Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.26711

213 (2021) 35–43
February

Productivity enhancement of the solar still by using water cooled finned condensing pipe

Mohammad Al-Dabbas[a], Ali Alahmer[b,c,*], Amer Mamkagh[d], Mohamed R. Gomaa[e,f]

[a]*Mechanical Engineering Department, Mutah University, P.O. Box: 7, Mutah, Karak 61710, Jordan, email: madabbas@mutah.edu.jo*
[b]*Faculty of Engineering and Technology, Department of Alternative Energy Technology, Al-Zaytoonah University, P.O. Box: 130, 11733 Amman, Jordan, Tel. +962 798277537; emails: a.alahmer@zuj.edu.jo/a.alahmer@ttu.edu.jo*
[c]*Department of Mechanical Engineering, Faculty of Engineering, Tafila Technical University, P.O. Box: 179, 66110 Tafila, Jordan*
[d]*Department of Plant Production, Mutah University, P.O. Box: 7, Mutah, Karak 61710, Jordan, email: amer_mam@mutah.edu.jo*
[e]*Benha Faculty of Engineering, Mechanical Engineering Department, Benha University, Benha Z. C.13512, email: Behiri@bhit.bu.edu.jo*
[f]*Faculty of Engineering, Mechanical Engineering Department, Al-Hussein Bin Talal University, Ma'an 71111, Jordan*

Received 9 April 2020; Accepted 18 October 2020

ABSTRACT

An innovative solar desalination system was designed, constructed, and tested to produce more freshwater than a conventional solar still system. The new system consists of a basin type solar still and an external condenser. The condenser itself contains finned condensing pipes and a reservoir for the cooling water. The effects number of the fins, volume of cooling water, and flow rate in the condenser on the distilled output of the proposed solar desalination system were studied. As compared to the conventional basin type solar still system, the proposed system significantly produced more freshwater when cooling water volume, cooling water flow rate, numbers of fins in the condenser were increased. Furthermore, the number of fins exerted the most significant effect on freshwater productivity. The maximum daily freshwater produced was 12,350 mL when 250 L cooling water, 400 L/h flow rate, and 80 fins on the outer surface of the condensing pipe were used, which is about 300% more than the productivity of the conventional solar still. To use this solar desalination system efficiently, it was concluded that the optimum rate of cooling water must be about 50 L/h. Moreover, the remaining water volume in the condenser must be about 79 L.

Keywords: Solar desalination efficiency; Single slope solar still; Still with an external condenser; Still productivity enhancement; Finned condenser with solar still

1. Introduction

With the dramatic growth in population and an increase in living standards, freshwater supplies are deteriorating. Water desalination could be a promising solution to minimize the shortage of freshwater, but it is economically inefficient for many countries that depend on imported oil. Solar desalination of brackish, impure, and seawater is considered the most attractive and simple technique among existing desalination processes to provide freshwater. It is suitable for small-scale units at locations where solar energy is abundant. It has been studied as a preferred process because of its energy efficiency and low environmental impact. In the Middle East, Jordan imports more that 97% of its energy and thus is considered one of the poorest countries in terms of energy sources [1] and the fourth

* Corresponding author.

poorest country in the world in terms of water resources [2]. But on the other side, it has an extraordinary solar intensity of 2,080 kWh/m^2 with more than 300 sunny days per year [3,4]. Therefore, the use of solar desalination alongside with the technological improvements in the solar devices could be suitable solutions for water desalination in remote areas with poor water quality and a lack of other treatment options. Basin type solar stills are options that can be used for water desalination and are considered one of the cheapest solutions for purifying brackish water [5]. They are suitable for the countries in the Middle East and Africa due to their low cost and ease of maintenance [6]. But their main drawback is the low water productivity, which is about 2–5 L/m^2/d under conventional conditions [7]. This low level of production makes it impractical for many uses. Many designs of the solar still have been constructed or modified to increase the solar still productivity and efficiency when of the integrated with heat storage, fins, air blower, reflectors, collectors, heat pump, different absorber plates, solar pond, nanofluids, wire mesh, wicks, glass cover cooling, and cooling condenser [7–9].

