AUT Journal of Mechanical Engineering

AUT J. Mech. Eng., 4(3) (2020) 301-314
DOI: 10.22060/ajme.2019.16796.5837

Experimental Study and Economical Analysis of a Cascade Solar still Integrated with an Evacuated Tube and a Conventional Flat Plate Solar Collectors

M. Vafaei[1], R. Karimi[1], S. Samadi Semnani1, A. Arbabi[2], M. BarzgarNezhad[2], S. E. Shakib[2*], Gh. Ghassabi[2], M. H. Shafiei Mayam[2]

[1] Mechanical Engineering Department, Ferdowsi University of Mashhad, Mashhad, Iran
[2] Mechanical Engineering Department, Bozorgmehr University of Qaenat, Qaenat, Iran

ABSTRACT: Many researchers have experimentally and theoretically studied fresh water productivity in solar stills. In this regard, water preheating can play a noticeable role in enhancing the productivity of solar stills. In the present study, in order to study the effect of water preheating at the inlet of desalination system, a cascade solar still is built and integrated with two different solar collector in separated modes; an evacuated solar collector and a conventional flat plate solar collector. The mentioned solar still includes an external condenser, fin, and internal and external reflectors. It is worth noting that the embedded fins in the water passage are applied to induce hot spots and increase the evaporation rate and fresh water. The experiments were performed in August 2015 and summer 2017. The results showed that the combined desalination system with conventional flat plate collector and evacuated tube collector enhace productivity %60 and %13, respectively. In addition, efficiency of solar still in combination with conventional flat plate collector and evacuated tube collector was %81.8 and %59.1, respectively. The price of produced fresh water of solar still with conventional collector obtained 0.035 $/lit and for solar still with evacuated tube collector was 0.045 $/lit.

Review History:

Received: 2019-07-31
Revised: 2019-10-22
Accepted: 2019-12-09
Available Online: 2019-12-23

Keywords:

Solar still
Flat plate solar collector
Evacuated tube solar collector
Combined system

1. INTRODUCTION

Regarding the population growth and descending trend of fossil fuel resources along with the hazards of these fuels to the environment, application of clean and renewable energy is of paramount importance. Sun is the biggest energy resource among all clean and renewable energy which is abundantly available in most parts of the earth [1,2]. Since supplying fresh water is still a serious challenge in most parts of the world, solar energy can be an appropriate substitute for the desalination process. Therefore, solar stills can play an effective role in tackling these problems[3,4]. One of the most central applications of solar energy in the domestic sector is to use it in order to supply the required energy for the desalination system. Numerous studies have been conducted so far that some of which will be explained in what follows.

Kabeel et al. [5] investigated an evacuated collector integrated solar still. Their results indicated an increase of 66.6% in the fresh water productivity for the combined system compared to the conventional single sloped solar still. Morad et al. [6] integrated it with a flat plate collector. Their results illustrated an augmentation in productivity by 30% compared to the lack of collector. Sharshir et al. [7] examined a combined system including a humidification-dehumidification unit, a single slope solar still, and an evacuated solar collector. The results illustrated that productivity of the combined system increased by 200% compared to the discrete mode. Arunkumar et al. [8] integrated a single slope solar still with a concentrator solar still. Their results showed an increase of 75% in the single slope solar still in the combined mode compared to the discrete mode. Saettone et al. [9] a stepped solar still with internal reflective walls in combination with five borosilicate vacuum heat tubes. Their results showed an increase in the performance by 32.4% compared to the lack of vacuum tubes. To improve the performance of an inclined solar still, Hansen and Murugavel et al. [10] combined it with a single slope solar still. Their results demonstrated that fresh water productivity increased compared to the single slope solar still per se. Elashmawy [11] combined a parabolic concentrator solar tracking system with a solar still. Their results showed an increase of 676% and a decrease of 45.5% in the daily production and fresh water cost per liter, respectively, compared to the solar still.

In another research, a single-slope active solar distillation unit integrated with some flat plate solar collectors in parallel was considered by Narayana and Raju [12]. Their results showed that the most amount of fresh water obtained when three collectors were used and consequently 4.229 kg/m^2/day fresh water was produced.

Manokar et al. [13] integrated an inclined solar still with photovoltaic panel. The enhancement of fresh water productivity was reported to be 58.9%. Kabeel and El-Said

*Corresponding author's email: se.shakib@buqaen.ac.ir

[14] studied a combined system consisting of a solar still, a humidification-dehumidification unit, and an air-water heater. They recorded the highest daily production equal to 18.251 lit/m^2.

Abdessemed et al. [15] studied a parabolic solar collector coupled to a four-stage solar still. The tested trays of the still have two different type. Their results showed the use of parabolic solar collector is not ecnomical and other methods should be studied for preheating feed water.

Al-harahsheh et al. [16] investigated a solar still with Phase Change Material (PCM) which connected to a solar collector was carried out, experimentally. The productivy of under study system reached 4300 ml/m^2 /day which about 40% of fresjh water was produced after sunset.

Fathy et al. [17] integrated a double slope solar still with a parabolic solar collector and their results showed an productivity enhancement of 89% for summer compared to the separated desalination system.

Feilizadeh et al. [18] investigated an experimental study on a solar still which an evacuated tube solar collectors were considered to adsorb solar energy. Analysis of the results showed the highest amoun of fresh water obtained 16.98 kg/m^2/day.

Patel et al. [19] Carried out an analysis on a stepped type basin still which connected to an evacuated tube collectors. The results showed by using the solar collector, the frsh water production enhanced 24%.

Bhargva and Yadav [20] studied a solar still which a typical heat exchanger was installed in its basin and an evacuated tube solar collector supplied the preheating energy of feed water. Their attempt showed that the highest amount of productivity obtained 7.38 lit/m^2/day.

Sharshir et al. [21] carried out an experimental study on a modified pyramid solar still coupled with evacuated tubes and nanofluids. They compared three diffrenent systems including a conventional solar still and two pyramid solar stills namely: conventional pyramid solar still and modified pyramid solar still. Based on the obtained results, the rate of productivity enhancement was 26.6% in the best performance.

According to the previous studies reviewed above, the investigations imply that water preheating can play a significant role in productivity of solar stills. In this respect, in the present study, an investigation is carried out into the combinations of the cascade solar still with the evacuated solar collector and with the conventional flat plate solar collector in separated modes. The effect of preheating the entering water to the desalination system is examined on the amount of produced fresh water of the main trough, produced

