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Solar still with a hemispherical chamber stepwise basin and additional heaters powered by a PV system

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ABSTRACT

In this work, design modifications were introduced to the traditional solar purifier to improve pure water production. A Hemispherical chamber step-wise basin and inserted electrical heaters powered by a PV generator were added to the conventional solar purifier. An experimental study was conducted, in winter time in Amman-Jordan, to investigate the effect of introduced design modifications on the pure water production of traditional solar still. The experimental results pointed out that the average values of purified water collection from traditional single slope solar purifier were 1.233 L/m^2/d, from the solar still with hemispherical chamber step-wise basin were 2.305 L/m^2/d, and from solar still with a hemispherical chamber step-wise basin and addition of electrical heaters were 4.105 L/m^2/d. The productivity of the modified solar purifier without the addition of electrical heaters was more significant than the traditional solar purifier by 86.9%, and for the modified design with electrical heaters by 232.9%.

Keywords: Solar water distillation; Hemispherical stepped basin; PV generator; Electrical heaters

1. Introduction

The supply of pure water is a very important necessity for human life besides air and food. Unfortunately, clean water is a precious resource that is becoming rare in many countries around the world.

The majority of water on Earth is salty, and only 3 percent is drinkable [1]. The desalination process can be defined as extracting salts and minerals from water. Membrane and thermal technologies are two methods used around the globe for water desalination. These two methods need energy to produce drinkable water [2]. Whereas using traditional energy sources, such as fossil fuels, is pollutive and expensive [3]. Therefore, green energy sources such as solar, wind, and biomass are more attractive than traditional energy sources. Implementing solar-assisted desalination is an ideal option to achieve significant energy and greenhouse gas emission savings [4].

Solar desalination is the cheapest method that can be used to separate pure water from saline water by using the thermal effect of solar radiation power. Single-slope solar still is considered to be the most straightforward device used to obtain pure water. However, a single slope solar purifier's productivity is low, ranging between 2–5 L/m^2/d [5–7].

Factors affecting the performance of solar distillers [6–11] are metrological factors such as atmospheric temperature, pressure, wind speed, humidity, beam, and diffused solar radiation. In addition to operational factors like the surface area of the basin, the inlet temperature of saline water, the distance between the glass cover and saline water surface, differences in temperature between saline water and inner glass cover, glass cover angle, and depth of saline water.

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Usually, metrological parameters cannot be changed. In parallel, operational factors can be controlled to improve the efficiency and productivity of the solar still. Taking into consideration the effects of these elements on the productivity of a solar still, many improvements have been made to the traditional single-slope solar purifier to increase its performance [5,12–22].

Badran [6] studied the effect of the different parameters on the performance of the traditional single-slope solar purifier. It is concluded that pure water output is inversely proportional to the basin's saline water depth. This work investigates the effects of the temperature difference between the inner side of the glass cover and the water basin by utilizing asphalt as a basin liner material and a film of cooling water at the outer glass cover. It is concluded that this procedure will enhance the performance of the solar still. The most affecting parameter in solar distillation is the temperature difference between the inner side of the glass cover and saline water in basin.

Arunkumar et al. [23] suggested a new design of single-slope solar purifier with a hemispherical cover. In this work, the productivity of a hemispherical solar purifier with and without a flowing film of water as the cooling fluid over the hemispherical cover was investigated. It was concluded that the hemispherical solar still productivity was improved due to the cooling effect of the film of water. Many methods and strategies mentioned in the literature can be applied to cool the glass cover of solar still [24–26].

Rajaseenivasan et al. [8] investigated the influence of increasing the temperature of saline water by preheating inlet saline water using a flat plate collector on the productivity of the solar purifier. Energy heat-storing materials in the basin of the still were used with various depths of salty water. The preheated saline water was proved to enhance the productivity of the solar purifier by about sixty percent more than that of the conventional solar still. A comprehensive review of solar still integrated with solar collectors for the improvement of the productivity of potable water has been reported [27].

Panchal [28] studied the effect of various materials inside the basin of a single-slope solar purifier on the improvement of producing pure water. The solar productivity will improve by increasing the difference in temperature between saline water in the basin and the inner side of the plexiglass cover. It is concluded that the maximum saline water temperature in the basin could be reached by adding heat storage materials like blue metal stones to the basin. Various studies have investigated the effect of different heat storage materials on the productivity of solar stills [29–33].

In [34], novel designs of solar purifiers are suggested. Spherical and pyramid shapes with chamber stepwise basin were introduced to the traditional solar purifier design. An experimental study was implemented to investigate the influence of added design modifications on the productivity of the modified solar purifier. The addition of spherical and chamber stepwise design increased the productivity of the modified distiller by up to 57% compared with the pyramid solar purifier.

Many hemispherical solar stills have been introduced in the literature with different designs and modifications. Recently, the addition of different metals at the still bottom to enhance water productivity of a hemispherical solar still were studied [35]. While another research paper suggested a floating solar still that could use the surrounded cold water to enhance the condensation and to feed the system by sea water, a hemispherical glass cover used in besides with a horizontal solar absorption layer wetted by sea water [36].

