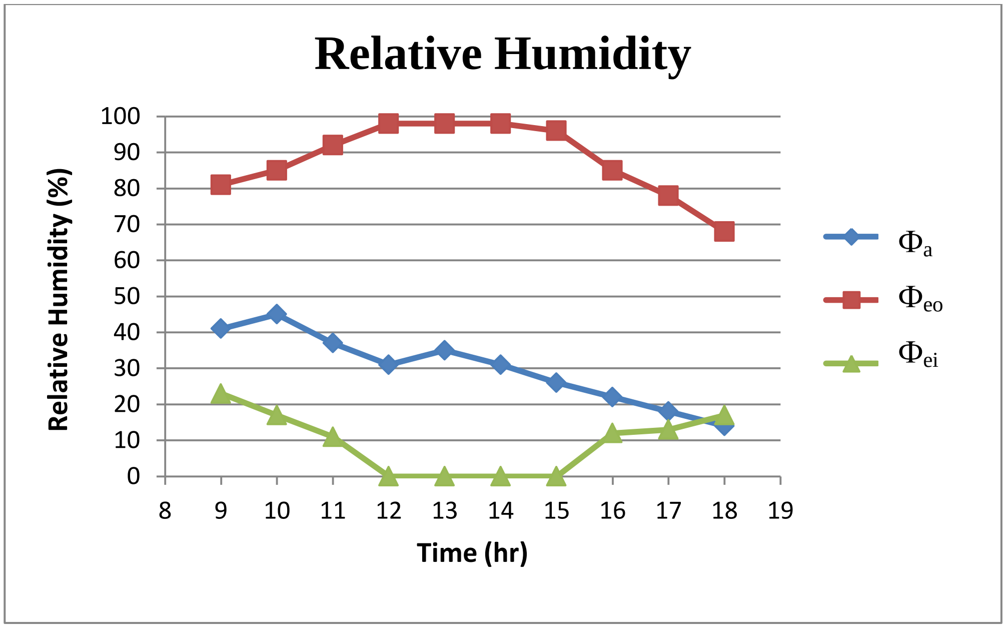


Figure 4.19: The relative humidity variation on July 7th

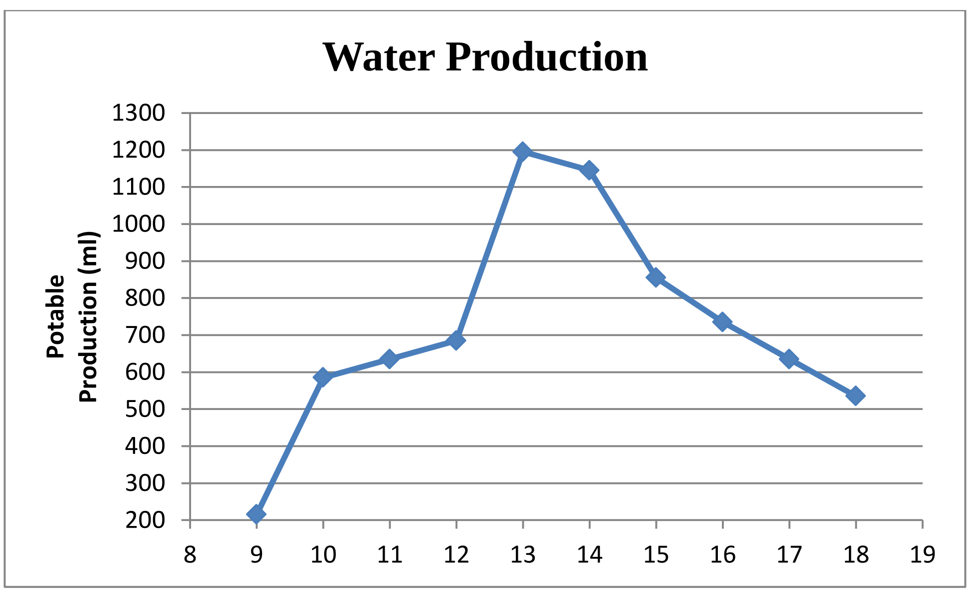


Figure 4.20: The water production on 7th of July

The experiment was repeated by increasing the air mass flow rate from 0.0216kg/s to 0.02352kg/s and the temperature difference of 8^0C between the combined solar collector and the evaporator.

