



Experimental Investigation of a Novel Solar Desalination System

Merwa Alhadrawi¹, Reza Husseini², Amir Arefian³, ⁴Vahid Ahmadi Kalkhorani, ⁵Armin khazaei

Dilshad A.H.Alhadrawi⁶

¹Department of Refrigeration and air Conditioning Techniques, College of Technical Engineering, the Islamic University,
54001 Najaf, Iraq

¹mereng@iunajaf.edu.iq

² Department of Mechanical Engineering, Amirkabir University of Technology (Tehran Polytechnic)
Tehran, Iran.

²hoseinir@aut.ac.ir

³ Department of Mechanical Engineering, Amirkabir University of Technology (Tehran Polytechnic)
Tehran, Iran.

³ a.arefian@aut.ac.ir

⁴ Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, USA

Ahmadikalkhorani.1@osu.edu

⁵ Department of Energy Engineering, Faculty of Engineering, Sharif university of technology, Tehran, Iran

⁶Department of building& Construction Techniques , College of Technical Engineering, the Islamic University

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Abstract— The shortage of potable water is the biggest problem of the world in this century because of the population growth and unsustainable water consumption rates. About half of the world's population in 88 developing countries are affected by water crises which results in 80-90% of all diseases and 30% of all deaths. Since water shortage is directly related to poverty, low cost, especially solar, seawater desalination methods can help alleviate this trouble.

In which present research, an experimental study was presented for a novel stepwise solar still accompanied by two units, a compound parabolic solar collector as a preheater and heat exchanger after condenser. A computer model has been developed, according to thermal energy balance equations to predict the transient performance of the system. The experimental in this study was achieved by constructing the test rig that verify the theoretical results by practically real field testing.

Results achieved from this study demonstrate clearly the importance of rising the feed (saline water) temperature, increasing the condensation surface area and further heating of evaporation surface; Using new still absorber design, that increase the system productivity (91.3%) compared with the conventional solar still yield. This shows obviously that solar still output is affected largely by changing design parameters.

Keywords— Desalination, solar still, seawater, stepwise, CPC



INTRODUCTION

Water is the most important thing for life continuity. In addition to this, it should be available in good quality suitable for human use. Where 3.575 million people all over the world die each year because of water related infections [1, 2]. Moreover, specialists have estimated that within the next 25 years, the number of people affected by severe water crises will increase fourfold [2].

Desalination is defined as any process removes dissolved salts from Seawater or brackish water. It is a method to produce water for human consumption, irrigation or industrial uses. With improvements in technology, desalination processes are becoming cost-rival with other methods of producing usable water for our developing needs which is doubling every 20 years, increasing by two times the rate of population growth.

The level of water salinity is expressed by the total dissolved solids (TDS) concentration, which differs for different water types. Water is considered potable when its TDS is below 1000 mg/L. Table (1-1) shows the tastiness of drinking water according to its concentration of (TDS)[3].

Table 1
Tastiness of water according to its concentration TDS [3]

Tastiness	TDS (mg/l)
Excellent	Less than 300
Good	300 to 600
Fair	600 to 900
Poor	900 to 1,200
Unacceptable	More than 1,200

The brackish water has total dissolved solids (TDS) of 3000–10,000 mg/L and seawater which may be similar to or higher than brackish water in salinity except that sea water may contain toxic trace elements (such as arsenic, chromium, selenium and uranium) [4, 5].

Waste water is another category containing dissolved salts mostly in the low brackish level and could be used for irrigation, cooling water or other industrial applications after treatment.

Water salinity can be reduced by using one of solar desalination processes Figure 1)Figure 1 which is largely alike the natural hydrological cycle. The crucial features of this process could be summarized as the production of vapor above the water surface, then the vapor will be transported by air where the mixture of air and vapor is to be cooled, vapor condensation falling down is the final stage of this cycle. This natural process is copied on a small scale in basin type solar stills Figure 2)

The structure of solar still can be simply performed even by local people using locally available materials. The operation is not hard and requires no expert person. It requires simple maintenance and almost no operation and maintenance costs.

1.1 WATER FACTS

More than three-fourths of the earth's surface is covered with water where the total amount of global water is about 1.4 billion cubic kilometres. Oceans constitutes about 97% of the total amount which



is salty, and the remaining 2.6% fresh water is presented in the atmosphere, polar ice, and ground water. This means that Less than 1% fresh water is within human reach as shown in Figure 3[6].

Although most of the earth surface is covered with water, over most of it is found as saline which cannot be used for drinking, vegetation or industrial utilization. Globally, 200 million hours are spent each day, mostly by females, to collect water from remote regions, often polluted sources [1].

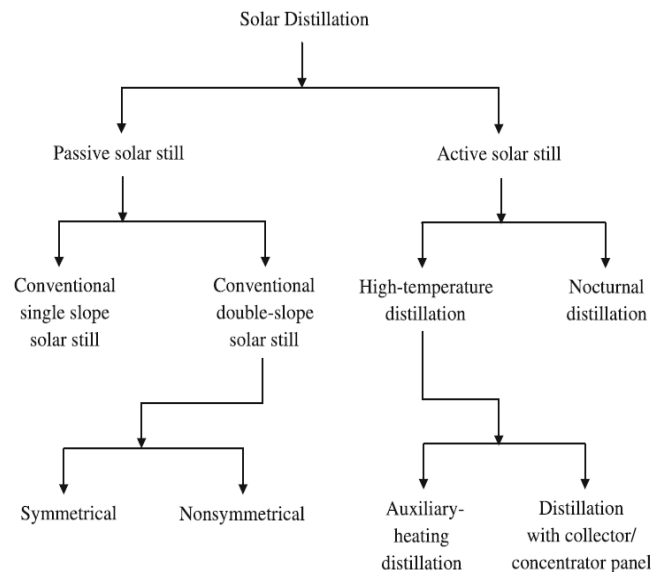


Figure 1. Classification of solar distillation unit [7]

