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Experimental measures on solar still applying internal cooling coil for optimum productivity under Riyadh Province ambient conditions

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ABSTRACT

This experimental work focuses on the effect of using an internal cooling coil under a cover glass of basin solar still in order to increase solar productivity. The data collected during the climatic conditions of September and October months in Riyadh, Saudi Arabia is used in this work. The average ambient temperature is recorded around 37°C (±2°C) at noon. The passing water through an internal cooling coil is cooled by a radiator heat exchanger, similar to those used in vehicles. The internal cooling coil used as an additional condensation surface with a cover glass. The droplets formed on the internal cooling coil by condensation are collected by a collector pipe in order to run down into a distillation channel. The solar parabolic trough and external film cooling technique is selected in this experimental setup to see its impacts on the internal cooling coil efficiency. Our topic of research on the internal cooling may be regarded as a new experimental technique to improve the productivity of the passive solar still by 25%. The modified solar still using the above techniques combined together increases the efficiency by 20.8% over the conventional solar still.

Keywords: Internal cooling; Parabolic trough; Solar desalination; Film cooling; Solar still.

1. Introduction

Normal life on earth depends on air, water, and food. More than two-thirds of the earth is water; however, 97% of the earth's water is salty and less than 1% is fresh [1]. Although water is widespread on earth, the amount that is suitable for human consumption is limited. Currently, there is a severe shortage of water worldwide, which threatens to increase in drought and desertification. The desalination of saltwater using basin solar still has attracted the attention of researchers due to its low cost, simplicity, and scalability as compared to conventional desalination systems. The production capacity of simple basin solar still ranges from 2 to 5 L/m^2/d [2].

Elango and Murugavel [3] demonstrated that single and double basin types achieve maximum production at a depth of 1 cm. Abdel-Rehim and Lasheen [4] developed another system containing one single slope still coupled with a parabolic trough using oil as a medium liquid passing through the parabolic trough loop. The freshwater produced in this system is 18% more than a passive still. Rai and Tiwari [5] found the gain productivity of single basin solar still coupled with a flat plate collector is 24% higher compared to single basin solar still. Badran et al. [6] demonstrated that a single basin still can produce about 2 L/m^2/d with an efficiency of 27.03%. Furthermore, they observed that a basin still coupled with a flat plate collector produces 231% more than the single still, with an efficiency of 25.8%.

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Omara et al. [7] studied stepped solar still with internal and external reflectors showing a 125% increment in productivity compared to a conventional still. Tanaka and Nakatake [8] demonstrated that internal and external reflectors on a conventional solar still (CSS) increase freshwater productivity by 48%.

Omara et al. [9] demonstrated that the water productivity increases by 145.5% of corrugated solar still (CrSS) containing wick and internal reflecting mirrors in contrast to a CSS at a brine depth of 1 cm. The daily efficiency increases in CrSS by 59% and decreases in CSS by 33%. Numerical modeling performed by Abu-hijleh and Mousa showed that cooling of cover glass water film increases the efficiency of a CSS by approximately 20% [10]. El-Samadony and Kabeel [11] applied a theoretical study of a single basin stepped solar still cooling, using cover glass water film, demonstrated that this technique increases freshwater productivity. Specifically, the yield increases by 8.2% at a film thickness of 2.5×10^{-4} to 5.5×10^{-4} m, with cooling water flow rate ranging from 4×10^{-5} to 8.5×10^{-5} m^3/s, and having cover glass length from 2 to 2.8 m. They proposed in their work that it is not efficient to reduce the temperature of water film cooling below ambient temperature to increase productivity. Abdullah et al. [12] found that cooling the glass of stepped solar still increases productivity by 65% as compared to a conventional still. Abu-Hijleh [13] found that poor combinations of film cooling parameters significantly reduce still efficiency.

Janarthanan et al. [14] obtained increased distillate output by cooling the cover of tilted-wick type solar still, especially during peak sunny hours, with optimum water flow at a rate of 1.5 m/s. Arunkumar et al. [15] presented a study of hemispherical solar still with and without a top cover. This study reveals that the efficiency of the solar still increased from 34% to 42% with a fixed flow rate of 10 L water feed/min over the top cover.

