# Evaluation of productivity enhancement of a solar still coupled with flat solar collector and parabolic trough under medina climate

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### ABSTRACT

Convectional solar stills coupled with either flat plate collector (FPC) or parabolic trough concentrator (PTC) have been investigated in different condition sets. In this experimental study, double slope solar still (DSSS) is coupled with FPC or PTC and the test was extended further to the coupling of both collectors to find out the performance of these different setups under the meteorological condition of the city of Medina west of Arabia. The three devices are connected in series where circulated water is heated first by FPC and then by PTC before entering a heat exchanger in a basin of DSSS. It has been found that solar still productivity can be improved substantially by such coupling. The experimental result shows that the accumulated yield from the standalone still, coupled with PTC, still coupled with FPC, and still coupled with both were 2.85, 4.27, 6.41, and 7.63 L/m²/d, respectively. The increase of productivity using these different enhancers were 61%, 142%, and 170%, respectively. Also, the experimental investigation found that the water temperatures increased by about 9% for solar still integrated with PTC to about 27% for solar still integrated with the two collectors relative to standalone solar still under similar climate conditions.

*Keywords:* Double slope solar still; Improved solar still yield; Solar desalination; Flat solar collector; Parabolic trough; Active solar still; Solar energy

## 1. Introduction

Challenges for worldwide water supply systems due to population growth, demographic changes, and urbanization, climate change, and increasing water scarcity are increasing. It is expected that more water-stressed areas will be seen in the near future with a higher percentage of the world's population [1].

Diarrheal diseases as cholera, typhoid fever, and dysentery among other water-borne tropical diseases are caused by unclean water. Water scarcity can also lead to diseases such as trachoma, plague, and typhus [1]. According to the United Nations Children's Fund (UNICEF) and the World Health Organization (WHO) estimation 1.1 billion people lack access to a water supply and 2.6 billion people live in places of inadequate sanitation. In developing countries, most illnesses are linked to poor water and sanitation

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conditions. Nearly one out of every five deaths under the age of 5 worldwide are due to a water-related disease. Clean water is essential to a healthy life. Nearly 785 million people lack a basic drinking-water service; while at least 2 billion people use a contaminated drinking water source [1].

In the Kingdom of Saudi Arabia (KSA), as the desalination process is depending mainly on petroleum fuel, increasing consumption of fossil fuels together with the high rate of depleting fossil resources is a major concern. This is not only increasing the carbon footprint and pollution levels but also putting pressure on the natural resources of the country. Future demand for electricity and water in Medina is set to rise with the growing population, pilgrimages and Umrah visitors, and increasing urbanization.

Solar distillation is one of the solar energy applications by which the available saline or brackish water is converted into potable water economically. Due to technical simplicity, low cost, shortage of potable water in many arid areas; solar distillation applications are recommended for Saudi Arabia and can be easily adopted by local rural people.

The solar distillation process can be utilized by two methods. These methods can be classified into passive distillation and active distillation. Passive distillation is a conventional use of direct solar radiation to evaporate the water and getting fresh water. Active solar distillation devices such as parabolic trough concentrator (PTC), flat plate collector (FPC), or heat pipes have been used and coupled with solar still by many researchers to enhance productivity.

Badran and Al-Tahaineh [2] studied the single slope solar still (SSSS) productivity compared to SSSS coupled with FPC and concluded that SSS coupled with FPC has a 36% increase in distillate from 2,240 to 3,510 mL/(m$^2$ d) at conditions of Amman, Jordan. Fathy et al. [3] evaluated the performance of three configurations of solar stills. Conventional solar still, solar still coupled with fixed PTC, and solar still coupled with tracking PTC. The range of year-round thermal efficiency of conventional double slope solar still (DSSS), and DSSS coupled with tracking PTC are 22.9%–36.8% and 16.6%–29.81%, respectively. The productivity of coupled tracking system is 28.1% higher than the conventional system. The effect of connecting one, two, three FPC in series with SSSS under summer conditions at the city of Kakinada, India was conducted by Ramachandra Raju et al. [4] and it is reported that the average daily yield is 41% and 89% more for still with 2 and 3 FPC, respectively, compared to the still coupled with 1 PTC which has a yield of 2.67 kg/d for still area of 1.0 m$^2$ and FPC area of 2.0 m$^2$. Omara et al. [5] surveyed to evaluate the influence of reflecting materials on the solar still design parameters and performance. They concluded that installing reflectors is more efficient in sites with weak solar radiation where the ambient temperature is relatively low. Also, they attributed that the productivity of the system can be improved by controlling the inclination angles for the still as well as the reflector mirror. Varun and Manokar [6] found that the yield decreases significantly with increasing basin water depth, and the effect of the heat transfer modes on the system performance was found to be significant. Saadi et al. [7] experimentally studied the performance of new stepped solar still where an internal multi-tray added to the rear-wall of the basin of SSSS in comparison

to the conventional SSSS. It is reported that the productivity increased by 48%–104% depending on the season and the thermal efficiency range for the stepped and conventional are 47%–55% and 24.8%–44%, respectively. In an earlier study by Tiwari et al. [8], the thermal efficiency of SSSS, and SSSS coupled with FPC was reported to be around 19% and 28%, respectively among other design alternatives. Kalogirou [9] presented a detailed thermal model of a parabolic trough collector. They used all the modes of heat transfer to analyze the thermal behavior of the collector. The engineering equation solver (EES) is utilized to solve the equations and the model validation is checked using the existing collectors which were tested previously.

An experimental study of a double slope still coupled with a flat plate solar collector by Badran et al. [10] was conducted in Amman, Jordan. The thermal efficiencies of the still alone and still coupled with FPC were 28.56% and 22.26%, respectively, and a significant increase in yield was seen in the coupled system. Mohamad et al. [11] identified the main factors that affect the system performances such as the heat losses from the collector. The reported results showed that using a double glazing cover improved the thermal efficiency of the collector. Al-Hayek and Badran [12], Badran and Fayed [13], Badran and Abu Khader [14] found that other parameters such as water depth, salinity, black dye, solar insulation, wind speed, and direction and enhancers affect the output of the solar stills. They concluded that the yield increases as water depth in the solar basin decreases. Kabeel et al. [15] found out that the parameters of water depth, solar intensity, ambient temperature, wind velocity, and area of the system are influential on the yield of the still. And the accumulated conventional and integrated solar still yield is higher when the water depth is maintained at 0.02 m. Also, they found that the inclined solar still system produced 18.87% higher productivity than the conventional solar still.

