Enhancement of the Performance of Stepped Solar Still Using Humidification-Dehumidification Processes

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Abstract: In this study, a stepped solar still using humidification- dehumidification processes (HD) is exploited for the desalination purpose. To investigate the performance of the solar still with humidification- dehumidification system, an experimental setup has been designed, constructed and assembled. A set of experimental runs have been carried out through out this study. As a result of this work, the humidification- dehumidification processes have an essential effect on improving the solar still performance. Each solar still has its own optimal value of water flow rate which gives the highest productivity and maximum efficiency. This optimal value is depending on the solar still configuration. Working at flow rates below or above this value leads to decrease the still performance. By increasing the air flow rate, the solar still performance is increased. The obtained results were compared with those of other studies and the comparison gives a good validity of the present results.

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1. Introduction

Seawater desalination is an important process to meet the increasing demand for fresh water; however, it is highly energy intensive due to the high salinity of the source. Due to the constraints of high desalination costs, many countries are unable to afford these technologies as a fresh water resource, which indicates the importance of finding suitable alternative energy resources for the desalination systems. Among all the alternative energy resources, solar energy is at the top of these resources for its potential to provide for the future energy needs, solar energy driven/assisted desalination is becoming more viable despite its high capital cost [1].

In a solar still, also called direct still system, the heat collection and distillation processes occur within the same system where solar energy is used directly for distillation by means of the greenhouse effect. Water vapor rises to the transparent cover by natural convection and condenses there. A solar still output might be affected by many factors including brine depth, vapor leakage, thermal insulation, cover slope, shape material, and climate [2, 3]. The latent heat is normally wasted on the cover, therefore the system efficiency is relatively low with a daily production of about 3-4 l/m^2 [4]. Solar stills have been extensively studied with detailed revision [5]. Later, researchers developed different kinds of solar still systems, such as: solar stills coupled with solar collectors, solar stills with condensers, solar stills under low pressure [6], solar stills with heat recycling [7], solar still configuration and color [8] multi-stage/multi-effect solar stills, solar stills with heat storage and hybrid solar still/PV systems [9].

The humidification– dehumidification process (HD) is an interesting technique adapted for water desalination when the demand is decentralized. This technique presents several merits such as flexibility in capacity, moderate installation and operating costs, and simplicity. Besides to these merits, this technique has a very important advantage that is the possibility of using low temperature energy sources such as geothermal, solar, recovered energy, cogeneration, etc. The HD process, which uses low grade heat that could be supplied by solar collectors, is based on the fact that the saturation humidity roughly increases with increasing temperature. When air comes in contact with saltwater, it extracts some amount of vapor at the expense of sensible heat of salt water, causing cooling. On the other hand, the distilled water is recovered by maintaining humid air in contact with the cooling surface, releasing the latent heat of condensation from the vapor.

Many studies that using this technique have been carried out. Radhwan [10] presented a numerical study for the transient analysis of a stepped solar still used for heating and humidifying agriculture greenhouses (GH). The results show that the still daily average efficiency was about 63%; total daily yield was about 4.92 L/m^2, out of which 0.81 W/m^2 is condensed on the glass cover, and the rest (4.11 L/m^2) enters the GH as humidity carried by the circulating air.

Some works have been carried so far in stepped solar still and constant depth trays are used in the basin plate. Abdallah *et al.* [11] studied three design modifications to improve the performance of a traditional single slope solar still. Firstly, addition of internal reflecting mirrors on all interior sides of still, secondly, using stepwise water basin instead of flat basin and thirdly coupling the solar still with a sun tracking system. The results showed that, coupling of the stepwise basin with sun tracking system gives the highest thermal performance with an average of 380%. Velmurugan *et al.* [12] enhanced the productivity of the solar still by using stepped solar still with two different depth of trays. The basin plate contains 25 trays with 10 and 18 mm depths. Integrating small fins in basin plate and adding sponges in the trays were exploited to improve the productivity. Theoretical, experimental and economic analyses for fin type, sponge type, and combination of fin and sponge type with stepped solar still were presented. The results show that, when the fin and sponge type stepped solar still issued, the average daily water production has been found to be 80% higher than ordinary single basin solar still. Velmurugan *et al.* [13] studied integrating the fin at the basin solar air heater with the stepped solar still, and two different depths of trays were used. They reported that, the production increases by 53.3% when using fins in the stepped solar still. The productivity increases by 68% for sponge, and 65% for pebble. When using both sponge and pebble in fin type stepped solar still, the productivity increases by 98% than the conventional stepped solar still.

Other studies have considered the use of phase change material (PCM) as storage media in stepped solar stills. Radhawan [14] theoretically investigated the transient performance of a stepped solar still with built-in latent heat thermal energy storage. The results showed that the basin still integrated with heat storage system is efficient for water provision during the lack of sunlight, especially at night. Also, El-Sebaii *et al.* [15] developed a new mathematical model under the simplifying assumptions to study the thermal performance of a single basin solar still with phase change material (PCM). Dashtban and Tabrizi [16] constructed a weir-type cascade stepped solar still with built-in latent heat as thermal energy storage system to improve the still productivity. Another stepped still solar with the same characteristics without PCM was also fabricated for investigation of the internal convective heat transfer coefficient. The results showed that the still with PCM is superior in productivity (31% improvement) compared with still without PCM by considering a limited set of data in a typical day. Using of PCM increases the daily productivity by about 32%.