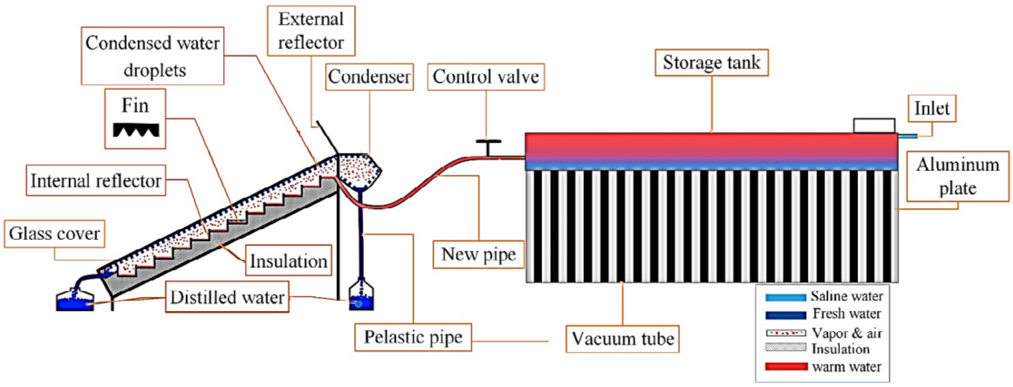

Fig. 1. Schematic view of the evacuated collector integrated solar still

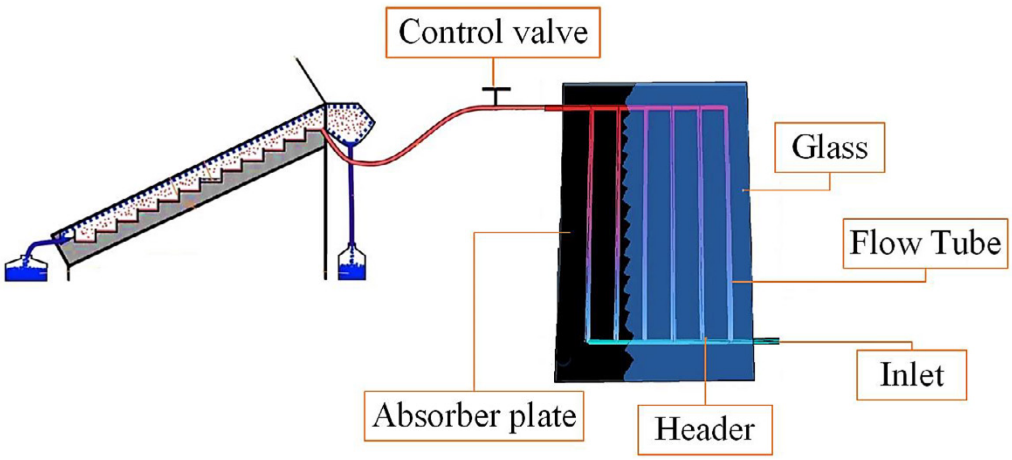

Fig. 2. Schematic view of the flat plate collector integrated solar still

fresh water in the external condenser, temperature of different parts of the desalination system, efficiency of the desalination system, and cost of the produced fresh water. The results associated with the performance of the concerned system are studied and an economic analysis is performed to calculate the costs incurred for the produced fresh water.

2. SYSTEM DESCRIPTION

The system under stuy is comprised of a cascade solar still with external condenser, fin, internal and external reflectors which combined with two different solar collectors; an evacuated solar collector and a conventional flat plate solar collector in separated modes. The evacuated tube collector includes 22 tubes. The external surface of tubes is covered by transparent glass in order to suitably transmit the light. The surface of the internal pipe is coated with a dark absorber to convert the light into heat. The space between the internal and external tubes is relative vacuum which acts as an insulator, minimizing the heat loss. The evacuated solar collector is thermosiphon-type, i.e. it does not need a pump and operated based on the natural circulation of water between the pipes of solar collector and water tank. The conventional flat plate solar collector has the dimension of 1760 mm*861 mm and absorber plate with 0.4 mm thickness. Sun's rays are absorbed by the absorber and transferred to the pipelines with saline water inside. The heated water enters the top header and leaves the collector. Fig. 1 depicts a schematic view of the Evacuated tube solar collector Integrated with cascade Solar Still (EISS). As it is shown in this figure, the saline water enters the tank of the evacuated solar collector, then the cold water flows from the tank towards the pipes and is heated in the vacuum tubes where it naturally moves towards the water tank. Now, the available warm water in the tank enters the cascade solar still as the preheated water. Furthermore, Fig. 2 shows the schematic view of a conventional Flat plate collector Integrated with Solar Still (FISS). In the flat plate collector, feed water enters the bottom header of the collector and then it is heated due to move through the absorber tubes, and finally moves from the top header towards the outlet. This water enters the solar still as the preheated water. According to Figs. 1 and 2, the saline water flow (preheated water) enters the surface of the first step of the desalination system and goes through a spiral path along the steps of the desalination system due to the provision of water stops in front of each step so that the water stays in contact with absorber plate for a longer period. A portion of the formed vapor is distilled over the glass cover of the desalination system and water drops are accumulated at the bottom of the glass cover. The other portion of the formed vapor enters the external condenser, distilled there, and is transferred from the condenser bottom to the fresh water collecting tray.

In fact, increase in the vaporization rate is one of the key issues in the applicability of desalination systems which can be accomplished by raising the temperature of the water basin interior. To meet this objective, a number of galvanized fins were embedded in different points on the horizontal surfaces of the steps and stainless steel internal reflectors were mounted on the vertical surfaces of the steps. This way, hot spots are generated in the surfaces of steps and the temperature of the bottom of steps is escalated, leading to an increase in evaporation. The applied fins, illustrated in Figs. 1 and 2, were manufactured and installed such that they would not disturb the water streamline. Furthermore, the external reflector was employed to reflect Sun's rays to the bottom of steps. Figs. 3 and 4 present the real model of integration the cascade solar still with the evacuated collector and with the flat plate collector, respectively.

3. EXPERIMENTAL SETUP

To evaluate the evacuated tube collector integrated with the cascade solar still, the experiments were conducted in August 2015. Also, to assess the combination of this desalination system with the conventional flat plate collector, the experiments were performed in June, July, and August 2017. All of the experiments were carried out in Qaen, Iran, with the latitude of 32°-33°. All experiments were carried out from 9 am to 18 pm since more than 90% of solar radiation occurs in this period in Qaen. Since Singh and Tiwari [22] concluded that the maximum annual production obtaines when the slope of the desalination system is considered equal

