Investigating the performance of a Novel Deep feeding Technique in All-Water Evacuated tube Collectors for Solar Desalination Systems

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Received: 01.02.2023 Accepted:22.03.2023

Abstract- Water desalination is one of the most branches investigated due to freshwater scarcity. One of the most effective water desalination techniques is solar desalination. Solar desalination works better under high temperatures of water due to the increase of the evaporation and desalination rates. Evacuated tube solar collector (ETSC) presents an advantage as a solar water heater in medium temperature ranges and is suitable for solar desalination. The enhancement of its performance has been a hot topic in the last years due to its high efficiency at high temperatures. However, the techniques with which the ETSC is implemented, differs in storage availability, as in the all-water systems, or high heat transfer rates, as in the direct flow system. In the present research a novel technique combining the benefits of both all-water and direct flow systems is presented to increase the temperature of the heated water. The combined system considers the injection of the feed water inside the ETSC directly to make use of the forced convection heat transfer and destruct the stagnation zone in the bottom of the tubes. Three water flow rates of 2, 4, 8 LPH were tested. The combined system achieved an enhancement in the thermal efficiency and the maximum temperature getting out from the ETSC by 27% and 14.7%, respectively, at a flow rate of 8 LPH. Moreover, the overall efficiency was enhanced by up to 27.3%, compared to all-water system. The economic study showed that the cost of heated water with the proposed system over the traditional system reaches 0.00195 $/kw.hr for 8 LPH extraction rate. Due to this increase in the system temperature, the proposed techniques can be applied for solar desalination. A numerical simulation model was created, and its results found to agree with the experimental results by 5.4% relative error.

Keywords ETSC; efficiency; Outdoor test; solar desalination; Experimental Test; Numerical Simulation.

1. Introduction

Water desalination is one of the most needed topics for the high need of fresh water all over the world. One of the promising desalination techniques, based on the renewable energy resources, is the solar desalination. Solar desalination systems can be divided into active and passive systems. The active systems need a backup source of heat with the solar energy. However, the passive systems are based on solar energy as the only source of heat [1]. The solar desalination techniques depend in most cases on raising the temperature of salt water to separate the fresh water by evaporation and then condensation. As the temperature of the saltwater increases, the evaporation rate increases, and the condensation rate increase as well. So, the need arises for a high efficiency type of solar collectors that can give the highest efficiency with the lowest costs. These conditions exist in the Evacuated Tube Solar collector (ETSC). ETSC is one of the promising solar water heaters due to its good insulation. It is composed of two glass layers with vacuum in between. This vacuum region makes good thermal insulation for conductive and convective heat transfer. The outer tube is transparent to permit the penetration of solar radiation. The inner tube is coated from outside by high absorptivity and low emissivity coating, to enlarge the heat absorbed from the solar radiation. The advantage of its good insulation due to the vacuum region is emphasized in the medium and high temperature ranges. The techniques with which the ETSC is used as a solar heater includes all water, heat pipe and direct flow system. All water system relay on the free convective heating of the water included in the ETSC and in the tank connected to it. The heat pipe system includes heat pipe inside the ETSC and a manifold at the ETSC opening. This manifold is used to collect the thermal energy through heat exchange with the heat pipe bulb. Many research works were presented in enhancing the performance of heat pipe ETSC systems [2], [3], and [4]. Both of all water system and the heat pipe system requires the inclination of the ETSC as they operate according to the free convection. On the contrary, the direct flow system considers an open loop passage for the heating medium inside the ETSC. This passage could be U-tube or concentric tube. The direct flow system depends on the forced convective heat transfer from the ETSC to the heat transfer fluid (HTF). So, it achieves higher thermal efficiency for its better heat transfer. Many research works were conducted in investigating the performance of ETSC systems with enhancements. Some of this research investigated the enhancement of the DF type ETSC, which depends on the forced convection heat transfer scheme and test multiple enhancements including different geometrical modifications [5], [6], [7] and [8]. Nitsas and Koronaki, [9] investigated the performance of DF-ETSC with mini-CPC reflectors for each tube. They found that the maximum optical efficiency achieved in the range of 0° to 25° inclination angle. Bhowmik et al. [10] investigated the effect of using multilayer precipitation on the fins for the U-tube DF-ETSC. They found that this effect achieves an average daily efficiency of 53%. Liang et al. [11] investigated the effect of using filler material inside the DF-ETSC. They found an enhancement of 12% in the efficiency. Gao et al. [12] compared the performance of DF-ETSC and all-water ETSC. They found that the DF-ETSC achieves higher thermal efficiency. However, all water system achieves higher storage efficiency. Kaya et al. [13] investigated the performance of the DF-ETSC with ZnO/Etylene glycol-water nanofluid, they found that the efficiency reached 62.86%. Essa et al. [14] investigated the effect of extending the surface of the DF-ETSC using helical tube. They found that the efficiency reached 38.6%. Some papers investigated the enhanced the performance of the DF-ETSC with phase change material (PCM) storage to solve the storage problem for U-tube [15] [16] and concentric tube DF-ETSC [17]. Kumar et al. [18] investigated experimentally the effect of longitudinal baffles inserts on the performance of air ETSC. They found a maximum temperature increase of 42.8^{o}C was achieved at the lowest tested flow rate of 100 kg/hr, and lowest thermal efficiency of 35.31%. They argued that the increase in the baffle's length increases the temperature rise and increases the pumping power. Moreover, Kumar et al. [19] investigated the effect of twisted tape inserts with various configurations, on the performance of air ETSC analytically. They found that the Loose-Fit Perforated Twisted Tape (LFPTT) achieves the highest energy effectiveness. The results showed that the highest energy efficiency of 62.33% was achieved with the LFPTT at the maximum tested flow rate of 400 kg/hr, with helical twist ratio and tap hole diameter ratio of 2 and 0.0714, respectively. The exergy efficiency reached its peak of 3.91% with the lowest flow rate and found to decrease with the increase of the flow rate. Regarding the all-water ETSC system, many research papers were presented for investigating its enhancements. Tabarhoseini and Sheikholeslami, [20] investigated numerically the effect of longitudinal fins in the ETSC within all-water system using nanofluid. They found that the longitudinal fins increase the thermal efficiency up to 65.21% with 5% nanofluid concentration of Cu. At these conditions, the optical efficiency reached 67.61%. Chai, et al. [21] proposed and fabricated an evacuated tube solar collector with inner concentrating (ETSC-IC) by reflective coating. They found that the thermal efficiency of the ETSC-IC was improved by approximately 10% compared with the conventional ETSC due to the enhanced irradiation concentrating and the reduction of heat loss caused by the coating on the outer glass tube. Bracamonte, [22] studied numerically the effect of the transient energy input on the performance of all-water ETSC. He discovered the existence of stagnant region at the bottom of the evacuated tubes in which the fluid does not renew and still. This was a problem that some researchers later tried to solve it. Jowzi et al. [23] investigated experimentally and numerically the effect of bypass tube inside the ETSC on its performance. This modification increased the efficiency by 11% and increased the temperature uniformity inside the tube and the tank. For a test period of one hour, the gained thermal energy of the modified system increased by 25% compared to the typical system. Li et al. [24] investigated the performance of a solar still connected to ETSC for water desalination. They found that the productivity of the system's performance can reach 4.23kg/m^2 of fresh water with a maximum thermal efficiency of 41%. Behnam and Shafii, [25] investigated the performance of a proposed desalination systems connected with a heat pipe ETSC. They found an increase in the systems performance when adding a filler oil in the space between the absorber plate and the heat pipe. They reported a daily productivity of fresh water reaching to 6.275 kg/m^2 with an overall efficiency of 65%. Abbaspour et al. [26] investigated the effect of vacuum on increasing the evaporation rate from the ETSC. They found that the hourly productivity of fresh water reached 1.134 kg/m^2 with an overall daily efficiency of 47.6%. Alshqirate et al. [27] investigated the effect of using natural fibers on the enhancement of the solar still desalination system. They found that the daily thermal efficiency reaches 44.9%. Many research work made use of the solar collectors in heating applications as well [28], [29], [30], [31] and [32].