Mamkagh et al. [10] constructed a solar desalination system consisted of a set of conventional basin-type solar stills, and a set of condensing pipes buried in the soil which were used as a condensers. The potable water distillate depends on the coolant mass flow rate in the condenser tubes, surface area of the condenser tube, and its volume [11]. Sellami et al. [12] modified a basin liner by adopting a 5 mm sponge layer, which acts as an extra heat storage area. The solar still productivity was enhanced up to 58% in comparison with a conventional solar still. Faegh and Shafii [13] attached a heat pipe solar collector to the solar still in order to accelerate the evaporation rate. A 6.5 kg/m^2 of water productivity was achieved by this method. Kabeel et al. [14] conducted an experimental study to enhance the productivity of the solar still by integrating vacuum with an external condenser. Their results showed that this integration increased the distillate water by about 53%. El-Samadony et al. [15] carried out a research study of stepped solar still with reflectors and external condenser. They found that the productivity of modified solar still was about 66% higher than the conventional still system. Mevada et al. [16] reported that the integration of fins to the conventional solar still enhances water productivity. The fin configuration, thickness, and material are crucial factors affecting the percentage of performance improvements. Rabhi et al. [17] enhanced basin solar still using a condenser and pin-shaped fins. Kumar et al. [18] improved the solar still productivity by joining square tubular fins and paraffin wax as a thermal energy storage. The percentage increments in the distillate water of both improved solar still with integrated fins only and with fin and energy storage were 64% and 95%, respectively, as compared to conventional solar still. El-Sebaii and El-Naggar [19] conducted the experiments to study the effect of different fin materials on the distilled output of the solar still. The results revealed that there is no substantial effect on water productivity by changing the fin materials. Gupta et al. [20] improved the evaporative rates and the performance of solar still by adding CuO nanoparticles. Experiments have been conducted at two water depths of 5 cm and 10 cm mixed with 0.12% by weight nanoparticles. The results revealed that 22.4% and 30% improvement in water productivity at water depths 5 and 10 cm, respectively, as compared to conventional solar still. Bahiraei et al. [21] employed nanofluid of copper oxide-water in a single trough solar still equipped with four thermoelectric modules to improve daily productivity of the distillate output. Khalifa and Ibrahim [22] studied the effect of adding an external and internal reflectors to basin solar still. The performance of basin solar still was improved by 35.5% when added to both external and internal reflectors and 19.9% when added only to internal reflectors as compared to still without reflectors. Bhargva and Yadav [23] improved the single slope solar still productivity by integrating the evacuated tube collector, external condenser, internal reflector, and heat exchanger with still basin to heat the basin water. The results showed that the output solar still was increased to 206.5% as compared to a conventional solar still. Das et al. [24] suggested integrating both reflector and condenser with a single basin solar still especially in the places of low radiation to increase the still output. Estahbanati et al. [25] studied the impact of internal reflectors on the solar still efficiency. The results revealed that potable water and overall efficiency were increased by 34% and 22%, respectively, as compared to conventional solar still. Furthermore, the percentage of the output water productivity improvement was more in winter as compared to the summer season. Younas et al. [26] developed a multistage solar still coupled with a Fresnel lens for desalination purposes. The results showed that the productivity of the freshwater was 5 kg/m^2/d. The influence of using phase change material (PCM) as a thermal energy storage on the efficiency of a single slope solar still integrated with the photovoltaic module was investigated experimentally by Abd Elbar and Hassan [27]. The results revealed improvements in their daily water output by around 9% and 11.7%, respectively. Al-Harahsheh et al. [28] improved the solar still performance by the use of phase change material. The results indicated that the solar still could produce up to 4,300 mL/d m^2 and 40% of the water produced was after sunset. Panchal et al. [29] revealed that the integrated thermoelectric parts with solar still is a prospective option to enhance the daily distillate output of potable water generated from groundwater. Mousa and Abu Arabi [30] improved basin solar still by the use of a double glass external solar collector. This system could produce about 4 L/(m^2 d) freshwater. Pakdel et al. [31] improved the conventional solar still shape to the side troughs instead of side glass walls. The results revealed that the innovative design enhanced the still productivity by 31.59% and improved the thermal efficiency by 81.72%. Kabeel et al. [32] used two solar dishes combined with the solar still to improve the daily freshwater productivity to be 13.63 at water depth of 10 cm. Arunkumar et al. [33] enhanced the performance of single slope solar still with new insulation material of a bubble-wrap and carbon permeated foam. Three operation scenarios of single slope solar still were investigated experimentally: without insulation, with insulation of bubble-wrap, and with insulation of both bubble-wrap and carbon permeated foam. The bubble-wrap and carbon permeated foam showed the most water productivity of 3.1 L/m^2/d amongst the other scenarios. Balachandran et al. [34] cooled the glass cover with water film and employed a fiber composite insulation to enhance the water productivity of solar still. The amount of water output from modified solar still was increased by 21% as compared to conventional solar still. Kabeel et al. [35] stated the reduced solar still cover temperature will increase the condensation rates. Alahmer et al. [36] demonstrated a method to harvest pure water from atmospheric air depending on intensifying the water vapor from the air in a manner of an economic and feasible way. Elashmawy and Alatawi [37] developed trapezoidal prism solar still to harvest the atmospheric water in low humidity climate condition of Hail city in Saudi Arabia. The results showed that a high potential of the atmospheric harvesting water technique from low-humid regions up to 26.5%.

The main concern of this work was as following: (i) enhance the productivity of the solar still by the use of external finned condensing pipe as a condenser for a single slope basin type solar still; (ii) increase the condensation rate by placing that condensing pipe inside a larger pipe filled with water; and (iii) study the effect of fins number, cooling water volume and flow rate in the condenser on the freshwater productivity of the proposed solar desalination system.

2. Materials and methods

2.1. Experimental site

The field experiments were carried out in the southern part of Jordan (31°16′N, 35°44′E, and 962 m above mean sea level). The field was chosen at a location where the proposed solar desalination system can be exposed to sunlight all the daytime without obstacles. During the experiments, a solar radiation intensity, ambient temperature, outside glass surface temperature, and water temperature at the basin, on 15th of June as example were measured and presented in Fig. 1. This figure shows that the solar radiation intensity increases quickly during the daytime from 25 W m^{-2} at 6:00 a.m. to 1,011 W/m^2 at 13:00, and then progressively drops to 21 W/m^2 at 19:00, which matches the same path with the ambient air temperature. It can be noticed that the outside glass surface temperature and water temperature at the basin follow the same behavior of solar radiation. The maximum value of ambient temperature is occurred at about 13:00 after 1 h of the time of maximum radiation intensity due to a little cloudy weather and the elevation of the thermal inertia of atmospheric air [38,39]. The rise in water temperature is due to the quantity of solar radiation received by the still basin and this solar intensity trapped inside the basin. The maximum value of the water temperature is about 52°C and achieved at 14:00. The maximum value of the glass temperature was achieved at the period of the highest water temperature. It is attributable to the high amount of absorption rate of the glass surface for the latent heat of the vapor condensation. The average daily global solar radiation on horizontal surfaces and average daily sunshine hours for 5 months of the experiments were measured and presented in Table 1.