Fig. 3. A view of the evacuated collector integrated solar still

Fig. 4. A view of the flat plate collector integrated solar still

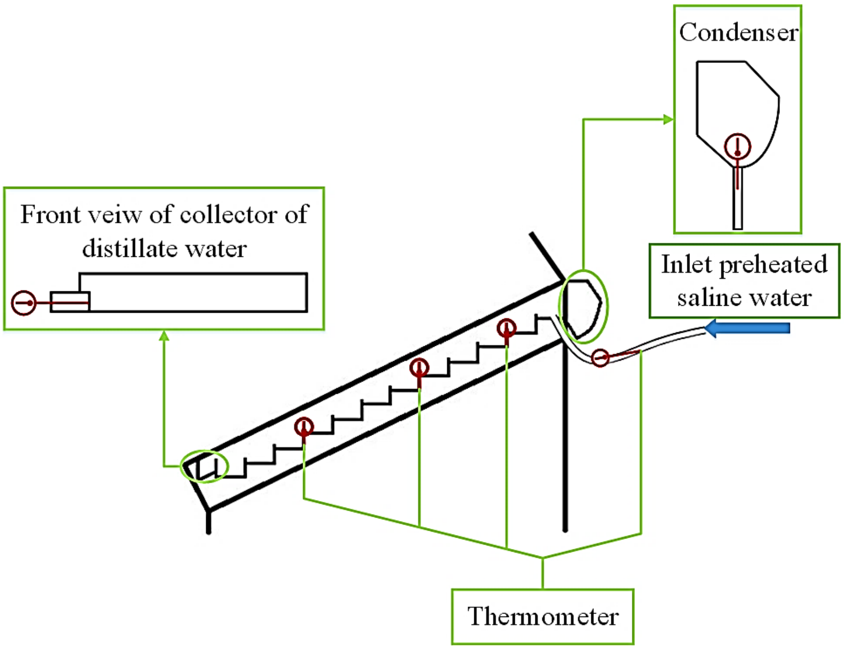

Fig. 5. Positioning of thermocouples

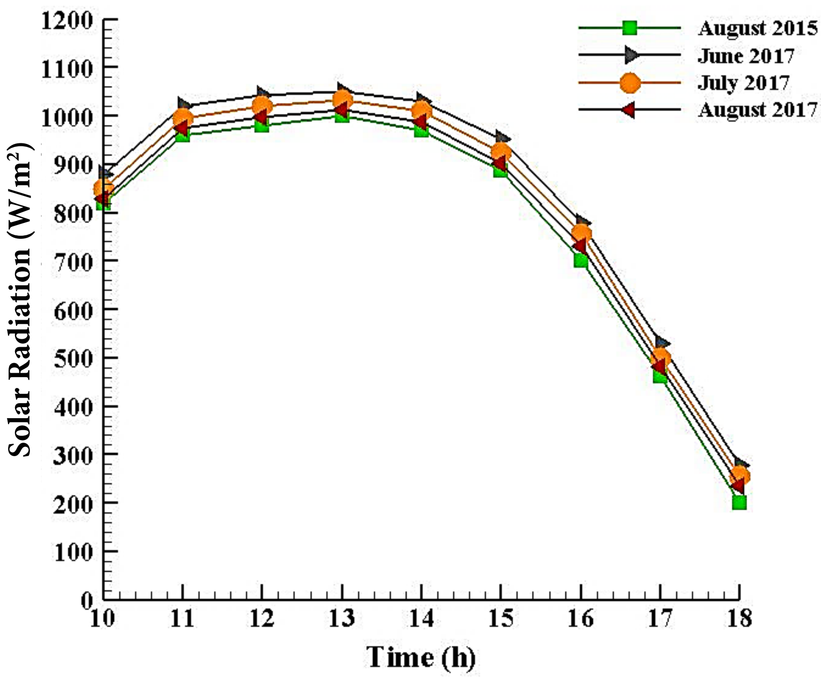

Fig. 6. Average radiation intensity per hour in months of the experiment

to the latitude of the concerned region, the angle of systems was adjusted so that Sun shines perpendicular to the surface of still and collectors glass. Wind blow was neglected in the present study and the experiments were performed in stable weather conditions. Desalination systems and collectors are connected to each other by five-layer pipe (new pipe) that its surface is also insulated with foam to avoid heat loss. The total salt available in the saline water is 1250 ppm in all experiments. The water temperature at the inlet of collectors is $25\,^{\circ}\mathrm{C}$. Moreover, six thermocouples (*k*-type with an precision of $\pm 0.5^{o}\mathrm{C}$) were used to measure the temperature of the interior of the desalination system, temperature of the fresh water at the main outlet, temperature of the fresh water at the outlet of the condenser, temperature of the water at the outlet of collectors (inlet of the desalination system), shown in Fig. 5. The acronyms used in the diagrams for the temperature and produced fresh water in each section are explained in the following. It is worth noting that temperatures are in °C and produced fresh water in mlit/m[2].

T_{in} : Temperature inside the still which is measured by the three thermocouples installed in three regions on the base of steps.

T_{mf} : Temperature of fresh water at the main outlet which is measured by a thermocouple mounted at the fresh water outlet.

T_{cf} : Temperature of the fresh water at the outlet of condenser that is reported by a thermocouple installed at the outlet of condenser.

T_a : Ambient temperature

T_{oc} : Water temperature at the outlet of collector that is reported by a thermocouple embedded at the outlet of collector.

P_m : Fresh water production at the main outlet

P_c : Fresh water production at the condenser outlet

The inlet, outlet mass flow rates of collectors and inlet mass flow rate of the desalination system have been considered stable. To more accurately evaluate the combined system, Fig. 6 depicts the variations in solar radiation per hour in the months of the experiment. These data have been calculate based on the average value of hourly intensity and after that presented in form of monthly intensity as shown in Fig. 6.

4. EFFICIENCY OF THE DESALINATION SYSTEM

The efficiency of the desalination system is equal to the ratio of the useful energy that used for fresh water production to the total solar radiation, given in Eq. (1) [11,23].

$$\eta = \frac{M * h_{fg}}{I * 3600} \tag{1}$$

where M stands for the total produced fresh water, h_{fg} denotes the latent heat of distillation, and I is the intensity of solar radiation.

5. ECONOMIC ANALYSIS

The cost of the fresh water by the solar still is dependent on the productivity, solar radiation, and also economic parameters including present worth, maintenance costs, salvage value and so forth [24,25]. To economically analyze the studied system, one of the most robust methods of economic analysis, called Equivalent Uniform Annual (EUA) benefit method, is applied. This is the only method in which lifespan of different systems does not make a shift in the calculations, i.e. there is no need for determining the common lifespan once the systems have unequal lifespans. This system converts the revenue and costs of the system into annual deposit and withdrawal, respectively. To conduct an economic analysis of the combined system, Capital Recovery Factor (*CRF*) and Sinking fund factor (*SFF*) are assessed by Eqs. (2) and (3), respectively. *i* and *k* represent the interest rate and exploitation years, respectively. In fact, *CRF* distributes the present worth to equal deposits based on the interest rate in the number of exploitation years while *SFF* distributes the future value of equipment (salvage value) based on the interest rate in the number of exploitation years [26].

$$CRF = \frac{i(1+i)^k}{(1+i)^k - 1} \tag{2}$$

$$SSF = \frac{i}{(1+i)^k - 1} \tag{3}$$

In the present study, to perform the economic analysis, the lifespan of equipment and interest rate are assumed to be 10 years and 15%, respectively, leading to *CRF* = 0.1993 and *SFF* = 0.0493. The production Cost of fresh water Per Liter (*CPL*) is estimated by Eq. (4). Average Annual Productivity (*AP*) and Net Equivalent Uniform Annual (*NEUA*) are assessed using Eq. (5) [26].

$$CPL = NEUA / AP \tag{4}$$

$$NEUA = EUAC - EUAB \tag{5}$$

Equivalent Uniform Annual Cost (*EUAC*) and Equivalent Uniform Annual Benefit (*EUAB*) are calculated by Eqs. (6) and (7), respectively [26].

$$EUAC = AFC + AMC + \sum_{d=1}^{365}\sum_{j=1}^{N} Op_j \tag{6}$$

$$EUAB = ASV \tag{7}$$

where *AFC* is the Annual Fixed Cost, *AMC* stands for the Annual Maintenance Cost, *ASV* is the Annual Salvage Value, Op_j denotes the Operational cost of system, j is the equipment counter, and d is the counter of days. Further explanation is provided in what follows for each of the former parameters.

$$AFC = P * CRF \tag{8}$$

$$AMC = \sum_{d=1}^{365}\sum_{j=1}^{N} Ma_j = 0.19 * AFC \tag{9}$$

$$Op = (E_b * \varepsilon_e) + (\dot{m}_f * \varepsilon_f) \tag{10}$$

$$ASV = S * SFF \tag{11}$$

P is the present worth which is multiplied by *CRF* to bear annual cost, as given in Eq. (8). Ma_j in Eq. (9) is the maintenance cost of different equipment which is assumed as