According to the presented literature, it can be concluded that all water system is preferred in cases of storage needs, and the direct flow is preferred in cases of the higher efficiency heating needs, which is preferred in solar desalination systems. However, the direct flow needs continuous flowing systems, which is not convenient for solar desalination to perform the evaporation and condensation process. In the present study, a novel system for combining all-water and DF types is considered to take the benefit of thermal energy storage with the high heating efficiency. This research presents a comparative study between the all-water system as the reference system and the new combined system (CS) to investigate its performance and convenience for solar desalination systems. Moreover, a numerical simulation was performed and validated with the experimental results.

2. Materials and Methods

In the present study, an experimental comparative study was conducted for investigating the performance of the new proposed combined heating system compared to the all-water system. Moreover, a numerical simulation was performed and validated with the experimental study.

2.1 Experimental Setup

A comparative study was conducted to study the performance of the modified system. The reference system is an all-water ETSC with 10 tubes and a 50litre storage tank connected to the tubes. The CS was a similar system in the number of tubes and the storage tank capacity. However, in the CS, the flow direction of the feed water was directed inside the ETSC using stainless stell tubes to fill the ETSC and then get out from the ETSC opening into the storage tank. This, in turn, makes the heating process combined between forced convection in the ET during the feeding process and free convective during the stagnation time. In the reference system, the water flows inside the tank from an opening in its base. Then water flows in the ETSC from its opening connected to the tank. In that case the heating is totally through free convection in the ET and the tank. The test system contains one primary storage tank of 200 litres. This primary tank feeds two level controlled secondary tanks connected to the reference and the CS ETSC, to keep the same water level in both systems. The system layout for both collectors is shown in Fig.1.