A semispherical and chamber stepwise basin solar purifier with and without PV-powered electrical heaters are suggested, were invented, and worked in parallel with the experimental setup to compare these models. The experimental results show that semispherical PV-powered electrical heaters and without PV-powered electrical heaters solar purifiers increased pure water productivity from a traditional solar purifier by 156.6% and 72.5%, respectively. Furthermore, the theoretically simulated model is obtained and compared with experimental results [37].

The main drawback of conventional solar purifiers is that the productivity of pure water is relatively low. Therefore, it is important to improve the efficiency of traditional solar still (TSS). The main target of this work is to enhance the pure water production of traditional solar purifiers by using novel design modifications, which are: (1) Hemispherical chamber stepwise basin. (2) Insert electrical heaters powered by a PV system in the bottom of each basin. In this work, the hemispherical glass cover besides to the chamber stepwise hemispherical basin solar still were suggested to absorb more heat directly from the solar radiation all the day, where the basin is facing the sun partially through the day.

2. Description of solar purifiers

This section covers the principle of work and the mechanical design of traditional solar still TSS, hemispherical solar still with chamber step-wise basin (HSS), and solar still with hemispherical chamber stepwise basin and inserted heaters (HSSH) at the bottom of the basin.

2.1. Mechanical design of traditional solar still

Traditional single slope solar still TSS with inclined glass cover consisting of a rectangular basin made of a cast-iron sheet of 1.5 mm thickness. The basin dimensions are: the width is 280 mm, the length is 600 mm, and the height is 95 mm. The maximum height of conventional solar still is 410 mm, and the face of the still is covered with a transparent glass of 6 mm thickness. The slope of the glass is 28°, and the transmittance of the glass cover is 88%. Fig. 1 shows the mechanical design of the TSS and Fig. 2 shows this solar purifier after manufacturing. The principle of work of TSS can be explained as follows: when solar radiation enters through the glass cover of TSS, the rise in temperature of the metal sheet and saline water causes the evaporation of saline water in the basin. The vapor condenses on the inner side of the inclined glass cover because of the temperature difference between the glass cover and the vapor. The drops of condensed water slip by gravity force, where it is collected into a pure water collecting bottle.

2.2. Modified solar still with hemispherical chamber stepwise basin

The suggested design of modified solar still has a hemispherical shape, as shown in Figs. 3 and 4. This design has the ability to receive solar radiation from all directions, which eliminates the need for a sun-tracking system and increases the basin's exposure to solar radiation. The saline water basin is divided into four circular chambers with diameters of 20, 40, 60, and 80 cm, respectively. The angle of inclination of the glass cover is 45°. As shown in Fig. 4, the saline water enters the top chamber through the vertical tube, which is replaced at the center of this chamber. In the walls of each chamber, four holes are placed 90° from each

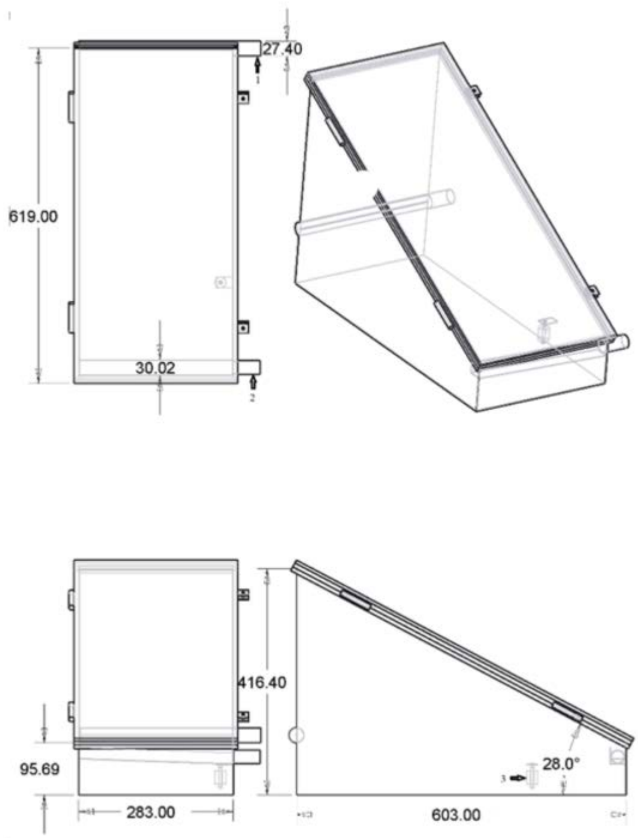

Fig. 1. Conventional solar still (dimensions are in mm).

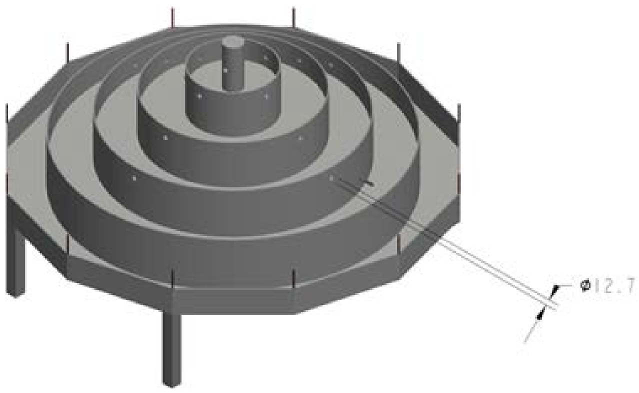

Fig. 3. Top-left view of hemispherical basin.