2.2. Design and construction

Fig. 2 demonstrates the designed and constructed solar desalination system in the current work. It consists of two main sections; the first section is the basin type solar still and the second section is the condenser.

A basin type solar still was used to evaporate the brackish water and generate a sufficient amount of vapor as shown in Figs. 2 and 3. It consisted of the following parts: a wooden frame, a transparent cover, a float valve, an inlet from the brackish water tank, and an outlet to the air blowers. The framework was made of wood to ease the system construction and to provide good isolation from the external environment. It was fabricated in a box type shape of 80 cm × 80 cm and 1 cm in thickness. The height of the front side was 10 cm and the backside was 20 cm high.

Table 1
Measured average daily global solar radiation on a horizontal surface and average sunshine hours for 5 months

	May	June	July	August	September
kWh/m^2 d	7	8	7.8	7.3	6
Sunshine hours	10.6	12.3	12.5	11.8	10.4

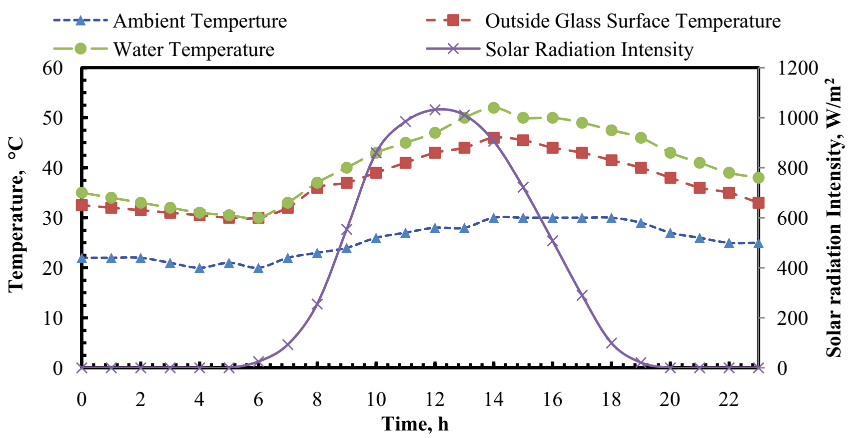

Fig. 1. Experimental measurements of solar radiation intensity, ambient temperature, outside glass surface temperature, and water temperature (on 15th of June, 2019).

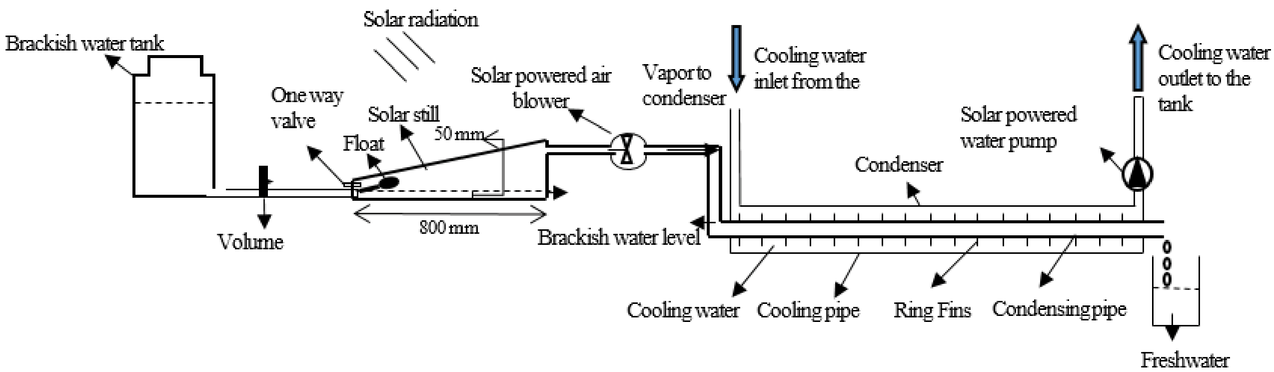

Fig. 2. Configuration of the experimental solar desalination system.

Fig. 3. Basin type solar still used in the experiment.

One conventional basin type solar still was used separately as a reference for the experimental control. The reference was tested separately under the same conditions as the proposed solar desalination system and its daily freshwater production rate of about 4,000 mL/m^2.

As shown in Fig. 2, brackish water flowed from the tank to the solar still under gravity. To ensure that the depth of the water remained around 5 cm, the stainless-steel float valve was installed inside the solar still. The water depth used was based on previous studies showing that this depth increases the evaporation rate inside the solar still [14,15]. The one-way valve was used to vent the solar still so air could enter the still but vapor could not exit. The air blowers then moves the vapor from the still through plastic pipes to the condenser. The freshwater that produced inside the condenser then collected at the outlet of the condensing pipe.

2.3. Condenser design

The condenser consists of two parts, the first part was a 4 m-long galvanized steel pipe with a diameter of 4 inch (114.3 mm), which served as a condensing pipe. The second part was a large steel pipe, which served as a reservoir for the cooling water.

The condensing pipe was placed inside the reservoir, which filled with cooling water. Since the idea of this study is to provide and save freshwater, brackish water was used as a coolant to prevent the waste of freshwater. To find the effect of the cooling water volume on the productivity of the whole solar desalination system, during the experiment was a possibility to choose from three volumes of the cooling water (97, 170, and 250 L). This has been achieved by using three large pipes with different diameters (8, 10, and 12 inch to place the condensing pipe inside them. The solar powered water pump was used for water circulation between the tank and the condenser. During the experiment flow rates of the cooling water were controlled by choosing the right speed of the pump with the help of a flow control valve thus rates were 0, 50, 100, 200, and 400 L/h. To increase the rate of heat transfer of the condenser, and thus can increase the productivity of the proposed solar desalination system, steel ring fins with a diameter of 6 inches were installed on the outer surface of the condensing pipe as shown in Fig. 2.