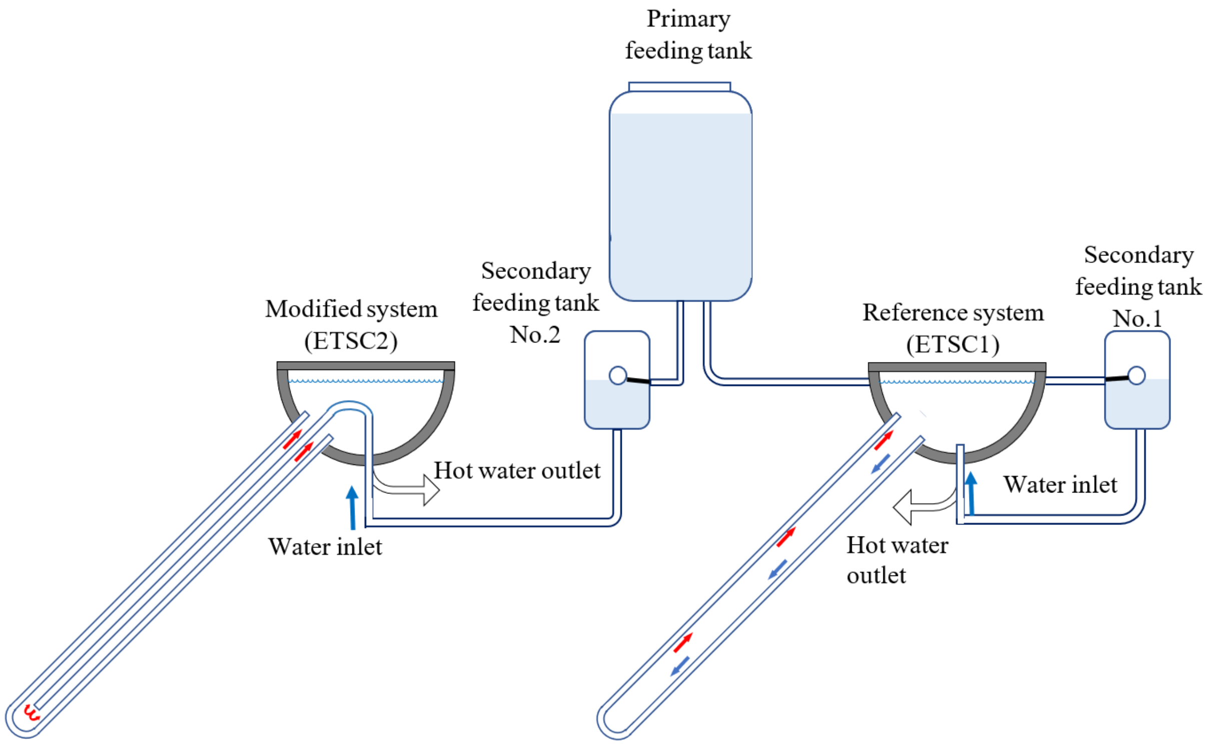


Fig. 1. Layout for the test reg including the reference system and the modified (combined) system.

2.1.1 Measurement Tools

The tests were performed at three different extraction frequencies of water, simulating the real extraction for the user of hot water. These rates were 0.5, 1.0 and 1.5 Litres every 15 minutes, which are equivalent to 2, 4 and 8 LPH. For measuring that rate, a stopwatch and 2 Litres vessel were used. The temperatures of the feeding water, extracted water, and storage tank water were measured using ANSI T-type thermocouple with USB-2408 DAQ that is provided with cold junction compensation (CJC). A weather station (AcuRite 01009M Atlas) was used for measuring the wind speed, direction, and ambient temperature with a frequency of 30 seconds. For measuring the solar radiation intensity, Apogee SP-420 silicon was used each 12 seconds. The specifications of the measuring instruments are as in Table 1.

Table 1. The specifications of the measuring instruments.

Measuring device	Range	Uncertainty
wind speed [m/s]	0 to 71	±0.4
wind direction [degree]	0 to 360	±3
Ambient temperature [ºC]	-40 to 70	±0.5
pyranometer [W/m^2]	0 to 2000	±5%
thermocouples [ºC]	0 to 400	±0.5

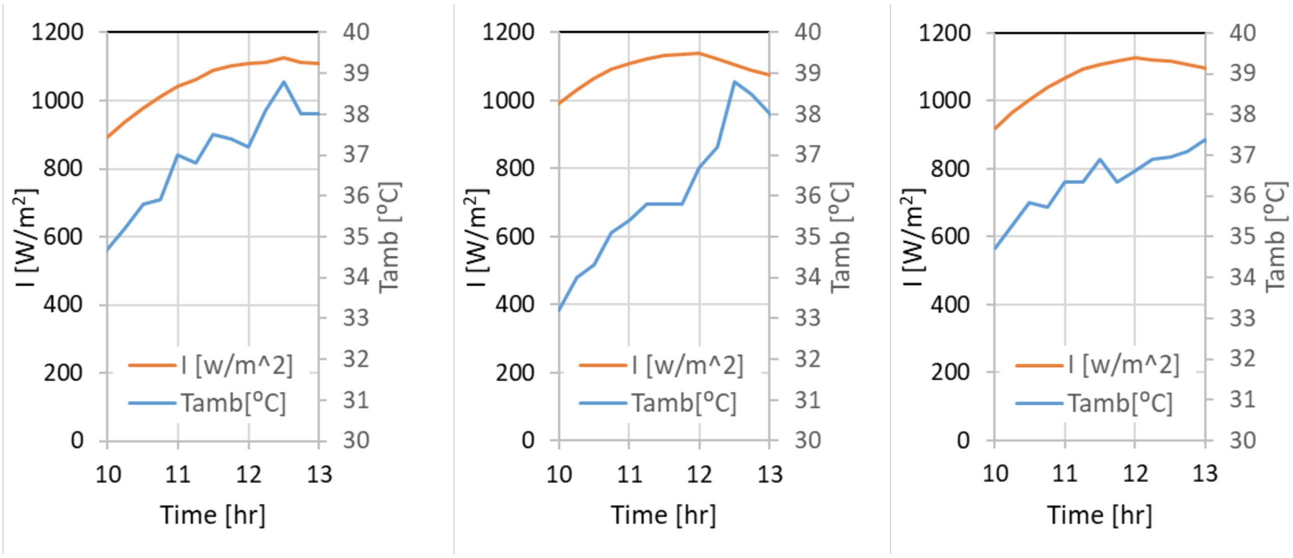
The temperature measuring location were at the top of the ET opening, the feeding tank, and a specified location inside the ETSC for validation, inlets and outlets of the systems. The location in the ET top opening used for recording the maximum temperature of the flow getting out from the tubes. The location in the tank used for measuring its average temperature. The validation location was on a depth of 30 cm in the tube from its opening and in its upper side. The thermocouples in the inlets and outlets was used for measuring the flow inlet and outlet temperature for calculating the collected heat.