The increase of the air mass flow rate from 0.0216 kg/s to 0.02352 kg/s in this experiment had decreased the productivity. The potable water produced was 6880 ml. Although the insolation was higher where the mass flow rate of air was higher (i.e., 0.02352kg/s) the production was lower. Therefore, it can be concluded that there is an optimal air mass flow rate in the system productivity.

Figure 4.21 shows the solar irradiance during the day when the air mass flow rate was the highest. The temperature variation is shown in Fig 4.22, Fig4.23 shows the relative humidity variation and Fig4.24 illustrated the hourly production of fresh water during the same day.

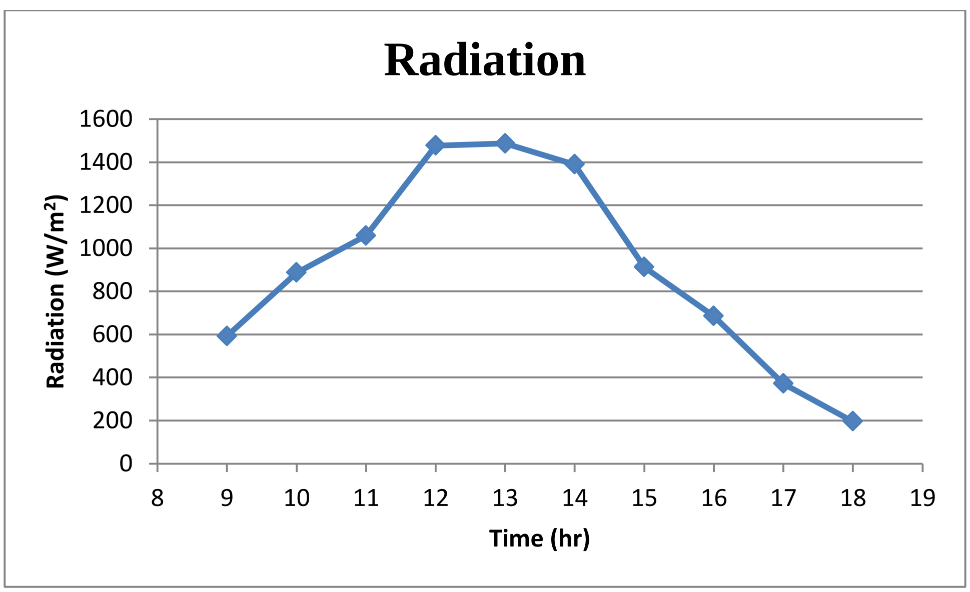


Figure 4.21: Variation of irradiance during 12th of July

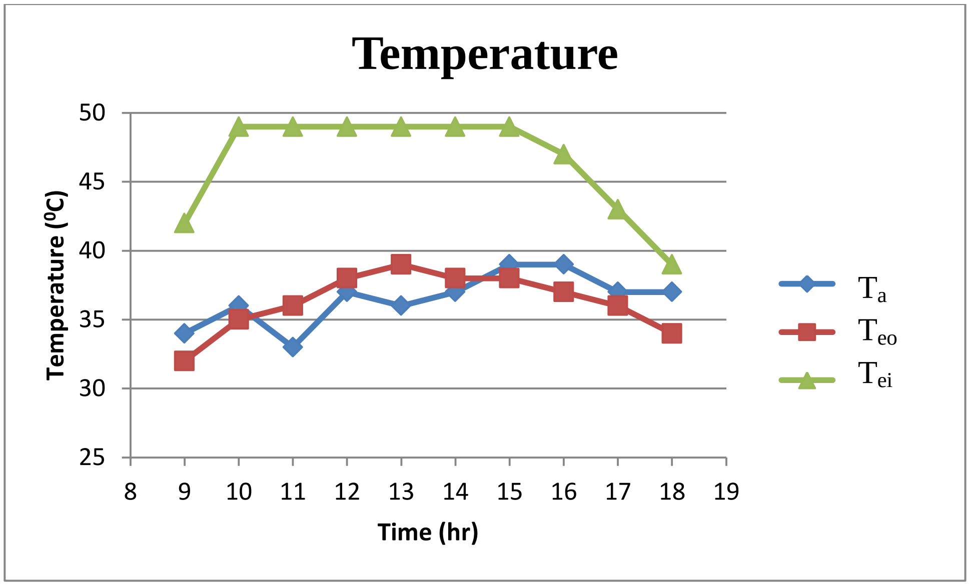


Figure 4.22: The temperature variation on 12th of July

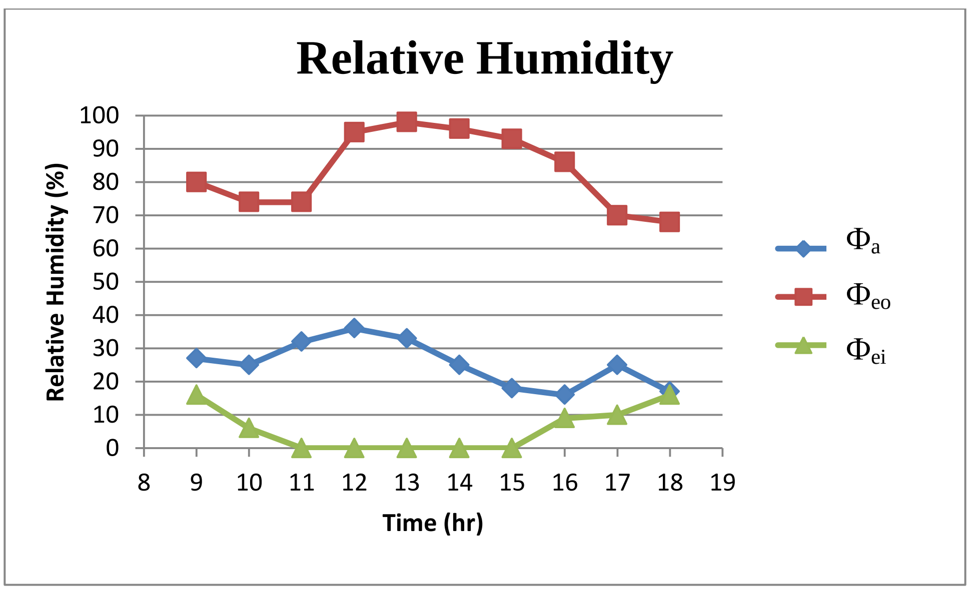