2.4. Error analysis

To evaluate the errors related to the experimental quantities, different apparatus such as (i) thermocouple to measure water temperature, glass surface temperature, and ambient temperature; (ii) pyranometer to measure solar radiation on glass surface; (iii) beaker to measure the distilled volume capacity; and finally (iv) stopwatch to measure volume flow rate were used. Table 2 displays the accuracy of the instruments used in the experiments. The percentage error was calculated according to the following equation [40]:

$$\text{Error \%} = \frac{\text{Apparatus accuracy}}{\text{Minimum value of apparatus measured}} \times 100\% \quad (1)$$

3. Results and discussion

Fig. 4 displays the observed significant effect of the cooling water volume inside the condenser on the hourly freshwater productivity. This figure also shows that the experimental solar desalination system produced the highest amounts of freshwater per hour around 13:00 for all used volumes of the cooling water inside the condenser. This is because the more cooling water flows inside the

Table 2
Calculated error for different measuring apparatus

Apparatus	Accuracy	Range	Minimum value measured	% Error
Digital thermometer	±0.1°C	0–100	20	0.5%
Solarimeter	±1 W/m²	0–2,000 W/m²	20	5%
Measuring breaker	±5 mL	0–1,000 mL	100	5%

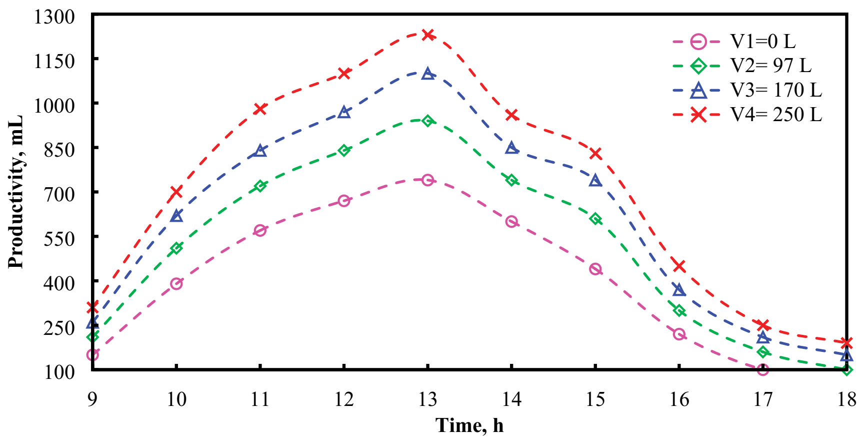

Fig. 4. Average hourly freshwater productivity for different volumes of the cooling water inside the condenser (on 15th of June, 2109). Where: $V1$ – without water, $V2$ = 97 L, $V3$ = 170 L, and $V4$ = 250 L.

condenser, the more vapor condensation will take place at which the temperature now is less than of dew point.

Moreover, solar radiation intensity and ambient temperature were high at that time. However, the amount of the desalinate freshwater is achieved at 13:00, which is 1 h after the maximum solar intensity and 1 h prior the maximum ambient temperature. This is because the increase of ambient temperature that impacts the rise glass temperature, which reduces the glass cooling. Consequently, the rate of a condensation process is reduced due to a low difference between the surface glass temperature and evaporated water temperature [41]. Moreover, the time passes in the condensation process and collection of freshwaters. The increase of heat transfer in the condenser with the increased solar radiation trapped inside the basin increased the evaporation rate.

Fig. 5 emphasizes that the water volume in the condenser can affect daily freshwater productivity. Because more water vapor contacts the cold surface and consequently the more condensation. Furthermore, the employment of an external condenser distills some of the water vapor extracted from the solar still and does not permit the increase in the internal glass temperature to high values. This in fact improves the evaporation rate along with the condensation rate inside the solar still basin. The minimum freshwater productivity (3,930 mL) was obtained when no water was used inside the condenser which means it has been cooled by the surrounding air convection only. Subsequently, the airflow used to drive the amount of the moist air to the external condenser, will boost the heat transfer by convection within the solar still and enhances the condensation rate, and increases the amount of water production. In other words, the fan pushes the non-condensable vapor away from the basin still to the condenser and avoids the impact of non-condensable vapor on the condensation rate reduction. The improvement in the distilled output is due to the increase in the air movement inside the still, avoiding non-condensable vapor, and increasing the evaporation rate. In this case, the experimental solar desalination system produced less freshwater as compared to the conventional solar still (the reference case). Therefore, cooling the condenser of the proposed solar desalination system by air only without water is useless.

The experimental solar desalination system produced the maximum daily accumulated freshwater (7,000 mL) when the volume of 250 L of cooling water was used to cool the condenser.

Fig. 5 shows that the productivity of the experimental solar desalination system was increased from 3,930 mL to 5,130 mL when a volume of 97 L of cooling water was used to cool the condenser instead of cooling it by air only. This means that the proposed solar desalination system produced 30% more freshwater than the reference case and more than the air-cooled condenser as depicted in Fig. 6.