El-Zahaby *et al.* [17] developed a new design of a stepped solar desalination system with flashing chamber to improve the fresh water productivity. The performance of stepwise water basin coupled with a spray water system by augmenting desalination productivity through using two air heaters was studied. The results showed that, the productivity and performance of the system is significantly positive dependent on both inlet sea water temperature and the power consumed. El-Zahaby *et al.* [18] investigated experimentally the effect of using the spray system for seawater at different velocities of the water spray's holder and flow rates on the performance of the solar still.

Abdel-Rahim and Lasheen [19] designed a modified solar desalination system to increase the productivity. The system had two modifications; the first one was using a backed layer and the second was using a rotating shaft installed close to the basin water surface. Comparing the obtained results with the conventional solar still (CSS), the overall efficiency of the modified system was higher than that of the conventional type. Modified solar desalination system used packed layer had higher productivity than that one used rotating shaft and both were better than the conventional type.

Karan *et al.* [20] applied nonlinear programming techniques to optimize humidification-dehumidification (HD) desalination cycles for operating conditions that result in maximum gained output ratio (GOR). Closed air open water as well as open air open water cycles, each with either an air or a water heater, were considered in this analysis. The results showed that, the GOR of all cycles was found to decrease with increasing component terminal temperature difference (TTD). Farsad and Behzadmehr [21] solved numerically the solar desalination unit with humidification-dehumidification cycle to analyze cycle parameters and to determine the amount of fresh water production. It is found that the mass flow rate, temperature of feed water, total heat flux and inlet air as well as the condenser characteristic parameter have significant effects on the cycle performance.

The gained output ratio (GOR) and recovery ratio (RR) of closed air water heated humidification-dehumidification (HD) cycles were analyzed, both with zero extractions and a single extraction was studied by Ronan *et al.* [22]. In addition, the effects of salinity and the validity of ideal gas assumptions upon the modeling of HD systems were studied. The results showed that, the (GOR) increases and (RR) decreases as the temperature range of the cycle decreases, i.e. as the feed temperature increases or the top air temperature decreases. A single extraction was shown to be useful only when heat and mass exchangers are large in size. GOR is limited to approximately 3.5 without extractions and approximately 14 with a single extraction. RR is limited to approximately 7% without extractions and approximately 11% with a single extraction.

Juan [23] developed a new humidification and dehumidification system. In this system, the air worked in a closed loop and the evaporator prepared of treated cellulose paper substratum. This system is designed to improve the heat recovery at the condenser. The mathematical and experimental results were presented and it was shown that they were in a good agreement. Also, some operating conditions for better heat recovery are presented. The direct contact humidification-dehumidification (HD) desalination process was modified by Morteza and Majid [24]. The influence of tube diameters ratio, air flow rate, temperatures and flow rates of inlet saline and fresh water on the performance of the HD unit have been studied. The results showed that, the optimal configuration of HD system was freely temperature dependent. They concluded that, if the humidifier inlet water temperature was high, recycling of the humidifier outlet water results in about 15-25% reduction in the specific thermal energy consumption.

From the above review, the studies dealing with stepped solar still using humidification-dehumidification systems are very few, therefore, the objective of present work is to study the performance of the stepped solar still with HD processes.

2. Experimental Setup

The Experimental Apparatus is constructed for desalination purpose using a humidification-dehumidification (HD) system. As shown in Fig. 1, the experimental loop is consisting of four major parts; (i) the humidifier (solar evaporator), (ii) the dehumidifier, (iii) water and air systems and (iv) measuring system.

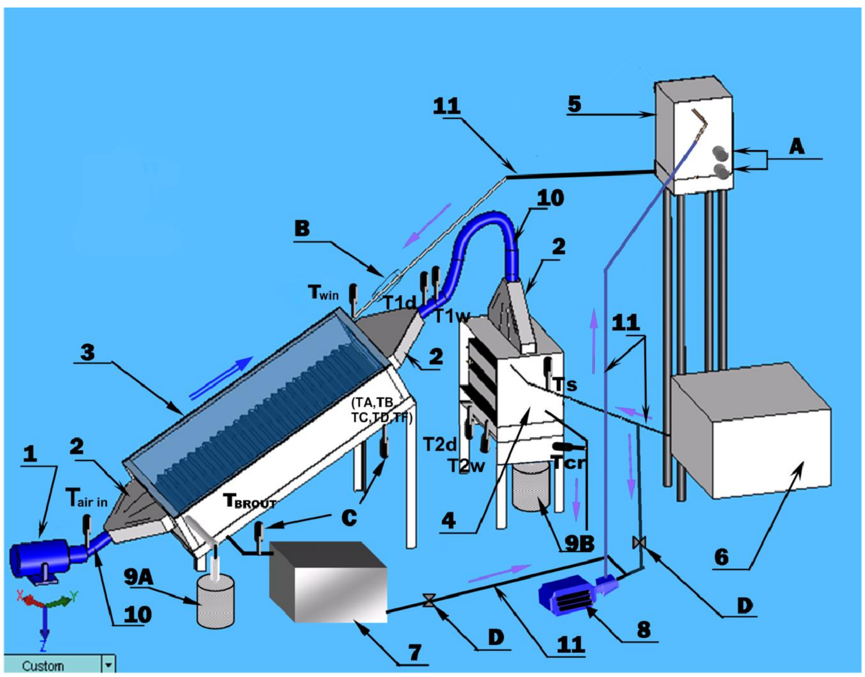

Fig. (1) The experimental set up

1 Air blower	5 Elevated water tank	9 Collecting vessel
2 Triangle ends	6 Water source tank	10 Plastic hosepipe
3 Humidifier	7 Recovery water tank	11 Plastic pipes
4 Dehumidifier	8 Water pump	A Electric heaters
B Water flow meter	C Digital thermometers	D Control valves