Somwanshi and Tiwari [16] calculated the performance of a CSS by cooling the cover glass with water at an ambient temperature of India Ca 41°C. A similar experiment was conducted in four Indian cities, showing that the annual yield ranges increase from 41.3% to 56.5% when the water is cooled by a desert cooler. In this experiment, the flowing water from the cooler is less than the flowing water at their ambient temperature by average 5°C for a typical day in summer. When ambient temperature water is used, the yields range between 21.8% and 30.1%. Somwanshi and Tiwari also found that the cover glass heating and the water temperature of the basin are significantly reduced when water flowed over the cover glass.

Morad et al. [17] performed two experiments one on passive double slope solar stills and the second on active solar stills with a flat-plate solar collector. This carried out at different brine depth by using different thickness of cover glass and flash tactics for cooling cover glass at different operating times. Their study exhibits the highest productivity of the passive solar still 6.38 L/m^2 d and by applying cover glass cooling 7.80 L/m^2 d. They also find among their experiments, the highest productivity of 8.52 L/m^2 d of the active solar still with a flat-plate solar collector and of 10.06 L/m^2 d by applying cover glass cooling. They found the best productivity yields with the cover glass having a thickness of 3 mm, brine level of 1 cm, and at the operation of flash tactics for cooling the cover glass (5 min on and 5 min off).

Al-Garni [18,19] conducted his experiments in winter and summer times for double and single slope solar stills. This showed that in winter the productivity decreases by 4% and 8% when using an external cooling fan with wind speeds of 7 and 9 m/s, respectively. In contrast, productivity exceeds the conventional still measurements by 5.2% and 10.3% with wind speeds of 7 and 9 m/s. Suneesh et al. [20] studied the effect on a "V" type solar still using a cotton gauze top cover cooling (CGTCC) with and without airflow over the cover glass. They found the production of a passive still is 3.3 $L/m^2/d$. They also found that CGTCC produces 4.3 $L/m^2/d$ and CGTCC combined with airflow produces 4.6 $L/m^2/d$. Agboola and Al-Mutaz [21] studied the effect of cooling the cover glass in inclined solar water distillation systems in which part of the glass shades around 30% with silver shade mesh. In addition, their results show that the use of silver shade mesh and water film cooling compared to passive solar still increases the yield of the solar still by 10.77% and 58.98%, respectively.

Since the literature focuses on the external cooling and no previous studies investigated internal cooling underneath glass cover of the solar still, the objective of the current study is to investigate the effect on the productivity of the desalinated water by using an internal cooling coil underneath the cover glass of a solar still. Water at ambient temperature is pumped through the internal cooling coil and the heat exchanger (radiator) is used to cool the water loop. This objective can be achieved by determining:

- The efficiency and productivity of a CSS with a parabolic trough.
- The efficiency and productivity of a CSS using external film water cooling with a parabolic trough.
- The efficiency and productivity of a CSS using an internal cooling coil coupled with categories 1 and 2 above.

2. Materials and methods

2.1. Experimental setup

The experimental setup consists of basin solar still, a cover glass, an anti-rust coil made of radiator, a pump, a flow meter, a parabolic trough, a pyranometer, type K thermocouples, and a data acquisition system. The saline water applied in the present experiment is tap water with TDS 707 mg/L. The area of the basin solar still is 1 m^2. The still has a 2 mm thick iron plate and is coated with black paint to absorb solar radiation, as shown in Fig. 1.

Wooden insulation of 18 mm thickness is used to prevent heat loss from the basin. It is covered with an inclined glass surface of 6 mm thickness utilized as a condensation surface. The slope of cover glass follows the latitude angle of 24° of Riyadh City [22] to receive the highest amount of solar radiation. The radiator is employed as a cooling instrument in this experiment. An internal copper coil 3/8″ in diameter is installed underneath the cover glass of the basin solar still and connected to a heat exchanger (radiator), as shown in Fig. 2. The internal coil is being used as an additional condensation surface as well as the cover glass. A collector pipe

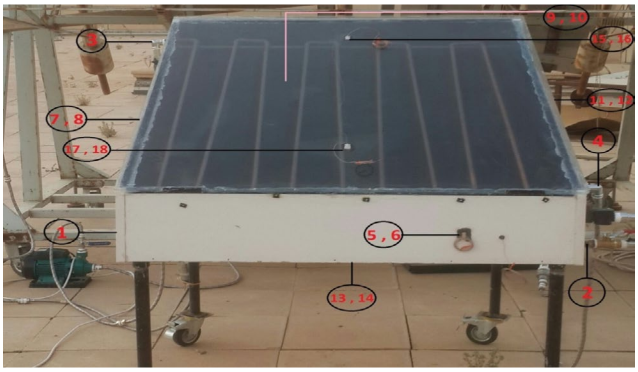

Fig. 1. Single solar still and thermocouples location numbers.