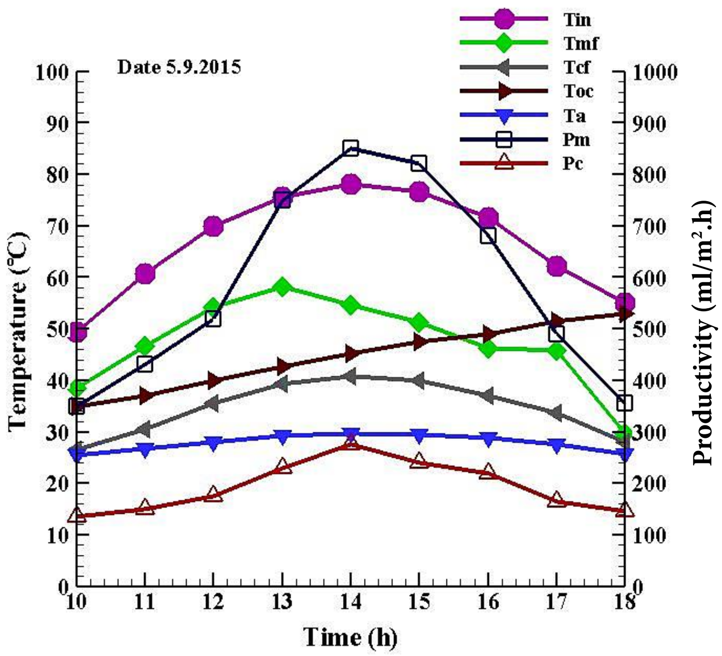

Fig. 7. Variations of temperature and productivity per hour in the experiment conducted on 5 August 2015

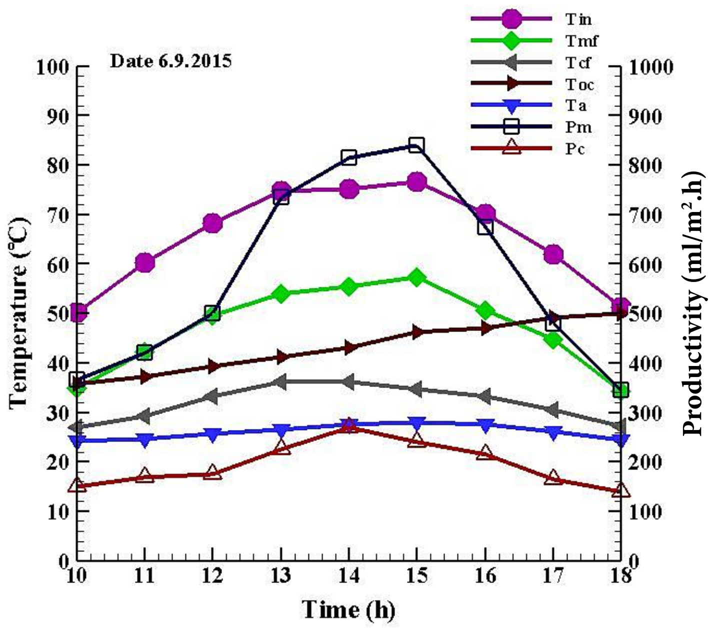

Fig. 8. Variations of temperature and productivity per hour in the experiment conducted on 6 August 2015

a fraction of the annual fixed cost. ε_f and ε_e are the purchase price of fuel and electricity, respectively, which are assumed to be zero in this project. *S* is the sum of system salvage value that is multiplied by *SFF* to bear the annual salvage value, as given in Eq. (11).

The present worth of system is equal to the sum of initial investment costs of different equipment based on Eq. (12).

$$P = \sum_{j=1}^{N} In_j \tag{12}$$

where In_j is initial investment costs of different equipment. The salvage value is equal to the value of the system at the end of its useful lifespan which is obtained by Eq. (13) as a fraction of the present worth.

$$S = \sum_{j=1}^{N} SV_j = 0.2 * P \tag{13}$$

In above equation, SV_j is Salvage value of different equipment.

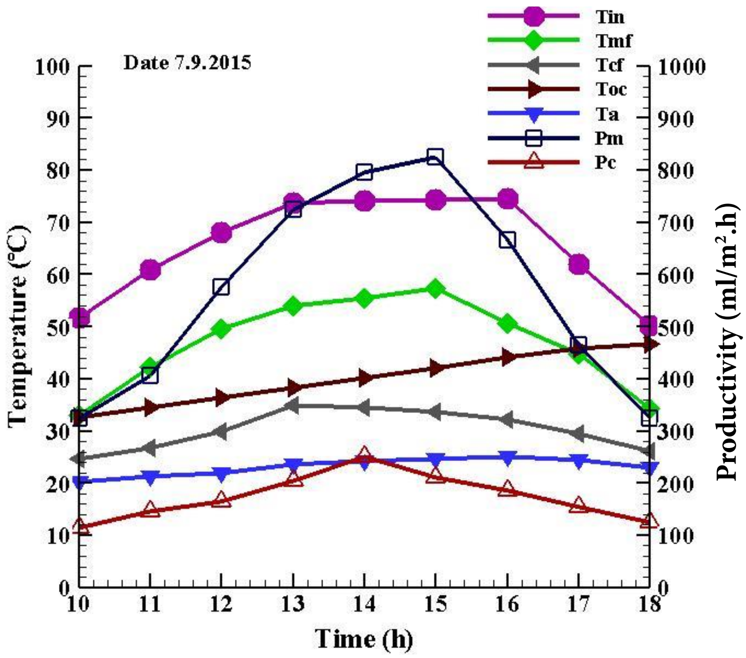

Fig. 9. Variations of temperature and productivity per hour in the experiment conducted on 7 August 2015

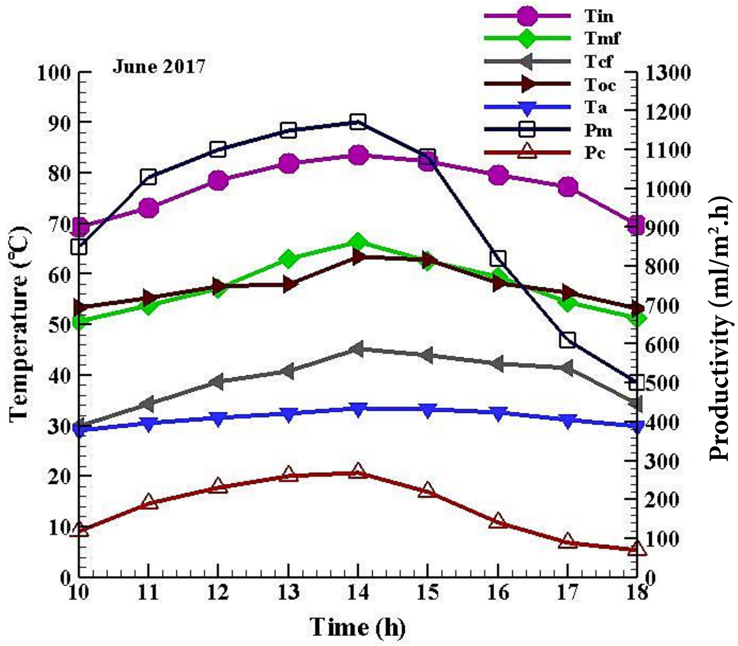

Fig. 10. Variations of temperature and productivity per hour in June

6. RESULTS AND DISCUSSION

The obtained results from different experiments are further presented in the form of temperature and productivity per hour. Figs. 7 to 12 show the recorded data for the temperature inside the desalination system, ambient temperature, water temperature at the outlet of collector, fresh water temperature at the condenser outlet, volume of the produced fresh water at the condenser outlet, temperature of the produced fresh water, and volume of the produced fresh water at the main outlet over different hours of the experiments in each combined system.

