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Design modifications of inclined-type single slope solar still with collecting element and sun-tracking mechanism

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ABSTRACT

In this paper, different design modifications were added to the traditional single slope solar still to improve the distilled water production. The design modifications were introduced to the traditional single slope solar still, involving the installation of the external mirror at the upper side of the solar still to collect and reflect the sunlight into the basin, coupling the solar still with the manual one-axis tracking system, the addition of collection mechanism for condensed water at the inner side of the glass cover, adding of PV generator-powered heating coil, and step-wise basin. An experimental study was conducted to investigate the effect of adding together the above-mentioned five modifications on the parameters of the traditional single slope solar still. The results pointed out that, the total collected water from conventional solar still was 0.952 L/d/m^2 and from the modified still was 3.251 L/d/m^2 on the typical winter day. The productivity of the modified solar still was greater than the conventional solar still by 242%.

Keywords: Solar distillation; Single slope solar still; One axis manual sun-tracking; Collecting element; Heating coil; External mirror

1. Introduction

Water is essential for human beings and other living creatures. It can't be used for daily life without being purified. Accordingly, water needs to be filtered by reverse osmosis or desalinated by oil and natural resources. Desalination processes can be vapor compression, multi-stage flash, or multiple effect distillation. The solar evaporative technique is increasingly becoming one of the most widely used alternatives. Solar still utilizes this concept to give distilled water [1–4].

To increase the amount of distillate of a basin still, researchers studied many proposals. A reflector was used [5], a photovoltaic powered turbulence system was used [6], a vacuum pump was used [7], the glass cover was cooled [8], vacuum tubes were attached [9], at the basin of the still, fins were integrated [10] and the evaporating surface was increased [11].

The effect of utilizing new working fluids in different conditions was studied [12–17]. The cost of solar heat collection depends on solar collector type [18]. The flow rate of a flat type solar collector was studied in Martinopoulos et al. [19].

Excess energy is usually collected during sunshine hours. This excess energy needs to be stored so it can be used at sunset times. High heat capacity materials are most effective in solar energy storage [20–23].

The effect of process parameters on the energy consumption of reverse osmosis systems was studied [24]. The best operational conditions that give minimum theoretical energy consumption were found. Also, a pilot photovoltaic reverse osmosis system was examined.

Computerized mathematical model is used to estimate the solar energy passing through the atmosphere and reaching the ground surface [25]. This model uses an algorithm to estimate the cloud cover. Also, the effect of

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the installation angle of a solar collector on the amount of solar radiation incident on inclined surfaces was estimated. A model that estimates the amount of diffuse solar radiation in Tabass, Iran, was proposed [26]. The relationship between solar collector installation angle and the intensity of solar radiation incident on inclined surfaces was studied. In addition to that, the value measured in the experimental setup was compared with each corresponding calculated result [27].

In a different research, a small-scale desalination setup was built [28]. Furthermore, amounts of freshwater gathered per hour were measured. To find the most effective installation angle for a solar collector, a simulation program was designed. No need for any cloud cover information in this program. In addition to that, a small-scale experimental setup was utilized to obtain the amount of freshwater gathered.

Kaouther Ghachem et al. [29] established a numerical study on an inclined solar distiller using a 3-D double-diffusive natural convection model. The governing equations were derived using vector potential-vorticity formalism in its 3-D form. They were solved using the finite volume method. Inclination angle and buoyancy ratio were varied through the study in order to study the variation of mass and heat transfer from one side to the other. The main purpose of the study was to find the best inclination angle of the distiller.

A thermal model was proposed to study the efficiency of an external reflector attached to basin solar still [30]. Energy balance equations were used for different parts of the solar still. Besides that, the precision and accuracy of this model were examined empirically. Experiments were conducted by measuring hourly temperature values for a different amount of distilled water and different areas of the still.

A thermal model was proposed and characteristics of double slope solar still (DSSS) were studied [31]. Regression curves, both linear and non-linear, were used to study the behavior of the solar still under a quasi-steady state. It was found that non-linear characteristic curves were better than linear characteristic curves.