Fig. 2. Heat exchanger (radiator).

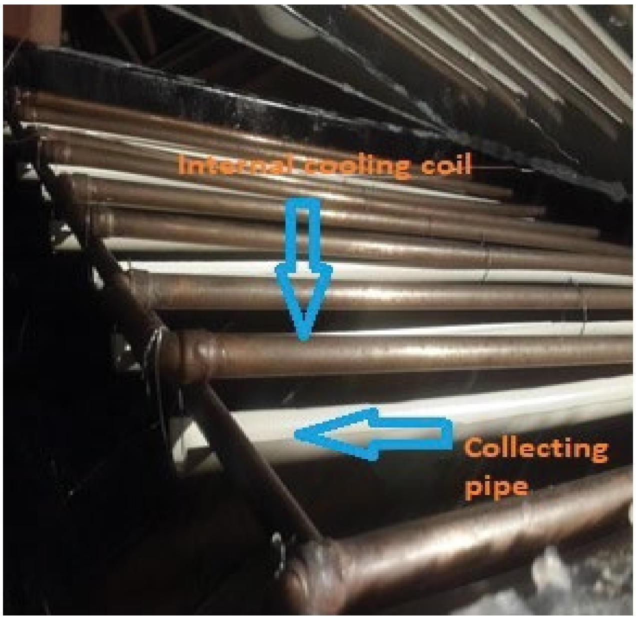

Fig. 3. Collector pipe under the internal coil.

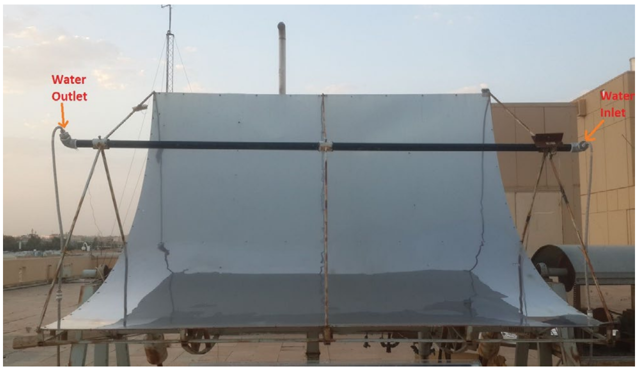

Fig. 4. Solar parabolic trough with iron pipe fixed on-axis line.

is used to collect water vapor condensation on the internal cooling coil with a diameter 3/4″, as shown in Fig. 3. The water vapor condensation runs down into a distillation channel from where it is fed to a storage tank.

A solar parabolic trough is fabricated from a 2.0 m long stainless-steel plate. Here the parabolic-trough collector is a linear-focus solar collector reflecting direct solar radiation onto an absorber tube located in the focal line of the parabola [23]. An iron pipe 2″ in diameter is fixed on the axis line and coated with black paint to promote absorption of solar radiation that heats the parabolic trough loop water, as shown in Fig. 4.

A heat exchanger copper coil 3/8″ in diameter is installed at the bottom of the solar still which is using the heated water by the parabolic trough to warm up basin water. A connected pipe, a tank for internal cooling and a parabolic trough loop, insulated along with glass wool to prevent any heat loss through water flow. This setup is designed to ensure the water flows through the internal cooling coil, the external cooling system and parabolic trough loops are under the forced flow by a small pump. Furthermore, an external cooling tank is connected to a heat exchanger; as it is in the internal cooling loop. The external cooling tank is connected to a nozzle over the top surface of the glass, as shown in Fig. 5.

A glass film cooling reduces the glass temperature while improving productivity. Thermocouples of 18 types K (Table 1) are uniformly placed over and under the glass surface, basin walls, at the inlet and outlet of the internal cooling coil and a heat exchanger coil, as shown in Fig. 1. The data acquisition system and the computer automatically record temperature variations. The schematic diagram of the internal cooling coil, external cooling and parabolic trough loops are shown in Fig. 6, illustrating how the circulation of each loop is working. In this diagram, the external cooling loop starts working from the tank where the water passes through the pump and the radiator to the nozzle over film cooling streams on the cover glass to back to the tank.

