Int. J. Environ. Sci. Technol. (2017) 14:1277–1284
DOI 10.1007/s13762-016-1231-9

ORIGINAL PAPER

Performance improvement of a passive solar still in a water desalination

F. M. Abed[1] · M. S. Kassim[2] · M. R. Rahi[1]

Received: 21 March 2016 / Revised: 20 November 2016 / Accepted: 21 December 2016 / Published online: 22 February 2017

Abstract Using a solar energy in water desalination system is regarded as one of the most effective ways to resolve the problem of freshwater shortages in this world. Experimental and theoretical approaches were carried out to design and test multistage solar still. The experimental tests were conducted for five months in the city of Kirkuk, north of Iraq, at 43.39° longitudinal and 35.17° latitude. The performance requirement of the design is dependent on many factors such as circumstances, work and designation variables. Designating variables, mainly length, width, height and volume of each stage besides the number of all stages, are determined via theoretical analysis approach. The results obtained by both approaches have shown that there is a 10% deviation in still water productivity. Also, the results indicated that the minimum and maximum daily average of still water productivity is 1.7 and 3.8 kg. MATLAB software was employed to model and simulate the experimental processes of evaporation and condensation. The simulation model results were found to agree well with the experiments carried out in many other papers and studies. The test results reported that the system produces about 5 kg of clean water per day with 87% distillation efficiency and 26% of the overall efficiency due to heat losses in the system. Such system is not only promising, but can offer a new technology that can particularly be used in remote and rural areas. The theoretical calculations were compared with the experimental results, and there is a good agreement between the two .

Keywords Solar still · Multistage · Solar collector parabolic type · Distilled water

Editorial responsibility: Mohamed Fathy Yassin.

✉ M. S. Kassim
munahdr@yahoo.com

[1] Department of Mechanical Engineering, Tikrit University, Tikrit, Iraq

[2] Department of Mechanical Engineering, AL-Mustansiriyah University, Baghdad, Iraq

Introduction

Shortage of freshwaters is considered one of the most serious environmental problems facing today's world. Most of the water available on earth is highly salty sea and ocean waters, which is not suitable for drinking. Thus, the world has no choice but to desalinate sea and ocean waters efficiently at low cost. Solar distillation process appears to be suitable to resolve this problem through purification of salty water. Distillation process uses solar radiation, which is a form of thermal energy produced by a multistage solar still connected to a parabolic trough collector to improve its performance and to increase production of distilled drinking water.

Solar distillation uses simple device called solar distillates in a process similar to the natural evaporation of water by sun heat. Solar distillates are classified into two main types: positive still and active solar still which adds a number of external components such as concentrates or solar collectors. Also, it includes two types with multiple distillates that involving single and multiple basins. Basins are of many types with oblique cover, two way cover, ring cover and cone cover in addition to vertical distillates. AL-Karaghouli and ALnaser (2004) conducted an experimental study on two stills, one with single basin and the other with double basin. Both have the same internal basin area (0.45 m^2) with internal dimensions of 50 × 90 cm for each still. The study was conducted based on two types of stills, one a solar still with thermally insulated walls on both sides and the other without insulated walls. A glass double basin cover is tilted at 12° angle horizontally while the single basin cover is tilted at 36° angle horizontally as well. Tests were out on the two stills for the period from February to June. Results showed that the highest average daily production of distilled water is in June for both types due to high solar radiation rate in June, and the average production of distilled water by the isolated still is higher than those obtained without isolation. Results also showed that the daily production rate of water in the double basin still was higher than single basin still by 40% with the same operation conditions. Attaseth et al. (1985) have manufactured two vertical identical stills to study the effect of different lids made of glass and plastic on productivity rate. Based on the same experimental operating conditions in terms of operational system, design and weather conditions thus showed that the productivity of distilled water with a glass cover is higher than the using plastic cover by 10%. Akash et al. (2000) studied the effect of using five different angles of inclination a transparent cover (55°, 45°, 35°, 25°, 15°) on the solar distilled productivity. The study was conducted in Jordan at different operating conditions. Results have shown that 35 angle inclination is the best for the production of distilled water. Nijmeh et al. (2005) conducted a theoretical and experimental study through the addition of three different absorbents, namely dissolved salt, coal and violet dye. The aim of adding the absorbent was to the productivity of distilled water, using solar still with single basin and double symmetrical inclination basin of 3-m^2 area. The study that has been conducted in Jordan during April and May showed that dissolved salts (potassium permanganate and potassium chromate) having a better impact on the distilled water productivity compared to coal and dye. Also, potassium permanganate improved the distilled water productivity by 26%. Ahmed et al. (2009) designed and manufactured a new system of solar distillers of multistage working under a certain pressure conditions to increase the productivity of distilled water. NASTRAN software was used for analyzing the process to find that internal pressure change significantly improves the productivity of distilled water and indicated that low-pressure values increase evaporation rate and consequently distilled water productivity. Khalifa and Ibrahim (2010) and Grawand et al. (2013) designed and manufactured a new type of multistage solar distillation system in order to study the effect of water depth on the productivity, and three depths were chosen (5, 7.5, 10 mm). Results have shown that the water productivity decreases when water depth increases. Water productivity at 5 mm depth increased by 14% over the one with 7.5 mm depth and the productivity of 7.5 mm increased by 22.26% over 10 mm depth productivity at the same operating conditions. Patel et al. (2014) conducted a study on solar system equipped with multiple layer of absorbent to find that their impact on distilled water productivity. Also, using multiple layers prevents the loss of thermal energy in the system. Thus, the main objective of the present study is to improve the performance of the multistage solar stills technology coupled with solar collector.