Figure 4.23: Hourly relative humidity variation during July 12th

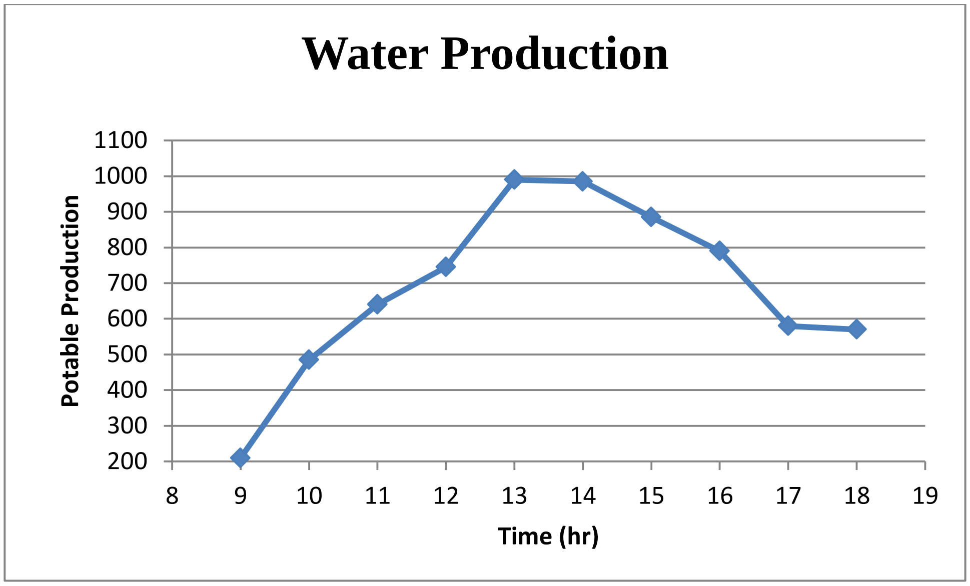


Figure 4.24: The water production on 12th of July

The fresh water production continued to decrease by increasing the air mass flow rate from 0.02352 kg/s to 0.03012 kg/where the differential temperature between the combined solar collector and the evaporator chamber was 8^0C. The potable water obtained for the mass flow rate of 0.03012 kg/s was 6850 ml/m^2day, whereas it was 6880 ml/m^2day for the air mass flow rate 0.02352 kg/s. By comparing the obtained results with the previous day productivity the results show that the system productivity decreases with increasing the air mass flow rate.

Fig 4.25, Fig 4.26, Fig 4.27 and Fig 4.28 illustrate the variation of total solar irradiance, temperature variation, inlet and outlet of the humidifier temperature and its humidity and the potable water production at a mass flow rate of 0.03012 kg/s.