2.1 The humidifier (solar evaporator):

The humidifier (solar evaporator) (3) is constructed as a stepped basin still with 10 steps which represents the absorber with area of 1.0 m^2 (1.54×0.65 m). The upper side and the two sidewalls are fabricated from 2mm blackboard coated iron while the casing is fabricated from 0.8mm galvanized steel. The stepped-bed, higher side and the two sidewalls of the still are insulated with 30mm glass wool (thermal conductivity of 0.036 W/m K) while the front wall (lower side) was normal to the bed and is made of a plastic sheet 3mm thickness placed in an aluminum frame. The main condenser is the still body cover which made of 3mm plastic sheet thickness (1.54×1.06 m) placed in an aluminum frame.

2.2. The dehumidifier

Two finned coil heat exchangers have been connected in series arrangement to be used as a dehumidifier (4). Each heat exchanger contains 30 tube passes. The finned tube passes are made of a copper tube 9.525mm in diameter and 0.8mm thick where the extended surface is made of 1mm thick aluminum sheet. Total surface area of each heat exchanger is 4.6m^2. The cooling water flows through the tube side and the humid air (air + water vapor) coming from the solar evaporator flows through the shell side in which the condensed produced fresh water is collected in the desalinated water vessel (9B).

2.3 The water and air systems

The saline water flows from the elevated storage tank (5) to the solar evaporator (3) through the pipeline (11). Evaporated water condenses on the evaporator cover and collected in the desalinated water vessel (9A). The non-evaporated saline water is collected in water tank (7) and returned back to the elevated tank (5) with some make-up saline water coming from the main source water tank (6). Air from atmosphere is delivered by a 0.3 kW blower (1) to the solar evaporator and then to the dehumidifier (4) through a PVC pipe (10) of 75mm diameter and two stratified triangles (2). These stratified triangles are installed to insure a good air distribution in the humidifier. The atmospheric air carries the non condensed water vapor to the dehumidifier where water vapor is released and collected in vessel (9B). Two electric heaters with variable power (A) are used for preheating the feed saline water to a specific desired temperature. The water flow rates are measured by flow meters (B) and controlled by control valves (D) where all inlet and outlet temperatures of both water and air are measured by digital thermometers (thermocouples) (C). The air flow rate is measured by using hot wire anemometer type x and controlled by a small gate mounted in the entrance of the air blower.

2.4 Measuring system

The water flow rates are measured by using flow meters with range (0.4 – 4 l/min) and accuracy of ±0.2 l/min. Air mass flow rate is measured by using hot wire anemometer with range (0 to 15 m/s) and accuracy of ±0.1 m/s. The temperatures at different points of the system are measured by using a digital thermometer type WT-1 with range (-50 - 300 °C) and accuracy of ±1 °C. All readings are sent to the PC through a data acquisition system. The produced water is measured by using a calibrated graduate lab vessel (2000 ml) with accuracy of ±10 ml.

3. Experimental Procedure

The experimental runs are carried out considering the following procedure:

1) The electrical heaters are adjusted at the desired value of supply water temperature (in cases of use of these heaters).
2) The flow rates of water and air are adjusted at the required values according to the running case.
3) The surface temperatures of the base plate and inlet water are measured to be sure that the heat sources are at uniform readings.
4) Temperatures, humidity, water productivity, are recorded every 1 hour during the whole test.
5) The system efficiency is calculated as:

$$\eta_h = \frac{M_w\, L_{w \cdot av} / 3600}{A_b\, H + P_{blower} + P_{heater}} \quad (1)$$

$$\eta_d = \frac{1}{n}\sum_{i}^{n} \eta_h)_i \times 100 \quad (2)$$

$$L_{w.av} = 10^3 \times (2501.9 - 2.40706 T_w + 1.192217 T_w^2 - 1.5863 \times 10^{-5} T_w^3 \quad (3)$$

Where η_h is the hourly efficiency, η_d is the daily efficiency, M_w is the hourly productivity (kg/hr), $L_{w.av}$ is the average of the latent heat of vaporization of water (J/kg), El-Dessouky.and Ettouney [25], A_b is the basin area (1.0 m^2), H is the incident solar radiation on the horizontal surface (W/m^2), P_{blower} is the power of air blower (W), P_{heater} is power of water heaters (W) and n is the number of effective running hours (duration of producing desalinated water).

The conductivity of the used brackish water was measured to be 3530 μs/cm^3 where it's salinity was 3260 mg/l at 27.8 ºC. Table 1 shows the composition of the total dissolved salts (TDS) of the used brackish water.