Materials and methods

Experimental setup

The main objective of the present study is to improve the multistage solar stills technology coupled with the solar collector. A water desalination system consists of three stages, a satellite dish solar collector, a heat exchanger and a circulation pump.

System description and operating principles

A water desalination test rig was built in Kirkuk city comprising a three-stage metallic stills coupled with a satellite solar collector. The rig is built within the framework of investigations on the development and improvement of the Static still, most important, the dynamic solar water desalination methods. Figure 1 presents a schematic diagram of the test rig with the multi-effect still. Each stage is made of steel and has a rectangular cross section of 1200 and 400 mm. The first (bottom) stage of the apparatus, with the largest volume, contained the main body of the saline water. The remaining stages of the still were identical in the design and are opened at the bottom and covered at the top of an angled water tray. The water depth was about 40 mm and covered a serpentine copper tubular heat exchanger fixed to its base using plastic clippers. Solar

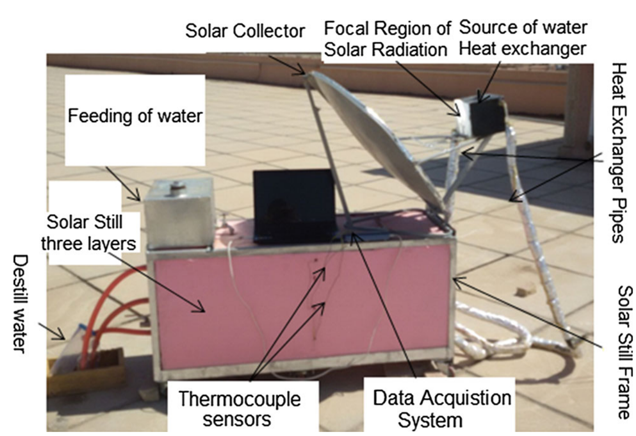

Fig. 1 Photograph of the solar still multistage

energy was utilized in the multi-effect still in several phases. First, the energy flux absorbed by the solar collector was used to increase the temperature of the liquid that was continuously circulated in the closed “solar collector manifold”-“heat exchanger” loop. Then, the energy was transferred to the brackish water in the first stage of the still above tubular heat exchanger. The temperature of the saline water in the bottom stage increased, and the resulted water vapor then condensates on the sloping surface of the second-stage tray, where the temperature of the saline water in the tray was lower than the water in the bottom stage. Droplets of the condensate with vapor that formed on the sloping surface flowed by gravity toward the edge of the tray; then, they gathered in the trough. From the trough, then it is taken out and collected in the metering cylinder. The latent heat of condensation was utilized to gradually increase the temperature of saline water in the tray of the second stage of the still, and then, the process of condensation was repeated between the second and third stages and the third and fourth stages, respectively. The overall structure is insulated with three layers of insulators; the first one is 1 cm of wood thickness, the second is 5 cm of glass wool, and the last one is a sheet of thermal plastic. The temperature of evaporation and condensation at each stage has been measured by thermocouples of type (*k*). Six sensors are fixed, and each stage consists of two sensors: one is attached to the surface of the condenser and the other is in the domain of evaporation.