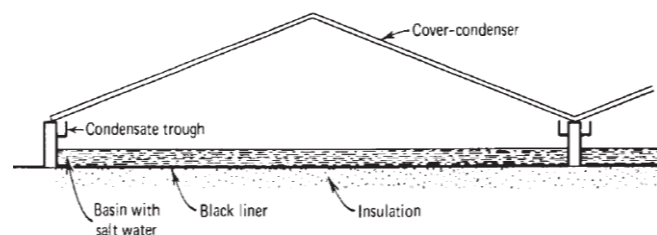


Figure 2 Schematic cross section of a basin-type solar still [8]

It has been predicted that the production of 1 million m^3/day by traditional desalination processes requires 10 million tons of oil per year, which results in the problem of water shortage to be bigger as fuel is becoming more expensive year after year in addition to its harmful environmental effects. These requirements have made it necessary to find an alternative energy source which is cheap and environment friendly [6].

Also this problem has been heightened by the pollution of fresh water resources (rivers, lakes and underground water) that results from industrial wastes.

Solar distillation process is being used for centuries when its first application was a still used in 1872 in Las Salinas on the northern deserts of Chile [8]. The still utilized a shallow black basin to hold the salt water operates on the same principal mentioned before.

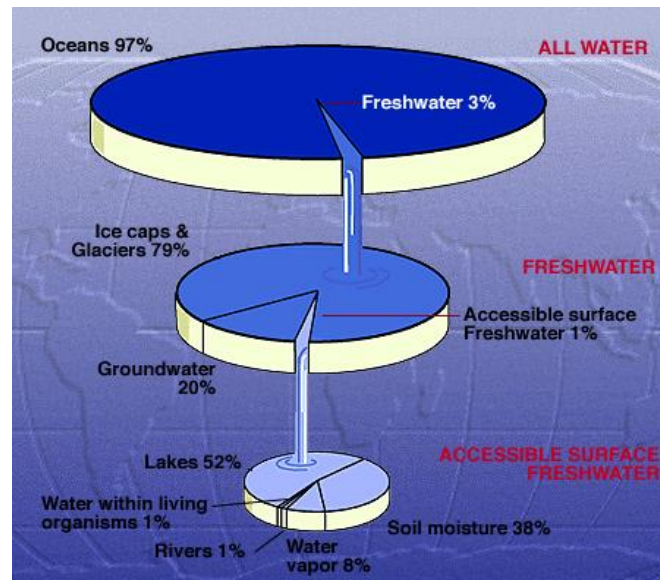


Figure 3 Earth's water supply [9]

1.2 SOLAR DESALINATION PROCESSES

Solar energy can be used in the form of thermal source or electricity to supply the required energy for a desalination process. In both cases, fresh water cost depends on if the desalination plant will consume the total energy delivered by the solar field. Therefore, solar desalination plant has to be designed so that it extracts as much as possible solar radiation.

There are two groups of processes, indirect and direct, utilizes sun as an energy source depending on how the solar energy will be used. Both of the categories, has the restriction that energy source, i.e. the sun is of a diffuse nature which is only about 0.6 to 1 kW/m^2 . Hence, to achieve the required energy, large collecting areas should be used.

1.2.1 Indirect Solar Desalination

Where the system consists of two devices, solar energy collector such as a flat plate, evacuated tube or solar concentrator, where the energy is to be collected, combined with one of the conventional desalination systems such as, multi-stage flash (MSF), multi-effect distillation (MED) or reverse osmosis (RO) systems in which water is to be desalinated [10].

These processes also need mechanical work, their operation with a solar energy requires that a part of this energy be converted to power, which might be very expensive.

1.2.2 Direct Solar Desalination

Where the energy collection and water distillation happen in one equipment. Solar still is an application of this method which acts as a trap for the solar radiation (greenhouse effect) and it is used for systems



with small production in areas with low demand of fresh water, less than $200 \text{ m}^3/\text{day}$. It represents an appropriate solution of water crisis for remote and rural regions where grid electricity is not available [10, 11].

Using solar desalination technology has some advantages and disadvantages:

The Advantages are:

- environmentally friendly
- Solar distillation makes possible the recycling of waste water.
- Can improve health standards, because solar distilled water is chemically pure.
- In specialized cases, still units could be used to supply all the pure water necessary for isolated hospitals and clinics.
- Important in desert where there are no drinking water supplies for workers.

The Disadvantages are:

- Requires large amounts of land and materials.
- The capital investment necessary to build the equipment is high.
- Some times the amount of glass, concrete, metal, or plastic required to trap radiant energy seems excessively high relative to the product.
- A unit supplying pure water to a poor family will be expensive and large in area.
- This technique may require changes in traditional life-style.

Several parameters affect the selection of desalination systems including; quality of salty water to be desalinated, salinity level of produced potable water, input energy, environmental impact and cost

1.2.3 PARAMETERS AFFECTING THE SOLAR STILL DESALINATION PRODUCTIVITY

Using the solar still desalination techniques is limited because of its low productivity rate comparing with other desalination techniques, such as other thermal systems or membrane systems. The productivity of a solar still desalination system is affected considerably by environmental and design parameters. These factors are summarized as follow:

Lots of parameters that affect the productivity of a solar distiller could be taken in consideration. Among these parameters are construction material, water depth, basin type, glass cover thickness and slope, space between water surface and condensation cover, insulating and coating, solar radiation, ambient temperature, cloud and dust cover and wind velocity as describe in the following sections.