Table (1) the composition of the brackish water, TDS

Composition	mg/l
Ca^{2+}	224
Mg^{2+}	177
$Na^+ + K^+$	783
$HCO3^-$	345
$SO4^{2-}$	535
Cl^-	1196

Throughout this work, three cases have been considered; the first case is carried out without use neither the electric heaters nor the air blower and therefore the evaporator was closed from its two ends so the humidifier was tested alone by passing water through it and without recovery (an open water cycle). The temperature of the water entering the humidifier was as the temperature of water source. In this case, the only variable was the feed water flow rate which was modified and controlled by the control valves. Four different values of water flow rate were used during this case; $\acute{m}_{w,in}$ = *0.19, 0.38, 0.57* and *0.76 LPM*. each value has been used during a whole working day.

In case 2, the electric heaters were turned on and the target temperature of the water entering the humidifier, $T_{w,in}$ was adjusted to be 40°C. The water flow rates were the same as case 1 and each value has been used during a whole working day with one value of air flow rate which was controlled to be $\acute{m}_{a,in}$ = *0.057 CMM*. The inlet air temperature equals the ambient temperature because the used air is drawn from atmosphere. In case 3, all the operating parameters were remain the same as case 2 except the inlet water temperature which increased to be 50°C.

4. Results and Discussion

As mentioned above, three cases of experiments have been carried out through out this work. The obtained results for each case have been presented in a separate set of graphs. The results from the experiments of case 1 are presented in figure (2). From Figs. 2a and 2b, it can be seen that the highest productivity and maximum hourly efficiency are due to the lowest feed water flow rate ($\acute{m}_{w,in}$ = *0.19 LPM*). This is because of the minimum convective and radiation heat losses dealing with the mass flow rate of circulating brackish water. Also, the lowest feed water flow rate gives minimum thickness of water film moving over the stepped surface of the solar evaporator and hence gives maximum surface water temperature and subsequently improves the evaporation process. Fig. 2c shows that the maximum base plate temperature is also occurred with lowest feed water flow rate. This may be due to the very thin water film moving over the plate and hence a high probability for the solar beam radiation to penetrate the water film reaching to the based plate. As shown in Fig. 2d, the solar radiation for the four working days are almost similar and the maximum radiation is reached at noon and subsequently the maximum efficiency and highest base plate temperature are achieved at noon (Figs. 2b and 2c).

The results of test case 2 are presented in figure (3). All discussion of figure (2) can be drawn to figure (3) with one exception which is the highest productivity and maximum hourly efficiency are occurred at a feed water flow rate ($\acute{m}_{w,in}$ = *0.57 LPM*) higher than the minimum flow rate. This is due to the turning on of the electric heaters and the air blower which increase the capacity of the evaporator as a result of increasing feed water temperature and increasing the air humidity. As in case 1, the highest efficiency is achieved at noon (Fig. 3b), the maximum base plate temperature is at minimum water flow rate (Fig. 3c) and the maximum solar radiation is at noon (Fig. 3d). As seen in Figs. 3a and 3b, both of productivity and efficiency are higher than their values in the conventional solar still (case 1) because of increasing feed water temperature and air humidity. The increment in productivity was about 57% and in the maximum efficiency of about 42%.

Figure (4) shows the results of case 3. All discussions of case 2 can be drawn to this case with one exception which is the lower values of productivity and efficiency comparing with their values in case 2 (Figs. 4a and 4b). This is because of the limitation of the evaporator capacity to be increased with the same flow rate of the air ($\acute{m}_{a,in}$ = *0.057 CMM*). As in cases 1 and 2, the highest efficiency is achieved at noon (Fig. 4b), the maximum base plate temperature is at minimum water flow rate (Fig. 4c) and the maximum solar radiation is at noon (Fig. 4d).

To recognize the effect of air flow rate on the solar still performance, an experimental run of case 2 ($\acute{m}_{w,in}$ = *0.38 LPM and* $T_{w,in}$ = *40°C*) has been re-carried out with increasing the air flow rate from *0.057* to *0.12 CMM*. The obtained results are presented in figure (5). From this figure, it is clear that both of the solar still productivity and efficiency are decrease by increasing the air flow rate. Doubling the air flow rate (from *0.057* to *0.12 CMM*) gives a decrement in productivity of about 40% and in the maximum efficiency of about 21%. That is due to the decreasing of base plate temperature as result of air flow rate increasing.

To examine the effect of inlet water temperature on the daily productivity and efficiency, a set of experiments have been carried out during August and September 2012 with inlet water temperature of 40°C and 50°C. The results of these experiments are presented in figure (6). From this figure, it can be seen that both of daily productivity and efficiency are decreased by increasing the water temperature. That is because of decreasing the temperature difference between water and the solar still cover in which the evaporation rate is increased by increasing the temperature difference. As seen in Figs. 6a and 6b, both the daily productivity and efficiency are achieved at water flow rate of 0.57 LPM which means that this value of water flow rate is the more compatible value with the used solar still configurations.