2.1.2 Experimental Procedure

The procedure followed to perform the experiments was the same in all the tests. The tests of different condition were performed in different days as each has different water flow rate. The experimental procedure followed was as follows:

- The measurement devices were turned on at the beginning of the test.
- The water was permitted to flow from the primary tank to the secondary tanks and the water level was adjusted to be the same in both the reference and the CS ETSCs.
- The system was transported outside the lab outdoors beside the weather station to start collecting heat.
- The test was continued through about three hours, for each test.
- After this period, the measuring systems were turned off, and the system was transported back inside the lab.

The performed test of the 2, 4 and 8 LPH were performed on 7th and 9th of October and 14th of September 2021, respectively. The solar radiation and ambient temperature conditions in the test days are illustrated in Fig.2.



(a) (b) (c)

Fig. 2. The variation of the solar radiation intensity (I) and the ambient temperature (Tamb) through the test period for (a) 2 LPH, (b) 4 LPH and (c) 8 LPH.

2.2 Numerical Modelling

In the present study, a numerical simulation was performed for the reference system and the data was compared with the experimental results for the 4 LPH test case. Ansys ICEM was used as the geometry and grid generator, while Ansys Fluent 14.5 was used as the solver. A structured mesh was constructed for a single tube and its part of the storage tank with 410036 hexahedral cells. The applied boundary conditions are as shown in Fig.3. The solver performed the calculations over the continuity, Navier-stokes, and Energy equations. The solver used SIMPLE algorithm for the velocity-pressure coupling. The flow in the present simulation was considered laminar.

Some assumptions were set for the simulation compared to the experimental test. These assumptions were as follows:

- The performance of all the tubes was considered identical. So, the simulation was performed for a single tube with its part of the storage tank.
- The sides of the storage tank were considered as symmetry boundary conditions.
- Both the flow inlet and outlet were set in the bottom of the storage tank as exist in the reference system.
- The motion of the sun rays over the tube with time is considered during the simulation.
- The natural convection was considered in the simulation with the change of density according to the temperature.

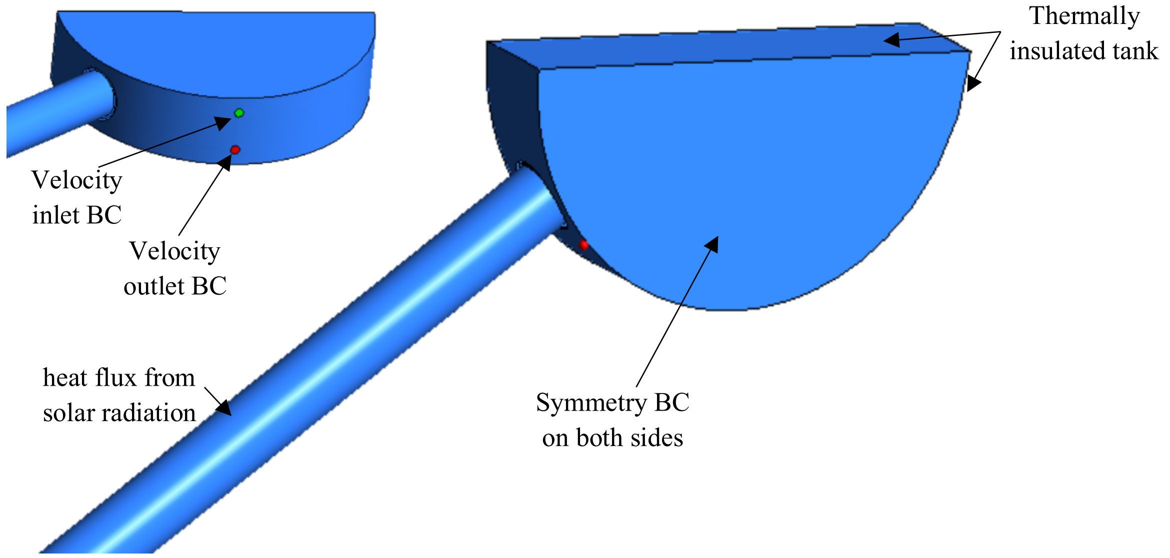


Fig. 3. The boundary conditions applied on the numerical model

A transient simulation was performed with time step of 0.1s for a period of 3900 seconds, which consumed 20 days of a Core i5-3470CPU@3.2 GHz with 6.0Gb RAM CPU operating parallel MPI for the 4 cores of the processor. The solar radiation, ambient temperature, wind speed and inlet water temperature were considered as boundary conditions in the simulation. The temperature contour of the mid plan of the model over the simulation time steps is shown in Fig.4.