1.3 Construction Materials

Represents the materials that could be used in fabricating the still absorber plate, the transparent cover, still insulation etc.

Absorber plate could be made of aluminum which is light in weight and has a good heat conductivity. Steel sheets similarly is suitable because it is relatively available and cheap material (half the cost of aluminum and copper) in spite of its reformation ability to any wanted shape at workshops but its thermal conductivity is relatively low compared with aluminum and copper ($k=48 \text{ W/mK}$, $k=200 \text{ W/mK}$, and $k=390 \text{ W/mK}$, respectively) [12].



Figure 4) shows the production of water hourly by using different material for absorbing plate. The theoretical results have been presented for when the experiments have been conducted. The average ambient temperature was 16.9°C, the average wind speed was 0.8 m/s and the feed water mass flow rate 0.011 kg/s.

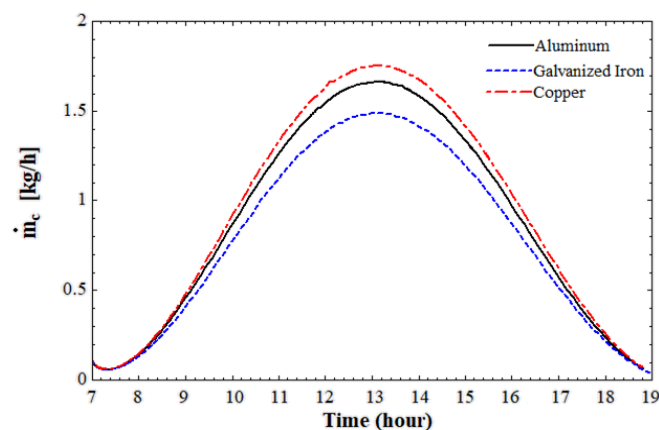


Figure 4 The relation between the productivity and absorber plate material

The condensation cover should be of transparent material such as glass to allow sun rays passing through it. Furthermore, it has to offer some degree of insulation to prevent excessive thermal radiation heat transfer from the basin to ambient.

Researchers have found that using plastic as a condensation cover is not suitable because of problems related to drop condensation of water vapor on the inner surface of the plastic cover.

1.4 Water depth

One of the main design parameters that affects the solar still productivity and has taken a wide attention of researchers, is the water depth in solar still basins.

It has been found by examining different water depths in solar still, that when water depth increases, the still productivity will decrease which means, solar still vaporization rate is inversely proportional to the water depth [16, 23]. Figure 5 shows the performance of the system.

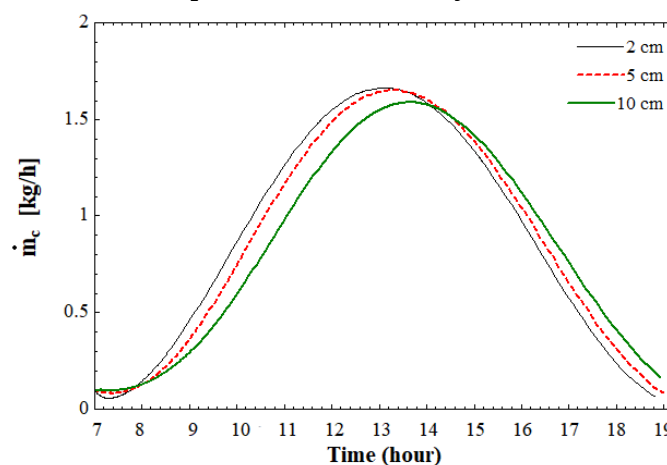


Figure 5 The relation between the productivity and water depth



A depth of two inches (5cm) is often used. Also researchers have verified that lower water depth such as 0.02–0.04 m has higher annual efficiency up to 44% compared to higher water depth such as 0.18 m [24]. so, water depth should be kept as low as possible but enough to confirm that there will no dry over heated zones due to an irregular basin bottom. In this work a 2 cm water depth has been used.

C. Basin size

Represented by the evaporation area which directly proportional to the still productivity i.e. increases by increasing the evaporation area, Figure 6). Small or moderate size is generally used to allow the ability of changing the still place or using it in portable applications.

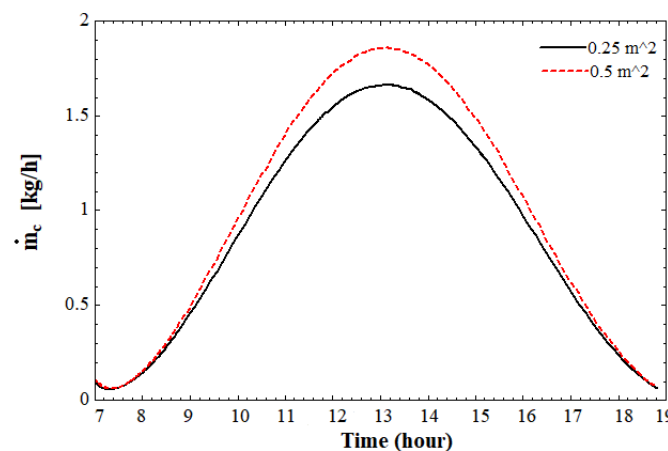


Figure 6 The relation between the productivity and evaporation area

D. Glass Cover Thickness and Slope

Increasing the condensation glass cover thickness leads to increase the temperature difference between saline water and the glass cover which rises the distilled water yield. In the same time, the heat transfer rate will also decrease causing in reducing the distillate productivity [22].