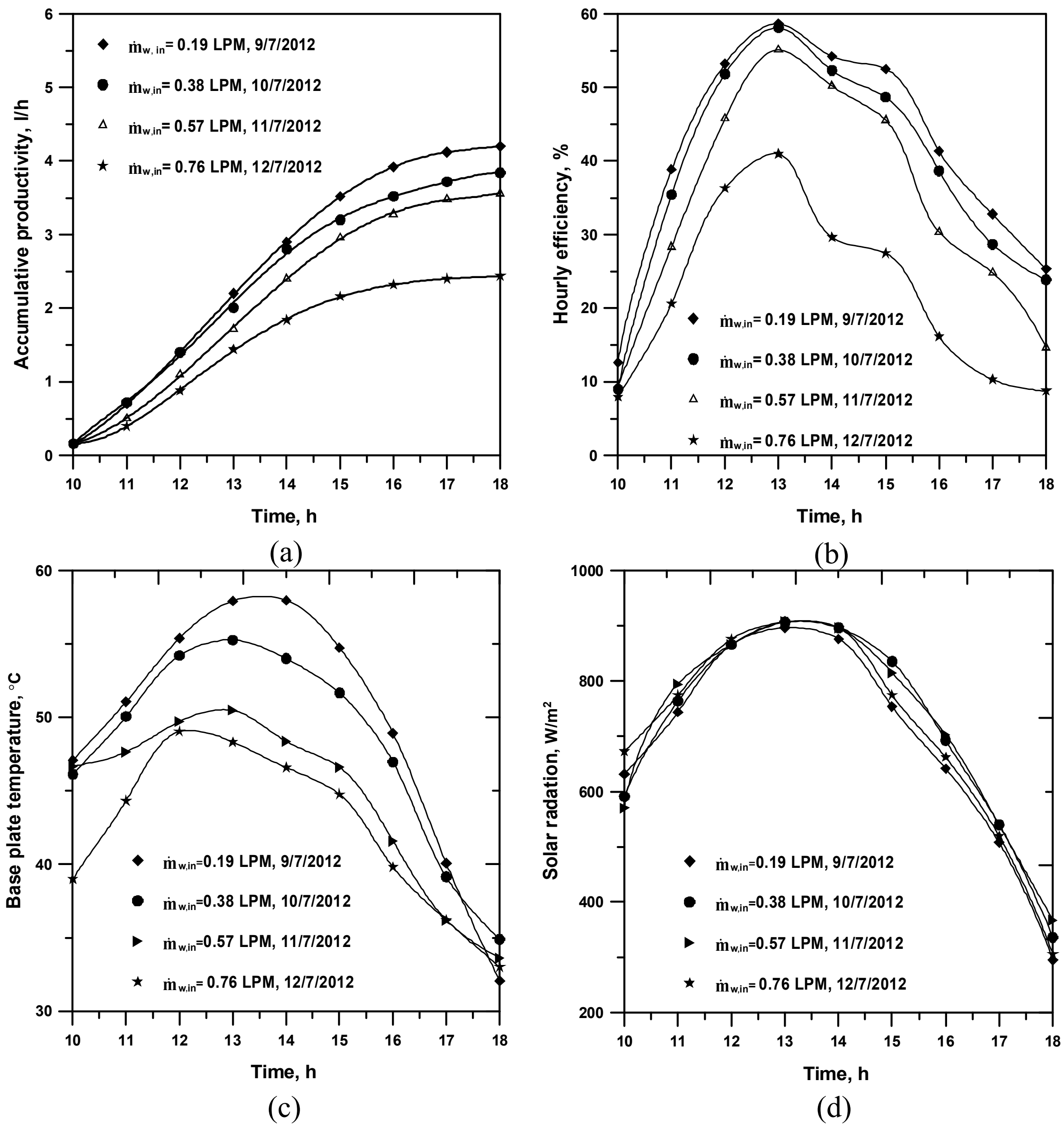

Fig. (2) The results of test case 1
(a) The accumulated productivity (b) The hourly efficiency
(c) The base plate temperature (d) The solar radiation