Generally, the increase of cooling water amount in the condenser leads to an increase in freshwater productivity of the proposed solar desalination system as shown in Fig. 5. Fig. 6 indicates that the growth in freshwater productivity of the system is exhibits a downtrend when the amount of cooling water increases in the condenser. Therefore, the increase of the water amount in the condenser more than 97 L leads to an increase in the size of the whole system,

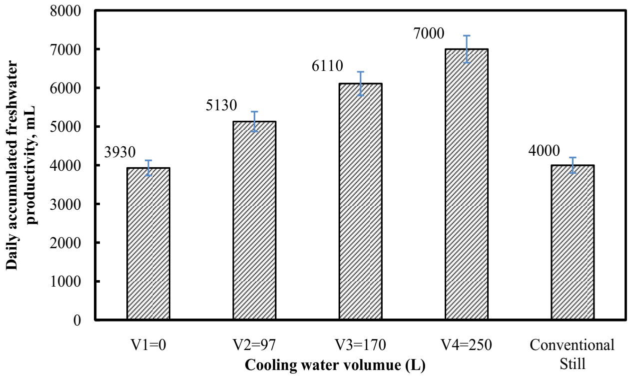

Fig. 5. Average accumulated daily freshwater productivity of the proposed solar desalination system at different volumes of the cooling water inside the condenser compared to the conventional solar still productivity (in June 2019).

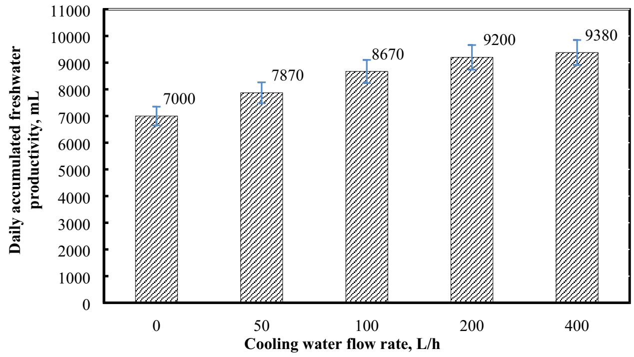

Fig. 7. Average accumulated daily freshwater productivity of the proposed solar desalination system under the effect of cooling water flow rate inside the condenser when the volume of the cooling water was 250 L (in June 2019).

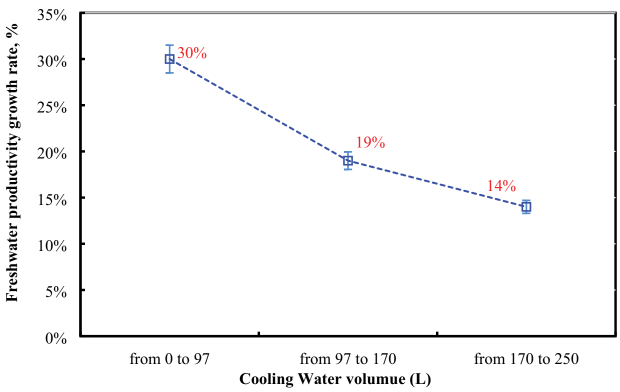

Fig. 6. Freshwater productivity growth rate of the proposed solar desalination system according to the cooling water volumes inside the condenser.

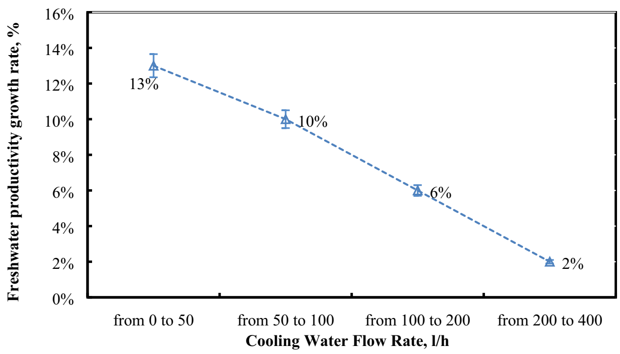

Fig. 8. Freshwater productivity growth rate of the proposed solar desalination system according to the cooling water flow rates when the volume of the cooling water was 250 L.

which increases the cost of construction and makes it impractical.

Fig. 7 shows that the increase in the flow rate of the cooling water inside the condenser also led to an increase in the freshwater productivity of the proposed solar desalination system. This happened because the heat transfer coefficient between the condensing pipe and the cooling pipe inside the condenser was enhanced due to the increased water speed.

The minimum freshwater productivity (7,000 mL) was obtained when the cooling water did not move in the condenser, while the maximum freshwater productivity (9,380 mL) was obtained when the cooling water flow rate in the condenser was 400 L/h.

Fig. 8 illustrates a downward trend in freshwater productivity growth from the proposed solar desalination system under the effect of the cooling water flow rate in the condenser. When the cooling water flow rate in the condenser was 50 L/h, the proposed solar desalination system produced 13% more freshwater than the case when the cooling water was stagnant in the condenser. For the flow rates higher than 50 L/h, the freshwater productivity of the proposed solar system is slightly increased. Therefore, increasing the cooling water flow rate in the condenser more than 50 L/h is unnecessary, because it requires more energy to operate a powerful pump to circulate the water between the solar still and the condenser at higher speeds.

Fig. 9 displays that the solar desalination system produced a minimum amount of freshwater when no fins were used in the condenser, while it produced the maximum amount of freshwater when 80 fins were used. Numerically, the daily freshwater productivity was improved by 10%, 21%, and 34.2% when 40, 60, and 80 fins were added to desalination system, respectively, as compared to the system without fins. Moreover, from this figure, a linear relationship between the fins number in the condenser and the freshwater productivity of the experimental solar desalination system can be observed. It is important that to note the number of fins should be optimized because of the increased number of fins leads to cast a shadow and decrease the distilled output and a simultaneously improve the absorbed solar radiation due to the increased surface area [42].