6.1. Results of experimental study

6.1.1. Results of EISS

Fig. 7 describes productivity and the temperature varioation of different parts of the desalination system in the experiment conducted on 5 August 2015. The maximum temperature inside the desalination system in this experiment was recorded at 14:00 with the value of 78 ℃. In fact, the temperature inside the desalination chamber is one of the most important parameters which directly related with the solar intensity, ambient temperature, and the feed water

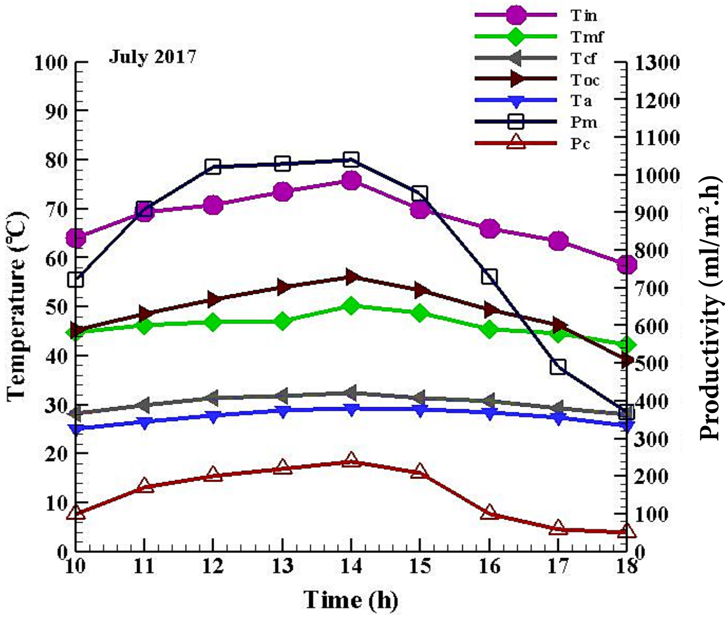

Fig. 11. Variations of temperature and productivity per hour in July

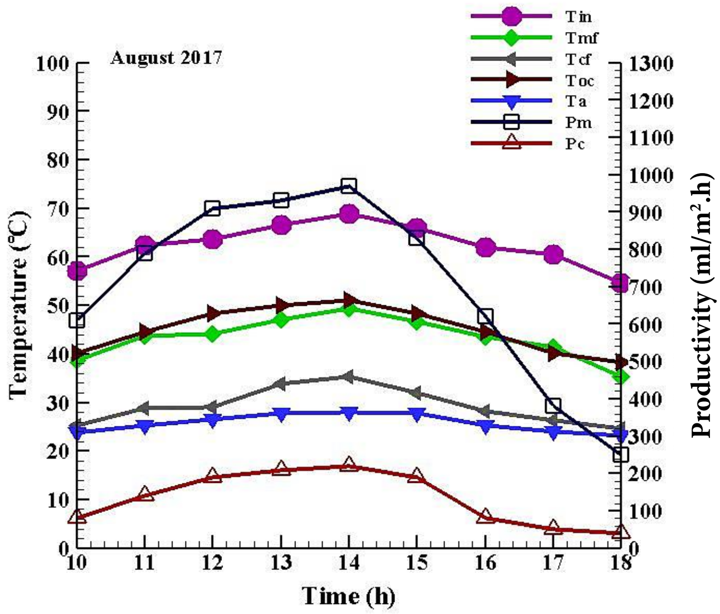

Fig. 12. Variations of temperature and productivity per hour in August

temperature. Since, the temperature inside the desalination shows the temperature of formed vapor, increasing this temperature could increse vapor production and consequently evaporation enhancement can lead to more fresh water production. Therefore, this parameter is directly related to the amount of fresh water produced.

The maximum temperatures of fresh water at the main outlet and condenser outlet were recorded at 13:00 and 14:00 with the values of 58 °C and 41 °C, respectively. The maximum and minimum ambient temperatures of 29.6 °C and 25.4 °C occurred at 14:00 and 10:00, respectively. Furthermore, the temperature at the outlet of collector and inlet of desalination system began from 35 °C at 10:00 and reached the maximum of 52.9 °C at 18:00. According to this figure, the maximum fresh water productivity at the main outlet and condenser outlet was obtained of 850 mlit and 275 mlit, respectively, between 13:00 and 14:00. Thus, the maximum fresh water productivity of the system was 1125 mlit in this period. Finally, the produced fresh water obtained 6980 mlit/m^2 from 9:00 to 18:00.

Fig. 8 demonstrates temperatures of different sections of the combined system and productivity of the desalination system in the experiment conducted on 6 August 2015. As can be observed in the figure, the average temperature in

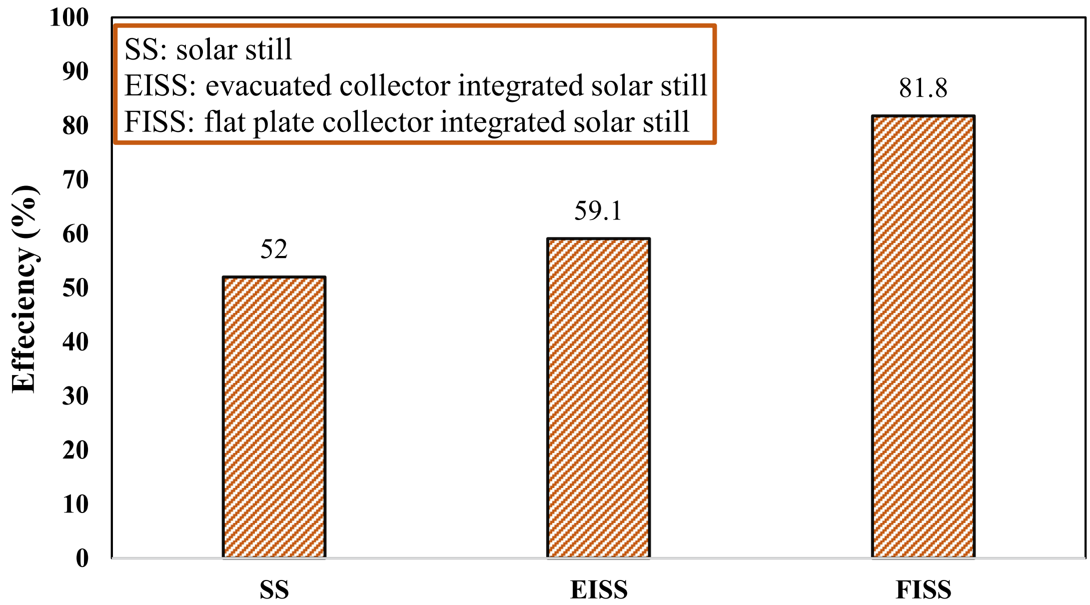

Fig. 13. Efficiency comparison between solar still and combined systems

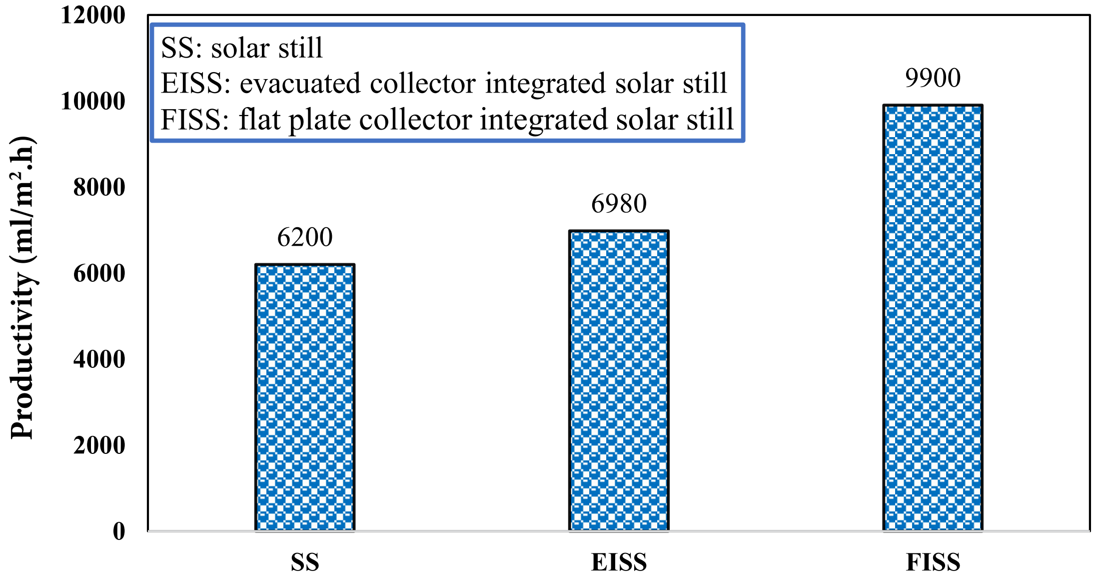

Fig. 14. Fresh water productivity comparison between solar still and combined systems