Collector design

A satellite dish is used as a collector, and some modifications have made to the dish together the sun rays and reflect them in a pot located in the focal point of the dish. The surface of the dish stickled with a sheet of anodized aluminum. The pot is fixed at the focal point and painted black. Two pipes of heat exchanger are connected to the pot pipe. The mechanism of moving the dish to be normal in sun direction is controlled by a timer-geared system. The size of the dish and the pot is designed to receive the energy and increase the temperature of the fluid inside the pot. The fluid is the carrier of the energy in order to evaporate the brackish water inside the first stage. Figure 2 shows the solar still multistage details.

Experimental procedure

Prior to the tests, the still was initially filled with synthetic brackish water from a single-inlet point at the top of the still. The level of the water in each stage is controlled by adjusting the height of the special overflow pipe. When the level of the saline water reaches the desirable height in the angled tray, the water overflows to the next stage. The

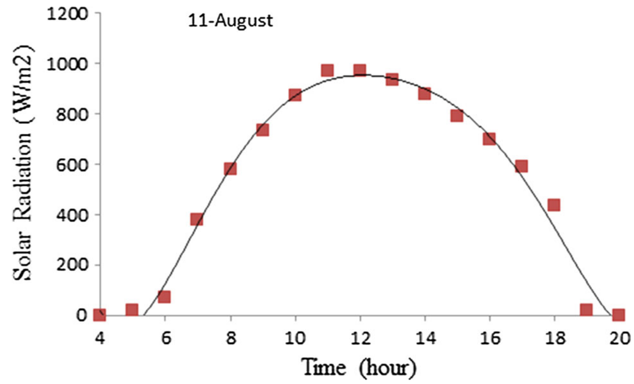

Fig. 2 Distribution of the solar radiation on August 11, 2015

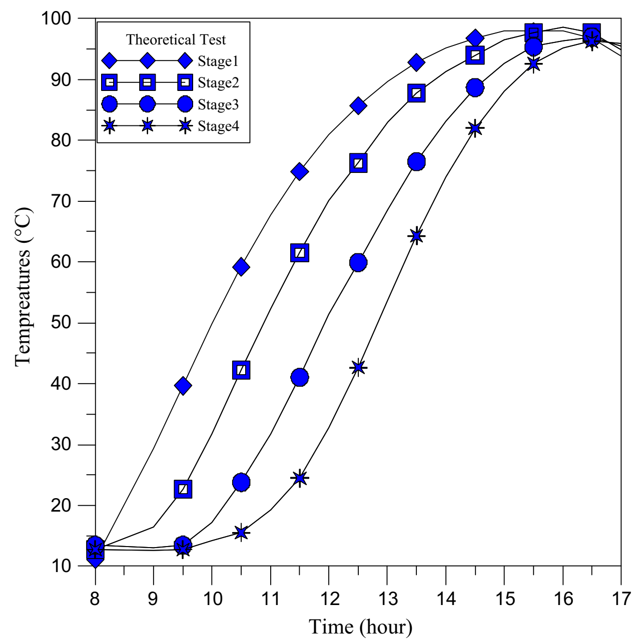

Fig. 3 Steady state condition of the solar still system

bottom stage is also equipped with overflow pipe, maintaining 40 mm water depth. When the system is full, the overflow pipe valve is closed. The volumes of the water in the first, second and third stages were 1.9, 3.5 and 3.8 L, respectively. The system was tested in conditions simulating typical seasonal days in Kirkuk city—Iraq. Thus, the information on the variation of the solar radiation on August 11, 2015, was used and is shown in Fig. 3. The mass flow rate of water through the collector was kept at 1.5 L/min in all tests. The tests have been repeated, and the water which condensed during the experiments was collected into three separate metering cylinders and then the amount of the condensate was measured after a 24-h period. An analysis of water quality was also performed at the end of the experiment. In the design process, it is taken into account that saline water is very corrosive toward metallic alloys. Thus, the materials used were carefully selected to have no adverse health impacts, such as titanium, stainless steel and aluminum alloys, which satisfy the above requirements.