The presence of fins inside the condenser increased the heat transfer surface, which enables a quicker removal of heat. The increased temperature difference between the inner and the outer surfaces of the condensing pipe improves the condensation rate and increases the

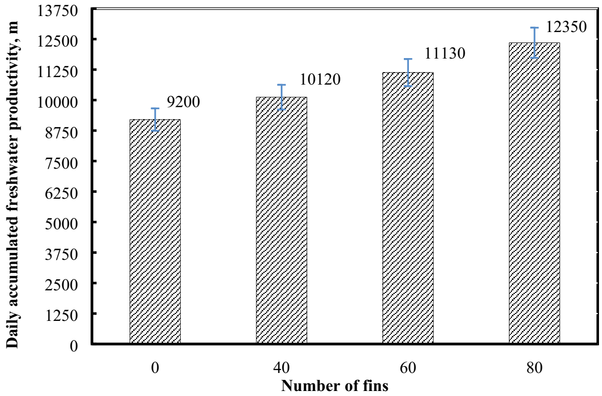

Fig. 9. Effect of the number of fins in the condenser on the system's freshwater productivity when the volume of the cooling water was 250 L and the flow rate was 400 L/h (in June 2019).

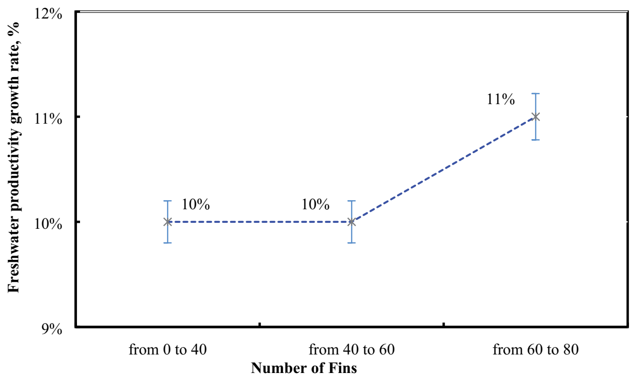

Fig. 10. Freshwater productivity growth rate of the proposed solar desalination system according to the number of fins on the outer surface of the condensing pipe when the volume of the cooling water was 250 L and the flow rate was 400 L/h.

freshwater productivity of the experimental solar desalination system as compared to a system without fins.

These results are in good agreement with other studies, which have shown that the improved performance of a solar still integrated into the basin. Rajaseenivasan and Srithar [40] studied the improvement of solar still with square circular fins incorporated in the basin. The results showed that the daily productivity of freshwater was increased by 36.7% for a solar still with square fins and 45.8% when the fins were wrapped with wick materials. Velmurugan et al. [43] stated the freshwater productivity of stepped solar still was increased up to 53.3% when fins are added.

Fig. 10 shows a stable growth in the freshwater productivity of the experimental solar desalination system. Generally, the increased in number of fins led to an increase in freshwater productivity as shown in Figs. 9 and 10. Moreover, taking into consideration other factors in this study, it is observed that the number of fins had the most significant effect on the freshwater productivity of this solar desalination system.

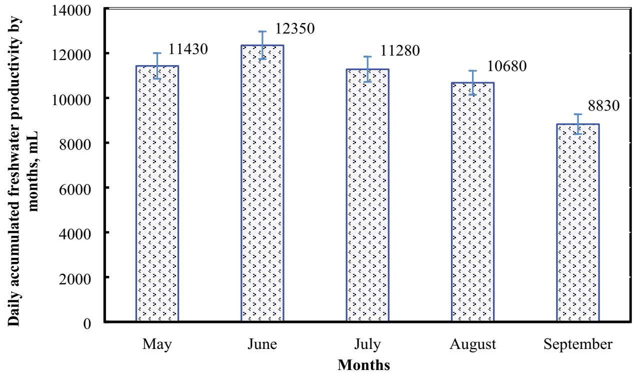

Fig. 11. Average daily freshwater productivity by months when the volume of the cooling water was 250 L and the flow rate was 400 L/h with 80 fins on the outer surface of the condensing pipe.

Fig. 11 shows the relationship between the time of the experiment and the freshwater productivity of the experimental solar desalination system. The system produced the highest amounts of freshwater in June 2019. The solar radiation levels are the highest during June as compared to other months and had sufficient sunny hours as shown in Table 1.

In comparison with the reference case for the conventional solar still, the amount of freshwater production rate in any of these months was much higher. Numerically, in June the average daily accumulated freshwater produced was 12,350 mL when the volume of the cooling water was 250 L and the flow rate was 400 L/h with 80 fins on the outer surface of the condensing pipe. While the productivity of the conventional solar still in the same month was 4,000 mL as depicted in Fig. 5. Which is about 300% more than the productivity of the conventional solar still system. This demonstrates the superiority of the solar desalination system used in this study. This increase was obtained because the external condenser was used for the solar still instead of the traditional solar still condenser consisting of the transparent cover.

4. Conclusions

The use of external water-cooled finned condensing pipe as an external condenser with the basin type solar still led to a significant increase in freshwater productivity. From the experimental results that have been undertaken, it can be drawn the following points:

- This experimental solar desalination system produced more freshwater than the conventional basin type solar still when cooling water volume, cooling water flow rate, number of fins in the condenser were increased. Moreover, the number of fins had the most significant effect on the freshwater productivity.
- The highest amounts of freshwater were produced in June, because it had higher solar radiation levels than other months, and had sufficient sunny hours.
- To increase freshwater productivity, it was found that the best cooling water rate was 50 L/h to cool the condenser

of this solar desalination system without extra costs. A 13% more freshwater was achieved compared to no cooling water moving in the condenser.