A simple solar still operating under Maltese climatic conditions was studied both theoretically and experimentally [32]. The distillation unit external and internal heat transfer modes were examined. It was found that condensation and evaporation processes increase with decreasing wind speed. Another remark states, that glass thermal conductivity improves condensation, while, glass optical transparency improves evaporation processes.

Farahbod and Omidvar [33] studied usage of a solar pond to produce potable and distilled water. Many parameters were proposed to compare experimental data and mathematical results. These parameters were thermal efficiency, conductivity efficiency, and collection efficiency.

The low amount of distilled water produced per unit area is the main drawback of the typical solar still shown in Fig. 1. Therefore, some design modifications can be used to improve the productivity of traditional stills. The target of this study is to improve the efficiency of typical solar still by the implementation of five different design modifications which are: (1) coupling the solar still with a manual one-axis sun tracking system, (2) addition of a condensed water collection mechanism at the inner side of the glass cover, (3) the installation of the external mirror at the upper side of the solar still to collect and reflect the sunlight into the basin, (4) adding of PV generator-powered heating coil, and (5) adding of chamber step-wise basin.

2. Description of modified solar still

The modified solar still is a conventional solar still with five modifications made to enhance productivity. These design modifications are explained in the following sections.

2.1. Manual one-axis sun tracking mechanism

A manual one-axis sun tracking mechanism was used to rotate the solar still with the movement of the sun to maximize the incident solar radiation.

The solar tracking device is shown in Fig. 2 consists of a 36 cm long and 3.25 cm diameter shaft. This shaft is welded at one end to a 5 cm diameter and 1.5 cm thick disc. A 6 cm long and 2 cm wide handle was used to rotate the disk manually. At the other end of the shaft, a 6.15 cm pitch diameter and 20 teeth bevel gear is mounted. Another 34 teeth and 9.13 cm pitch diameter bevel gear has meshed to the first gear. The second gear is mounted on another 13 cm long and 4 cm in diameter shaft clinging to the solar still. This second shaft is responsible for moving the still. The motion of the solar still is done by moving the handle which moves the shaft. The first bevel gear moves

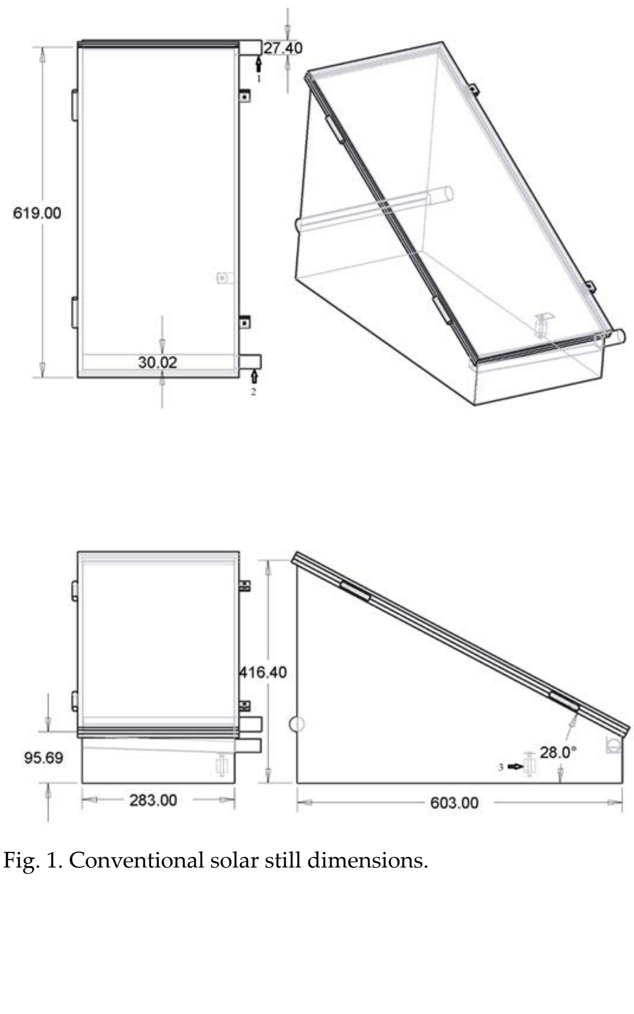

Fig. 1. Conventional solar still dimensions.