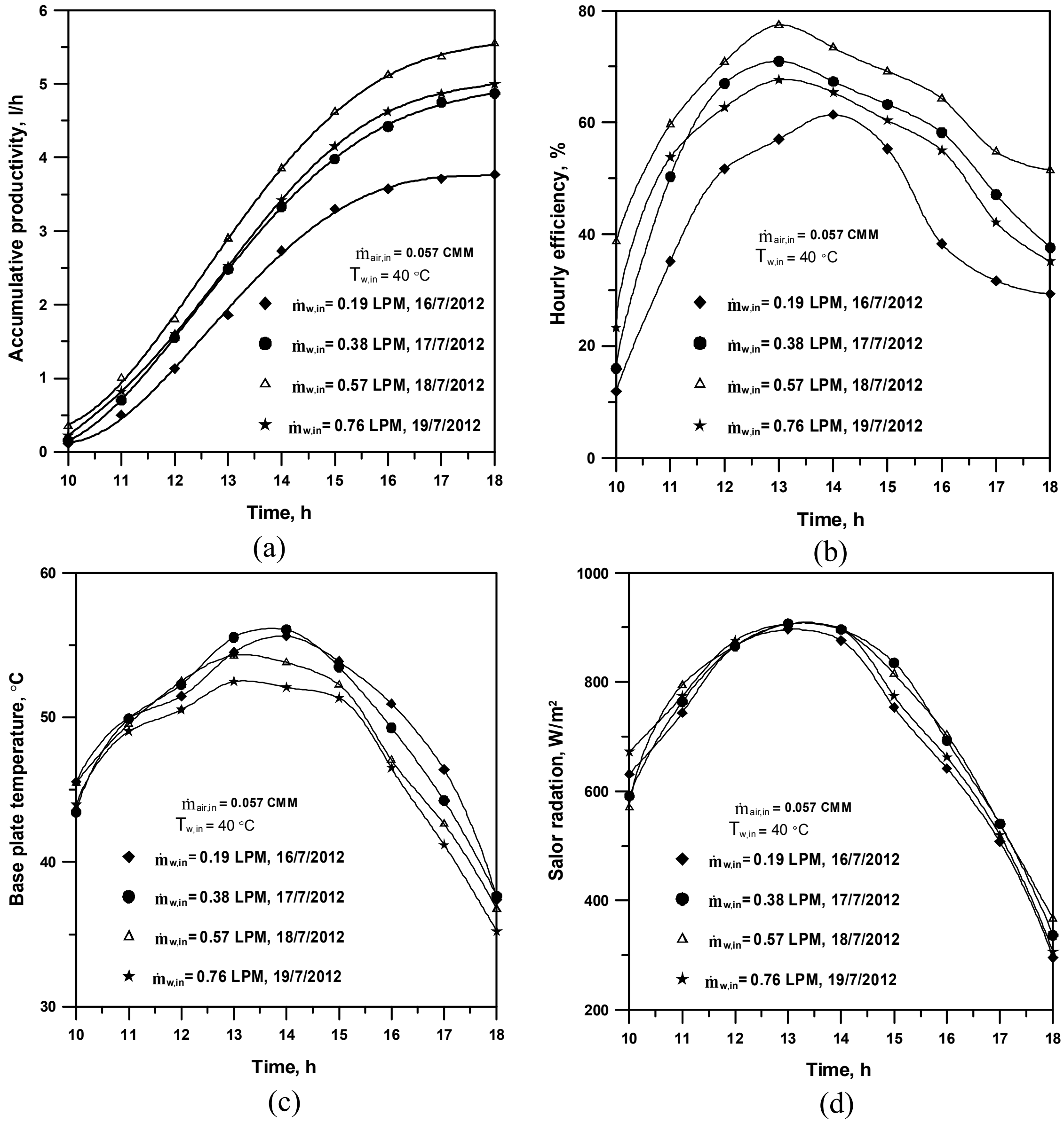

Fig. (3) The results of test case 2
(a) The accumulated productivity (b) The hourly efficiency
(c) The base plate temperature (d) The solar radiation