- When the cooling water flow rate in the condenser was 50 L/h, the proposed solar desalination system produced 13% more freshwater than when the cooling water does not move in the condenser. For the flow rates higher than 50 L/h the freshwater productivity of the proposed solar system is also increased but with small amounts so increasing the cooling water flow rate in the condenser more than 50 L/h is unnecessary because it requires more energy to operate a powerful pump to circulate the water between the solar still and the condenser at higher speeds.
- Using more cooling water in the condenser will increase the freshwater productivity but with small amounts. If the volume exceeds the 79 L, an increase in the size of the whole system may occur, which increases the cost of construction and makes it impractical.
- Elevation ambient temperatures are undesirable for solar still productivity. The evaporation process rate reduces if the ambient temperature rises. This is because a high ambient temperature impacts to the rise glass temperature that reduces the glass cooling. Consequently, less the rate of a condensation process due to a low difference between the surface glass temperature and evaporated water temperature.
- A linear relationship between the fins number in the condenser and the freshwater productivity of the solar still was observed. Furthermore, the number of fins should be optimized because of the increasing number of fins will lead to the fins' shadow effects.
- Because one shape and limited numbers of fins were used in this solar desalination system, there is a need for additional studies focusing on the relationship between the different shapes and numbers of fins in the condenser and the freshwater productivity.

References

[1] M. Hochberg, Jordan's Energy Future: A Path Forward, Middle East Institute, 2015. Available at: www.mei.edu/publications/jordans-energy-future-path-forward

[2] E. Denny, K. Donnelly, R. McKay, G. Ponte, T. Uetake, Sustainable Water Strategies for Jordan, International Economic Development Program, Gerald R. Ford School of Public Policy, University of Michigan, Ann Arbour, MI, 2008.

[3] A. Alahmer, X. Wang, R. Al-Rbaihat, K.C.A. Alam, B.B. Saha, Performance evaluation of a solar adsorption chiller under different climatic conditions, Appl. Energy, 175 (2016) 293–304.

[4] A. Alahmer, S. Ajib, X. Wang, Comprehensive strategies for performance improvement of adsorption air conditioning systems: a review, Renewable Sustainable Energy Rev., 99 (2019) 138–158.

[5] A. Mamkagh, E. Anderson, Condensation rate enhancement of the inclined condenser in the solar still connected with a solar water heater, Eng. Technol. J., 3 (2018) 492–497.

[6] A.E. Kabeel, Z.M. Omara, F.A. Essa, A.S. Abdullah, Solar still with condenser–a detailed review, Renewable Sustainable Energy Rev., 59 (2016) 839–857.

[7] T. Arunkumar, K. Raj, D.D.W. Rufuss, D. Denkenberger, G. Tingting, L. Xuan, R. Velraj, A review of efficient high productivity solar stills, Renewable Sustainable Energy Rev., 101 (2019) 197–220.

[8] A.E. Kabeel, S.A. El-Agouz, Review of researches and developments on solar stills, Desalination, 276 (2011) 1–12.

[9] G. Xiao, X. Wang, M. Ni, F. Wang, W. Zhu, Z. Luo, K. Cen, A review on solar stills for brine desalination, Appl. Energy, 103 (2013) 642–652.

[10] A.M. Mamkagh, S.M. Herzallah, M. Al-Dabbasb, Efficiency Improvement of the condensation pipes in the soil for a basin type solar desalination unit, Nat. Appl. Sci. Ser., 35 (2020) 13–30.

[11] K. Yahia Mahammed, R. Kerfah, M. Bezzina, Improving the water production of a solar still by adding an internal condensation chamber: a theoretical study, Environ. Prog. Sustainable Energy, 38 (2019) 13198, doi: 10.1002/ep.13198.

[12] M.H. Sellami, T. Belkis, M.L. Aliouar, S.D. Meddour, H. Bouguettaia, K. Loudiyi, Improvement of solar still performance by covering absorber with blackened layers of sponge, Groundwater Sustainable Dev., 5 (2017) 111–117.

[13] M. Faegh, M.B. Shafii, Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes, Desalination, 409 (2017) 128–135.

[14] A.E. Kabeel, Z.M. Omara, F.A. Essa, Enhancement of modified solar still integrated with external condenser using nanofluids: an experimental approach, Energy Convers. Manage., 78 (2014) 493–498.

[15] Y.A.F. El-Samadony, A.S. Abdullah, Z.M. Omara, Experimental study of stepped solar still integrated with reflectors and external condenser, Exp. Heat Transfer, 28 (2015) 392–404.

[16] D. Mevada, H. Panchal, K. Kumar Sadasivuni, M. Israr, M. Suresh, S. Dharaskar, H. Thakkar, Effect of fin configuration parameters on performance of solar still: a review, Groundwater Sustainable Dev., 10 (2020) 100289, doi: 10.1016/j.gsd.2019.100289.

[17] K. Rabhi, R. Nciri, F. Nasri, C. Ali, H. Ben Bacha, Experimental performance analysis of a modified single-basin single-slope solar still with pin fins absorber and condenser, Desalination, 416 (2017) 86–93.

[18] T.R.S. Kumar, S. Jegadheeswaran, P. Chandramohan, Performance investigation on fin type solar still with paraffin wax as energy storage media, J. Therm. Anal. Calorim., 136 (2019) 101–112.

[19] A.A. El-Sebaii, M. El-Naggar, Year round performance and cost analysis of a finned single basin solar still, Appl. Therm. Eng., 110 (2017) 787–794.

[20] B. Gupta, P. Shankar, R. Sharma, P. Baredar, Performance enhancement using nano particles in modified passive solar still, Procedia Technol., 25 (2016) 1209–1216.