Fig. 4. Hemispherical still basin after manufacturing.

Fig. 2. Traditional solar purifier after manufacturing.

other at the height of 3 cm from the bottom of the chamber. Fig. 5 shows the solar purifier after mounting the glass cover.

The principle of work of HSS can be explained as follows: first, saline water enters the upper top chamber, then goes to the lower second chamber through the four holes in the walls, then goes this way until saline water reaches the fourth chamber. A level sensor is mounted at the level of 3 cm in the fourth chamber. When the level of saline water reaches 3 cm the level sensor activates the directional control valve which stops the saline water flow from the vertical tube in the first chamber. The fifth chamber is used to collect the pure water. The hole in the bottom of the fifth chamber is added to pass pure water through it to the collecting bottle. Dividing saline water into four chambers increases the surface area to be exposed to solar radiation and increases the surface of saline water facing the solar radiation. The average distance between the surface of saline water in chambers and the inner side of the glass cover is about 4 cm, so the kinetic energy required to move the vapor up will be less, and the time needed to achieve the evaporation and condensation process is shorter.

Fig. 5. Solar still with glass cover.

The depth of saline water in the basin will be controlled to be constant at the level of 3 cm. This selected value is based on previous studies in this field which found that the productivity of saline water is inversely proportional to the depth of saline water in chamber [14,39,42]. When the saline water flows from the upper chamber to the next chamber, it gains some heat from the metal sheet before it gets filled in the following chamber.

The hemispherical chamber stepwise design keeps the solar radiation perpendicular to the metal sheet of basins. In traditional design, the solar radiation will be parallel to the basin surface at sunset and sunrise. When the solar radiation falls through the glass cover into hemispherical basins filled with saline water, saline water evaporates and starts condensation at the inner side of the glass cover. The drops of fresh water slip by gravity to the fifth chamber designated for collecting pure water, then released to the pure water collecting bottle.

2.3. Modified solar still with hemispherical chamber stepwise basin and PV powered electrical heaters

This modified design HSSH has the same characteristics as in the previous section except that, there are three heaters that will be inserted in three chambers at the north face of solar still. Heaters will be inserted at the north face of solar still because it is less exposed to solar radiation. The heaters are inserted in the chambers at the height of 1 cm above the bottom of basins as shown in Fig. 6. The added electrical heaters powered by PV system are used to heat saline water in chambers to increase the evaporation rate and the productivity of pure water. The technical characteristics of added heaters are as follows: rated voltage is 24 VDC, rated power is 60 W, length is 99 mm, and diameter is 6 mm. The technical characteristics of used PV module used to operate the heaters are as follows: nominal power is 245 W, rated voltage is 30.20 VDC, the length is 165 cm, the width is 99 cm, and the module type is Yingli/YL245/P129b.

As shown in Fig. 7 three heaters are inserted into hemispherical solar still in the second, third, and fourth basin

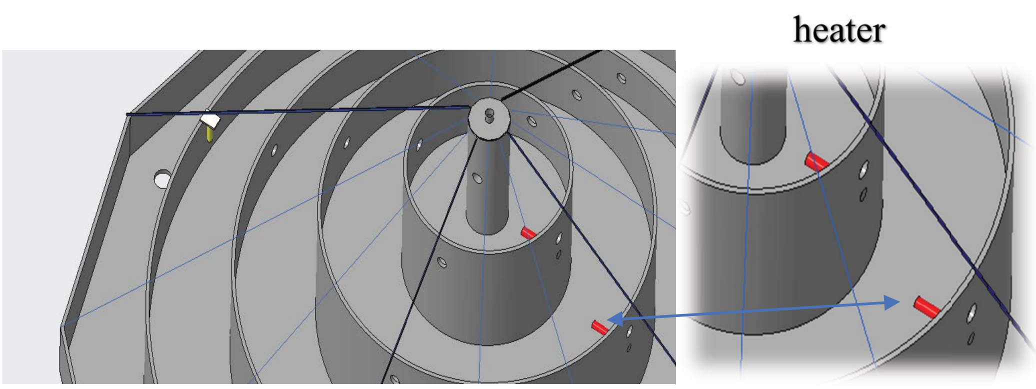

Fig. 6. Top view of hemispherical basin with concentration in heater.

Fig. 7. Solar still with installed heaters.

chambers to increase the temperature of the water inside the basins. The electrical heater is not inserted in the first chamber due to its small size and small mass of water in this chamber.

3. Mathematical model of hemispherical solar still

Experimental work was carried out during the period from the 10th to the 13th JAN 2021 at the Renewable Energy Center of the Applied Science Private University-Amman, Jordan.

To find the productivity of both the traditional and the modified stills, a mathematical model was developed based on the energy balances of the glass cover, the water, and the basin.

The only source of energy in the system is solar radiation, which will heat up the basin and the water. Due to the temperature difference between the water and the inclined glass cover, the water will evaporate from the basin and condensate on the glass cover. So, pure water will be collected during this process.