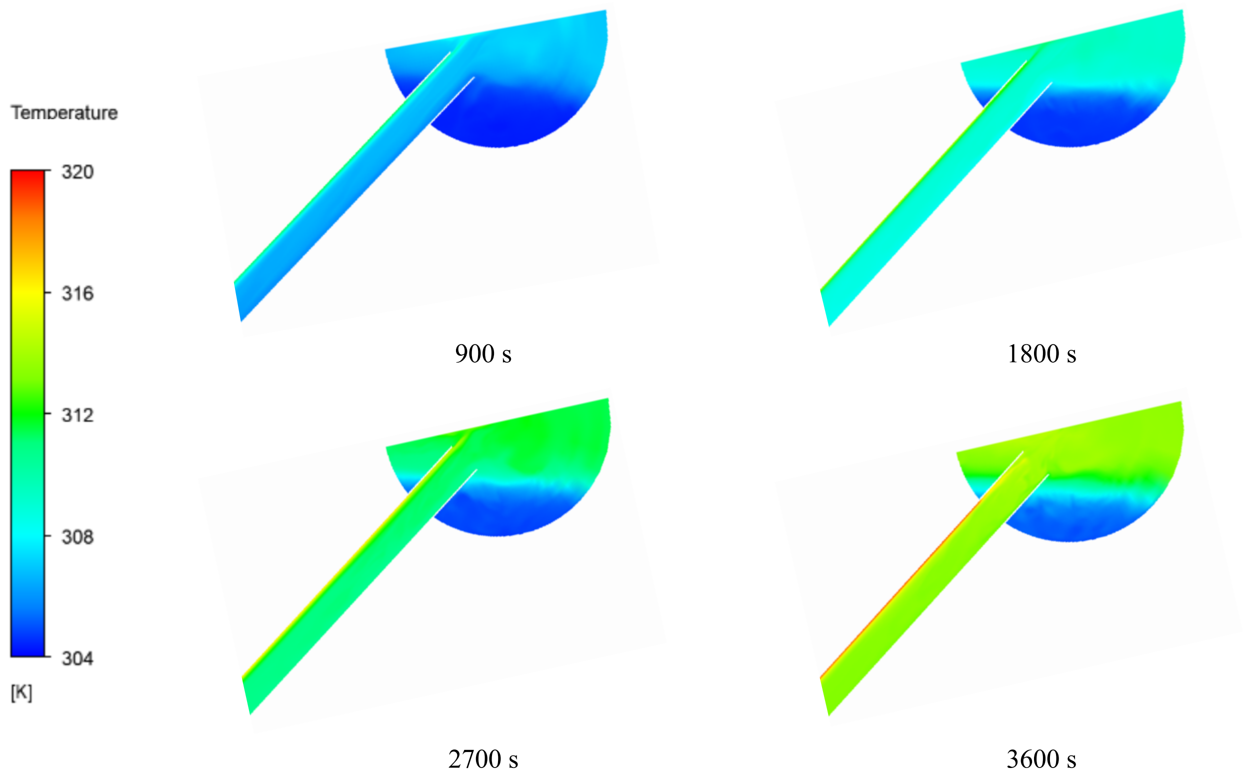


Fig. 4. The temperature contours in a vertical mid-plan of the model indicating the variation of temperature over time.

According to the solar radiation conditions illustrated in Fig. 1. It can be observed that during the time of the simulation, from 10:00 AM to 11:00 PM, the solar energy incident on the system increases, which causes the fluid to be heated. As a result, the hot fluid rises in the tank by free convection. The stratification of the tank can be observed from Fig. 4 in all the time steps illustrated. As the time passes, the temperature of the water in the tube increases, and the temperature of the water in the tank as well. The value of the temperature measured inside the tube on a 30 cm depth in the tube from its opening and on its upper side of the glass was recorded in the experiment. The simulation shows agreement with the experimental data by an absolute relative error (ARE) of 5.4 % maximum. The comparison of the temperature measurement at the point of the validation is shown in Fig.5.

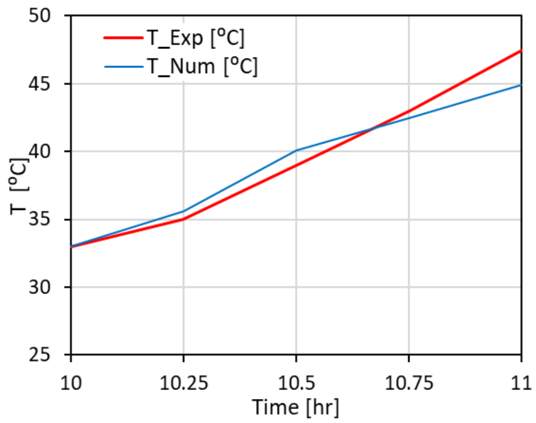


Fig. 5. Validation between the numerical and the experimental data.

2.3 Data Reduction

The energy extracted from the collector is q_{ext} expressed as follows:

$$q_{ext} = \dot{m} * c_p * (T_{out} - T_{in}) \qquad (1)$$

where $\dot{m}$ is the mass flow rate of water, c_p is the specific heat of water, T_{out} is the temperature of the extracted water in [K] and T_{in} is the feed water temperature in [K].

The extracted energy efficiency (η_{ext}) is a ratio between the extracted energy q_{ext}, and the solar energy input. This efficiency is expresses as follows:

$$\eta_{ext} = q_{ext}/(I_g * A) \qquad (2)$$

where I_g is the global inclined solar radiation incident on the collector in [W/m^2], and A is the aperture area of the collector in [m^2].

Some of this collected heat is stored in the Evacuated tubes and the storage tank. The heat stored in the tank ($q_{stor-tank}$) is expressed as follows:

$$q_{st\_ta} = m_{ta} * c_p * \left(T_{ta}^{i+1} - T_{ta}^{i}\right)/\Delta t \qquad (3)$$

Where m_{ta} is the mass of water in the storage tank, the superscript index on the temperature indicates the time step of the measurement for the average tank temperature. Δt expresses the time step between every two measurements of the temperature considered as 900 s in the present study.