Numerous experimental researches have been performed for different conditions and design parameters, insight on the findings of such studies are presented in review articles by Muftah et al. [16], Selvaraj et al. [17], Prakash et al. [18], Tiwari et al. [19], and Vishwanath Kumar et al. [20]. Different factors such as ambient temperature, incident of solar radiation, wind velocity, basin design and dimensions, salt concentration, and design conditions inclination of the cover, solar still materials, storing materials, reflectors, and insulation have been investigated by researchers. The following factors have been reported to increase the yield: increased solar intensity increased wind speed, actively heated basin, cooling of cover, and reduced water height in the basin besides using wicks, dye, and internal or external reflectors in addition to increasing gap distance and the temperature difference between water and condensing cover and other less effective parameters. The productivity of solar still has been improved by using a tracking system. Sodha et al. [21] and Tiwari and Madhuri [22] discussed the factors that affect the yield of conventional solar still such as the effect of hot water daily feeding. It is clear from these results that the daily distillate increases with the depth of water in the basin as a result of the nocturnal effect, which is just reverse of the performance of conventional solar still in the day.

## 2. Study problem statement

From the above literature, it is seen that the inheritent low productivity of solar still leads to the investigation of ways to improve its productivity using various chemical, electrical, or thermal processes by researchers. In the present research, an active solar device such as a parabolic trough solar concentrator and a flat plate solar collector, designed, and manufactured locally has been coupled with conventional passive solar still (double slope) to enhance the distilled water yield.

The research concentrated on an East–West axis sun tracking system for the parabolic trough, and a solar collector fixed toward the south. They have been designed and constructed for use under the climate conditions of Medina in Arabia (24.47°N, 39.61°E). In this study, the solar still performance analysis has been conducted for different configuration cases.

No previous studies have been conducted on the solar still applications under Medina climatic conditions and this was our motivation to conduct this investigation to the effect of coupling FPC or PTC and to extend the experimental investigation to coupling both collectors in series with solar still and evaluate its performance and cross-compared with previous studies.

## 3. Experimental setup

Double slope solar distillation still was fabricated for the present experimental work. The basin area is 0.5 m in width and 1.0 m in length made of steel coated with black paint. The bottom and all sides of the basin are thermally insulated with 5 cm polyethylene boards to avoid heat losses to the surrounding. The still roof consists of 6 mm clear glass fixed on a thin metal trough. The frame was covered with silver color tape and there is a thick layer of silicon applied for attaching glass to the frame. Fig. 1 shows the dimensions of the tent glass still roof. The glass cover is tilted at an angle of 50° and the condensate is collected in trough channels. Yield is directed to a bottle and measured at the end of 1 h. The still was placed in the horizontal position and maintained in the orientation of an East–West orientation to receive maximum solar radiation.

To enhance the evaporation process, a stainless steel tube of 2.5 cm diameter and a total length of 2.9 m is used as an immersed heat exchanger (IHE) in the water basin of the still as shown in Fig. 1. The water depth in the still's basin is kept at 5.5 cm to ensure that the IHE is immersed all the time. The IHE is connected to a flat solar collector and/or parabolic trough collector, and a special pump is used to circulate the hot water, as a forced convection system, between the heat exchanger, solar collector, and/ or parabolic trough collector.

The water hoses connected between collectors and still for circulating hot water are thermally insulated to reduce heat loss.

Geographically, the systems test site is located in the research center yard at Taibah University in Medina, west of Arabia. Solar radiation is measured by KIPP&ZONEN pyranometer Model CM11. The accuracy of the pyranometer was estimated as ±1 W/m² based on a previously published study by Benghanem et al. [23]. Data logging of 10 temperature measurement channels as shown in Table 1 was performed by two Pico Technology USB TC-08 temperature data acquisition board and associated Omega Engineering logging software, with a range of 0°C–150°C and accuracy of ±1°C, connected via USB interfaces to a computer. The thermocouples of Omega Engineering WTJ-6-60-TT and WTJ-HD-72-s J-type and K-type, were calibrated before use. They can measure temperatures ranges between 0°C and 150°C with an accuracy of ±1°C. A measuring flask, with a range of 0–1,000 mL and accuracy of ±10 mL, was used to measure



Fig. 1. Layout of DSSS.

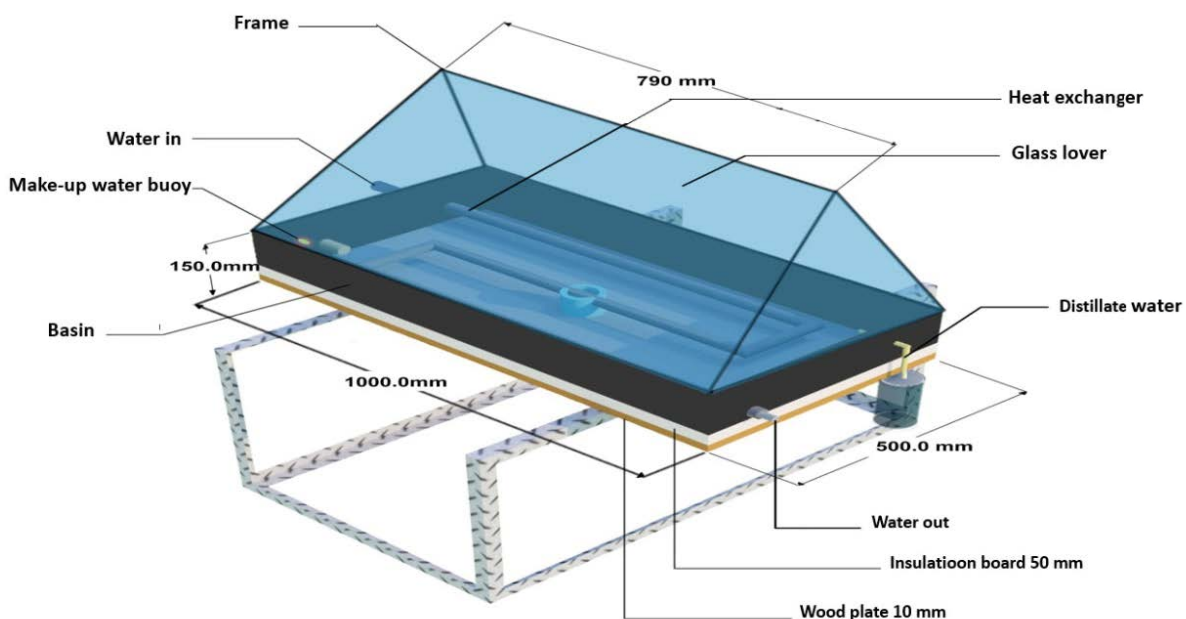Table 1
Temperatures measurements for different tests' cases