this experiment is lower than that in the former experiment. Therefore, temperatures of different parts of the desalination system and the temperature at the collector outlet are lower than that of the former case. The maximum temperatures of the system interior and the fresh water at the main outlet in this experiment are 76.6 °C and 57.3 °C, respectively, at 15:00. In this figure, compared to the previous figure, due to the decrease in temperature inside the system, fresh water production is expected to decrease.

Furthermore, the maximum temperature of fresh water at the condenser outlet was recorded equal to 36.2 °C at 13:00. The difference of pick hours of these three temperatures is due to the different locations of thermocouples, i.e. the condenser is located behind the desalination system while the thermocouples for measuring the temperatures of system interior and fresh water at the main outlet are positioned in front of the desalination system where the instantaneous variations of weather conditions yield different changes in them. The minimum and maximum ambient temperatures were reported equal to 24.2 °C and 28 °C at 10:00 and 15:00, respectively. Furthermore, the maximum temperature at the collector outlet in this experiment was recorded equal to 70 °C at 18:00. Due to the general reduction in this experiment, the aggregate produced fresh water was negligibly diminished on this day. The maximum produced fresh water at the main outlet was 840 mlit between 14:00 and 15:00. Furthermore,

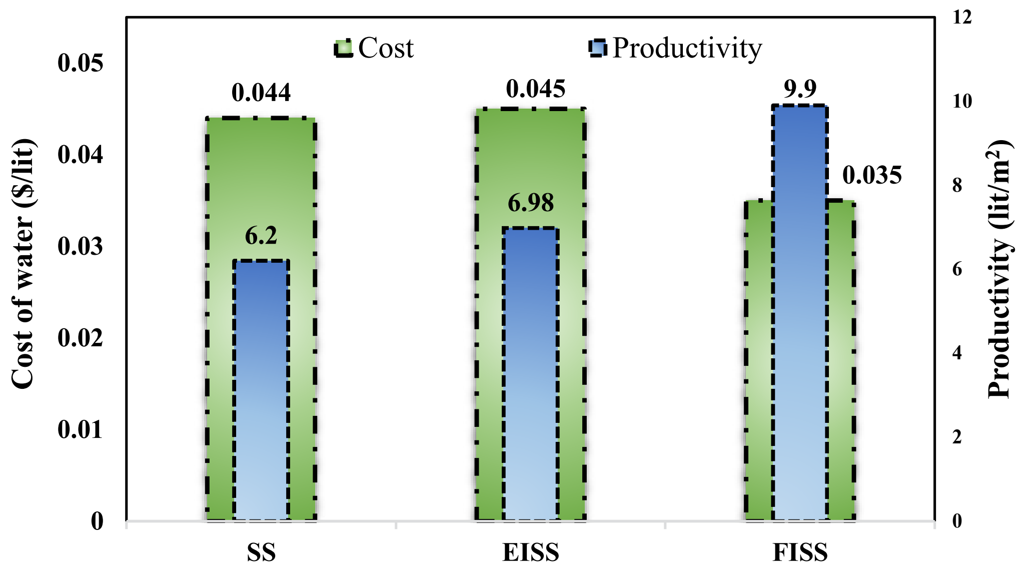

Fig. 15. Comparison of productivity and fresh water cost between combined systems and palin solar still

the maximum condenser production was reported equal to 270 mlit between 13:00 and 14:00. The produced fresh water was recorded equal to 6925 $mlit/m^2$. The productivity of the experiment on this day was reduced by 55 mlit compared to the experiment of previous day which can be attributed to the temperature drop as a natural phenomenon on this day.

Fig. 9 depicts the variations of temperature and productivity of the system during the experiment performed on 7 August 2015. Compared to the experiments performed in previous days, the ambient temperature was lower in this experiment such that the maximum temperature was reduced by 5.4 °C and 3.8 °C compared to the experiments of first and second days, respectively. The maximum ambient temperature and the maximum temperature inside the system were reported equal to 25 °C and 74.5 °C, respectively, at 16:00 and the maximum temperature of fresh water at the main outlet was 57.3 °C at 15:00. The the temperature inside the system is lower than that of obtained from two privieous experiments, furthemeore lower amount of fresh water is expected.

Moreover, the maximum temperature of fresh water at the condenser outlet was 34.6 °C at 13:00 and the maximum and minimum temperatures of the collector outlet were recorded equal to 66.7 °C and 52.6 °C, respectively. The maximum productivity was obtained of 825 mlit in the period of 14:00 to 15:00. The maximum and minimum condenser productivity was recorded equal to 250 mlit and 115 mlit between 13:00 and 14:00 and between 9:00 and 10:00, respectively. The overall produced fresh water was 6660 $mlit/m^2$ which decreased by 320 mlit and 256 mlit compared to the experiments of the first and second days, respectively. Due to the reduction in the ambient temperature and the decrease in the maximum temperatures by 3-4 °C compared to previous days, this drop of fresh water productivity is rational.

The maximum radiations of the experiments performed in the first, second and third days are 1076 W/m^2, 1068 W/m^2 and 1066 W/m^2 at 13:00, 13:00, and 12:00, respectively. Regarding the obtained data for the radiation and according to Fig. 6, it is observed that there was more radiation in the experiment on the first day and decreases as the days went on with its minimum on the third day. Based on the radiation diagram, the obtained results seem rational for temperatures and fresh water productivity. Furthermore, the maximum radiation occurred between 12:00 and 13:00 while the maximum temperature between 14:00 and 15:00. This is attributed to the rotation of the system in all of the experiments by some degrees to the southwest so as to benefit from more heat in the afternoon. Hence, sun radiated perpendicular to the system between 14:00 and 15:00 where higher temperature was recorded.