The transient energy balance for the water could be expressed as follows:

$$\frac{dT_w}{dt}c_w m_w = Q_{c,w-b} + \alpha_w \tau_g A_w I_b - Q_{r,w-g} - Q_{c,w-g} - Q_{e,w-g} \quad (1)$$

Due to the climate conditions, the solar radiation intensity was taken from a pyranometer.

The energy balance for the glass could be expressed as the following:

$$\frac{dT_g}{dt}\, c_g m_g = Q_{r,w-g} + Q_{c,w-g} + Q_{e,w-g} + \alpha_g A_g I_b - Q_{r,g-s} - Q_{c,g-s} \quad (2)$$

The energy balance for the glass could be expressed as the following:

$$\frac{dT_b}{dt}\, c_b m_b = Q_{c,w-b} - \left(1-\alpha_w\right)\left(1-\alpha_g\right)\alpha_b A_b I_b + U_b A_b \left(T_b - T_a\right) \quad (3)$$

The convection heat transfer between water and glass is expressed as the following:

$$Q_{c,w-g} = h_{c,w-g} A_w \left(T_w - T_g\right) \quad (4)$$

where the convective heat transfer coefficient between water and glass is expressed as the following [38]:

$$h_{c,w-g} = 0.884\left[\frac{\left(T_w - T_g\right) + \left(P_w - P_g\right)\left(T_w + 273\right)}{\left(268.9\times 10^3 - P_w\right)}\right]^{1/3} \quad (5)$$

The radiation heat exchange between water and glass is expressed as the following:

$$Q_{r,w-g} = h_{r,w-g} A_w \left(T_w - T_g\right) \quad (6)$$

The radiative heat transfer coefficient between water and glass is expressed as the following [38]:

$$h_{r,w-g} = \frac{\sigma}{1/\varepsilon_w + 1/\varepsilon_g - 1}\left[\left(T_w + 273\right)^2 + \left(T_g + 273\right)^2\right] \left(T_w + T_g + 546\right) \quad (7)$$

The evaporation heat transfer between water and glass is expressed as the following:

$$Q_{e,w-g} = h_{e,w-g} A_w \left(T_w - T_g\right) \quad (8)$$

The evaporation heat transfer coefficient between water and glass is expressed as the following [38]:

$$h_{e,w-g} = \left(16.273\times 10^3\right) h_{c,w-g} \frac{P_w - P_g}{T_w - T_g} \quad (9)$$

where P_w and P_g are the water saturation pressure at the water temperature and the glass temperature and can be calculated as the following [39]:

$$P_w = \left(610.94\right)\exp\left[\frac{17.625 T_w}{243.04 + T_w}\right] \quad (10)$$

$$P_g = \left(610.94\right)\exp\left[\frac{17.625 T_g}{243.04 + T_g}\right] \quad (11)$$

The radiation heat transfer between glass cover and skey is expressed as the following:

$$Q_{r,g-s} = h_{r,g-s} A_g \left(T_g - T_s\right) \quad (12)$$

The radiation heat transfer coefficient between glass cover and skey is expressed as the following [38]:

$$h_{r,g-s} = \varepsilon_g \sigma \frac{\left(T_g + 273\right)^4 - \left(T_s + 273\right)^4}{T_g - T_s} \quad (13)$$

where the sky temperature is calculated as the following [38]:

$$T_s = T_a - 6 \quad (14)$$

The convection heat transfer between glass cover and skey is expressed as the following:

$$Q_{c,g-s} = h_{c,g-s} A_g \left(T_g - T_s\right) \quad (15)$$

The convection heat transfer coefficient between glass cover and skey is expressed as the following [38]:

$$h_{c,g-s} = 4.8 + 3.33 V_{\text{wind}} \quad (16)$$

The wind speed was taken from the weather station at the lab.

The convection heat transfer between basin and water is expressed as the following:

$$Q_{c,b-w} = U_b A_b \left(T_b - T_w\right) \quad (17)$$

where the convection resistance between water and basin were neglected, and the overall heat transfer coefficient is expressed as the following:

$$U_b = \frac{1}{L_{\text{ins}} / k_{\text{ins}} + 1 / h_o} \quad (18)$$

where the L_{ins} = 1.0 cm, k_{ins} = 0.03 W/m·K, and h_o = 5 W/m^2·K.

The productivity of the still was calculated using following equation:

$$\dot{m}_w = \frac{Q_{e,w-g}}{h_{\text{fg}}} \; \left(\text{kg/s}\right) \quad (19)$$

where h_{fg} is function of water temperature as following [40]:

$$h_{\text{fg}} = 2.49 \times 10^6 \begin{pmatrix} 1 - 9.48 \times 10^{-4} T_w + 1.31 \times 10^{-7} T_w^2 \\ -4.5 \times 10^{-9} T_w^3 \end{pmatrix} \quad (20)$$

Eqs. (1)–(18) were solved numerically using MATLAB Simulink to find all variables along the day and calculating the productivity instantaneously.