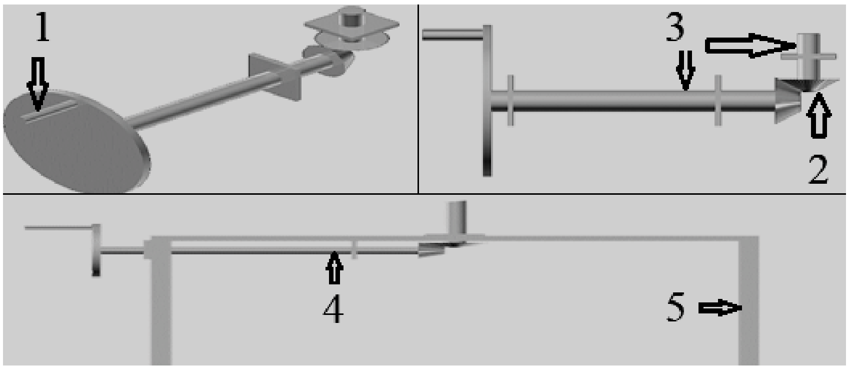

Fig. 2. Manual single-axis tracking mechanism.

with a horizontal motion to move the second bevel gear. The second bevel gear changes the motion to vertical motion. This moves the other shaft, and the whole solar still is rotated.

In Fig. 2, 1 is a handle, 2 are the two bevel gears, 3 are the two intersected shafts, 4 is bearing support, and 5 is the table at which modified still sits.

2.2. Rubber edged collection mechanism

The addition of a rubber-edged collection mechanism for the collection of condensed water at the inner side of the glass cover is to minimize the drops of water going back to the saline water basin. It is also used to remove the condensed water vapor from the glass surface because this vapor can prevent sun rays from entering the glass to heat water.

The collector element shown in Fig. 3 is an inclined collector with a rubber edge. Two rods carry the collector element. The first rod has a threaded end. A motor with a nut is welded to the collector part to allow it to move upward and downward easily. The second one is a track for bearing located at the end of the collector part. Its width equals 24.2 cm. where: 1 is a motor with threaded rod, 2 is a track for bearing, 3 is a collector, and 4 is a rubber edge.

The programming method of control is used to operate the collection element automatically. A programmable logic controller (PLC) is a digital controller which has a programmable memory in which a program can be stored. PLC LOGO 24-RC was chosen to control the operation of the electric motor-driven power screw in the forward and backward directions. The hardware connections of PLC LOGO24-RC are shown in Fig. 4. PLC LOGO 24-RC has eight inputs, only four are used. These inputs are as follows:

- I1 pushbutton to start the automatic operation of collecting elements.
- I2 pushbutton to stop the automatic operation of collecting elements.
- I3 pushbutton for manual operation of collecting element downward to adjust the system.
- I4 pushbutton for manual operation of collecting element in upward to adjust the system.

Also, PLC LOGO 24-RC has four outputs, only two of which are used. The used outputs are as follows:

- Q1 represents the operation of relay R1, which operates the motor downward.
- Q2 represents the operation of relay R2, which operates the motor upward.

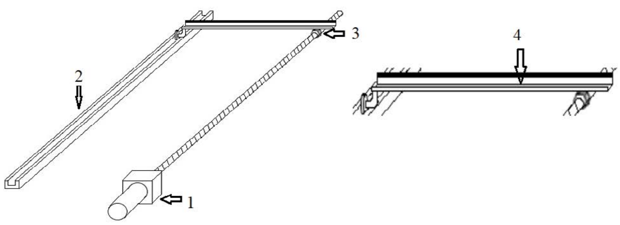

Fig. 3. Collector element design.