| Case 1 | Case 2 | Case 3 | Case 4 |
|---|---|---|---|
| Still alone | Still and PTC | Still and FPC | Still, PTC, and FPC |
| 6 thermocouples | 10 thermocouples | 10 thermocouples | 12 thermocouples |
| $T$ basin | $T$ basin | $T$ basin | $T$ basin |
| $T$ water | $T$ water | $T$ water | $T$ water |
| $T$ glass in and out | $T$ glass in and out | $T$ glass in and out | $T$ glass in and out |
| $T$ vapor | $T$ vapor | $T$ vapor | $T$ vapor |
| $T$ ambient | $T$ ambient | $T$ ambient | $T$ ambient |
| | $T$ still heat exchanger in and out | $T$ still heat exchanger in and out | $T$ still heat exchanger in and out |
| | $T$ parabolic trough in and out | $T$ flat collector in and out | $T$ flat collector in and out |
| | | | $T$ parabolic trough in and out |

the amount of collected water yield. The depth of water inside the still (5.5 cm) is measured with an accuracy of ±0.1 cm. Table 2 lists the uncertainties in measurements.

The PTC has a reflecting metal surface fixed on a support structure fabricated with dimensions shown in Fig. 2. The PTC and the absorber are fixed on two bearings mounted on two pylons on the north–south line, the absorber tube with black coating and 4 cm diameter is fixed at the focal line of the PTC and the tracking of one axis from east to west is implemented hourly. PTC face area is 1.33 m$^2$ and the total reflection area is 1.48 m$^2$.

The flat solar collector was installed with the optimal tilt angle of 27° facing south. Its base has a dimension of (208 cm × 82 cm) and an area of 1.7 m$^2$ was painted black and has transparent glass covering six riser pipes welded to a copper sheet and two header pipes. The collector is insulated with 4 cm polyurethane, and the collector capacity is 4 L. Hot water is circulated by the pump in the lower inlet opening of the collector. Solar collector

has a black surface plate welded on riser pipes to transmit heat to the water circulating in the riser pipes through the absorbance of solar radiation falling on it. Fig. 3 is a photograph of the whole experimental setup.

## 4. Results and discussion

A total of nine experimental tests have been done to investigate the productivity performance of the DSSS under various types of enhancers (solar collector, parabolic trough, and parabolic trough with solar collector) as illustrated in Table 3. The experimental tests were divided into four cases as shown in Table 3, for comparison purposes, as follows: case I [standalone solar still (ST)], case II [solar still coupled with the parabolic trough, (ST+PTC)], case III [solar still coupled with solar collector, (ST+SC)], case IV [solar still coupled with solar collector and parabolic trough, (ST + SC + PTC)]. Average and maximum values of solar radiation, ambient temperature, and wind
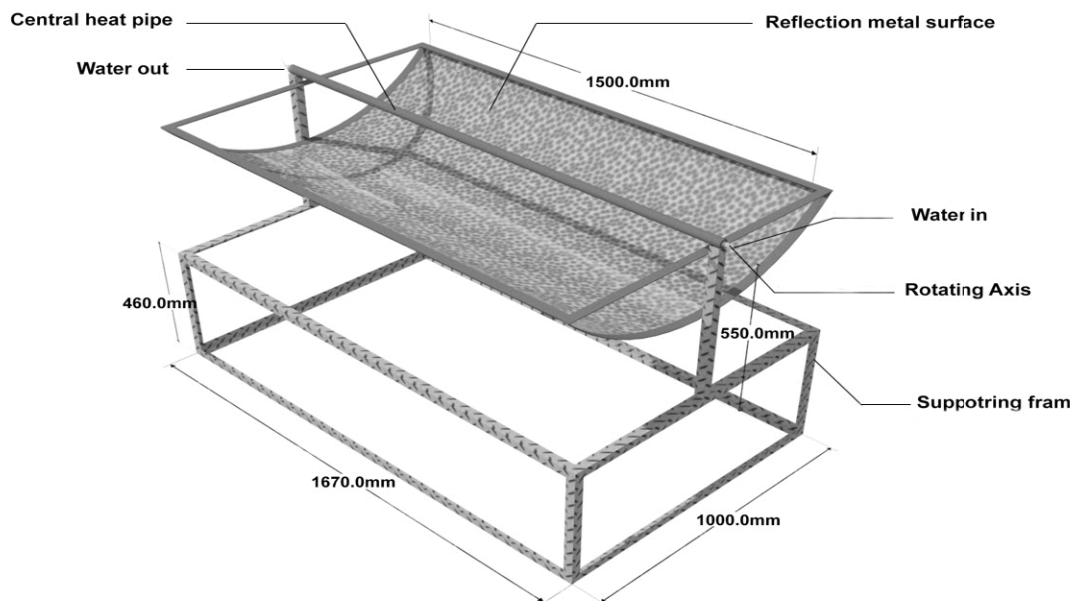


Fig. 2. Layout of PTC.

Table 2
Sensors and instruments uncertainties

| Device/instrument | Uncertainty | Experiments range |
|---|---|---|
| J – thermocouple (Omega) | ±0.5°C | 20°C–100°C |
| Data logger (Omega TC-08) | ±0.5°C (<0.1°C resolution) | 20°C–100°C |
| Solar radiation pyranometer (Kipp and Zonen CM 11) | ±5% | 0–1,400 W/m2 |

Table 3
Test days and cases

| Test # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|---|
| Data | May 13 | June 2 | June 4 | June 5 | June 20 | June 24 | June 25 | June 26 | June 28 |
| Test of | Still | Still, collector, and PT | Still | Still and collector | Still and collector | Still + PTC | Still + collector | Still | Still + collector + PTC |
| | ST | ST + SC + PTC | ST | ST + SC | ST – SC | ST + PTC | ST + SC | ST | ST + SC + PTC |
| Case # | Case I | Case IV | Case I | Case III | Case III | Case II | Case III | Case I | Case IV |



Fig. 3. Experimental setup.

speed over the 9 test days are presented with the total still yield in Table 4.

### 4.1. Case 1: still standalone

Fig. 4 presents the hourly variations of temperature of vapor, cover glass outside surface, water, basin, and ambient for test# 8 which is for the case I (still standalone case). Solar radiation is also presented on the secondary scale. The temperatures show an upward trend until they reach peak values around 3:34 P.M. before gradually declining. Vapor temperature is the highest followed by the glass outside surface, water, and the basin plate. The highest rate of increase in all temperatures occurs around solar noon where the radiation is the highest. The local averages of maximum temperatures for glass outside surface, water, basin were 69.6°C, 64.8°C, 64.6°C, respectively.