One of the important limits which decides the amount of solar radiation will the absorber receive is the still cover inclination. Small angles should be avoided as it causes condensed water droplets to fall inside the basin instead of being collected at the bottom edge of the glass cover. Also large angles causing the amount of condensed water to drop [25]. For receiving maximum solar radiation, the still tilt angle should be as same as the latitude of the location where the still is to be used [8, 23].

Space between vaporizing surface and condensing cover reducing the gap between the evaporating surface and the condensing cover enhances the still performance. It decreases the height of the cover walls and hence decreases the shadowing effect of these sides causing in receiving more heat energy and increasing the productivity subsequently. It has been found that reducing the gap distance from 13.0 to 8 cm for the same cover slope increases the output by 11 % [19].

1.5 E. Insulating and Coating

It is very important to insulate the bottom and the side walls of the solar still so as to avoid heat losses to the external environment. Lots of materials could be used for insulating purposes such as; sawdust supported by wooden frame, glass wool, polystyrene foam board etc.



It has been reported that using different insulation materials (i.e., an air gap, plywood, hay, and glass wool) in different stepped solar stills, increases the productivity over that of a non-insulated still [12, 13, 20].

For good solar radiation absorbing, plate might be coated with a black paint. Black polycarbonate can be used also as a base material for solar still basin.

1.6 F. Basin Design

The shape of solar still is important to control the amount of saline water inside the basin because it is difficult to keep a lowest level of water in the conventional type. Stepped solar still type was used in this research trying to increase yield per unit area by decreasing the thermal inertia of the water mass.

1.7 G. Solar Radiation

The solar distiller yield depends deeply on the amount of solar radiation it receives. Researchers have found that when solar radiation increases which has a maximum value at 12:00 it results in increasing the solar still production reaching its maximum rate at 13:00. Figure 7) shows the system results.

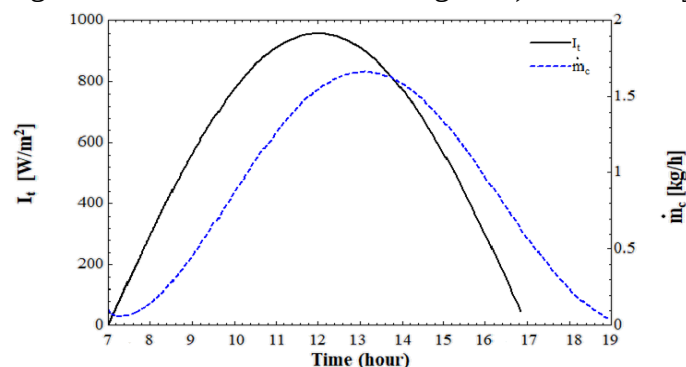


Figure 7 The variation of solar intensity and system output

This interval between reaching the maximum radiation and maximum productivity is due to a time delay in the system. The direct affecting of still by solar radiation results from increasing the temperature differences between the saline water and the glass cover of still.

H. Ambient Temperature

Studies have proved that the production rate of a solar still increases with the increase of ambient temperature. Figure 8) shows that the system average productivity increases in a rate of 14% when the ambient temperature increase by 5 °C.

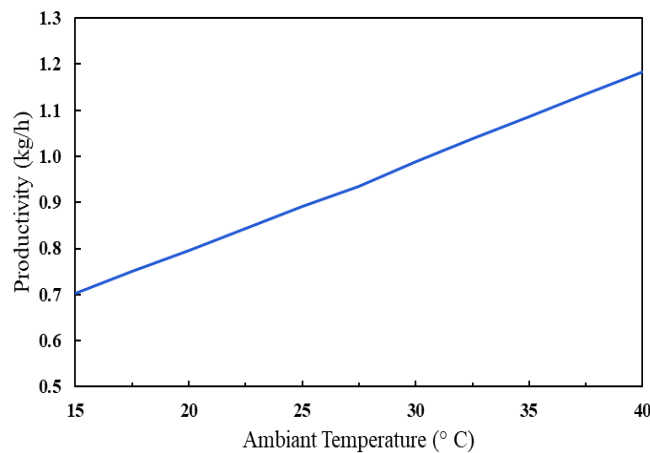


Figure 8 The effect of ambient temperature on the average productivity

I. Cloud and Dust Cover

The dust accumulation over the still glass cover affects the solar transmittance intensely where the transmittance drops as a result of dust deposition increasing. It has to be mentioned that the dust accumulation is directly related to the tilt angle of the glass cover.

Researchers have implemented by experiments that when the glass cover being covered by dust this will cause a 1% loss of incident solar radiation, when the tilt angle is 30° [12, 15].

J. Wind Velocity

One of the parameters that insignificantly affects the solar still productivity [15]. Nevertheless, even low wind velocities rise the yield of solar still compared with no wind circumstances [18, 19].

Increasing the wind speed decreases the glass cover temperature leading the amount of distilled water to increase. That was proved by using stand fans to cool the glass cover at the outside which increases the condensation rate of water vapor [17]. Therefore, any wind problems nearby a solar still cover has a negative consequence on the yield. Figure 9) shows that changing wind speed from 1 to 10 m/s enhancing the productivity of the system by 7.4%.