Measurements

The test data are obtained via thermocouples at various locations in the rig including the water body and the condenser surfaces in each stage, in addition to the average ambient temperature variation. All these values were measured using K-type thermocouples connected to a multiple data logger acquisition system to a laptop computer where the average values at 1-min intervals that have reported with using the recorder software as shown in Fig. 1. The mass flow rate through the solar collector and heat exchanger was recorded. The solar radiation (insulations) was measured using a Sky star solar meter. Distilled freshwater was collected from all three still stages separately using metering cylinders. Readings were taken every 1 h from 08:00 Am to 17:00 Pm.

Mathematical model

A lumped parameter model is developed to describe the operation of the system. It consists of a system of ordinary differential equations of energy and mass conservation written for each stage of the still. Figure 5 shows a calculation scheme of the still with energy balance diagram. The following assumptions are taken into consideration: (1) the thermo-physical properties of brackish water are identical to those of pure water, (2) the effect of non-condensable gases released from water, when it is heated or expanded is neglected, and (3) the amount of evaporated water and the distillate output in all stages are equal and the system's heat losses to the ambient environment through the still walls and the mineral wool insulation were evaluated based on the material's thermal insulation and thermal balance. The following equations are employed to obtain the distilled water of the three stages, Shatat (2008):

$$Q^{\cdot}_H - m^{\cdot}_{e1}\left(h^{\cdot}_{fg1} + C_p T_{c1}\right) = M_{s1} C_p \frac{dT_{s1}}{dt} + \Delta Q^{\cdot}_{\text{losses1}} \quad (1)$$

$$m^{\cdot}_{e1} h^{\cdot}_{fg1} - m^{\cdot}_{e2}\left(h^{\cdot}_{fg2} + C_p T_{c2}\right) = M_{s2} C_p \frac{dT_{s2}}{dt} + \Delta Q^{\cdot}_{\text{losses2}} \quad (2)$$

$$m^{\cdot}_{e2} h^{\cdot}_{fg2} - m^{\cdot}_{e3}\left(h^{\cdot}_{fg3} + C_p T_{c3}\right) = M_{s3} C_p \frac{dT_{s3}}{dt} + \Delta Q^{\cdot}_{\text{losses3}} \quad (3)$$

$Q^{\cdot}_H$ in Eq. (1) can be calculated from the following equation, Shatat (2008)

$$Q^{\cdot}_H = m^{\cdot}_c C_P (T_{SC\text{inlet}} \_ T_{\text{scoutlet}}) \quad (4)$$

Mass conservation equation for each stage can be written as, Shatat (2008)

$$\frac{dMsi}{dt} = -m^{\bullet}_{ei} \quad (5)$$

The dependence of the magnitude of the latent heat, Cooper (1969), and the refined latent heat of vaporization of water, Bergman et al. (2011), from current temperatures were determined as proposed

$$h_{fgi}(T_i) = 1000 * [(3161.5 - 2.40741(T_i + 273)] \quad (6)$$

$$h^{\cdot}_{fgi} = h_{fgi} + 0.68 c_{pi}(T_{si} - T_{ci}) \quad (7)$$

The condensing surface temperature was determined as a function of water surface temperature, Shatat (2008)

$$\left.\begin{array}{r} T_{C1} = T_{S2} - 2K \\ T_{C2} = T_{S3} - 2.7K \\ T_{C3} = T_{S4} - 1.11K \end{array}\right\} \quad (8)$$

$$T_{C4} = T_{S4}\left(0.00007 T_{s4}^3 - 0.015 T_{s4}^2 + 0.9763 T_{s4} - 10.324\right)$$

The heat capacity of water is defined as a function of its temperature, Eames et al. (2007).

$$C_{pi} = 1000 * \left[4.2101 - 0.0022 \times T_i + 5 * 10^{-5} \times T_i^2 - 3 * 10^{-7} \times T_i^3\right] \quad (9)$$

Heat transfer coefficients

The rate of heat transfer coefficient from the water surface to the bottom surface of the next stage upward can be obtained according to this equation, Tiwari et al. (2002)

$$h_{sci} = 0.884 * ((T_{si} - T_{ci}) + (T_{si} + 273) * (P_{si} - P_{ci}))/(268.9 * 1000 - p_{si})^{\wedge}(1/3) \quad (10)$$