The heat absorbed by the black basin and water initiates the phase change from water to vapor, and the heat rejected by vapor to ambient causes its phase change to condensate. The thermal capacity of water will also depend on the optimal volume of the water in the basin. For all experiments conducted the depth of water in the basin remained the same at 6 cm to be enough to immerse the heat exchanger and for comparison purposes. The distillate yield for this test is around 2,652 mL/(m$^2$/d), two other tests for this case, Table 4, the yields are 2,956 and 2,940 mL/(m$^2$/d), making the average of the three tests 2,849 mL/m$^2$/d. The variation in production is due to variation in solar insolation and wind speeds as shown in Table 4. Fig. 5 presents the solar irradiation and hourly variation of yield which peak from 2 to 4 P.M. with the value of 272 mL/(h m$^2$). For further analysis, this case I is taken as a reference case for all tests where the setup is still without any enhancers. The drop in distillate rate around 12:30 was not due to solar insolation variation and the same applies to the almost linear yield later on. It is expected that variation of wind speed, and the temperature difference between basin water and inside surface of cover glass, the ambient temperature, and the thermal capacity of the basin and its water all play important role in the amount of hourly distillate. Only average daily wind speed is available which on that day had a mean of 9.2 and a maximum of 29.6 m/s (Table 4). Otherwise, the hourly presentation of wind speed would have given more insight into this discussion.

The daily still thermal efficiency is defined as the ratio of thermal output to thermal input which is namely the percentage of evaporation energy of the 24 h yield divided by the total received incident solar energy $\eta_{th} = (m_w \times i_{fg})/(I \times A \times time)$. The average efficiency for the case I tests was around 16%.

### 4.2. Case II: still coupled with parabolic trough collector

Fig. 6 presents the temperature hourly variations for test # 6 which is for case II (still and parabolic trough

Table 4
Meteorological parameters over the test's days and total 24 h. Still yield (received from National Center for Meteorology – Medina Munawara Branch)

| Test # | Data | Solar radiation (W/m²) | | Ambient (°C) | | Wind speed (km/h) | | Total still yield (mL) | Yield (mL/m²/d) |
|--------|------|---------|---------|---------|---------|---------|---------|---------|---------|
| | | Average | Maximum | Average | Maximum | Average | Maximum | | |
| 1 (case I) | May 13 | 578.9 | 999.3 | 38.2 | 43.7 | 20 | 46 | 1,478 | 2,956 |
| 2 (case IV) | June 2 | 593 | 1,024 | 37.9 | 45.3 | 13 | 29 | 4,042 | 8,084 |
| 3 (case I) | June 4 | 590 | 1,025 | 42 | 45.3 | 16.6 | 40.7 | 1,470 | 2,940 |
| 4 (case III) | June 5 | 581 | 1,011.8 | 41.6 | 44.8 | 5.5 | 22 | 3,090 | 6,180 |
| 5 (case III) | June 20 | 548.6 | 1,034 | 46.2 | 49.7 | 14.8 | 35 | 3,311 | 6,622 |
| 6 (case II) | June 24 | 552.7 | 955.8 | 43 | 47 | 13 | 31 | 2,138 | 4,276 |
| 7 (case III) | June 25 | 499.4 | 1,013 | 42.5 | 47 | 13 | 37 | 3,213 | 6,426 |
| 8 (case I) | June 26 | 502.9 | 935.8 | 45.4 | 48.1 | 9.2 | 29.6 | 1,326 | 2,652 |
| 9 (case IV) | June 28 | 526 | 961 | 47.8 | 51.7 | 18.5 | 37 | 3,584 | 7,168 |
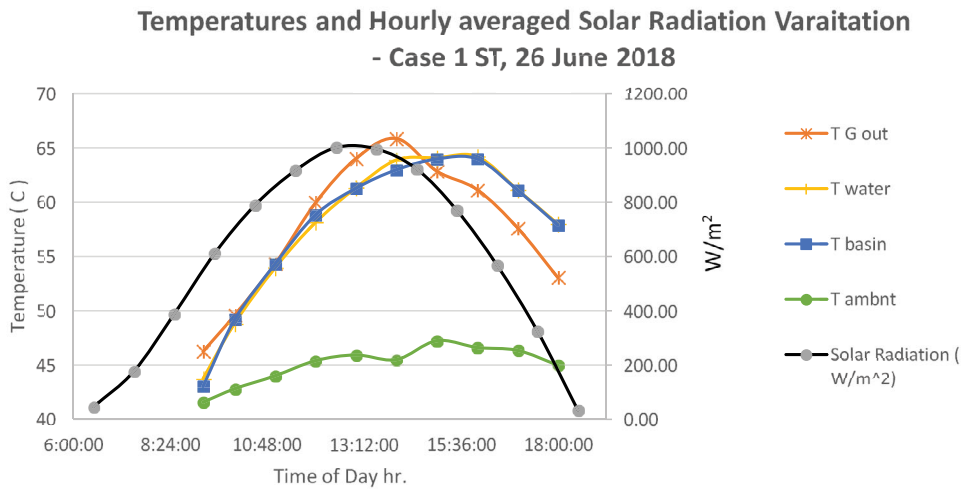


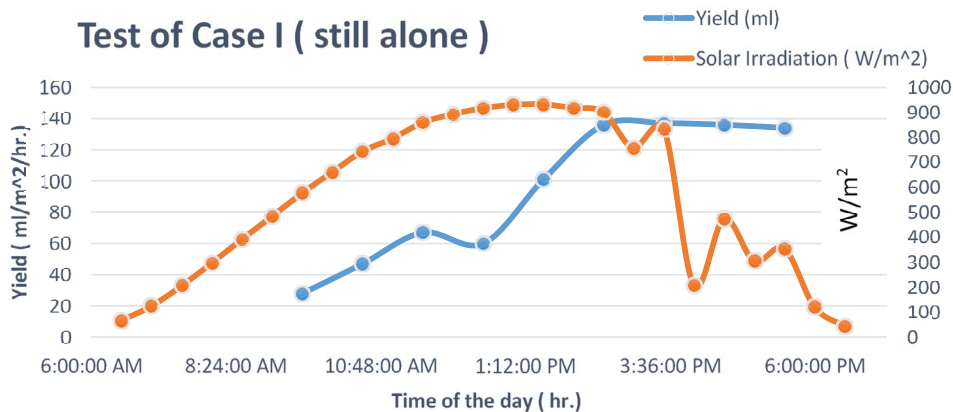Fig. 4. Hourly temperature variations for standalone solar still (case I).