For the HSS and HSSH, the equations were solved for each glass cover. Where the glass temperatures were different due to the difference in the incident solar radiation at each glass cover. To simplify the problem, the water temperature was assumed the same for all glass covers. The summation of productivities of all glass covers is the productivity of this modified solar still.

Regarding the solar intensity, as mentioned above, the experimental values were used due to the weather conditions. The experimental values are the solar radiation at the horizontal surface. To transfer it at a tilted surface, the following equations were used [41]:

$$I_b = I_o \frac{\cos\theta}{\cos\theta_z} \quad (21)$$

The zenith angle, θ_z, is given by [41]:

$$\theta_z = \cos^{-1}\left(\cos\varphi\cos\delta\cos\omega + \sin\varphi\sin\delta\right) \quad (22)$$

where ω is the hour angle, equals zero at 12:00 solar time (noon time), and increases or decreases 15° with each hour added or deducted, respectively.

Angle of incidence, θ, is given by [41]:

$$\theta = \cos^{-1}\begin{pmatrix} \sin\delta\sin\varphi\cos\beta - \sin\delta\cos\varphi\sin\beta\cos\gamma \\ +\cos\delta\cos\varphi\cos\beta\cos\omega \\ +\cos\delta\sin\varphi\sin\beta\cos\gamma\cos\omega \\ +\cos\beta\sin\beta\sin\gamma\sin\omega \end{pmatrix} \quad (23)$$

where β equals 28° for the traditional solar still, and 45° for the hemispherical solar still. And the latitude, ϕ = 32° in Amman. And surface azimuth angle, γ equals zero for the traditional solar still and it's varying for each glass cover from 15° to 345°.

The declination angle, δ, is expressed as [41]:

$$\delta = 23.45 \sin\left(360 \frac{284 + n}{365}\right) \quad (24)$$

where n is the day number in the year.

4. Experimentation of modified solar stills

4.1. Experimental results

The experiments were carried out on stills at the same time, at the same climate conditions, and at the same location in the Renewable Energy Center at the Applied Science Private University in Amman-Jordan. The experiments were carried out in winter on three different days from January 10th to January 13th 2022 throughout the period from 8 AM to 4 PM.

Fig. 8 shows the productivity of the three solar stills. Obviously, the productivity of HSSH is the highest. On the other hand, the productivity of HSS is higher than the traditional one.

Fig. 9 shows the basin water temperature. HSSH had the highest temperature as the heaters heating the water, the effect of the heaters is recognized after 10:00 AM compared to HSS, this due to the increase in the power of the heaters from PV cells as shown in Fig. 10. The PV module were tilted 27° from the horizontal and directed to the south.

Water temperature of HSS starts to rise over the traditional solar still, after 10:00 AM to become equal or lower than the water of the traditional solar still. This could be illustrated as following; first the glass in the HSS is facing to all directions so will receive heat from the sunrise until the sunset, which will yield to rise the temperature rapidly at the morning. Secondly, the lower insulation to basin area ratio and in the HSS will not help to rise the temperature. Moreover, the high productivity will help more energy to be absorbed by from basin water in the HSS.

Fig. 11 shows the ambient temperature and the solar radiation readings from the weather station. Both were used in the simulation to find the productivity of the solar stills.

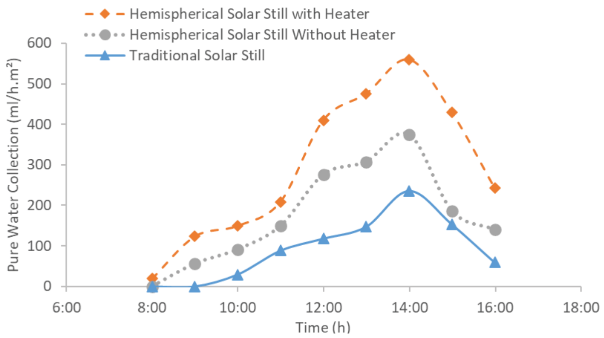

Fig. 8. Actual productivity of the three solar stills along the day (10 Jan 2022).

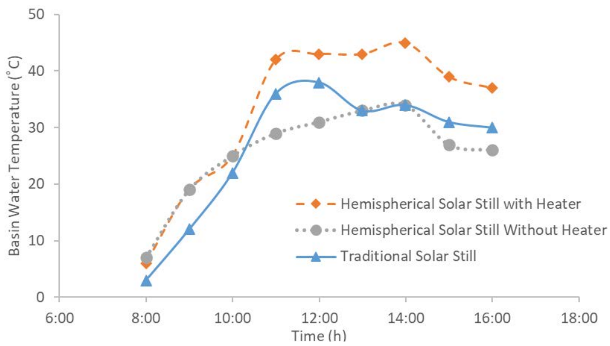

Fig. 9. Basin water temperature of the three solar stills along the day of (10 Jan 2022).