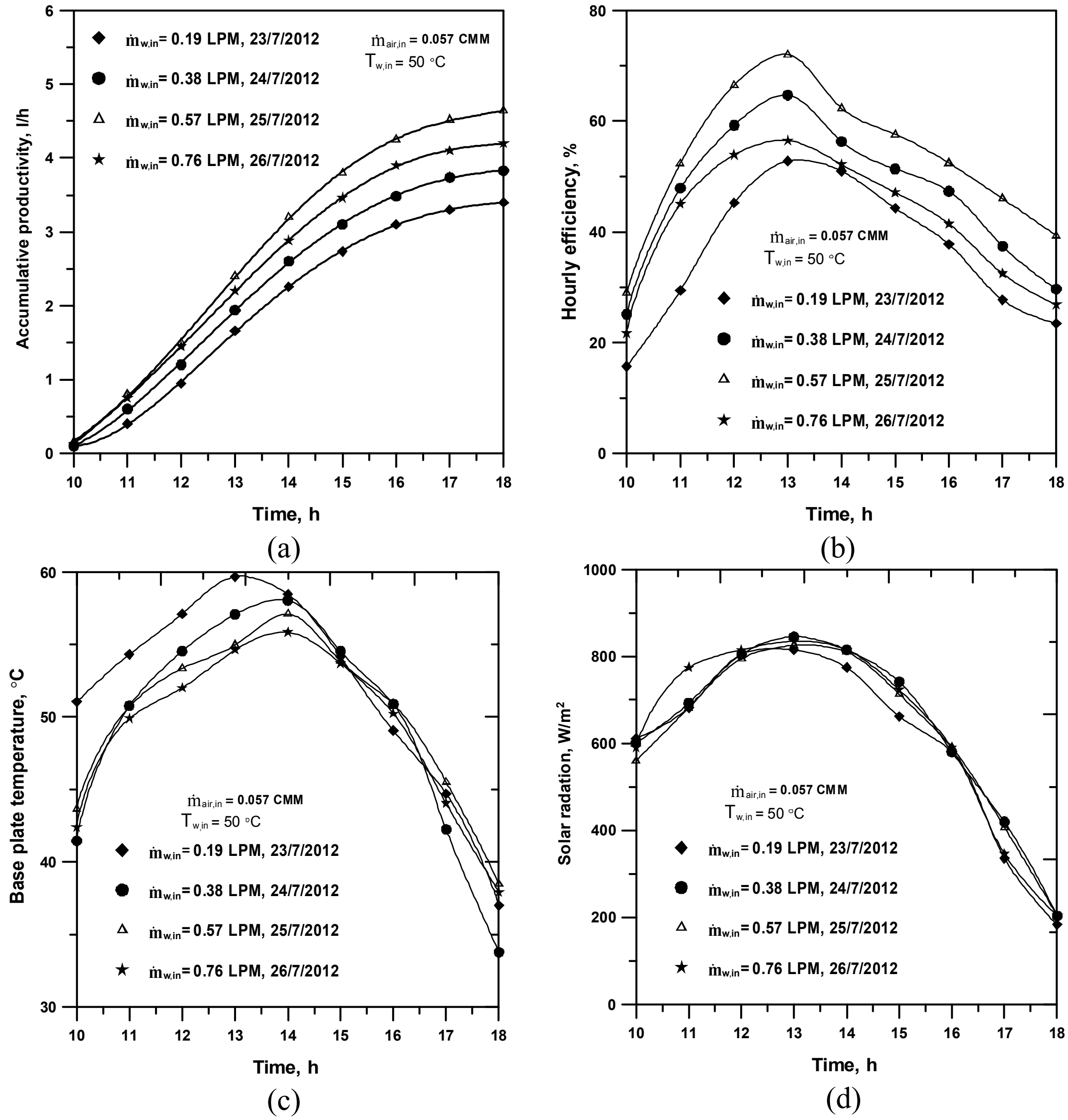

Fig. (4) The results of test case 3
(a) The accumulated productivity (b) The hourly efficiency
(c) The base plate temperature (d) The solar radiation

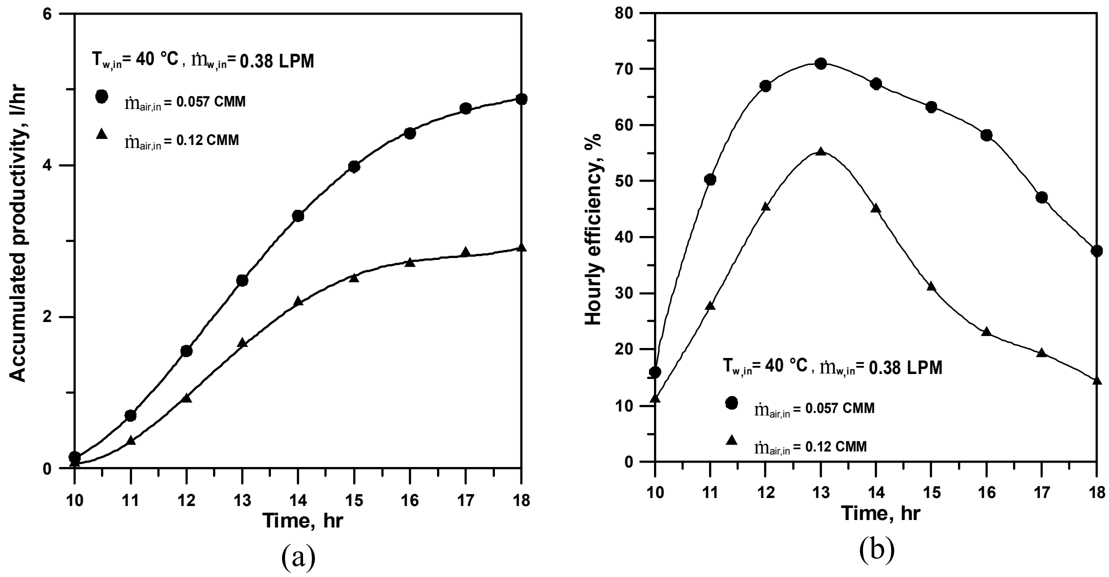

Fig. (5) The effect of air flow rate on the solar still performance
(a) The accumulated productivity (b) The hourly efficiency