Fig. 5. Yield and solar irradiation for the standalone solar still (ST), case I test 26 June 2018.

collector case). As shown, it has a trend similar to the previous case. The maximum temperatures local averages at 4:01 P.M. and it's for glass outside surface, water, basin, PTC out and heat exchanger out are 73.9°C, 70.6°C, 70.1°C, 73.2°C, and 72.9°C, respectively. The temperature difference in the heat exchanger is 0.3°C and the heat losses in the insulated tubes are negligible as can be noticed from temperature measurements. It has been noticed that the

Hourly Variation of Temperatures and Hourly Averged Solar Rad. - Case II - Test of (ST-PTC ) 24 June 2018
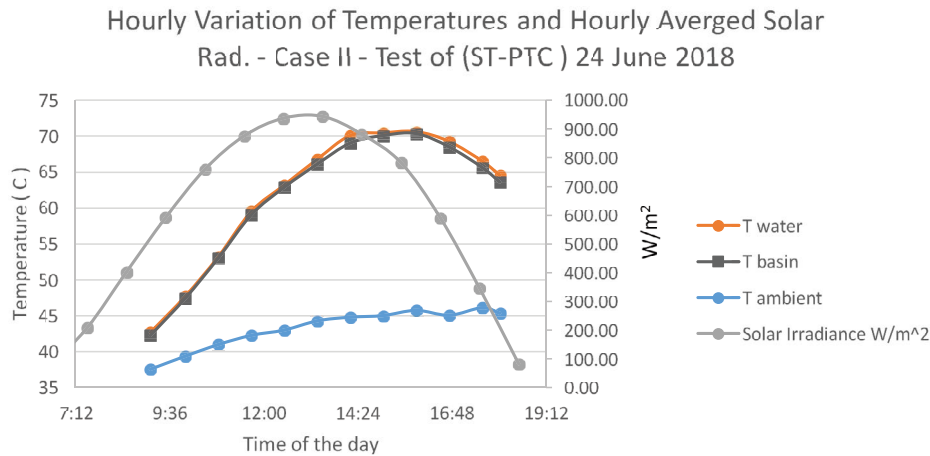
Fig. 6. Hourly temperature variations and radiation of case II-24 June 2018 (ST + PTC).

maximum temperature of the water is 70.6°C represents a 9% increase over the case I.

Fig. 7 shows the hourly variation of distillate output and the solar irradiation of the solar still coupled with parabolic trough enhancer for case II (ST + PTC) from 9:00 A.M. to 6:00 P.M. It peaks from 2 to 3 P.M. with a value of 530 mL/(h m²). The accumulated yield over 24 h is measured early next morning and found to be about 4,276 mL/(m²/d), while that from the standalone is about 2,652 mL/m²/d. The yield is slightly down after 2 P.M. and again it is rising after it. This could be explained partly by the variation seen in solar irradiation where it went through rapid decrease and then stayed constant before going back to a more gradual decline symmetrical to the morning side of the curve. So that a higher rate of distillation is achieved by coupling the PTC with DSSS which increased the productivity by about 61%. The heat exchanger (Fig. 3) immersed inside the water in the basin contains circulated hot water coming from the concentrated tube fixed at the focal point of the parabolic trough reflector. This increased the thermal capacity of the water in the basin hence improving the still yield.

*4.3. Case III: still coupled with flat plate solar collector*

Fig. 8 presents the temperature hourly variations for test # 7 on 25 June 2018 which is for case III (still and flat plate solar collector case). As shown, it has a similar trend to previous cases. The local abrupt decrease in solar insolation at 1:00 P.M. reduced the local rate of temperature increase as a consequence. The maximum temperature of the water is 79.9°C compared with those of 64.8°C in case I, which has been increased by 15.1°C. Hence, the percentage increase in water temperature represents 23.3%.

In Fig. 9, the temperature difference ($T$ water – $T$ cover glass out) is plotted vs. time for this test, as shown $\Delta T$ starts as a negative value in the morning due to the faster increase in cover temperature compared to the water which has a higher thermal mass and encounters the solar radiation afterward. As water receives more solar heat with time its temperature becomes higher than the cover temperature and the difference between the evaporation and condensation surfaces indicates the continuity of the process for the rest of the day until the next sunrise. These $\Delta T$ variations show a somehow similar trend for other tests and it is expected to have very consistent results if the temperature of the four sides of the cover is measured and averaged.

Fig. 10 shows the hourly variation of distillate output of the solar still coupled with solar collector enhancer [case III (ST + SC)]. It peaks from 2 to 4 P.M. with an average value of 810 mL/(h m²). The 24 h accumulated yield is about 6,426 mL/(m²/d). Therefore, the SC increased the rate of condensed distillate yield up to 142% compared to
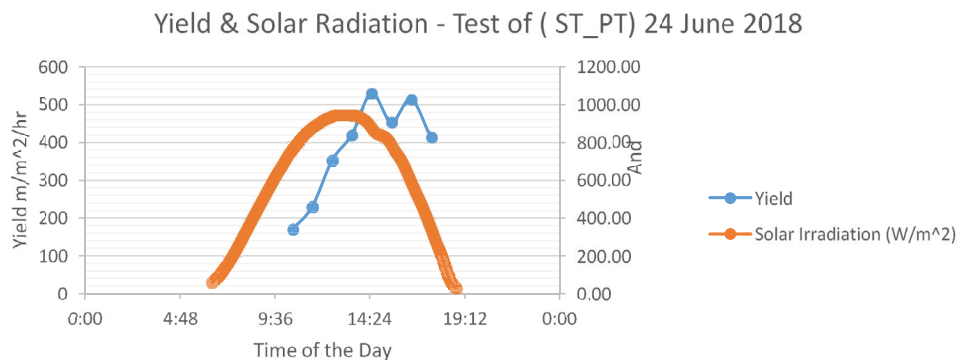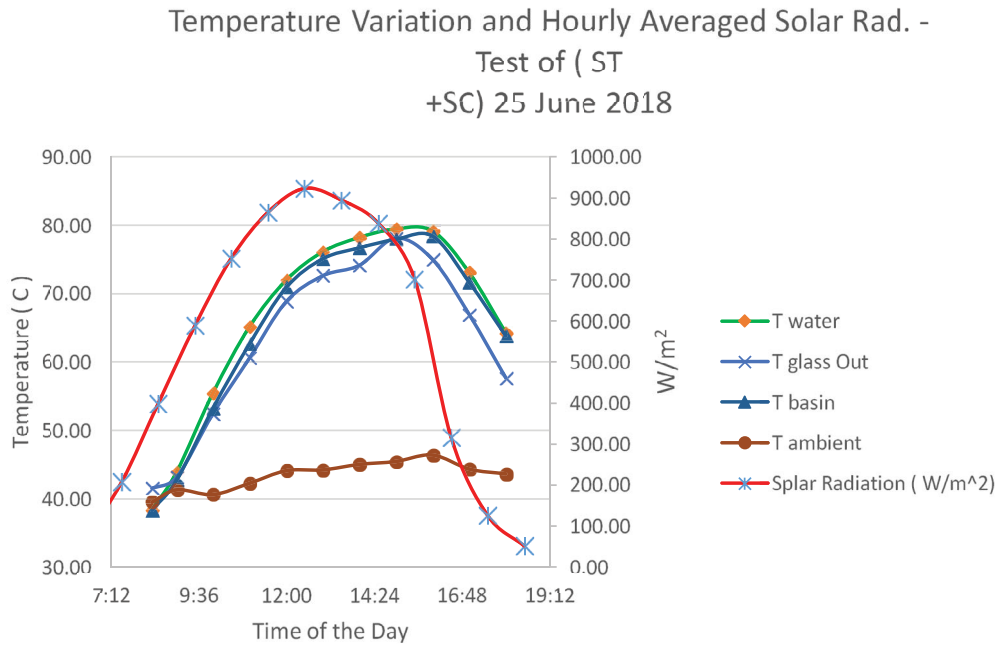
Yield & Solar Radiation - Test of ( ST_PT) 24 June 2018