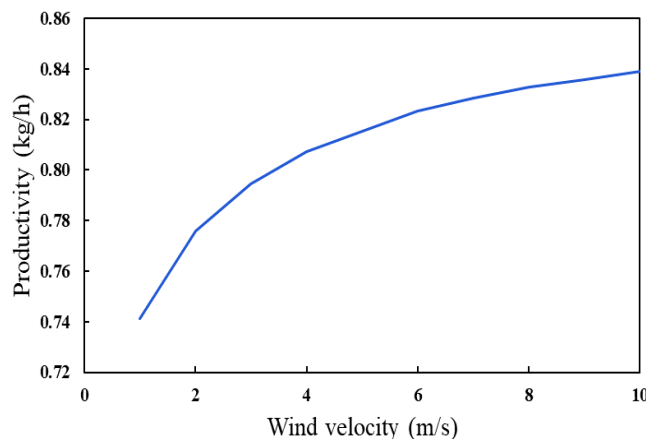


Figure 9 The effect of wind velocity on the productivity

EXPERIMENTAL WORK

In this paragraph, the equipment construction, measuring devices and testing method used to investigate (experimentally) distilled water production are described in detail. Figure 10) represents a schematic diagram of the test rig.

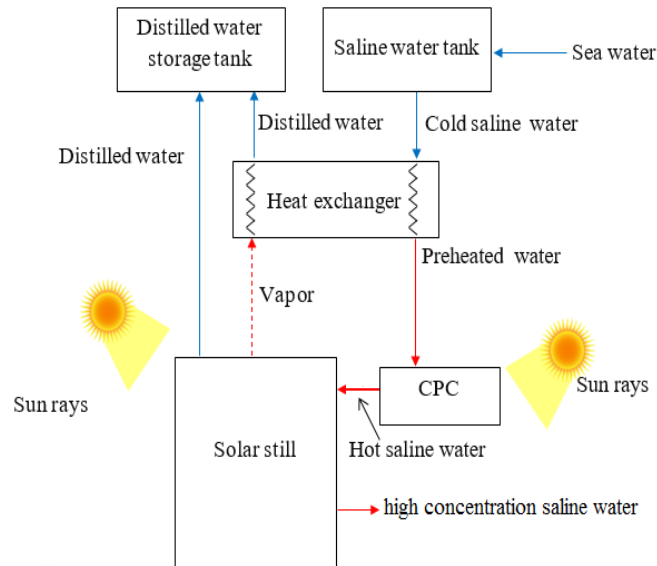


Figure 10 Schematic representation of the water desalination system

2.1 Equipment Description

This part deals with system components, materials and methods of fabrication in more extensive explanation. A view of the rig is presented in Figure 11)

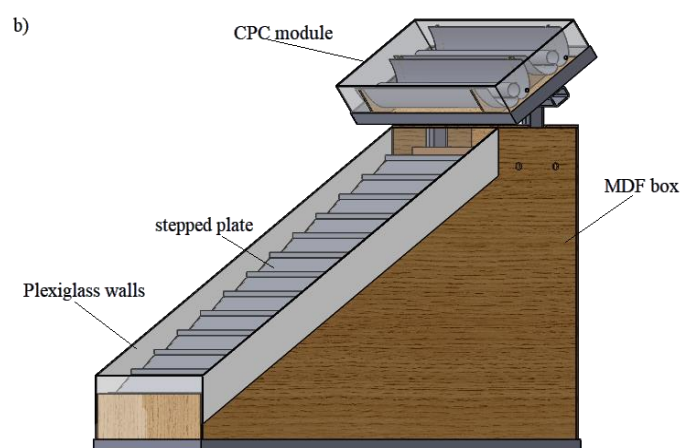


Figure 11 Novel solar desalination system.

2.2 Stepped Solar Still: The still consists of a wooden box with an area of $(0.8) \cdot (1.64) \text{ m}^2$ and height $(1.17) \text{ m}$ in one end and $(0.21) \text{ m}$ at the other end. A stepped absorber plate made of $(0.3) \text{ mm}$ thickness aluminum sheets, is placed at the top of the wooden box. Aluminum sheets were used in

fabricating the stepped absorber plate as follows: rust resistivity, good formability, easy cleaning, high strength, light weight and high thermal conductivity comparing with other available materials.

Figure 12) depicts a schematic shape of a modified design absorber plate. Instead of conventional absorber stepped design used in most of researches in which the steps consist of horizontal and vertical surfaces, Figure 13), the new design depends horizontal and inclined surfaces with angle of 135° found according to the latitude of Tehran city (35°), between the two surfaces to minimize the water falling velocity [14].

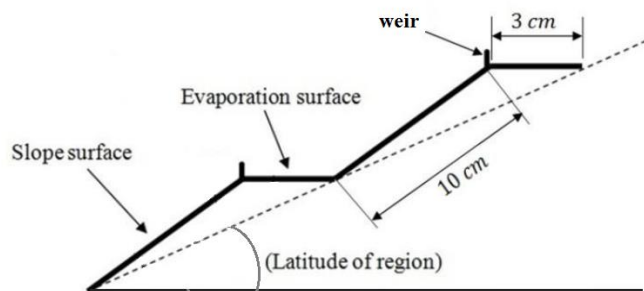


Figure 12 Modified stepped absorber plate design

Rationally, sloped surfaces provide more solar energy absorbing than that vertical one as it faces the sun causing the absorber plate to reach higher temperature and consequently, more quantities of water will be evaporated.