The heat stored in the evacuated tubes ($q_{stor-ET}$) is expressed as follows:

$$q_{st\_ET} = N_{et} * m_{et} * c_p * \left(T_{ET}^{i+1} - T_{et}^{i}\right)/\Delta t \qquad (4)$$

where N_{et} is the number of the evacuated tubes connected to the tank, which is 10 for each collector in the present study, m_{et} is the mass of water in the single evacuated tube, $T_{et}^{(i+1)}$ is the average water temperature inside the tube at time step i+1.

The overall system efficiency (η_{ov}) is defined as the ratio between the summation of converted thermal energy (extracted and storage), and the solar energy input. This can be expressed as follows:

$$\eta_{ov} = (q_{ext} + q_{st-ta} + q_{st-et})/I_g * A \qquad (5)$$

The modified system and the reference system were compared based on η_{ov}.

3. Results and Discussion

A comparative experimental investigation was conducted to study the performance of the modified CS-system compared to all-water system as the reference system. Three extraction rates of 2,4 and 8 LPH were applied. The comparison between the two systems is based on three main parameters. These parameters are the temperature difference between the collector inlet and outlet, the water temperature at the top opening of the ET, the instantaneous efficiency and the overall efficiency.

3.1 Test results for 2 LPH flowrate

As the used hot water temperature is important as a performance parameter in the solar heaters, The temperature difference between the outlet and inlet for both systems is discussed firstly. This comparison is shown in Fig. 6. It can be observed that during the experiment, the CS achieved higher temperature differences than the traditional system (All water). The maximum temperature difference reached 13.7ºC in the CS and 11.1ºC in the traditional system, which achieves 23.4% enhancement in the outlet temperature. This performance proves the enhancement of the heat transfer by the proposed CS.

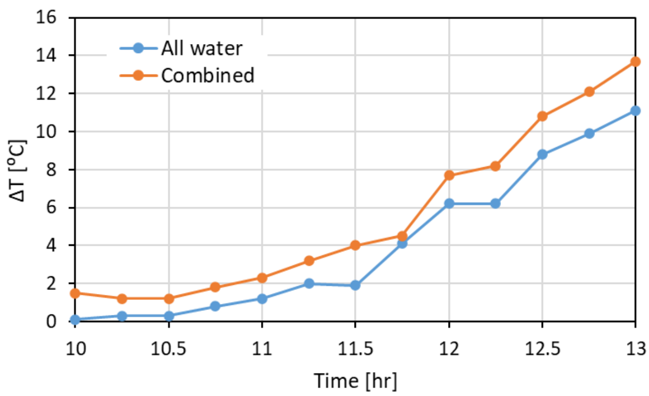


Fig. 6. The temperature difference between the outlet and the inlet water for both all-water and CSs for 2 LPH extraction rate.

Another comparison was performed between the maximum temperature flow getting out from the tube opening in both systems. This comparison is shown in Fig.7.

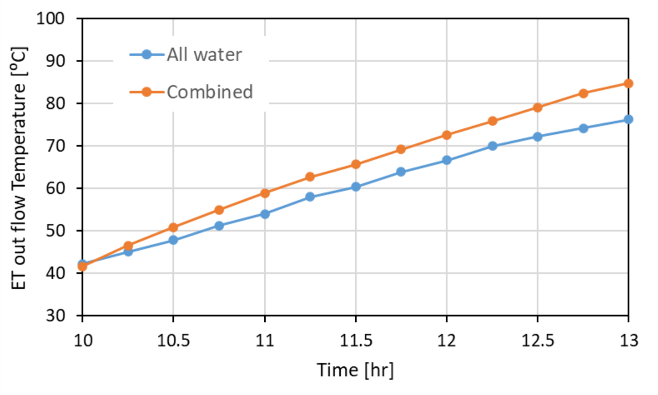


Fig. 7. A comparison between the traditional and the CS in the maximum temperature getting out from the tube opening for 2 LPH extraction rate.

It can be observed that, over the test period, the CS gives higher temperature than the all-water system. The difference of this temperature between the two systems reaches maximum of 8.5ºC, with enhancement of 11.1% for the CS over the all-water system. To evaluate the overall efficiency performance of the two systems, Fig. 8. shows the overall efficiency for the all-water and the CSs over the day.

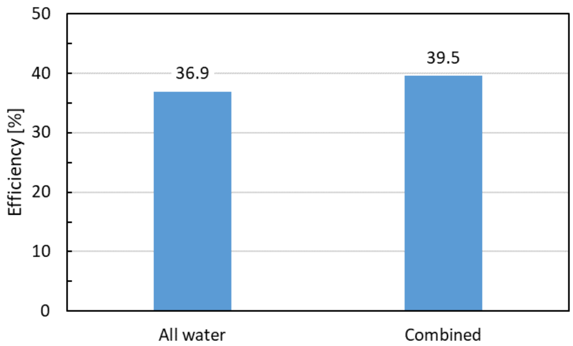


Fig. 8. The overall efficiency comparison between All water system and the CS for 2 LPH extraction rate.

It can be observed that the overall average efficiencies reach 39.5% and 36.9% for the CS and all-water system, respectively. This represents 7.3% enhancement in the overall efficiency for the CS. This in turn indicates that, over the test period, the CS achieved higher performance than that of the all-water system.