Fig. 7. Yield of (ST + PTC) case II.

Temperature Variation and Hourly Averaged Solar Rad. - Test of ( ST +SC) 25 June 2018

Fig. 8. Different temperature measurements of the case III (ST + SC).

Temperaure Diffrance, T water minus T cover glass out versus time - Test of (S+SC) 25 IIUne 2018
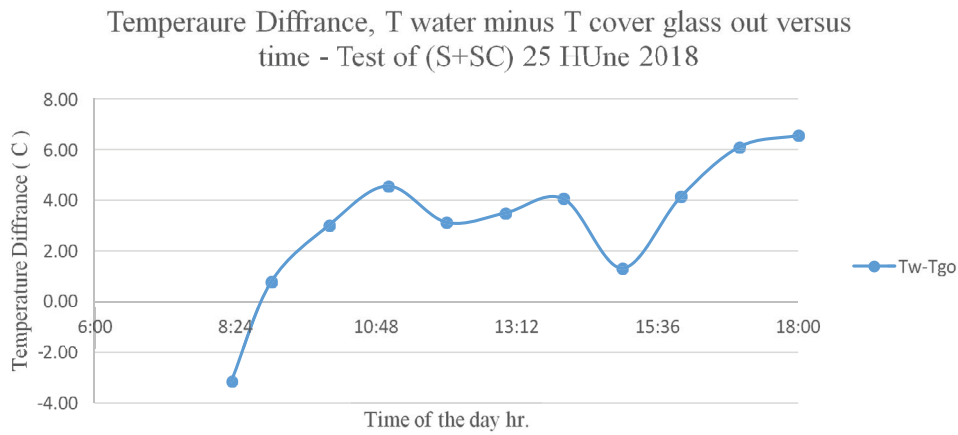
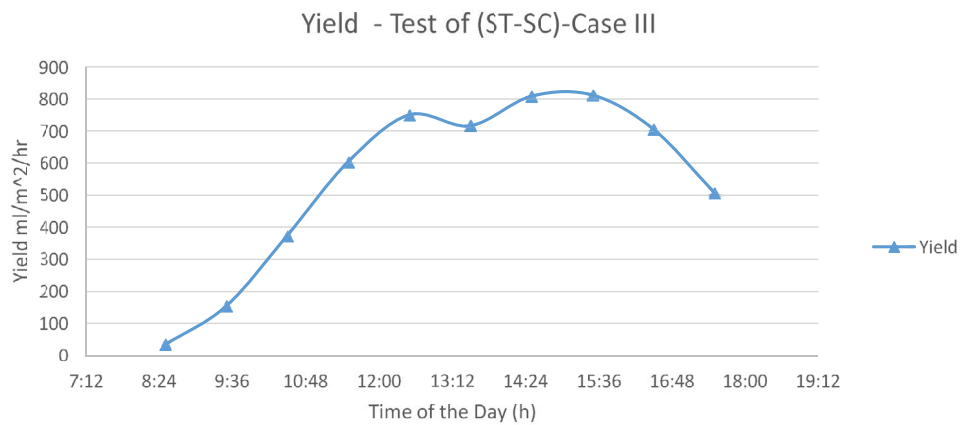Fig. 9. Hourly variation of temperature difference ($T_w - T_g$ out).

Yield - Test of (ST-SC)-Case III

Fig. 10. Yield of the solar still coupled with solar collector.

the yield from the standalone solar still. The higher thermal capacity of water in the basin occurred due to the heat exchanging between the U tube heat exchanger that circulates hot water coming from the solar collector exit, and the temperatures of the water and vapor have increased compared to standalone solar still as explained above and can be seen from Fig. 8. The average for the three tests performed for this case is 6,409 mL/(m²/d).

## 4.4. Case IV: still coupled with flat solar collector and parabolic trough collector

Fig. 11 shows the variation in temperature of the water, glass, ambient, and basin of the integrated system of ST + SC + PTC test #9 performed on June 28, 2018. During the morning hours, the solar intensity starts low and gradually increases to a maximum at noontime, the temperature trends follow. In the afternoon, the local drop-in solar insolation is reflected clearly on the rate of change of water temperature and hence its thermal capacity and the evaporation rate as seen in Figs. 11 and 12 as will be explained later. The maximum temperatures local averages at 2:24 P.M. for glass outside surface, water, basin, and PTC out are 80.6°C, 82.3°C, 80.9°C, and 87.5°C, respectively. The maximum temperature of the water is 82.3°C compared with those of 64.8°C in case I, which has increased by 17.5°C. Hence, the percentage increase in water temperature represents 27%.

Fig. 12 shows the hourly variation of distillate output of the solar still coupled with flat solar collector and parabolic trough collector [case IV (ST + SC + PTC)]. It peaks from 1 to 3 P.M. with an average value of 927 mL/(h m²). A further increase in yield rate is also observed by integrating the solar still with both a parabolic trough and solar collector under the same operating conditions of previous cases. Thus, this result confirmed that adding more enhancers certainly increases the yield rate of distilled water. So, the 24 h accumulated yield for this test is about 7,168 mL/m²/d. Therefore, FPC and PTC increased the rate of

condensed distillate yield up to 170% compared to the yield from the standalone solar still. There are two tests done for this case and the average 24 h yield is 7,626 mL/(m²/d).