6.1.2. Results of FISS

Fig. 10 shows the temperatures of different parts and productivity in the flat plate collector integrated cascade solar still in June. The maximum temperature of the desalination system interior was recorded 83.57 °C at 14:00. The maximum fresh water temperatures at the main and condenser outlets were 76.29 °C and 50.20 °C at 14:00. The maximum and minimum ambient temperature in this experiment were recorded 33.36 °C and 29 °C at 14:00 and 10:00, respectively. Moreover, the maximum and minimum fresh water temperatures at the desalination system inlet in this experiment were 63.5 °C and 53.2 °C at 14:00 and 18:00, respectively. According to this figure, the maximum productivity at the main and external condenser outlets obtained equal to 1170 mlit and 270 mlit, respectively, from 13:00 to 14:00. The minimum fresh water productivity at the main and condenser outlets was reached of 500 mlit and 70 mlit, respectively, between 17:00 and 18:00. Finally, the total

Table 1. Present worth, maintenance costs, salvage value, net equivalent uniform annual, and average annual productivity for the solar still and combined systems

System	SS	EISS	FISS
Present worth ($)	228.58	285.71	300
Annual fixed cost ($/year)	45.54	56.93	59.78
Salvage value ($)	45.7	57.14	60
Annual salvage value ($/year)	2.25	2.81	2.95
Annual maintenance cost ($/year)	8.65	10.8	11.36
Net equivalent uniform annual ($/year)	51.95	64.9	68.18
Average annual productivity (lit/year)	1172	1456.6	1953
Cost of fresh water ($/lit)	0.044	0.045	0.035

Table 2. Comparison between the results obtained by the present study and results of previous studies

Reference	Combined system	Daily productivity (mlit/m^2)	Enhancment produvtivity (%)	efficiency	Fresh water cost ($/lit)
Sharshir et al. [21]	Evacuated collector integrated with solar still	6080	-	53	0.039
Morad et al. [6]	Flat plate collector integrated with solar still	8520	33	33	-
Fathy et al.[17]	Parabolic collector integrated with solar still	8530	89	23.26	-
Patel et al.[19]	Evacuated collector integrated with solar still	4050	29	-	0.0056
Present study	Flat plate collector integrated solar still	9900	60	81.8	0.035

fresh water production of this system was 9900 mlit/m^2 from 9:00 to 18:00.

Fig. 11 depicts the temperatures of different parts and productivity of the system in July 2017. The maximum temperature of the desalination system interior was recorded 75.88 °C at 14:00. The maximum fresh water temperatures at the main and condenser outlets were 70.2 °C and 44.4 °C at 14:00. The maximum and minimum ambient temperature in this experiment were recorded 31.26 °C and 27 °C at 14:00 and 10:00, respectively. Moreover, the maximum and minimum fresh water temperatures at the desalination system inlet in this experiment were 56.12 °C and 39.11 °C at 14:00 and 18:00, respectively. The maximum productivity at the main and condenser outlets was obtained equal to 1040 mlit and 240 mlit, respectively, between 13:00 and 14:00. Therefore, the maximum productivity of the system was 1280 mlit. The minimum fresh water productivity at the main and condenser outlets was reached of 370 mlit and 50 mlit, respectively, between 17:00 and 18:00. Finally, the total fresh water production of this system was obtained of 8610 mlit/m^2 from 9:00 to 18:00.

Fig. 12 shows the temperatures of different parts and productivity of the system in August. The maximum temperature of the still interior was recorded 68.88 °C at 14:00. The maximum fresh water temperatures at the main and condenser outlets were 61.32 °C and 41.3 °C at 14:00. The maximum and minimum ambient temperature in this experiment were recorded 28 °C and 23.2 °C at 14:00 and 18:00, respectively. Moreover, the maximum and minimum fresh water temperatures at the desalination system inlet in this experiment were 51.05 °C and 38.23 °C at 14:00 and 18:00, respectively. According to this figure, the maximum productivity at the main and condenser outlets was obtained equal to 970 mlit and 220 mlit, respectively, between 13:00 and 14:00. Therefore, the maximum productivity of the system was 1190 mlit. The minimum fresh water productivity at the main and condenser outlets was reached of 250 mlit and 40 mlit, respectively, between 17:00 and 18:00. Finally, the total fresh water production of this system was obtained of 7490 mlit/m^2 from 9:00 to 18:00.

By comparing the above diagrams while FISS and EISS produced the highest amount of fresh water (comparing Figs. 7 and 10), it could be concluded that the amount of fresh water produced in the main desalination condenser of EISS is higher than the amount produced in the FISS, but on the other hand the fresh water production in the external condenser EISS is higher than that of the FISS. Although, the total fresh water produced by FISS in higher that that obtained by EISS. This issue is found to be affected by ambient temperature and thus the temperature inside the desalination.

Fig. 13 compares the efficiency of the cascade solar still with

NOMENCLATURE

AFC	Annual fixed cost ($/year)
AMC	Annual maintenance cost ($/year)
AP	Average annual productivity (lit/year)
ASV	Annual salvage value ($/year)
CPL	Cost of fresh water per liter ($/lit)
CRF	Capital recovery factor
d	Counter of days of year
EISS	Evacuated collector integrated solar still
EUAB	Equivalent uniform annual benefit ($/year)
EUAC	Equivalent uniform annual cost ($/year)
FISS	Flat plate collector integrated solar still
h_{fg}	Latent heat of evaporation (J/kg)
i	Interest rate (%)
I	Intensity of solar radiation W/m^2
In	Initial cost, ($)
k	Number of exploitation years
M	Total production, (kg/m^2)
Ma	Maintenance cost ($)
NEUA	Net equivalent uniform annual ($/year)
Op	Operational cost ($)
P	System present worth ($)
Pc	Fresh water produced at the condenser outlet (ml/ m^2)
Pm	Fresh water produced at the main outlet (ml/ m^2)
Pt	Total volume of produced fresh water (ml/ m^2)
S	Salvage value ($)
SS	Solar still
SSF	Sinking fund factor
SV	Salvage value ($)
T	Temperature (°C)
Greek Symbols	
ε	Purchase price
φ	Sales price
Subscripts	
a	Ambient
c, cf	Fresh water at condenser outlet
e	Electricity
f	Fuel
in	Interior of solar still
j	Equipment counter
m, mf	Fresh water at the main outlet
oc	Outlet of condenser

the efficiency of combined systems at maximum productivity. The efficiency of the flat plate collector integrated solar still increased by 30% compared to the solar still and reached the value of 81.1%. Also, the efficiency of the evacuated collector integrated solar still was equal to 59.1%.

Fig. 14 provides a fresh water productivity comparison between solar still and combined systems. The still production was 6200 mlit/m^2 and the maximum production of the evacuated collector integrated solar still was 6980 mlit/m^2 . Thus, the productivity of the combined system increased by 780 mlit compared to the plain solar still. Furthermore, the maximum production of the flat plate collector integrated solar still was 9900 mlit/m^2 in June, i.e. 3700 mlit more than the production of solar still.

6.2. Results of economic analysis

Table 1 presents the present worth, maintenance costs, salvage value, net equivalent uniform annual, and average annual productivity for the solar still and combined systems.

The obtained results from the economic analysis shows the cost of fresh water produced by the solar still equal to 0.044 $/lit. The cost of fresh water produced by the evacuated collector integrated solar still and by the flat plate collector integrated solar still at maximum reported productivity was calculated of 0.045 $/lit and 0.035 $/lit. Fig. 15 compares the cost of fresh water produced by the solar still and combined systems. It is worth noting that the combined systems were compared at maximum productivity in the experiments. As can be observed, the amount and cost of fresh water produced by the evacuated collector integrated solar still are escalated by 0.78 lit and 0.001 $/lit, respectively, compared to the plain solar still. Furthermore, the amount and of fresh water produced by the flat plate collector integrated solar still increased by 3.7 lit and the cost of water obtained 0.009 $/lit, respectively.

Table 2 makes a comparison between the obtained results from the present study with the results of previous studies. The mentioned results have been reported with respect to the type of combined solar collector and still. It is worth mentioning that the solar stills which investigated by Patel et al. [19] are stepped type basin still. However, in their works, water in each stair overflows into the next step, whereas in the desalination cascade used in this study, water in each staircase leads to a spiral path to the next stage and passes a longer distance with longer time. This fact causes the productivity of solar still without using solar collector is higher than the amount of product which repoeted by these two references and certainly by preheating feed water through solar collector, the product enhances more. As a result, the percentage of product growth in the present study is higher than the mentioned researches. In Morad et al. [6] and Fathy et al. [17] papres, a double slopes basin type solar still have been considered which Morad et al. [6] applied a flat plate solar collector and Fathy et al. [17] used a parabolic solar collector in order to preheat the feed water. They reported 33% and 89% enhacement in fresh water production. According to these issues , as it is cocluded from Table 2, the under study combined system in the present work have been suitable performance.