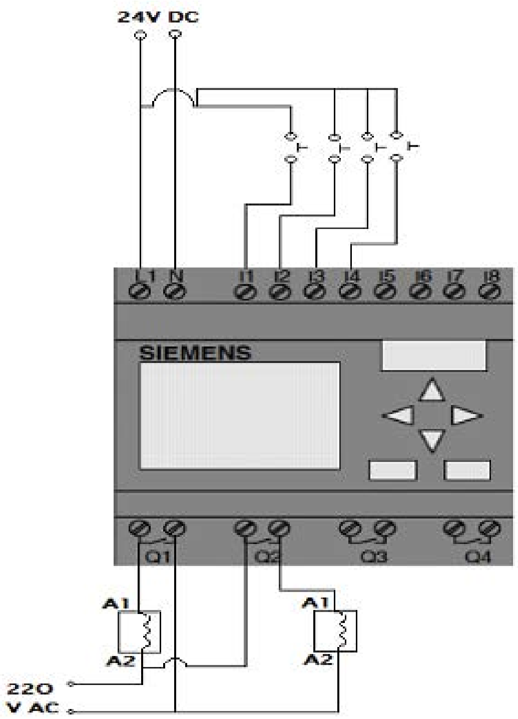

Fig. 4. PLC logo-24-RC hardware connections.

The PLC-LOGO24R-C uses the functional block diagram language described in Siemens Company [34].

PLC program of operation the collecting element consists of two parts related to the two types of motion, upward and downward.

Fig. 5 shows the functional block diagram program in upward (B) and downward (A). The blocks B5 and B11 are "AND" blocks where the output is on when both inputs are on. The blocks B1, B3, B6, B12, and B9 are "OR" blocks, where the output is on when any of the inputs are on. Blocks B4 and B10 are inverters, where the output is on when the input is off and vice versa. Blocks B2 and B8 are "Set–Reset" blocks, where the output is on when the upper input is triggered, and the output is off when the lower input is triggered.

The blocks B7 and B13 are "On timer", with a preset value equals 4 min. That means when the input of the block is on the output will be on after 4 min, and the output is off when the input is off without delay of time.

The time required to move the collecting element all the distance downwards is 4 min and the same time is required to move the collecting element upwards. The automatic mode of operation can be started by pressing the start pushbutton at the input I1. After pressing the start pushbutton at the input I1, the set input of block B2 will be on, and the output will be on. Also, the output of block B3 will be on and Q1 will be on. This means that the collecting element will work downward. When Q1 starts work, the timer in block B7 will be on. In this case, the output of B6 will be on and the output of B2 will be off, and Q1 will be off. When the output of B7 becomes on, also the output of block B8 becomes on, and Q2 which represents the operation of collecting element in upward direction becomes on. When Q2 starts work, the timer in block B13 starts the calculation of time, and when the time equals 4 minutes, the output of block B12 will be on and the output of block B8 will be off, and Q2 will be off. When the output of timer B13 becomes on, also the output of block B1 becomes on and the system will work downward, so on so forth.

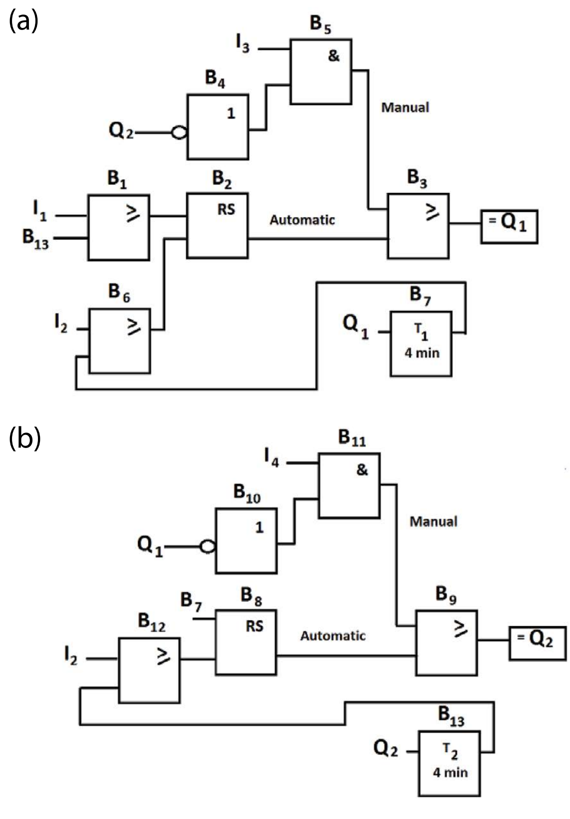

Fig. 5. PLC program for the operation of collecting elements upward and downward.