## 4.5. Comparison of the four cases

Fig. 13 shows the hourly variation of distillate output for the four cases as discussed above. Case IV has the highest production followed by case III and then case II. However, case I has the lowest production rate. This is because the surface area exposed to solar radiation has increased, which extracts more heat to water circulated in the heat exchanger that makes the evaporation process higher than in other previous cases. PTC face area is 1.33 m² while the flat solar collector plate area is 1.7 m². This results in an area ratio of 1.4 including the still area for these two cases. The current yield result for cases II and III have a ratio of 1.5 which is proportional to the area ratio. Though it is expected that the PTC design can be improved by insulating its focal pipe with around evacuated clear glass tube.

In the present study, the accumulated productivity of different enhancers coupled with solar still were analyzed, as shown in Figs. 14 and 15. It reveals that the solar still coupled with solar collector plus the parabolic trough produces a higher yield rate (7,168 mL/(m²/d)) followed by solar still coupled with the solar collector (6,426 mL/(m²/d)), and then solar still with parabolic trough (4,276 mL/(m²/d)) and the least is from standalone solar still (2,652 mL/(m²/d)).

The productivity of the solar still entirely depends on the enhancement devices to increase the water temperature and hence the evaporative process. Therefore, these techniques have enhanced the performance of the still output. The present study matched the various scientist's findings who attempted to maximize the daily yield per m²/d in a solar still in a passive and active mode by modifying the design to get maximum temperature difference between the evaporative and condensing surfaces [16–20]. These modifications on the conventional solar stills will augment their productivity which will ease
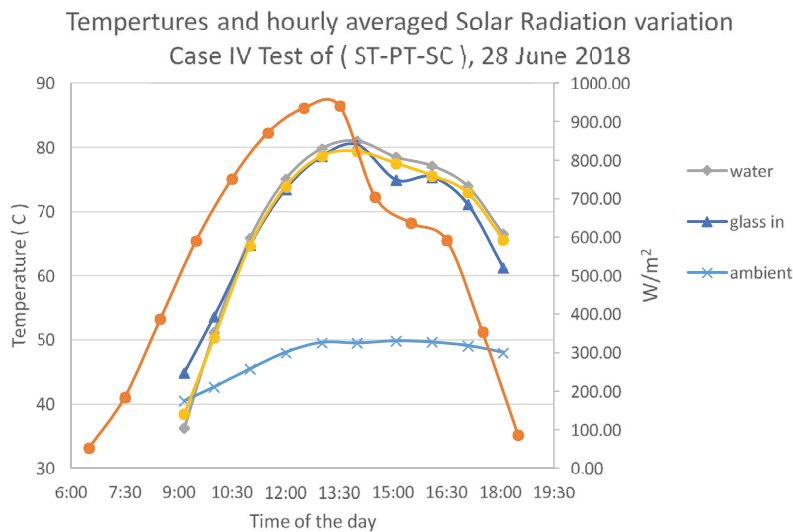


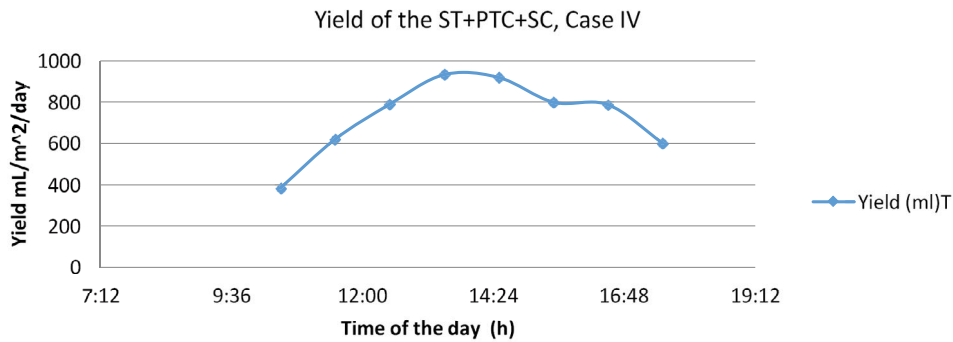Fig. 11. Different temperature measurements of the case IV (ST + PTC + SC).

Fig. 12. Yield of the solar still coupled with flat solar collector and PTC, June 28, 2018.
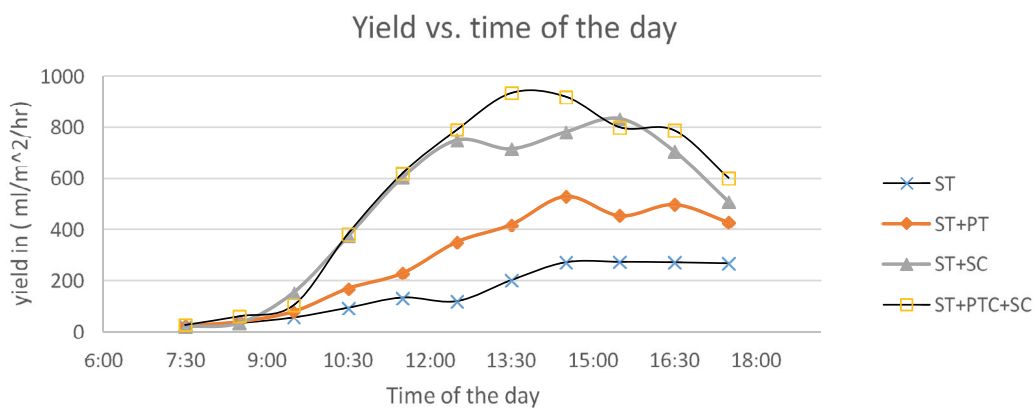


Fig. 13. Comparison of the hourly variation of distillate for the four cases.
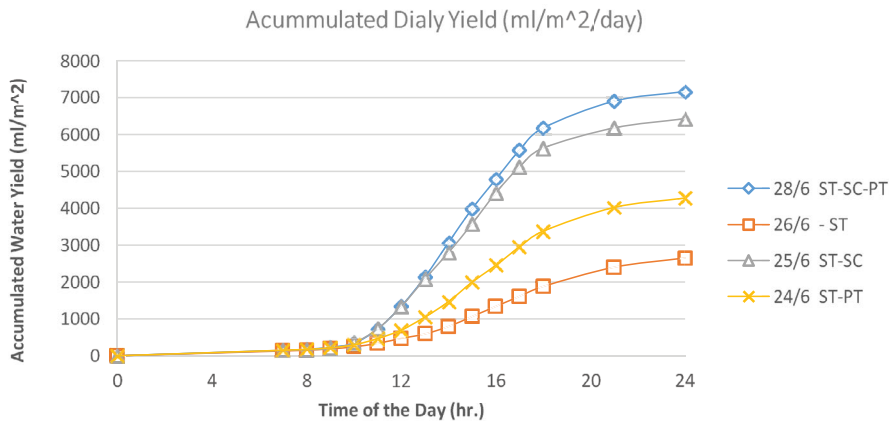


Fig. 14. Comparison of the accumulated 24 h distillate for the four cases.

slowly the pressure on the use of natural resources and encourage the implementation of renewable systems.