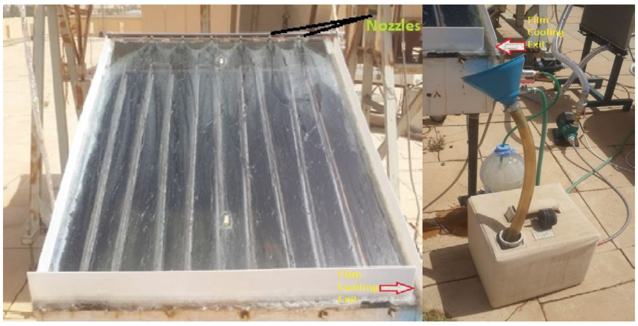

Fig. 5. Solar still system showing the external film water-cooling cycle.

Table 1
Thermocouple locations in the system (see Fig. 1 for details)

No.	Measurement location	No.	Measurement location
1	Heat exchanger inlet	10	Outer wall (north)
2	Heat exchanger outlet	11	Inner wall (east)
3	Internal cooling inlet	12	Outer wall (east)
4	Internal cooling outlet	13	Basin water (ground)
5	Inner wall (south)	14	Outer wall (ground)
6	Outer wall (south)	15	Inner glass
7	Inner wall (west)	16	Outer glass
8	Outer wall (west)	17	Inner glass
9	Inner wall (north)	18	Outer glass

2.2. Experimental procedures

The experiment is conducted between 9 a.m. and 5 p.m. with the following fixed conditions:

- Brine depth of 3 cm.
- A water flow rate of 5 L/min for the internal cooling loop.
- Water flow rate of 1.5 L/min for the external cooling loop.
- Water flow rate of 4 L/min for the parabolic trough loop.

3. Experimental uncertainty

The experimental setup takes into account several uncertainties made by the measuring instruments. The sources of these errors are the pyranometer, the graduated beaker, thermocouples, and flow meter. These are used to measure the solar intensity, distillate collection, temperature, and water flow through the internal cooling, external cooling, and parabolic trough loops. The method recommended by Moffat [24] is used to determine the uncertainty propagation of the above-mentioned errors. The accuracy and measurement errors of various measuring instruments are provided by the manuals of each respective instrument, as listed in Table 2.

4. Results and discussion

The solar still is tested in eight cases in which the internal cooling coil is installed. These cases are listed in Table 3. Average solar radiation and ambient temperature are shown in Fig. 7. The maximum recorded ambient temperature