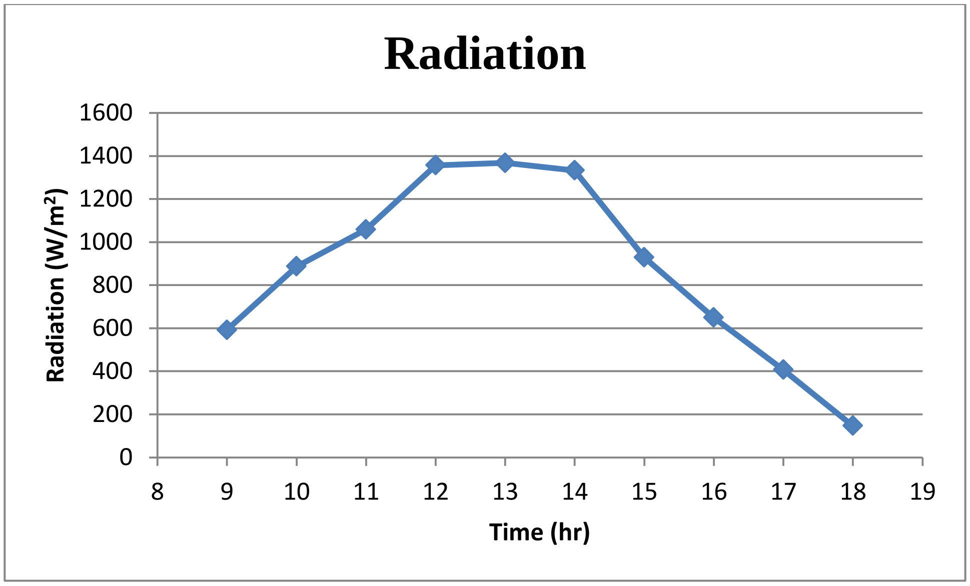


Figure 4.25: Variation of irradiance during 11th of July

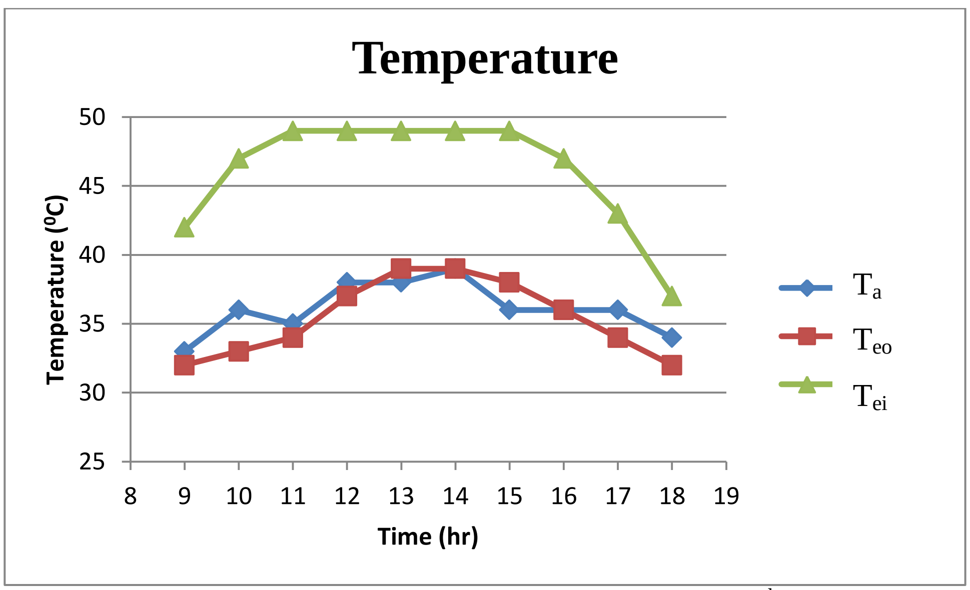


Figure 4.26: The temperature variation during 11th July

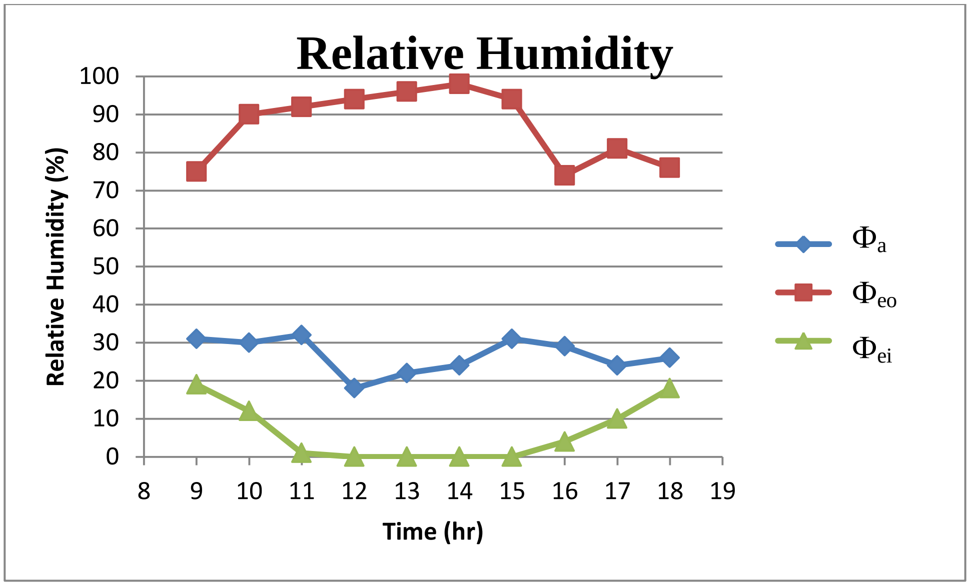


Figure 4.27: The relative humidity variation on July 11th

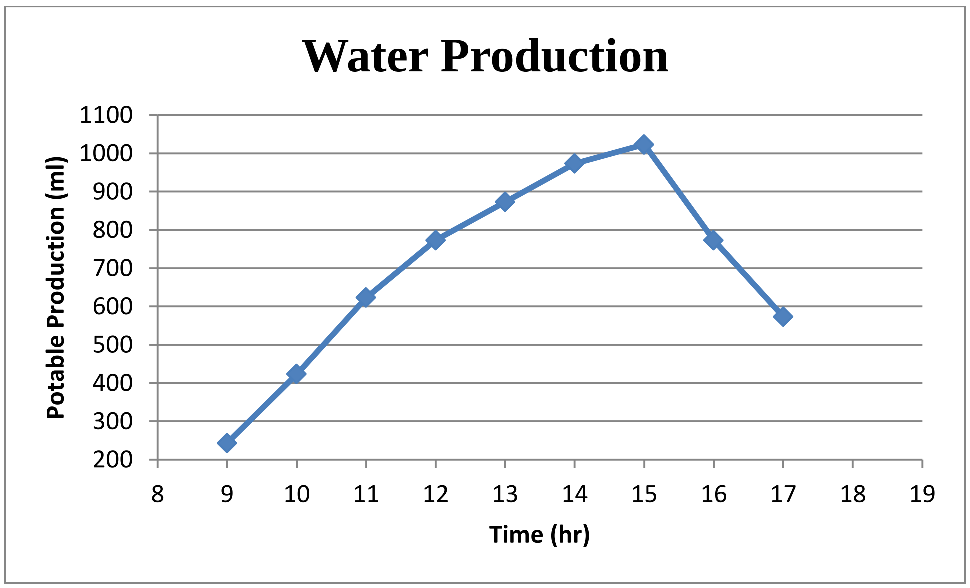


Figure 4.28: The water production on 11th of July

As mentioned at the beginning of this chapter two parameters were controlled to see their effect on the productivity. These parameters were the differential temperature and the air mass flow rate. The study showed that the first parameter (i.e., differential temperature) has negligible effect on the system productivity but the air mass flow rate has a direct effect on the system productivity.