### 4.6. Comparison with previous studies

The findings of this study were compared to that of previous studies. As already covered in the introduction no previous study coupled DSSS with both FPL and PTC so the comparison presented below will start with still coupled with PTC and then still coupled with FPC.

Results of this study will be cross-compared with previously reported results in the matter of distillate productivity and thermal efficiency. The findings of similar previous studies are presented in Table 5. The findings in the four cases in this study are included for comparison. The results are comparable in the overall ranges even though different meteorological conditions will play significant roles as it is well-established especially solar intensity and wind speed. The following measures can be used to improve the efficiency and increase productivity further: adding fins to
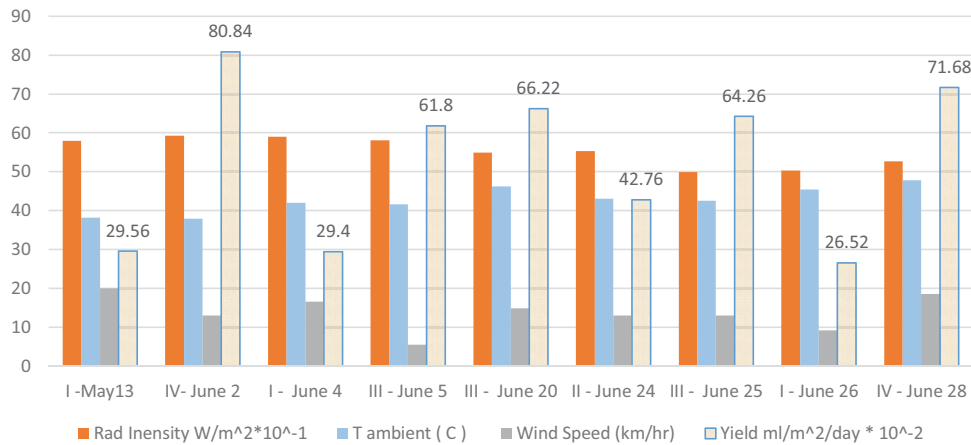
Fig. 15. Average metrological conditions and daily yield for different cases.

Table 5
Comparison with previous studies

| St no. | Author(s) and place | Specification, data, and area | Yield (mL/d/m²) | Efficiency (%) |
|---|---|---|---|---|
| | | Still alone | | |
| 1 | Badran O. [5] Amman, Jordan | Single slope still, October–December 2002, $A$ = 1 m² | 2,240 | – |
| 2 | Badran AA. [6] Amman, Jordan | Double slope still, $A$ = 0.96 m² | 1,500 | 28.56 |
| 3 | Fathy M. [8] Sohag, Egypt | Double slope still alone, ST = 1.5 m², summer and winter | 2,310–4,510 depends on the season | 36.8 |
| Case I | Medina, Arabia | Double slope still, May–June 2019, $A$ = 0.5 m², basin water height 60 mm | 2,956 | 16 |
| | | Still + PTC | | |
| 4 | Fathy M. [8] Sohag, Egypt | Double slope still coupled with parabolic trough collector, ST = 1.5 m², PTC total area = 3 m², summer and winter | 4,030–8,530 depends on the season | 29.8 |
| Case II | Medina, Arabia | This study case II: ST + PTC, May–June 2019, ST = 0.5 m², PTC face area = 1.4 m² | 4,276 | |
| | | Still + FPC | | |
| 5 | Badran O. [5] Amman, Jordan | Single slope still coupled with flat plate collector, October–November 2002, ST = 1 m², FPC = 1.3 m² | 3,510 | |
| 6 | Badran AA. [6] Amman, Jordan | Double slope still coupled with flat plate collector, ST = 0.96 m², FPC = 1.34 m² | 2,300 | 22.26 |
| 7 | Ramachandra Raju [7] Kakinada, India | Single slope still coupled with flat plate collector(s), ST = 1 m² FPC = 2 m², summer | 2,670 | 6.82 |
| Case III | Medina, Arabia | This study case II: ST + FPC, May–June 2019, ST = 0.5 m², FPC area = 1.7 m² | 6,622 | |
| | | Still + PTC + FPC | | |
| Case 4 | Medina, Arabia | May–June 2019 ST + PTC + FPC | 8,084 | |

the basin heat exchanger, reducing the basin water height, and insulating the pipe of the PTC in an evacuated glass tube.

## 5. Conclusions

This study presented the performance evaluation of the standalone solar still, solar still coupled with a flat solar collector or parabolic trough, and solar still coupled with both parabolic trough and flat solar in converting brackish water into clean water for drinking purposes under Medina climate conditions. From the experimental results it is shown:

- Solar still coupled with both solar parabolic trough and flat solar collector shows the maximum amount of yield

due to the multiple effects in transferring more heat to basin water through the heat exchanger circulating hot water from both enhancers.

- The yield of the solar still entirely depends on the climatic parameters as well as increasing the basin water temperature. The enhancers' effect increases the water temperature up to high values (80°C) compared to standalone solar still (64°C).
- The accumulated yield in the summertime from standalone DSSS, solar still coupled with PTC, solar still coupled with FPC, and solar still coupled with both were 2.85, 4.27, 6.41, and 7.63 L/m²/d, respectively.
- The water temperatures are increased by about 9% for solar still integrated with PTC to about 27% for solar still integrated with the two collectors relative to standalone solar still under similar climate conditions.
- The average efficiency for the still alone case was around 16% and it is lower for the coupled cases. It is expected that the efficiency of the test setups will improve in cases of adding fins to the basin heat exchange, reducing the basin water height, and insulating the pipe of the PTC in an evacuated glass tube.

## Acknowledgments

## Symbols

| | | |
|---|---|---|
| $I$ | — | Solar irradiance, W/m² |
| $A$ | — | Basin area, m² |
| $i_{fg}$ | — | Enthalpay of evporaziation, kJ/kg |
| $m_w$ | — | Mass of distillate, kg |

## Greek

| | | |
|---|---|---|
| $\eta_{th}$ | — | Thermal efficiency |

## Abbreviations

| | | |
|---|---|---|
| DSSS | — | Double slope solar still |
| EES | — | Engineering equation solver |
| FPC | — | Flat plate collector |
| IHE | — | Immersed heat exchanger |
| PTC | — | Parabolic trough concentrator |
| SC | — | Solar collector |
| SSSS | — | Single slope solar still |
| UNICEF | — | United Nations Children's Fund |
| WHO | — | World Health Organization |

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