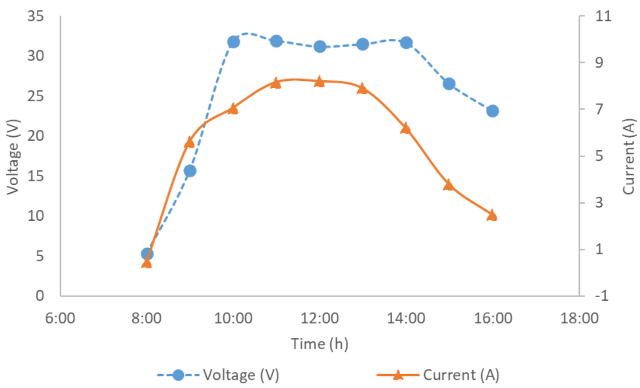

Fig. 10. Current and voltage from PV cells to HSSWH along the day of (10 Jan 2022).

4.2. Simulation results

The mathematical model was solved numerically using MATLAB Simulink. The mathematical model differential equations were solved for 8 h simulation. The simulation results for different systems are shown in Figs. 12–15 and compared with experimental results. The max error found in Fig. 13 is around 25%, the variation between the experimental and the simulation results is due to flow head loss in the pipes and fittings, also duo to the winter weather at that time, that cause the wind and the solar radiation vary over the day. However, the simulation results show good agreement with the experimental results.

The effect of hemispherical design with and without inserted electrical heaters added to the traditional solar purifier is shown in Table.1. The average gain of three winter days is 86.9% for hemispherical solar purifier without inserted heaters, and 232% for hemispherical solar purifier with inserted heaters as compared with traditional solar purifier.

The high productivity of HSS can be explained by many factors such as: (1) The hemispherical shape of solar purifier basin makes the incident beam radiation more

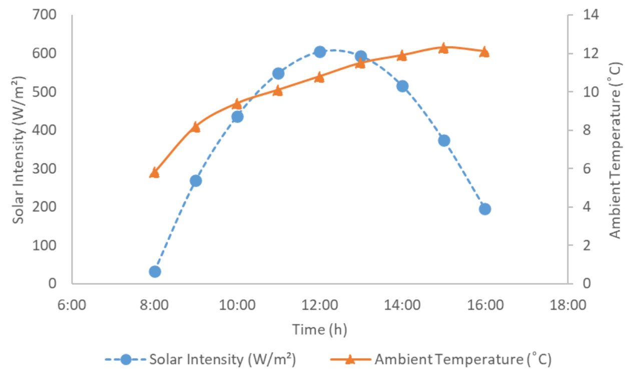

Fig. 11. Solar intensity and ambient temperature from the weather station along the day of (10 Jan 2022).

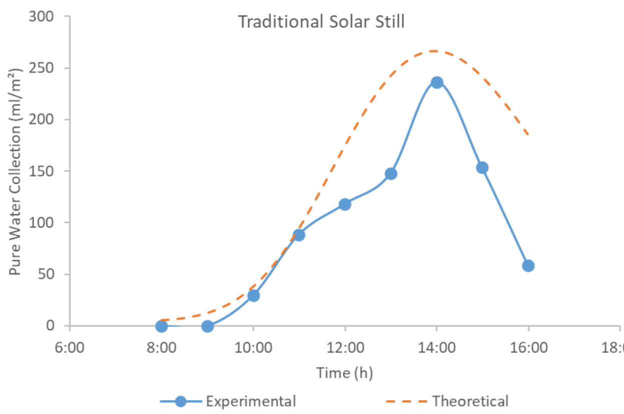

Fig. 12. Experimental and theoretical results of the pure water productivity of the traditional solar still.

perpendicular to the surface of metal sheet from sunset to sunrise which enables this type to collect more solar radiation. (2) When the sun altitude angle is more than 45^0 the beam radiation will cover the basin from all directions, but more perpendicular to the surface of metal sheet from south direction. (3) The air gap between the inner side of glass cover and the water surface is about 4 cm which is very small. Consequently, the kinetic energy required to raise the vapor up is lesser and the required time to complete evaporation process is shorter. (4) The surface area of hemispherical basin exposed to beam radiation is relatively large, as compared to traditional purifier, which gives more mass and heat transfer surface. The huge productivity of HSSH can be explained, besides the previously mentioned factors, using the heat generated by inserted electrical heaters in basin chambers.

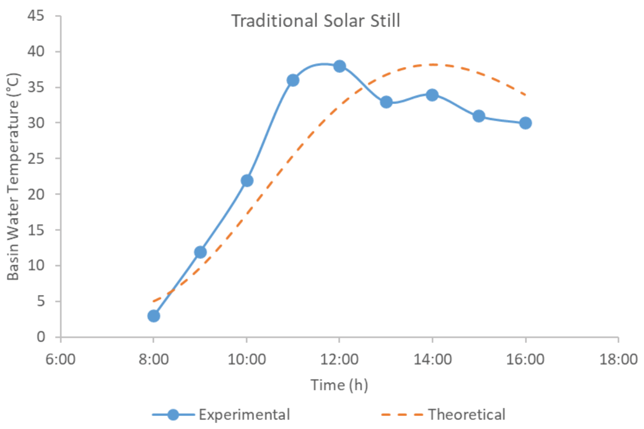

Fig. 13. Experimental and theoretical results of the basin water temperature of the traditional solar still.