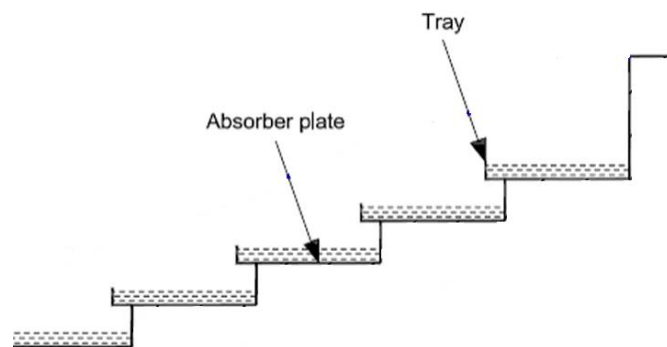


Figure 13 conventional stepped absorber plate design [21]

The absorber plate is of 12 steps, (80) cm width fabricated by bending process. The horizontal and inclined step surfaces are of (3) and (10) cm length, respectively. Every step has a (2) cm height weir at its horizontal end to assure uniform distribution of the saline water along the step surface.

The plate was painted with black matt color to increase its absorptivity. It is supported by the wooden still box side walls, shaped by the aided of CNC machine, have the same profile of the stepwise plate.

The still box is covered by window glass plate of 3 mm thickness over which the condensation process takes place. Plexiglass walls have been used so that the gap between the walls and the glass cover becomes (9) cm. these plexiglass walls have a role to seal the water leakage from the still sides. In order to collect the distilled water, a water channel was attached to the lower end of the condensation glass cover.

The most lower step of the absorber plate has a number of holes through which the high concentration saline water falls down and accumulated in a container then extracted out of the still. The absorber plat is shown in Figure 14).



Figure 14 Absorber plate. a) Solidworks design, b) real shape

2.3 Heat Exchanger: Some of the water vapor that does not condense on the glass cover surface, leaves the still and condenses as a result of passing over a heat exchanger plate fins, Figure 15, where it exchanges heat with the cold saline water inside the condenser pipes causing its temperature to rise.

The used heat exchanger is consisted of 302 plate fins each of $(28 \times 9) \text{ cm}^2$ area and 54 pipe of (65) cm length and (8.6) mm outer diameter.

a)



b)



Figure 15 a) Condenser, b) Condenser location in the system

A container has been located under the condenser to collect the water condensed over its plates surfaces. This water is then transmitted out of the still by a plastic tube and collected in another container.

2.4 CPC Collector: After the leaving the condenser, the preheated saline water enters a CPC solar collector to increase its temperature further. The CPC module used in this experiment consists of two complete units each is of 1 m length, (2) inches absorber pipe made of stainless steel painted with black matt color to enhance the absorptivity.

The CPC reflector, is made of galvanized iron sheets covered with thin glossy sheet to increase the reflectivity. It is supported by two wooden stands have the same parabolic profile of the reflector.

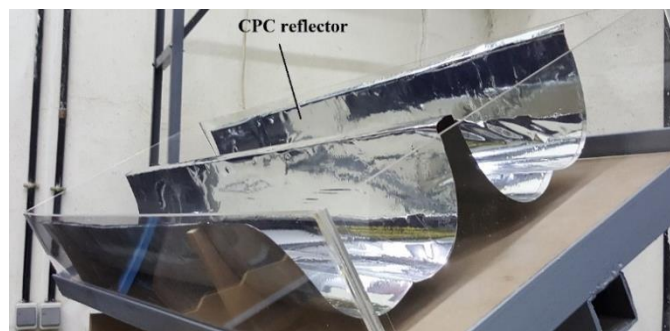


Figure 16 CPC collector

The group has been placed inside a closed box to decrease heat losses to the environment. The box is of $(1.2*0.4) \text{ m}^2$ wooden plate base, the walls are made of plexiglass plate and covered by glass plate Figure 17).

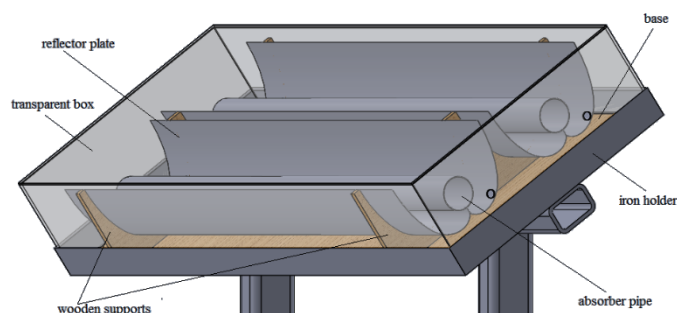


Figure 17 CPC module

All the equipment parts are fixed by a holder made from iron of corner and square cross section welded together and painted with rust resistive paint to form the shape shown in Figure 18).



Figure 18 System holder.



The holes for the inlet and outlet of saline water and outlet of pure water are made as per the convenience. The feed water inlet has been made at the top of left wooden box wall (seeing from front of the model); The outlet of brackish water at left bottom of the still wall and the outlet of the pure water at the end of the channel.

2.5 Measuring Instruments: In this work, the parameters needed to investigate the system performance were measured using the following measurement devices; the absorber plate, CPC absorber pipes, water and the condensation glass cover temperatures were measured using K-type thermometer.

Solar radiation was measured by means of a solar pyranometer. A (0.5) liter capacity bottle was used to measure the distilled water hourly yield. Hot wire anemometer was used to measure the wind speed.

a. 2.6 Testing Procedure

Experiments were carried out in Tehran City weather conditions at (11th) of February 2018 from 11 a.m. until the sunset. The system was directed towards south. The solar radiation, ambient temperature, and the temperature of basin plate, saline water, glass cover and distilled water were measured every 30 minute. The accumulated productivity during the day was also measured.

The depth of the saline water in the solar still was kept constant during the experiment. All measurements were performed to evaluate the performance of the stepped solar still.

RESULTS AND DISCUSSION

The results obtained from the simulation models for the system were listed and also compared with the obtained results from the experimental work.

3.1 Performance charts of 11th February 2018

Figure 19) shows the output where the productivity is 9.565 l/day.