2.3. Chamber stepwise design

Dividing the saline water basin into three inclined chambers helps in reducing the amount of needed water to fill the chambers by 50% compared to the amount needed in conventional still for the same maximum depth of water. The surface of the water is too close to the inner side of the glass cover where the distance equals 3 cm so, it makes the shaded period on the water much less compared to the conventional still. The surface area exposed to solar radiation is bigger from the geometric point of view. Because of that, the kinetic energy needed to raise the vapor is less and the time required to achieve this process is shorter.

During the flow of water from the upper step to the next step, water will flow on the steel sheets that exist amongst the steps allowing water to gain some heat from steel sheets before it gets filled in the next step.

The modified still has been designed so that it consists of three chambers. Each chamber is higher than the previous one by 4.14 cm. The area for each chamber is 20 cm long and 28 cm wide to make as much heat as possible to be transferred from the heater to the surrounding drops of water. The chamber design is shown in Fig. 6.

2.4. Adding of electrical heaters

An electrical heater 24 V and 3.33 A is inserted in each chamber to heat the water faster. Three heaters are parallel connected as shown in Fig. 7. The type of module is a Yingli-YL245-P29b has a rating current of 8.11 A, a rating voltage of 30.2 V, nominal power is 245 W, and the area is 99 by 165 cm. Electrical power generated by PV module increases during early hours of the day until it reaches the ultimate value around solar noon then decreases as sunsets. The heater is 14 cm long and 1 cm in diameter. The heater is placed 1 cm below the upper surface of the water because it is more important to heat the upper section of water than the water in the bottom. One cm is left as a factor of safety to make sure that the heater is covered with water to prevent it from burning.

2.5. External reflective mirror

To evaporate the saline water faster and increase the production rate of distilled water, an external reflective mirror was added.

The previously mentioned modifications were included in the design of the modified solar still. This modified solar still is made from black painted cast iron. The still has a maximum height of 51.4 cm and a minimum height of

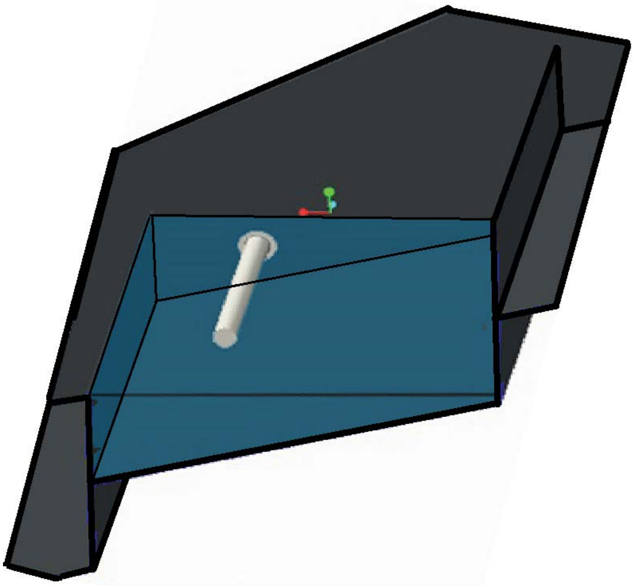

Fig. 6. Design of one chamber with an inserted heater.

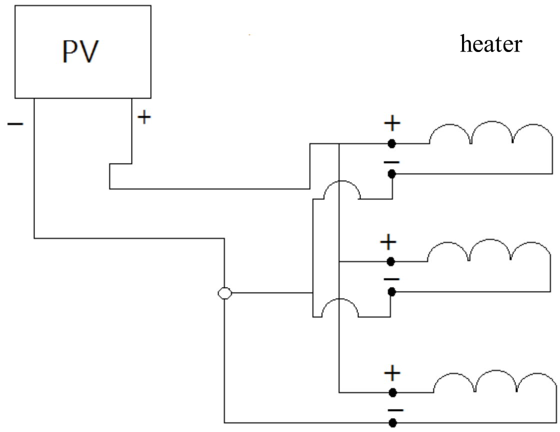

Fig. 7. Diagram for PV cell connection with heaters.