Abdallah and Saleet [42] found that the solar purifier with a pyramid stepped basin has improved the productivity of purified water by up to 85% as compared to the conventional one. On the other hand, the solar purifier with a spherical stepped basin has shown better results than the solar purifier with a pyramid stepped basin that reaches up to 57.1%. In [37] a semispherical and chamber stepwise basin solar purifier with and without PV-powered electrical heaters are suggested, were invented and worked in parallel with the experimental setup to make a comparison between these models. The experimental results show that semispherical with PV-powered electrical heaters and without PV-powered electrical heaters solar purifiers increased the productivity of pure water from a traditional solar purifier by 156.6% and 72.5%, respectively.

The suggested design in this paper is considered to be the first of its type. Comparing the results of the previous works with the results of this work, it is clear that there is a big difference in favor of solar purifier with hemispherical shape and chamber stepped basin. Indeed, these results will be much better if taken during summer. In future work, the inclination angle of glass cover in conventional solar still and the modified to be the same and close to the range

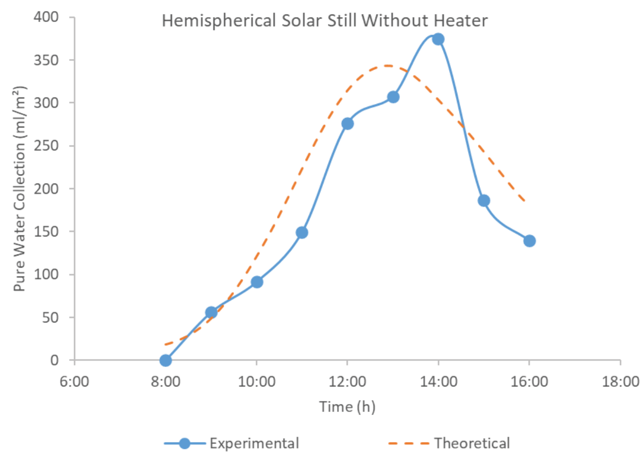

Fig. 14. Experimental and theoretical results of the pure water productivity of the HSSWOH.

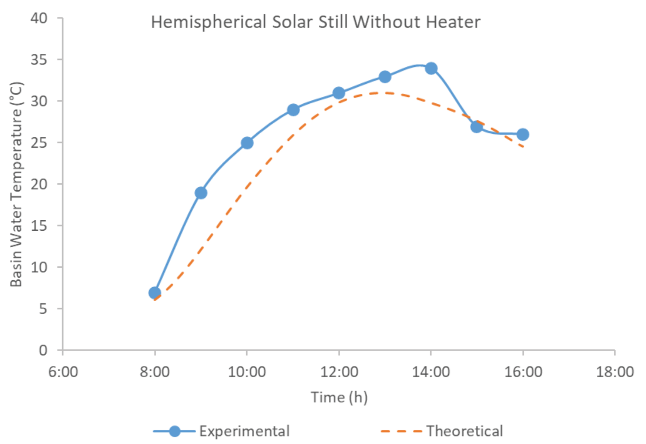

Fig. 15. Experimental and theoretical results of the basin water temperature of the HSSWOH.

Table 1
Pure water collection for traditional and improved stills

	Traditional solar still	Hemispherical solar still without heater	hemispherical solar still with heater
Average collection 3 d (mL)	209	1,236	2,201
Average collection 3 d (L)	0.209	1.236	2.201
Area (m^2)	0.1694	0.5361	0.5361
Productivity ($L/m^2 \cdot d$)	1.233	2.305	4.105
Gained percentage %	–	86.9	232

between 20^0 and 25^0 in purpose to improve the productivity, and the power of electrical heaters mut be increased.

5. Cost comparative estimation of different solar stills

To make a cost comparison between the distillate output from modified and conventional stills, simple payback period method will be used.

The capital cost of each solar still, traditional, hemispherical with electric heaters, and hemispherical without electric heaters are shown in Tables 2–4. The cost of each still is estimated based on Jordanian market prices for basin area equals 1 m^2. The cost of 1 L of purified water in Jordan is US$0.06.

The life span of used PV module to operate the electric heaters is 25 y and its cost is US$62.5. Assuming that the life span of each solar still is 10 y, then the cost of PV module during this period of time is US$25. The yearly average production of pure water for each solar still is assumed to be the values given in Table 1.

The annual amount of produced pure water, the annual cost of produced pure water, and the payback period for each solar still are shown in Table 5. The annual amount of produced pure water is found by the multiplication between average yearly production of pure water (L/m^2/d) and 365 (d/y). The annual cost of produced water is calculated by the multiplication between the annual amount of produced water (L) and the cost of 1 L of purified water

Table 2
Traditional solar distiller

Equipment	Specifications	Amount	Cost (US$)	Total (US$)
Sheet metal 2 m^2	Thickness 1.8 mm	1	18	18
Latte wood 2 m^2	Thickness 18 mm	1	12	12
Iron tube	Thickness 40 mm	4	1	4
Primer paint	1 kg	5	2	10
Black matte paint	1 kg	5	2	10
Connector pipe – muff	1 inch	2	0.5	1
Solenoid valve		1	35	35
Welding wire 2.5 mm	0.5 kg	75	0.04	3
Faucet	0.5 inch	1	3	3
Silicon (stiction)		12	2.5	22.5
Insulation foam		4	3	12
Level sensor	Normally closed	1	12	12
Glass 1 m^2	Thickness 3 mm	1	50	50
Manpower with work				60
Total				252