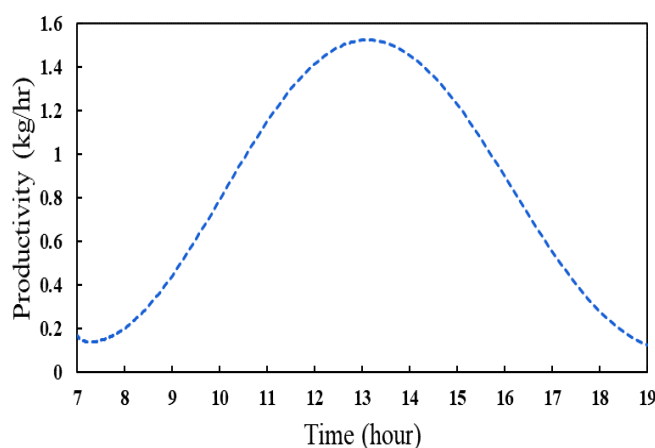


Figure 19 Relation between the productivity and time

The still temperature change with time is presented in Figure 20).

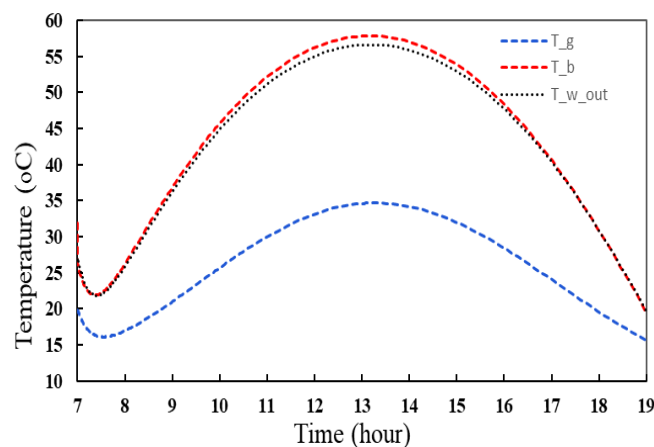


Figure 20 Relation between temperatures at different locations on the still and time

The temperature of few locations on the CPC shown in Figure 21.

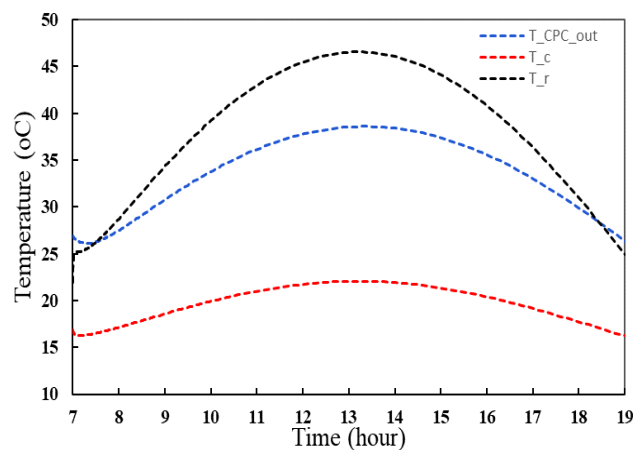


Figure 21 Relation between the temperatures at different locations on the CPC and time

1.8 Experimental Results

Figure 22) Measures radiation with time, where the maximum value was 958 W/m^2 .

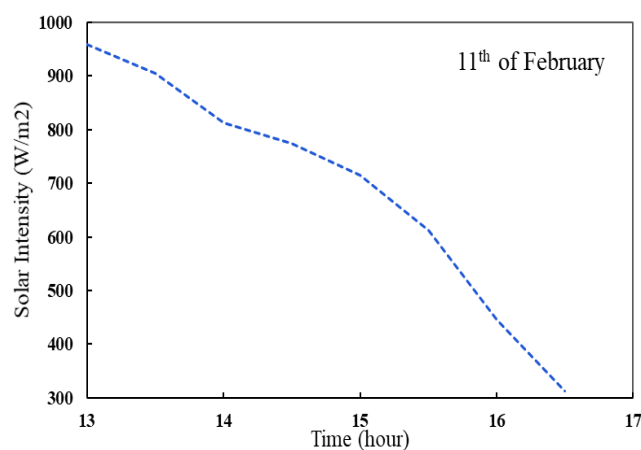


Figure 22 Relation between the solar intensity and time



Figure 23) depicts measured temperatures at different system locations.

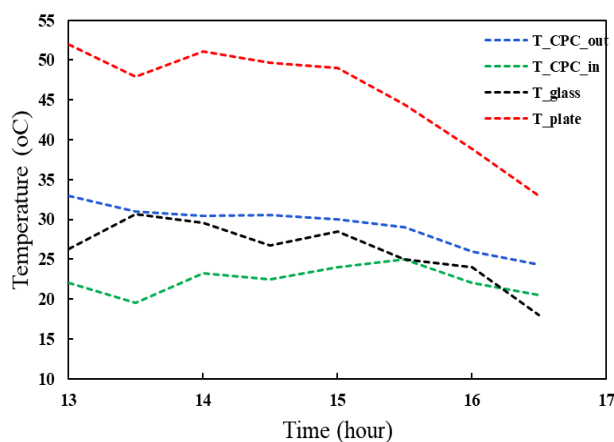


Figure 23 Relation between the temperatures at different locations on the system and time

A comparison between theoretical and experimental data of solar radiation is shown in Figure 24).