3.2 Test results for 4 LPH flowrate

As the extraction rate increases from 2 to 4 LPH, the forced convection heat transfer increases and the thermal energy extracted from the ET increases as well. This can be observed from the outlet and inlet temperature difference for both systems shown in Fig.9. The temperature difference reached maximum of 16.6ºC and 9.7ºC for both the CS and traditional system, respectively. This difference achieves 71.1% enhancement in the temperature difference for the CS over the traditional system. This emphasizes the increase of the forced convection effect created by the direct feeding of the flow inside the ET in the CS.

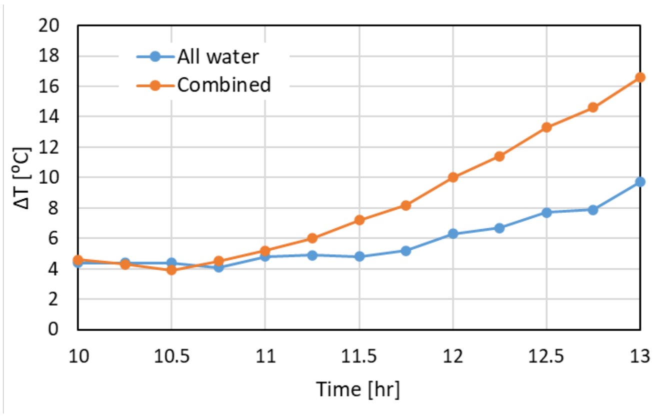


Fig. 9. The temperature difference between the outlet and inlet water temperature for both all-water and CSs, for 4 LPH extraction rate.

The temperature of water exiting from the ET opening for both systems is compared as well, as shown in Fig.10.

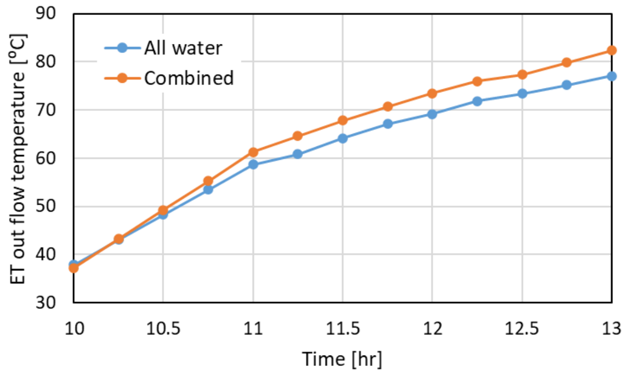


Fig. 10. A comparison between the traditional and the CS in the maximum temperature of the flow getting out from the tube for 4 LPH extraction rate.

As can be observed, the temperature reaches maximum of 82.3ºC and 77ºC in both the combined and the all-water systems, respectively. This achieves an enhancement of 7% for the CS over the all-water system. This indicates that the CS offers better performance in the 4 LPH extraction rate as well.The overall efficiency of both systems is shown in Fig.11.

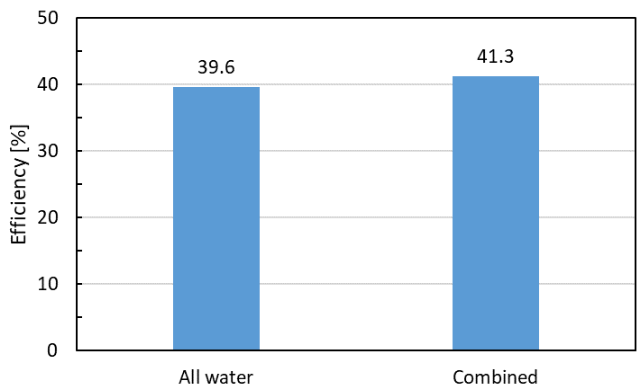


Fig. 11. The overall efficiency comparison between All water system and the CS for 4 LPH extraction rate.

The average overall efficiency of the combined and the all-water systems found to be 41.3% and 39.6%, respectively. So, the CS achieves enhancement in the overall efficiency by 4.3% over the all-water one.

3.3 The results for 8 LPH flowrate

The maximum extracting rate in this experimental test set is the 8 LPH. ΔT for this extraction rate for both systems is shown in Fig.12. The value of ΔT reached a maximum of 21ºC and 9ºC in the combined and the all-water system respectively. This level of difference between the two systems achieves enhancement of 133.3% for the CS over the traditional one.

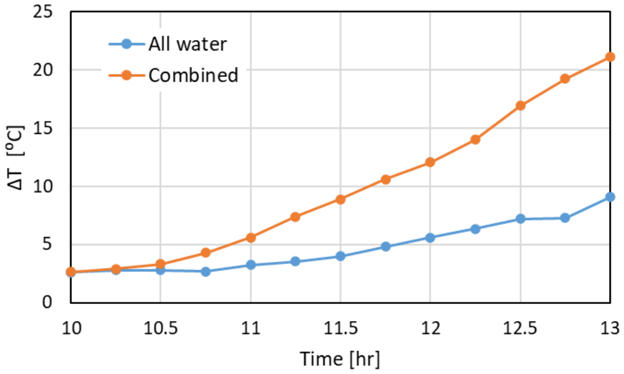


Fig. 12. The temperature difference between the outlet and inlet water for all-water and CSs for 8 LPH extraction rate.

This large difference in the performance between the two systems appeared in the high extraction rate of 8 LPH. This performance refers to increasing the dependence on the forced convection heat transfer in the CS, while the all-water system remains in the free convective scheme. Although the extraction temperature is not the maximum temperature in the tank, the CS shows superior enhancement over the traditional system. The temperature of the flow from the ET opening in both systems is shown in Fig.13.