Table 3
Hemispherical solar distiller with electric heater

Equipment	Specifications	Amount	Cost (US $)	Total (US$)
Sheet metal 2 m^2	Thickness 1.8 mm	5	30	150
Latte wood 2 m^2	Thickness 18 mm	2	12	24
Primer paint	1 kg	2	2	4
Black matte paint	1 kg	4	2	8
Connector pipe – muff	1 inch	2	0.5	1
Welding wire 2.5 mm	0.5 kg	90	0.04	36
Faucet	0.5 inch	1	3	3
Thermal silicon		8	7	56
Insulation foam		4	3	12
Level sensor	Normally closed	1	5	5
Glass 1 m^2	Thickness 3 mm	1	100	100
Manpower with work				88
Electric heater (9 cm length)	6 mm diameter	3	5	15
Solenoid valve		1	35	35
PV panel	245 W		25	25
Total				563

Table 4
Hemispherical solar distiller without electric heater

Equipment	Specifications	Amount	Cost (US$)	Total (US$)
Sheet metal 2 m^2	Thickness 1.8 mm	5	30	150
Latte wood 2 m^2	Thickness 18 mm	2	12	24
Primer paint	1 kg	4	2	8
Black matte paint	1 kg	4	2	8
Connector pipe – muff	1 inch	2	0.5	1
Welding wire 2.5 mm	0.5 kg	90	0.04	36
Faucet	0.5 inch	1	3	3
Thermal silicon		8	7	56
Insulation foam		4	3	12
Level sensor	Normally closed	1	5	5
Glass 1 $^{m}2$	Thickness 3 mm	1	100	100
Manpower with work				100
Solenoid valve		1	35	35
Total				538

Table 5
Payback period for each solar still

Type of solar still	Capital cost (US$)	Annual amount of produced water (L)	Annual cost of produced water (US$)	Payback period (y)
Traditional	252	450	27	9.3
Hemispherical	538	841	50.5	10.6
Hemispherical with heaters	563	1498	89.9	6.2

in Jordan (US$0.06). The following equation is used for payback period calculation:

$$P = \frac{\text{Capital cost of solar still}}{\text{Annual cost of produced water}} \tag{25}$$

The payback period for hemispherical solar still with heaters is 6.2 y which is acceptable. The payback periods for traditional solar still is 9.3 y and 10.6 y for hemispherical solar still without heaters, which are not profitable from economical point of view. From analysis of theoretical model, experimental data, and economical evaluation it can be seen that the pure water produced by hemispherical solar still with added electrical heaters in Jordan can provide an alternative water source. If the ecological effect of using solar energy is taken into consideration, as a clean power supply with zero CO_2 emissions, the results of modified hemispherical solar still with electrical heaters are considerable and certain. These systems can be practically used for fresh water production in arid zones, where solar radiation is high enough. In future work, it is suggested to add more electrical heaters and study the technical and economic aspects of added heaters.

6. Conclusions

In this study, design modifications were introduced to the conventional solar purifier to improve the productivity of pure water. Hemispherical chamber step-wise basin and inserted electrical heaters powered by PV generator were added to the conventional solar purifier. The suggested modified solar stills were experimented and mathematically modeled. The experimental results show that, the average values of purified water collection, in winter time in Amman-Jordan, from traditional single slope solar purifier were 1.233 L/m^2/d, from the solar still with hemispherical chamber step-wise basin were 2.305 L/m^2/d, and from solar still with hemispherical chamber step-wise basin and addition of electrical heaters were 4.105 L/m^2/d. The productivity of the modified solar purifier without the addition of electrical heaters was more significant than the traditional solar purifier by 86.9%, and for the modified design with electrical heaters by 232.9%. From an economical point of view it can be seen that the pure water produced by hemispherical solar still with added electrical heaters in Jordan can provide an alternative water source, where the payback period of this system equals 6.2 y.

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Symbols

A — Area, m^2
c — Specific heat, kJ/kg·K

h — Heat transfer coefficient, W/m²·K
h_{fg} — Latent heat of vaporization, kJ/kg
I — Solar intensity on the horizontal surface, W/m²
I_b — Solar intensity on a tilted surface, W/m²
k — Thermal conductivity
L — Thickness, m
$\dot{m}$ — Mass flow rate, kg/s
P — Vapor pressure, kPa
Q — Heat transfer, W
T — Temperature, °C
U — Overall heat transfer coefficient, W/m²·K
V — Wind speed, m/s

Greek

α — Absorptivity
ε — Emissivity
τ — Transmissivity
β — Slope angle of the surface
θ — Angle of incidence
θ_z — Zenith angle
δ — Declination angle
ω — Hour angle
γ — Surface azimuth angle
ϕ — Latitude angle
σ — Stefan Boltzmann constant = 5.67×10^{-8} W/m²·K⁴

Subscripts

b — Basin
c — Heat transfer by convection
g — Inclined glass cover
e — Evaporation heat transfer
Ins — Insulation material
r — Heat transfer by radiation
w — Water

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