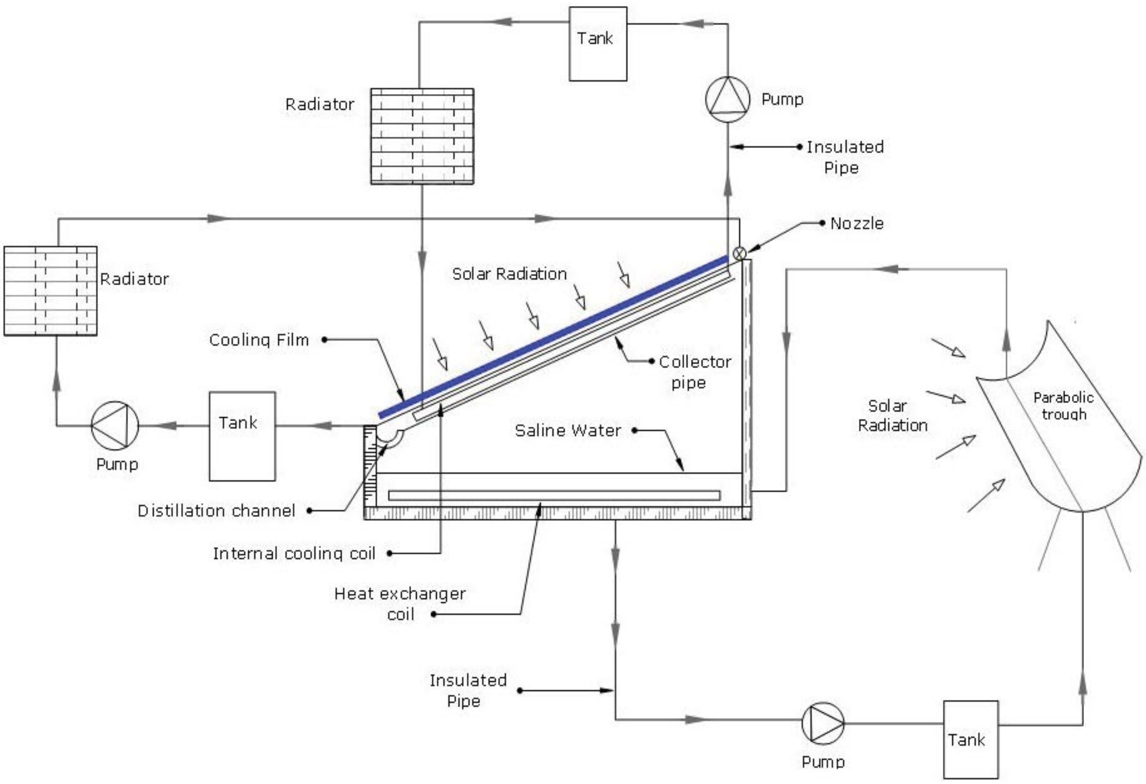

Fig. 6. Schematic diagram of the solar still system showing the internal cooling coil, external cooling, and parabolic trough loops.

Table 2
Accuracy and measurement error of various instruments

Instrument	Accuracy	Range	% Error
Pyranometer	±1 W/m^2	0–1,600 W/m^2	1.8
Graduated beaker	±5 mL	0–1,000 mL	1
Thermocouples	±1.1°C	0–1,200°C	0.4
Flow meter	±0.7 L	1.5–18 L/min	4

Table 3
Cases used in the experiments

Case	System components
1	Solar still
2	Solar still with internal cooling
3	Solar still with external cooling
4	Solar still with internal and external cooling
5	Solar still with parabolic trough
6	Solar still with parabolic trough and internal cooling
7	Solar still with parabolic trough and external cooling
8	Solar still with parabolic trough, internal and external cooling

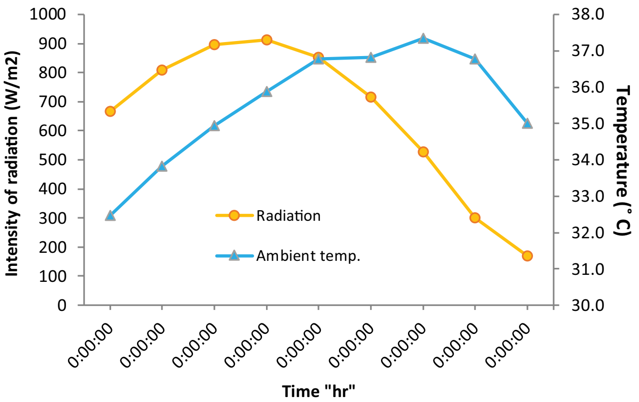

Fig. 7. Average variation of radiation intensity and ambient temperature.

is 37.4°C at 3 pm. Moreover, the maximum average radiation intensity is 913 W/m^2 at 12 pm. Fig. 8 illustrates the temperature differences for the cover glass used in the eight cases carried out. However, in the same figure, we can see four cases with lower cover glass temperatures; this might be ascribed to employing internal and external cooling. The hourly variations of basin water temperatures are shown in Fig. 9 to compare the eight cases mentioned above. The maximum recorded water temperature for the basin water still is 74.9°C as a result of using an internal heating coil in case 5. In contrast, the minimum recorded temperature for the basin water in case 4 is due to the use of internal and external cooling techniques. Somwanshi and Tiwari [16] found that when the temperature of the cover glass decreases, the basin water temperature also decreases accordingly. This decrease of basin water temperature can

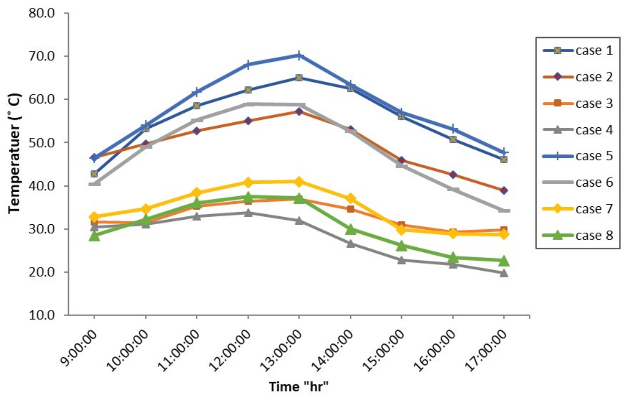

Fig. 8. Hourly variation of average glass temperatures of a solar still.