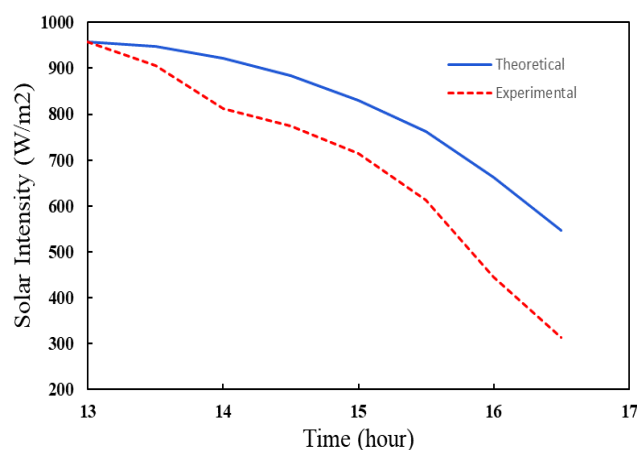


Figure 24 Solar radiation intensity data

A comparison between calculated and measured results at different system components is shown in Figures (25 to 27).

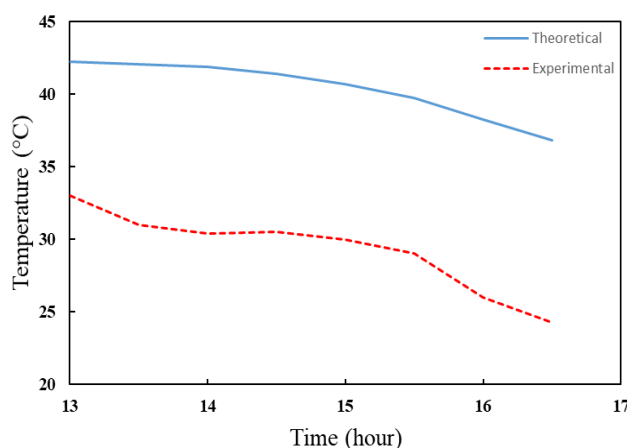


Figure 25 Temperature data of the water leaving the CPC

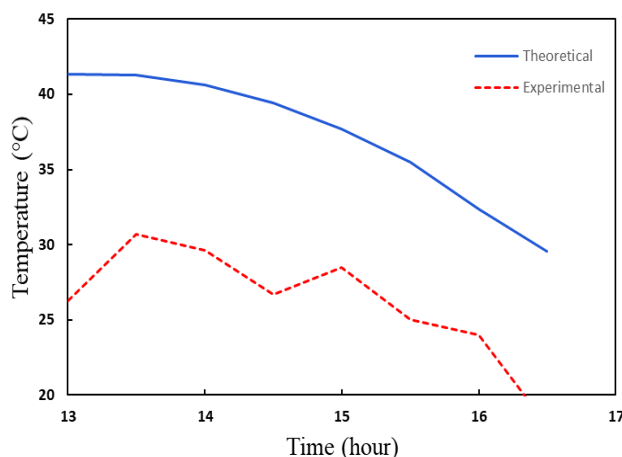


Figure 26 Temperature of glass condensation cover

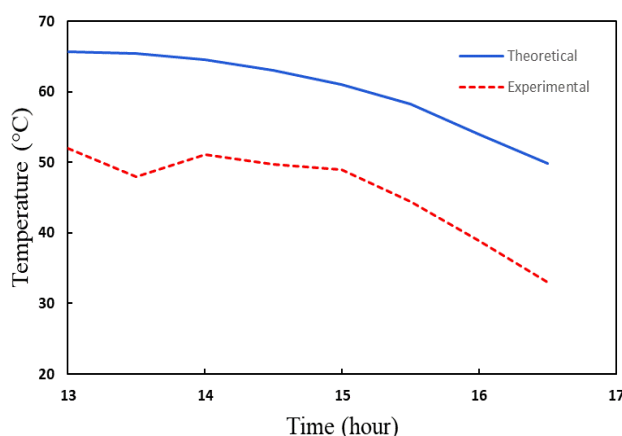


Figure 27 Absorber temperature

Figure 19 to Figure 27) present the system performance. Different variables were calculated hourly such as glass temperature (T_g), absorber plate temperature (T_b), temperatures of water entering and leaving the CPC, solar radiation (I), wind speed (V_w), and productivity (Pr).

Figure 19) shows that the solar productivity increases until reaching the maximum value at 13 p.m. then decreases. Figure 20) and Figure 21) show that the temperature of the stepped absorber plate is maximum followed by the temperature of water leaving the CPC and the temperature of the glass cover the CPC outlet temperature, and minimum temperature will be the ambient temperature.

Figure 22) and Figure 23) depict the outcomes gained from the experimental work in the 11th of February 2018. Figure 24) to Figure 27) represent a comparisons between the theoretical and experimental results which are in a good convenience.



CONCLUSION

The results of the test rig have been used to study the effect of solar radiation, ambient temperature, wind speed, glass cover temperature, transparent cover properties, etc. on the system output. The following conclusions are:

- A higher temperature difference is obtained by increasing the wind velocity.
- The increase of ambient temperature decreases the heat loss from solar still, resulting in higher distillation rate.
- The results of the calculations are in good agreement with those of the experimental model of the system consisted of a solar still with a stepped absorber plate, CPC as a preheater and heat exchanger as an after condenser. These modifications have improved the system productivity by (91.3%) over the conventional basin still type.
- According to calculations, it can be concluded that utilization of absorber plate with modified design in solar still results in increasing in the absorber temperature compared to ordinary type absorber plate.
- Finally, it should be noted that one of the major reasons for efficiency loss in solar stills was the incomplete sealing. Hence, the proper sealing, which will be costly and difficult, must be one of the major concerns with solar still designers.

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