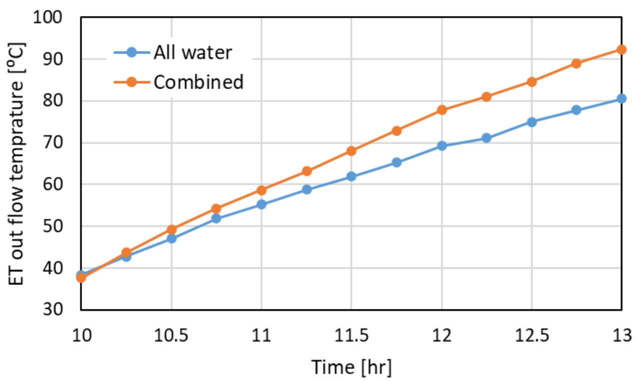


Fig. 13. A comparison between the traditional and the CS in the maximum temperature of the flow getting out from the tube for 8 LPH extraction rate.

It can be observed that the temperature of the fluid getting out from the ET opening reaches a maximum of 92.4ºC and 80.5ºC in the combined and the all-water systems, respectively. This gives an enhancement of 14.7% of the CS over the all-water system. This performance proves the high effect of the extraction rate in both systems, especially the combined one. The overall efficiency of both systems is illustrated in Fig.14. The average overall efficiency of the combined and all-water systems is found to be 48.5% and 38.1%, respectively. This achieves an enhancement in the overall efficiency of 27.3% for the CS over the all-water system.

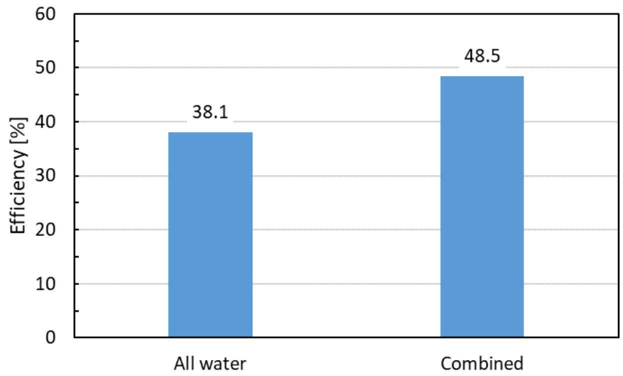


Fig. 14. The overall efficiency comparison between All water system and the CS for 8 LPH extraction rate.

It can be observed that the performance of the systems is not consistent with the extraction rate, especially with the medium extraction rate of 4 LPH. This can refer to the higher solar radiation in that day compared to that in the others two test days of the 2 LPH and 8 LPH as shown in Fig. 2. The high solar radiation in that day cased the difference between the two systems in the efficiency is small compared to the other two systems. This emphasises that the CS shows its advantage more clear in the normal radiation. Even in the high solar radiation condition, the performance of the CS is higher than that of the traditional.

4. Economic Study

The cost analysis study performed in the present research was based on the equations in [33] and the calculation results are illustrated in Table 1.

Table 1. Cost analysis details and price of heating energy

Parameter	Unit	CS 8 LPH
Tube length required	m	18.0
Annual increase in cost (OPC)	$	0
Principal cost (P)	$	14.40
Salvage value (S) (10% of P)	$	1.44
Life of the system (n)	year	20.0
Interest rate (i)	%	0.12
Capital recovery factor (CRF)	-	0.134
Sink fund factor (SFF)	-	0.014
First annual cost (FAC=CRF × P)	$	1.928
Annual salvage value (ASC=SFF × S)	$	0.020
Annual maintenance cost (AMC=0.05 × FAC)	$	0.096
Annual cost AC (AC=FAC+AMC-ASV+OPC)	$	2.004
Annual yield	kW.hr	219.0
Cost per kW.hr	$/kW.hr	0.0096

The study considered the fixed cost of the modifications performed on the system. The cost analysis details are illustrated in table 2. The production cost of the hot water due to the modification of the CS reached 0.00915 $/kW.hr for the maximum test extraction rate of 8 LPH as shown in table 2.

5. Conclusion

An outdoor comparative experimental study was performed for investigating the effect of a proposed combined feeding ETSC system respect to the traditional all-water system using 2,4 and 8 LPH extraction rates. Moreover, a numerical simulation was performed and validated with the experimental results for the all-water system. The conclusions from this work are as follows:

- The numerical simulation results agree with the experimental results with maximum ARE of 5.4%.
- For all the tested flow rates, the CS achieves higher ET out flow temperature than that in the all-water system with maximum enhancement of 14.7% in the case of 8 LPH.
- The overall average efficiency over the test period found to be higher in the CS than the all-water system in all the extraction rates with maximum enhancement efficiency of 27% in the case of 8 LPH extraction rate.
- The performance of the CS found to be enhanced over the all-water system as the extraction rate of the hot water increases. This refers to making use of the forced convection that increases with the increase of the flow rate.
- The performance of the CS presents an advantage of applicability for this system in solar desalination as it performs better with higher temperatures. The CS system provides a hot water cost of 0.00915 $/kW.hr over the traditional systems for extraction rate of 8 LPH.

The future work that is intended to be performed is using the modified system in the desalination field. This refers to its higher efficiency of heating. This should increase the evaporation rate of the solar desalination system.

Acknowledgement

The authors extend their appreciation to the deanship of scientific research at Shaqra university for funding this research work through the project number (SU-ANN-202234).

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