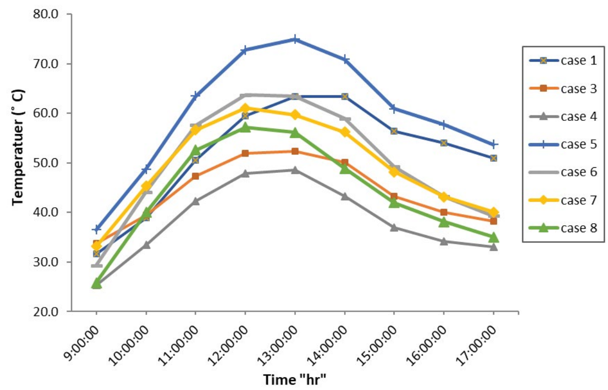

Fig. 9. Hourly variation of water temperatures in basin.

be attributed to passing water over the cover glass making a shade reducing the solar radiation passing through the cover glass to the basin water. However, the temperature difference increases between the cover glass and the basin water when the cover glass is cooled; this leads to higher water vapor condensation. Fig. 10 manifests the phenomena pointed out by Somwanshi and Tiwari [16] which states that when the differential temperature between the cover glass and the basin water increases, the yield distillation increases. It is necessary to point out here that in case of internal cooling this would not subject to Somwanshi and Tiwari statement since here are two surfaces for condensation. This can be seen in case 8 showing the highest yield in which the internal cooling is used without having the highest temperature difference between the cover glass and basin water.

Figs. 11–14 show the temperature differences for the inlet and outlet of water pumping through the internal cooling giving a comparison between the cover glass and the internal cooling temperatures. It has been observed that temperatures of the water inlet to the coil are lower than the temperatures of the water outlet from the coil. This may indicate the performance of an internal cooling system. Figs. 11 and 13, display that the temperature of the cover glass is higher than the temperature of internal cooling. This leads to an increase in the condensation on the surface of the internal cooling coil. This is a very well-known phenomenon

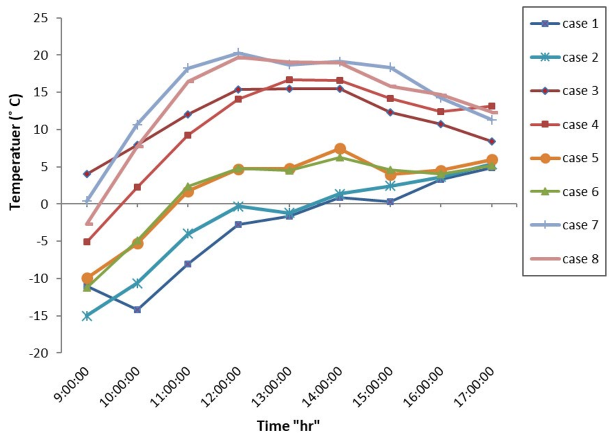

Fig. 10. Hourly variation of water – glass difference temperature of solar still.

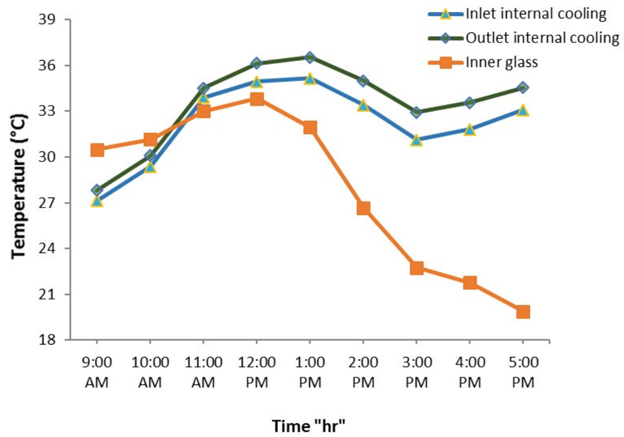

Fig. 12. Hourly variation of inlet and outlet temperatures of an internal cooling coil for conventional solar still using external film water cooling and an internal cooling coil (case 4).