[21] M. Bahiraei, S. Nazari, H. Moayedi, H. Safarzadeh, Using neural network optimized by imperialist competition method and genetic algorithm to predict water productivity of a nanofluid-based solar still equipped with thermoelectric modules, Powder Technol., 366 (2020) 571–586.

[22] A.J.N. Khalifa, H.A. Ibrahim, Experimental study on the effect of internal and external reflectors on the performance of basin type solar stills at various seasons, Desal. Water Treat., 27 (2011) 313–318.

[23] M. Bhargva, A. Yadav, Productivity augmentation of single-slope solar still using evacuated tubes, heat exchanger, internal reflectors and external condenser, Energy Sources Part A, (2019) 1–21, doi: 10.1080/15567036.2019.1691291.

[24] D. Das, U. Bordoloi, P. Kalita, R.F. Boehm, A.D. Kamble, Solar still distillate enhancement techniques and recent developments, Groundwater Sustainable Dev., 10 (2020) 100360, doi: 10.1016/j.gsd.2020.100360.

[25] M.R.K. Estahbanati, A. Ahsan, M. Feilizadeh, K. Jafarpur, S.-S. Ashrafmansouri, M. Feilizadeh, Theoretical and experimental investigation on internal reflectors in a single-slope solar still, Appl. Energy, 165 (2016) 537–547.

[26] O. Younas, F. Banat, D. Islam, Seasonal behavior and techno economical analysis of a multi-stage solar still coupled with a point-focus Fresnel lens, Desal. Water Treat., 57 (2016) 4796–4809.

[27] A.R. Abd Elbar, H. Hassan, Experimental investigation on the impact of thermal energy storage on the solar still performance

coupled with PV module via new integration, Sol. Energy, 184 (2019) 584–593.

[28] M. Al-harahsheh, M. Abu-Arabi, H. Mousa, Z. Alzghoul, Solar desalination using solar still enhanced by external solar collector and PCM, Appl. Therm. Eng., 128 (2018) 1030–1040.

[29] H. Panchal, K.K. Sadasivuni, C. Prajapati, M. Khalid, F.A. Essa, S. Shanmugan, N. Pandya, M. Suresh, M. Israr, S. Dharaskar, Productivity enhancement of solar still with thermoelectric modules from groundwater to produce potable water: a review, Groundwater Sustainable Dev., 11 (2020) 100429, doi: 10.1016/j.gsd.2020.100429

[30] H. Mousa, M. Abu Arabi, Desalination and hot water production using solar still enhanced by external solar collector, Desal. Water Treat., 51 (2013) 1296–1301.

[31] M.A. Pakdel, M. Hedayatizadeh, S.M. Tabatabaei, N. Niknia, An experimental study of a single-slope solar still with innovative side-troughs under natural circulation mode, Desalination, 422 (2017) 174–181.

[32] A.E. Kabeel, M.M.K. Dawood, K. Ramzy, T. Nabil, B. Elnaghi, Enhancement of single solar still integrated with solar dishes: an experimental approach, Energy Convers. Manage., 196 (2019) 165–174.

[33] T. Arunkumar, A.E. Kabeel, K. Raj, D. Denkenberger, R. Sathyamurthy, P. Ragupathy, R. Velraj, Productivity enhancement of solar still by using porous absorber with bubble-wrap insulation, J. Cleaner Prod., 195 (2018) 1149–1161.

[34] G.B. Balachandran, P.W. David, A.B.P. Vijayakumar, M.M. Athikesavan, R. Sathyamurthy, Enhancement of PV/T-integrated single slope solar desalination still productivity using water film cooling and hybrid composite insulation, Environ. Sci. Pollut. Res., 27 (2020) 32179–32190.

[35] A.E. Kabeel, R. Sathyamurthy, S.A. El-Agouz, E.M.S. El-Said, Experimental studies on inclined PV panel solar still with cover cooling and PCM, J. Therm. Anal. Calorim., 138 (2019) 3987–3995.

[36] A. Alahmer, M. Al-Dabbas, S. Alsaqoor, A. Al-Sarayreh, Utilizing of solar energy for extracting freshwater from atmospheric air, Appl. Sol. Energy, 54 (2018) 110–118.

[37] M. Elashmawy, I. Alatawi, Atmospheric water harvesting from low-humid regions of Hail city in Saudi Arabia, Nat. Resour. Res., 29 (2020) 3689–3700.

[38] A. Agrawal, R.S. Rana, Theoretical and experimental performance evaluation of single-slope single-basin solar still with multiple V-shaped floating wicks, Heliyon, 5 (2019) e01525, doi: 10.1016/j.heliyon.2019.e01525.

[39] A. Alahmer, X. Wang, K.C. Alam, Dynamic and economic investigation of a solar thermal-driven two-bed adsorption chiller under Perth climatic conditions, Energies. 13 (2020) 1005, doi: 10.3390/en13041005.

[40] T. Rajaseenivasan, K. Srithar, Performance investigation on solar still with circular and square fins in basin with CO_2 mitigation and economic analysis, Desalination, 380 (2016) 66–74.

[41] M. Khan, M. Mustafa, Solar still distillate productivity enhancement by using reflector and design optimization, Innovation Energy Res., 8 (2019) 1463–2576.

[42] A.A. El-Sebaii, M.R.I. Ramadan, S. Aboul-Enein, M. El-Naggar, Effect of fin configuration parameters on single basin solar still performance, Desalination, 365 (2015) 15–24.

[43] V. Velmurugan, K.J.N. Kumar, T.N. Haq, K. Srithar, Performance analysis in stepped solar still for effluent desalination, Energy, 34 (2009) 1179–1186.