11.9 cm which makes the slope of the glass 28°. The thickness of the steel is 1.5 mm and with a reflector mirror having a length of 20 cm and a width of 28.3 cm with flexible inclination which can be manually controlled to reflect the incident solar radiation. The inside inclined basin is divided into three chambers each one has a length of 20 cm and a width of 28 cm with an inclination angle that equals 15°. The tracking system was added with a handle and four supporting bearings and two bevel gears on two cylindrical shafts. The four wheels were installed on the base of the solar still. The main components of the modified solar still are shown in Fig. 8 as following: (1) is a saline water inlet, (2) is an inclined path which takes the condensed clean water to the distilled water tank, (3) is a level sensor that keeps the level of water at a fixed value which is 5.5 cm. 4, 5, and 6 refer to the three chambers. 7, 8, and 9 refer to the three heaters each of which is inserted in one chamber. 10 are two bevel gears where the axes of the two shafts intersect. 11 is a bearing 3 cm diameter. 12 is a reflection mirror.

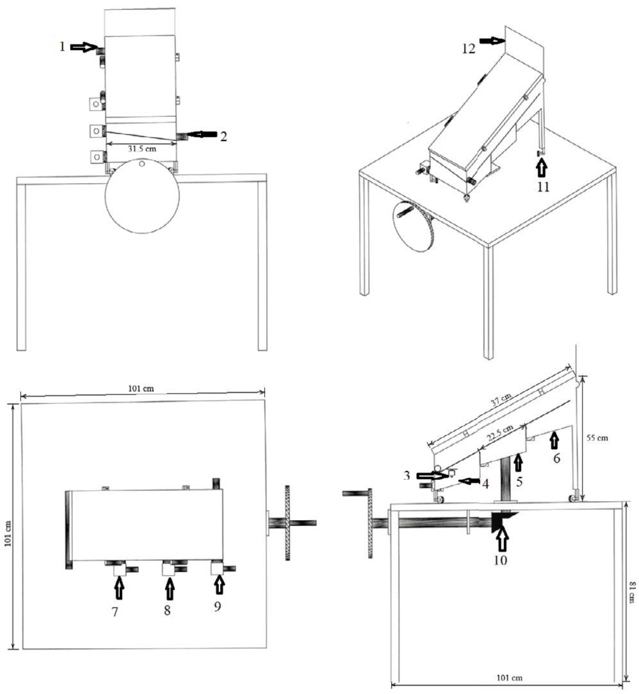

Fig. 8. Modified solar still.

3. Construction and experimentation

According to the dimensions of the design process, the internal surfaces of traditional and modified stills are made from black painted cast iron with the thickness of 1.5 mm. Black paint was used because it is well-known that a black body absorbs all the radiation incident on it. The thickness of the bodies was taken to be 1.5 mm because there is no need for high thickness since these surfaces carry almost no load while decreasing the thickness of these surfaces reduces the weight of the system. These surfaces were made from cast iron because the thermal properties of cast iron allow it to evenly distribute and retain heat over a long period of time, making it a popular option for thermal applications. The electrical heaters are replaced in the designed positions. To reduce the heat losses, both solar stills are covered with a wooden box leaving 2 cm space between the wood and the metal sheet, these spaces are filled with foam as shown in Fig. 9.

In each solar still, a normally closed water level sensor is installed. The sensors are connected to normally closed solenoid valves. When the water level decreases, the water level sensor sends a signal to the solenoid valve to allow the salt water to flow to the still from the saltwater tank. When the water level reaches the demanded level, a signal is sent from the level sensor to the solenoid valve to return to its normal position (normally closed) and the water will stop flowing to the still.

The complete assembly of both stills traditional and modified with a saline water tank and bottles of purified water is shown in Fig. 10.