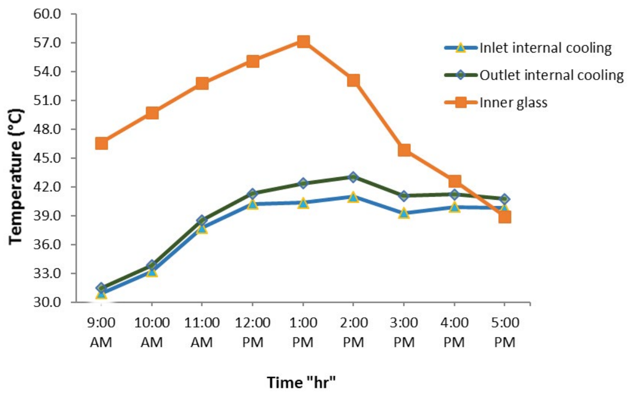

Fig. 11. Hourly variation of inlet and outlet temperatures of an internal cooling coil for a conventional solar still using an internal cooling coil (case 2).

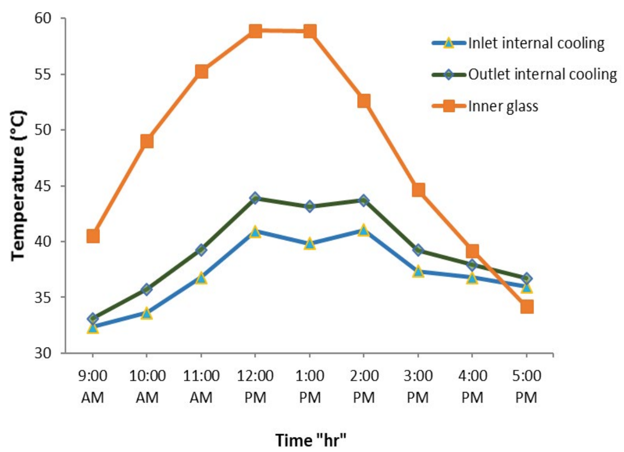

Fig. 13. Hourly variation of inlet and outlet temperatures of an internal cooling coil for a conventional solar still using parabolic trough heating and an internal cooling coil (case 6).

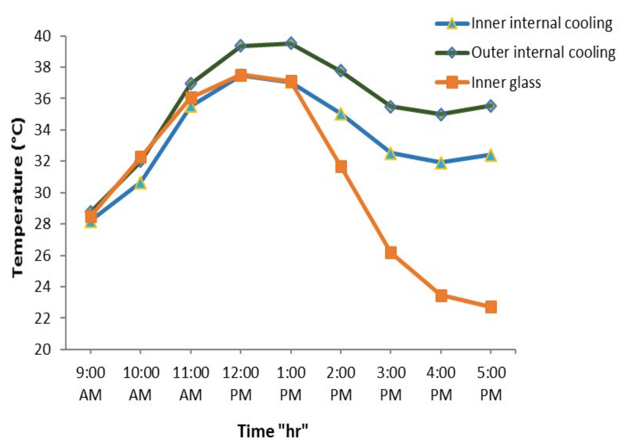

Fig. 14. Hourly variation of inlet and outlet internal cooling coil temperatures for a conventional solar still using parabolic trough heating along with internal and external cooling (case 8).

of increment between the inlet and the outlet of the internal cooling temperatures. The experimental results of Figs. 12 and 14 show the decrease of temperature for the cover glass under the internal cooling while using external cooling for the cover glass. It is also seen in Fig. 12 that case 4 records the lowest difference in the temperature of the inlet and outlet internal cooling among the four cases. This measure indicates that a decrease in efficiency in case 4. Besides, it has been noted that the water vapor condensation on the cover glass and the internal cooling is low. Surprisingly, the droplets keep hanging without dropping on the internal cooling device or slipping on the cover glass. This problem may be ascribed to the low condensation as in case 4. However, there is an increment for water vapor condensation in case 8, due to the use of the heating coil. Heating leads to a high condensation rate due to the increased temperature of basin water. Additionally, the highest difference in temperature of inlet and outlet of internal cooling is logged for case 8 as indicated by Fig. 14.