7. CONCLUSION

The present study investigated an experimental investigation of a solar still which its feed water preheated by two differenet solar collector; an evacuated tube solar collector and a conventional flat plate solar collector. Then, an economical evaluation for calculating the cost of produced fresh water was carried out. The obtained results are summarized as follows:

· The maximum fresh water productivity of the flat plate collector integrated solar still was recorded 9900 mlit/m^2 that was higher than that of the plain solar still by 60%.

· The maximum fresh productivity in the experimental period was 6980 mlit/m^2 for the evacuated collector integrated solar still that was larger than that of the plain solar still by 13%.

· The cost of fresh water produced by the solar still and the flat plate collector integrated solar still were obtained of 0.044 $/lit and 0.035 $/lit, respectively. The cost of fresh water produced by the combined system reduced by 20% compared to that of the plain solar still.

· The cost of fresh water produced by the evacuated collector integrated solar still was calculated equal to 0.046 $/lit that was higher than that of the plain solar still by 4.5%.

· The efficiency of solar still was 52% while it was 81.8% and 59.1% for the flat plate collector integrated solar still and evacuated collector integrated solar still, respectively.

ACKNOWLEDGMENT

The authors would like to acknowledge the financial support of Bozorgmehr University of Qaenat for this research under contract number.

REFERENCES

[1] H.N. Panchal, S. Patel, An extensive review on different design and climatic parameters to increase distillate output of solar still, Renewable and Sustainable energy reviews, 69 (2017) 750-758.
[2] G. Tiwari, A. Tiwari, Handbook of solar energy, Springer, 2017.
[3] H.K. Jani, K.V. Modi, A review on numerous means of enhancing heat transfer rate in solar-thermal based desalination devices, Renewable and Sustainable Energy Reviews, 93 (2018) 302-317.
[4] 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 and Sustainable Energy Reviews, 101 (2019) 197-220.
[5] A. Kabeel, A. Khalil, Z. Omara, M. Younes, Theoretical and experimental parametric study of modified stepped solar still, Desalination, 289 (2012) 12-20.
[6] M. Morad, H.A. El-Maghawry, K.I. Wasfy, Improving the double slope solar still performance by using flat-plate solar collector and cooling glass cover, Desalination, 373 (2015) 1-9.
[7] S. Sharshir, G. Peng, N. Yang, M.A. Eltawil, M.K.A. Ali, A. Kabeel, A hybrid desalination system using humidification-dehumidification and solar stills integrated with evacuated solar water heater, Energy conversion and management, 124 (2016) 287-296.
[8] T. Arunkumar, R. Velraj, D. Denkenberger, R. Sathyamurthy, K. Vinothkumar, K. Porkumaran, A. Ahsan, Effect of heat removal on tubular solar desalting system, Desalination, 379 (2016) 24-33.
[9] E. Saettone, Y. Valencia-Tovar, A. Gómez-de-la-Torre-Gastello, Preliminary overview and evaluation of a stepped solar distiller with internal reflective walls and borosilicate vacuum tubes, Desalination, 413 (2017) 136-143.
[10] R.S. Hansen, K.K. Murugavel, Enhancement of integrated solar still using different new absorber configurations: An experimental approach, Desalination, 422 (2017) 59-67.
[11] M. Elashmawy, An experimental investigation of a parabolic concentrator solar tracking system integrated with a tubular solar still, Desalination, 411 (2017) 1-8.
[12] R. Lalitha Narayana, V. Ramachandra Raju, Effect of flat plate collectors in parallel on the performance of the active solar still for Indian coastal climatic conditions, International Journal of Ambient Energy, 40(2) (2019) 203-211.
[13] A.M. Manokar, D.P. Winston, A. Kabeel, R. Sathyamurthy, Sustainable fresh water and power production by integrating PV panel in inclined solar still, Journal of cleaner production, 172 (2018) 2711-2719.
[14] A. Kabeel, E.M. El-Said, Experimental study on a modified solar power driven hybrid desalination system, Desalination, 443 (2018) 1-10.
[15] A. Abdessemed, C. Bougriou, D. Guerraiche, R. Abachi, Effects of tray shape of a multi-stage solar still coupled to a parabolic concentrating solar collector in Algeria, Renewable energy, 132 (2019) 1134-1140.
[16] M. Al-harahsheh, M. Abu-Arabi, H. Mousa, Z. Alzghoul, Solar desalination using solar still enhanced by external solar collector and PCM, Applied Thermal Engineering, 128 (2018) 1030-1040.
[17] M. Fathy, H. Hassan, M.S. Ahmed, Experimental study on the effect of coupling parabolic trough collector with double slope solar still on its performance, Solar Energy, 163 (2018) 54-61.
[18] M. Feilizadeh, M.R.K. Estahbanati, M. Khorram, M.R. Rahimpour, Experimental investigation of an active thermosyphon solar still with enhanced condenser, Renewable Energy, 143 (2019) 328-334.
[19] J. Patel, B.K. Markam, S. Maiti, Potable water by solar thermal distillation in solar salt works and performance enhancement by integrating with evacuated tubes, Solar Energy, 188 (2019) 561-572.
[20] M. Bhargva, A. Yadav, Experimental comparative study on a solar still combined with evacuated tubes and a heat exchanger at different water depths, International Journal of Sustainable Engineering, (2019) 12-1.
[21] S.W. Sharshir, A. Kandeal, M. Ismail, G.B. Abdelaziz, A. Kabeel, N. Ynag, Augmentation of a pyramid solar still performance using evacuated tubes and nanofluid: Experimental approach, Applied Thermal Engineering, (2019) 113997.
[22] H. Singh, G. Tiwari, Monthly performance of passive and active solar stills for different Indian climatic conditions, Desalination, 168 (2004) 145-150.
[23] M.M. Ghafurian, H. Niazmand, E. Ebrahimnia-Bajestan, H.E. Nik, Localized solar heating via graphene oxide nanofluid for direct steam generation, Journal of Thermal Analysis and Calorimetry, 135(2) (2019) 1443-1449.
[24] M.M. Ghafuoryan, S.E. Shakib, F.T. Dastjerd, Modeling and optimizing of a combined CHP system, compression chiller and reverse osmosis plant (CHP+ C+ W) in two strategies of connections with grid, Journal of the Brazilian Society of Mechanical Sciences and Engineering, 37(6) (2015) 1751-1763.
[25] M.M. Oskoonejad, Engineering Economy, Amirkabir University, 2007.
[26] A. Kabeel, S.W. Sharshir, G.B. Abdelaziz, M. Halim, A. Swidan, Improving performance of tubular solar still by controlling the water depth and cover cooling, Journal of Cleaner Production, (2019).

HOW TO CITE THIS ARTICLE

M. Vafaei, R. Karimi, Samadi S. Semnani, A. Arbabi, M. BarzgarNezhad, S.E. Shakib, Gh. Ghassabi, M.H. Shafiei Mayam, Experimental Study and Economical Analysis of a Cascade Solar still Integrated with an Evacuated Tube and a Conventional Flat Plate Solar Collectors, AUT J. Mech Eng., 4(3) (2020) 301-314.

DOI: 10.22060/ajme.2019.16796.5837