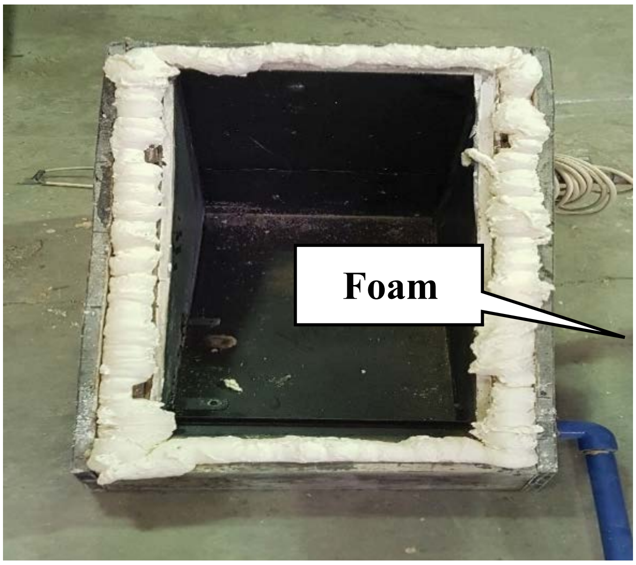

Fig. 9. Manufactured traditional still in the workshop of Applied Science Private University.

Fig. 10. Experimental setup of traditional and modified stills.

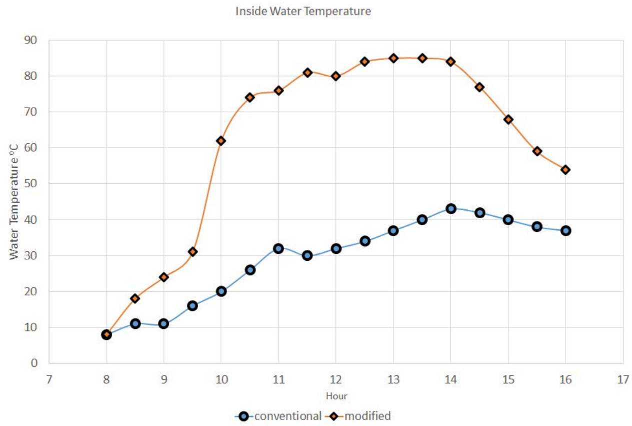

Fig. 11. Inside water temperature for the conventional and modified stills.

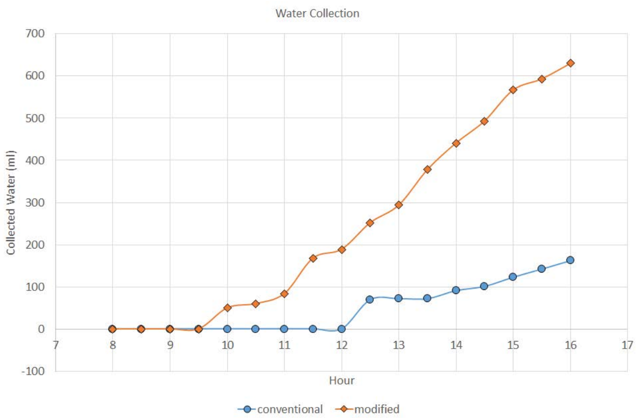

Fig. 12. Distilled water collection for conventional and modified stills.

4. Results and discussion

The experiments were performed in Applied Science Private University-Energy Center in Amman-Jordan. The experiments were conducted on both stills, conventional and modified during the period from 8 AM to 4 PM for different winter days (6, 7, 8, and 9/1/2018). The readings were taken at the same conditions in 30 min-time intervals for the above-mentioned days.

The readings were taken on 9/1/2018, as a representative day for the above-mentioned days, for inside water temperature, collected distilled water, solar radiation, and ambient temperature. Figs. 11 and 12 show the variation of inside water temperature function of time and the hourly collected distilled water for both the traditional and modified solar stills, respectively. Inside water temperature for both stills increases rapidly during early hours of the day until it reaches the maximum value of 95°C for modified still and 42°C for traditional still around the solar noon then, decreases near the sunset time. Distilled water in the modified still increases continuously for the whole day because the manual sun tracking system and step-wise design increase the receiving area and the time for solar radiation exposure. This will improve the thermal efficiency and the heat transfer inside the still. This phenomenon was noticed by Tanaka and Nakatake [35], who found that the absorbed solar radiation and distilled water productivity of solar still can be significantly increased by rotating the still just once a day towards the sun.

Figs. 13 and 14 show the solar radiation variation function of time and the variation of ambient temperature function of time, respectively.