The results that obtained during the experiment period indicated that the increasing of the air mass flow rate results in improving the system freshwater productivity to a certain level and then productivity declined for further increase in the mass flow rate. Figure 4.29 illustrates the effect of the air mass flow rate on water production for the whole span of the mass flow rate.

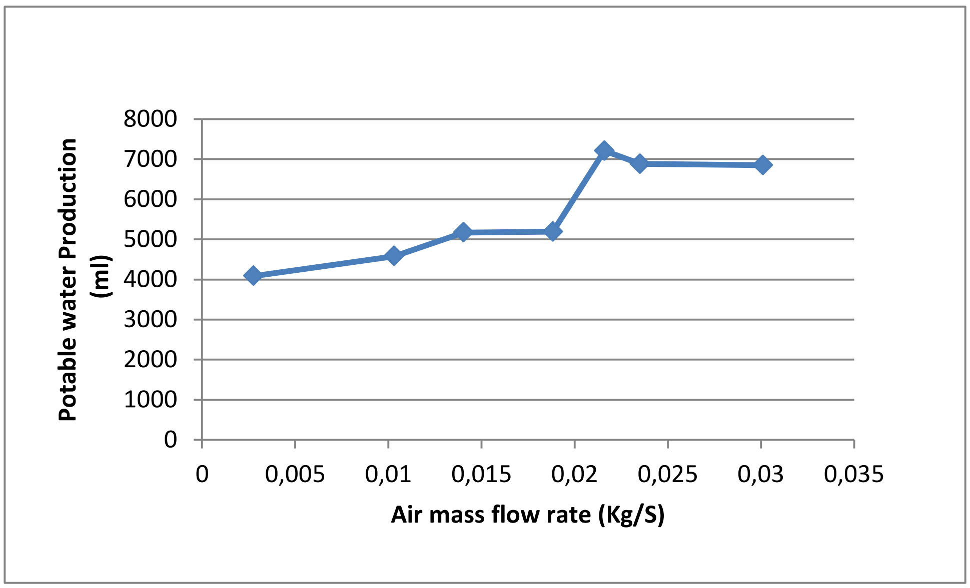


Figure 4.29: The air mass flow rate versus potable water

The evaporator used in this experiment was designed and constructed in the Mechanical Engineering Department Workshop. The volume of the humidifier that used in this experiment was 0.0405 m^3, and the produced water was 7210 ml/m^2day. The obtained results compared with the other works available in the literature. Adel M. Abdel Dayem 2006 carried out an experimental work in his experiment that had an evaporator volume of 1.616 m^3, and the unit produced about 24000 ml/m^2day. K. Shawnee et al 2010 in their experimental work they used an evaporator volume of 0.2688 $m^3$of the humidification chamber and the system produced 20000 ml/m^2day. Thus by comparing the volume of evaporator with its result for three experiments, the production of the evaporator for the present experiment is greater than the others.

It is clear that even the mass flow rate is a key parameter the sizing of the system components plays an important role in the performance.

Chapter 5

ECONOMIC ANALYSIS

5.1 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 combined solar air/water heater, fan, pump and condenser. Operating and maintenance costs include energy consumed by the desalination unit, cleaning of the system and the cost of brackish or saline water.