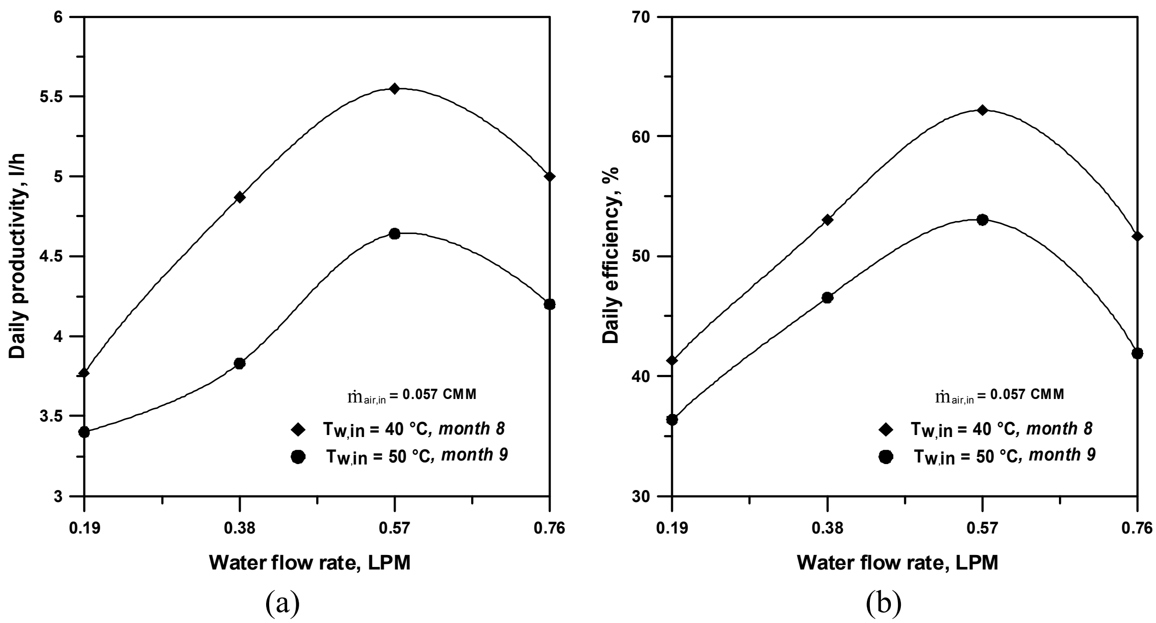

Fig. (6) The effect of inlet water temperature on the daily still performance
(a) Daily accumulated productivity (b) Daily efficiency

Comparison with other published results

To examine the validity of the present results, the daily accumulated productivity and daily efficiency obtained from the present still are compared with those obtained from other published results. The type of the solar still and the climatic conditions of the comparative studies are listed in Table (2) and the compared data are represented in figure (7). As seen in this figure, although the overall behavior of the accumulated productivity curves of all compared data is similar, the productivity due to the present work is the highest one. May be this is due to the humidification- dehumidification processes.

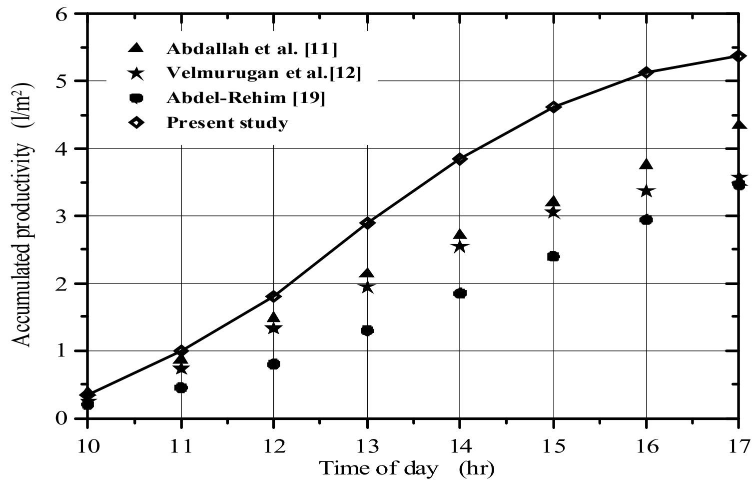

Fig. (7) Comparison between the present study and other previous studies

Table 2: The different types of comparative solar stills and climatic conditions

Study	Type of solar still	Climatic condition
Present	Stepped with humidification- dehumidification system	Egypt
Abdallah *et al.* [11]	Stepped with sun tracking	Jordan
Velmurugan *et al.* [12]	Stepped with fins and sponges	India
Abdel-Rehim and Lasheen [19]	Conventional solar still (CSS)	Egypt

Conclusions

In the present study, the performance of stepped solar still with humidification-dehumidification system has been experimentally investigated. The effects of feed water flow rate, the inlet water temperature and air flow rate on the solar still performance have been considered. Based on the obtained results, the following conclusions can be drawn:

- The humidification-dehumidification processes increase the hourly productivity of the conventional solar still (CSS) by about 57% and the hourly efficiency by about 42%.
- Increasing the feed water flow rate to an optimal value leads to increase the solar still productivity. After this optimal value, the productivity is decreased because of the limitation of the evaporator capacity.
- Each solar still has its own optimal value of water flow rate. This value is depending on the solar still configuration.
- Increasing the air flow rate leads to decrease the solar still performance.
- Increasing the feed water temperature leads to decrease the still productivity due to decrease of temperature difference between water surface and the still cover.
- Comparing the obtained results with those of other studies, gives a good validity of the present results.

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Nomenclature

A_b	basin area, *m^2*
H	incident solar radiation on the horizontal surface, *W/m^2*
$L_{w.av}$	average of the latent heat of vaporization of water, *J/kg*
$\acute{m}_{a,in}$	inlet air flow rate, *CMM*
M_w	productivity, *LPM*
$\acute{m}_{w,in}$	inlet water flow rate , *kg/hr*
P_{blower}	power of air blower, *W*
P_{heater}	power of water heaters, *W*
T_{1d} , T_{1w}	dry and wet air temperature leaving the humidifier, *^oC*
T_{2d} , T_{2w}	dry and wet air temperature leaving the dehumidifier, *^oC*
$T_{air\ in}$	temperature of air entering the humidifier, *^oC*
$T_{BR,out}$	brine temperature, *^oC*
T_{wout}	temperature of water leaving the dehumidifier, *^oC*
T_D	average temperature of humidifier step shape plate, *^oC*
T_S	temperature of water source, *^oC*
$T_{w,in}$	inlet water temperature, *^oC*
T_{win}	temperature of water entering the humidifier, *^oC Greek letters*
η_d	daily efficiency
η_h	hourly efficiency
Abbreviations	
CMM	cubic meter per minute
CSS	conventional solar still
GOR	gained output ratio
HD	humidification–dehumidification
LPM	liter per minute
PCM	phase change material
RR	recovery ratio
TTD	terminal temperature difference

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