The effect of using design modifications on the single solar still is clear where the total collected water from the conventional still was 162.4 mL and the total collected water from the modified still was 630 mL. When referring these values to the productivity of 1 m^2 and taking into consideration the surface area for each still, the total collected

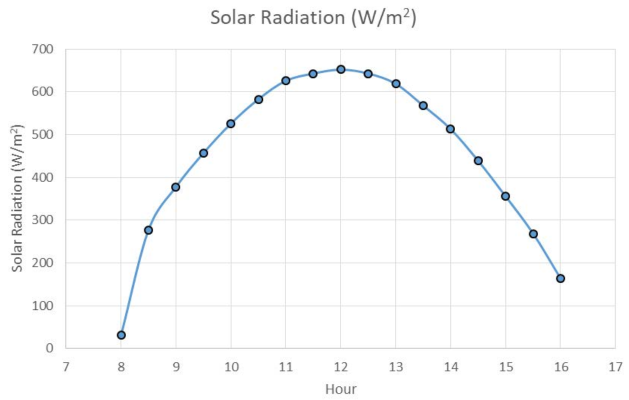

Fig. 13. Solar radiation variation function of time.

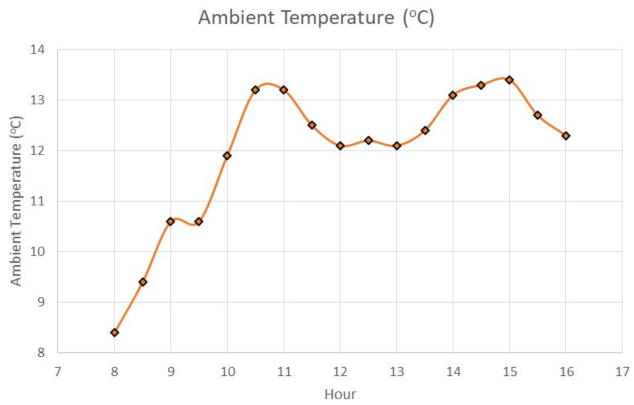

Fig. 14. Ambient temperature variation function of time.

water from conventional solar still was 0.952 L/d/m^2 and from the modified still was 3.251 L/d/m^2. The modified still gave a higher production rate for the above-mentioned day, reaching 242%. The nominal required value of PV power to produce 3.251 L/d/m^2 of pure water from the modified still is 1,458.3 W, and the area required by this PV system is 9.72 m^2.

Abdallah et al. [36] found that the inclusion of internal mirrors to the traditional still has improved the pure water production up to 30%, while the stepped basin enhanced the productivity up to 180% and the combination of the step-wise basin with single-axis sun tracking system gave the highest performance with an average of 380%.

Abdallah and Badran [37] designed and constructed a controlled single-axis sun-tracking system. They conducted an experimental study to investigate the effect of this system on the performance of a single slope solar distiller. The results showed that the solar still with single-axis sun-tracking system increased the productivity by up to 22% as compared to the fixed one. Abdallah [38] used photovoltaic generator-powered electrical heater and chamber stepped basin to the conventional single slope solar still. It was found that the added design modifications improved the productivity of solar distiller on average up to 904%. It is important to notice that the result of this work mainly depends on using a photovoltaic generator-powered electrical heater as an external source of power.

Comparing the results of the previous works with the results of this work, it is clear that the thermal performance and distilled water productivity of conventional single slope solar still can be improved through the suggested different design modifications. Of course, these results will be much better if taken during summer time.

5. Conclusions

The performance of single slope solar still with five different and integrated design modifications was investigated. These design modifications, involved the installation of an external mirror at the upper side of the solar still to collect and reflect the sunlight into the basin, coupling the solar still with the manual one-axis sun tracking system, the addition of a collection mechanism for condensed water at the inner side of the glass cover, adding of PV generator-powered heating coil, and a step-wise basin.

An experimental study was conducted to investigate the effect of adding the above-mentioned modifications on the output parameters of modified solar still. The inclusion of design modifications enhanced the productivity of the distiller by up to 242%. The results are considerable for single slope solar still applications. Consequently, the solar still with added design modifications can be used efficiently for pure water production in the zones of the world, where solar radiation levels are high.

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