Figs. 15 and 16, display the hourly and accumulated results of fresh distilled water belonging to solar still cases in Table 3. Peak yield is obtained between 1 and 2 pm as

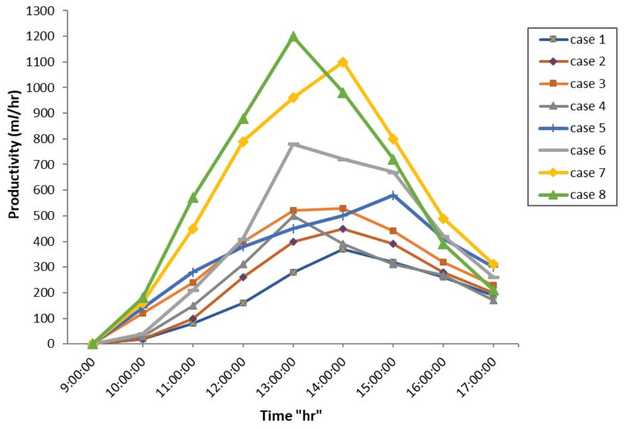

Fig. 15. Hourly variation in productivity of a solar still.

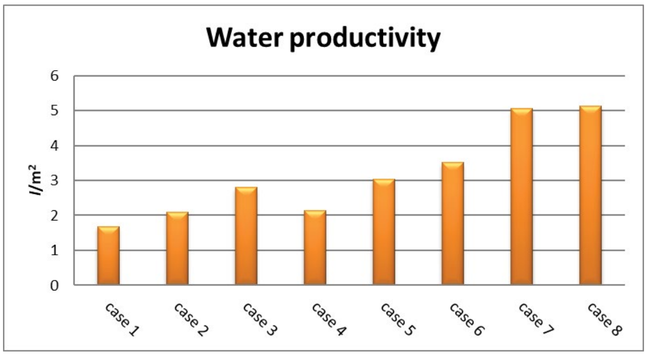

Fig. 16. Daily accumulated productivity of solar still.

Table 4
Results of different cases used in the experiments

Case	Productivity (mL)	Efficiency (%)	Maximum uncertainty of efficiency (%)	Efficiency enhancement (%)
1	1,680	27.2	0.77	0
2	2,100	31.5	0.81	4.3
3	2,800	38.6	0.93	11.4
4	2,130	34.9	0.94	7.7
5	3,040	39.6	0.98	12.4
6	3,510	41.5	1.05	14.3
7	5,060	46.2	1.29	19
8	5,130	48	1.41	20.8

illustrated in Fig. 15. This may be ascribed to the highest difference of temperature between the cover glass and the basin water in hours 1 and 2 pm as shown in Fig. 10. The highest productivity of distillates is shown in case 8 in which parabolic trough are used along with internal and external cooling systems as in Fig. 16. Meanwhile, the CSS (case 1) obtains the lowest yield between the other tested cases.

Lawrence and Tiwari [25] observe that the efficiency of the passive solar still at 3 cm brine depth becomes 29%, particularly when compares to the efficiency of our passive solar still (case 1). The variance of 1.8% is found between the efficiency of the two stills. As a comparison with standard published results, our result as in (case 1 in Table 3) may be viewed being a new standard result. Solar still productivity, efficiency, maximum percent uncertainty in efficiency, and efficiency enhancement are shown in Table 4.

5. Conclusion

The conclusion of the experimental results is the following:

- Applying an internal cooling coil increases the efficiency by 4.3% relative to a passive solar still (case 1).
- Applying an internal cooling coil increases productivity by 25% relative to a passive solar still (case 1).
- Applying an internal cooling coil while using a parabolic trough and applying a parabolic trough with external film water cooling increases the efficiency by 1.9% and 1.8%, respectively, relative to a case that did not use an internal cooling coil.
- Combined internal and external cooling reduces the efficiency by 3.7% relative to external cooling, due to minimal saline water evaporation.
- The highest water productivity and efficiency yields in case 8 using parabolic trough heating along with internal and external cooling.

Based on the aforementioned aspects, it is suggested that the next steps in this research be focused on expanding work on the internal cooling coil to improve productivity and efficiency. This may be achieved by doing similar experiments with different variables impacting the yield such as change of the depth of basin water, water flow rate of internal cooling, external cooling and parabolic trough loops. Also, change the medium of fluid of the internal cooling loop.

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