The choice of desalination technology is an economic factor. For example, a reverse osmosis is cheaper than a solar desalination system having the same capacity but, the cost of water produced from a reverse osmosis is more expensive compared to a solar desalination system.

There are various methods for economic evaluation of design alternatives. The most commonly used methods are:

- Investment profitability analysis
- Annual cost method
- Present worth method
- Capitalized cost method

5.2. Profitability Analysis

Profitability analysis is concerned with the assessing feasibility of a new project from the point of view of its financial results. Several methods for investment profitability analysis of design alternatives have been developed. The following profitability analysis methods are commonly used to compare the profitability of alternative designs:

- Internal rate of return
- Return on investment
- Net present value
- Pay-back period
- Simple rate of return

Internal rate of return, return on investment and the net present value is discounted methods because they take into consideration the entire life of a project and the time factor by discounting the future inflows and outflows to their present values. Simple rate of return and the pay-back period, are two other methods used for profitability analysis, and are usually referred as simple methods since they do not take into consideration the whole life span of the project.

Annual cost method, present worth method and capitalized cost method are the three methods used to compare lifetime cost of alternative parameters. Life cycle costing is important to help the designer see the coupling between the initial cost and the long-term economic performance. In the present study simple pay-back period is employed for the economic analysis.

5.3. Cost of Electricity and the System Capital Cost

The electricity used in the system was about 76 W/h and the price for each kw in north Cyprus is 0.4 TL/h, This means that the price of electricity consumed per hour is 0.03 TL and assuming the system operates 10 hours in a day, the total daily energy cost is 0.3 TL. The unit cost of producing water can be estimated by dividing output to total cost. The capital cost of the system is estimated to be 900 TL.

5.4. Simple Payback Period (SPP)

The Simple Payback Period is employed to find out for how long the desalination system will pay back the money invested. The average productivity of the HDH unit during the summer season is 7.2 L/day and for winter season it is about 4 L/day and the average productivity for the whole year is about 5.6 L/day. The sale price of a 19 liters water bottle is 5.0 TL. The SPP is calculated as follows:

Daily turnover (savings) = litters produced × price/litter ………………………… (5.1)

Therefore, the daily savings is 1.47 TL

Net savings/day = Daily savings - Running cost………………………………….. (5.2)

The net savings are estimated to be 1.17 TL

The investment cost of the system is 900 TL this figure includes all the equipment and other parts in the purification system.

The Simple Payback Period is calculated

$$SPP = \frac{Investment\ cost}{Income\ per\ day} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(5.3)}$$

$$= 770 \text{ days}$$

The simple pay-back period is calculated to be 770 days (i.e., 2.1 years). The simple payback period is not acceptable for time spans greater than 10 years. As the payback period is less than 10 years it is acceptable.

Chapter 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions

The present work concerns an experimental study to desalinate the salty water by using the humidification dehumidification principle. The study was carried out under the climatic conditions of Gazimagusa; North Cyprus. The results obtained were much higher compared to solar stills. In the study it is found that the most important parameter was the air mass flow rate.

By comparing the obtained results with the other works in the literature the results show that the evaporator that was used in this experiment was more efficient. The maximum productivity of the system was achieved on the 7^{th} of July with 7210 ml/m^2day at an air mass flow rate of 0.0216 kg/s. The price of potable water costs about 0.041 TL and the considered system can payback the invested money in 770 days. Therefore, it can be concluded that the system is economically feasible and there is no need to conduct any further economic analysis as the payback period is less than 3 years.

6.2 Suggestion for Future Work

In this study the effect of mass flow rate and temperature difference between the combined solar collector and the evaporator was considered. The current work is open to any modification and additions. The followings are the future recommendations.

- The humidification chamber volume, although the evaporator size was very small compared with other evaporators in the literature, its production was the greatest. Therefore, recommended that increase the volume of the humidifier.
- The water temperature that circulating in the dehumidification chamber in the present work was not constant. Keeping the water temperature constant and as low as possible will increase the productivity.

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