Vapor pressures, Fernández and Chargoy (1990)

$$p_i = e^{\left(\frac{25.317 - 5144}{T_s + 273}\right)} \quad (11)$$

The mass transfer coefficient h_{ew} as a function of the convective heat transfer coefficient h_{sc} can be calculated, Tiwari et al. (2002)

$$h_{ew} = 16.273 * 0.001 * h_{sci} * (P_s - P_c)/(T_s - T_c) \quad (12)$$

Results and discussion

Some measurements of solar intensity through the day from sunrise to sunset are plotted. The corresponding plots for water condensation and evaporation temperatures inverting different for a day are displayed. Theoretical analysis of the heat and mass transfer mechanisms inside the still also has been developed depending on the experimental investigations related to the distillation performance of the solar still. All test results achieved on the condition of the solar still are fully insulated. The results showed that the water distillate increases with the increase in the number of stages and solar intensity as well. The steady-state condition of the solar still system for all the stages is presented in Fig. 3. Such results indicated that the temperature at each stage was reached by the same level at 96 °C. The amount of water produced in the period of the test in both of simulation and experimental was about 3.9 and 3.1 kg/day, respectively, as shown in Fig. 4. Based on these results with giving insulation conditions, the evaporation area of the still should be considerably increased in order to take advantage of the high radiation level. Consequently, they still should be filled up by a large amount of brackish water. In order to reduce the water temperature in all the stages by the start of the next day's operation, the still or a part of it should be freed from the thermal insulation.

Depending on the weather, design conditions, and how many stages are needed, the length of solar still is selected. Twenty lengths are tested from 50 to 210 cm. The maximum productivity of the freshwater with the smallest length is the condition selected for the solar still length as shown in Fig. 5.

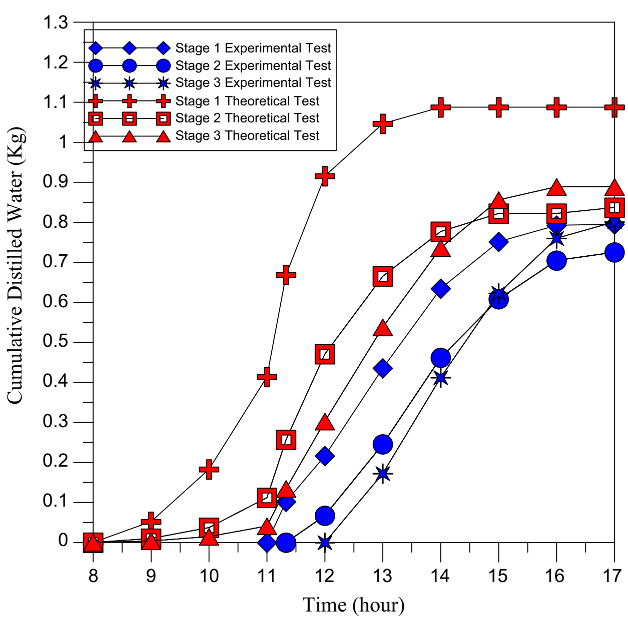

Fig. 4 Distillated water output with time

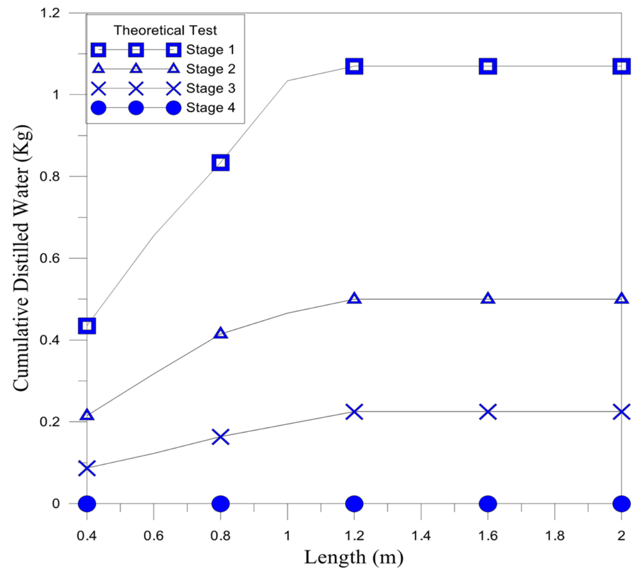

Fig. 5 Variation of productivity with still length

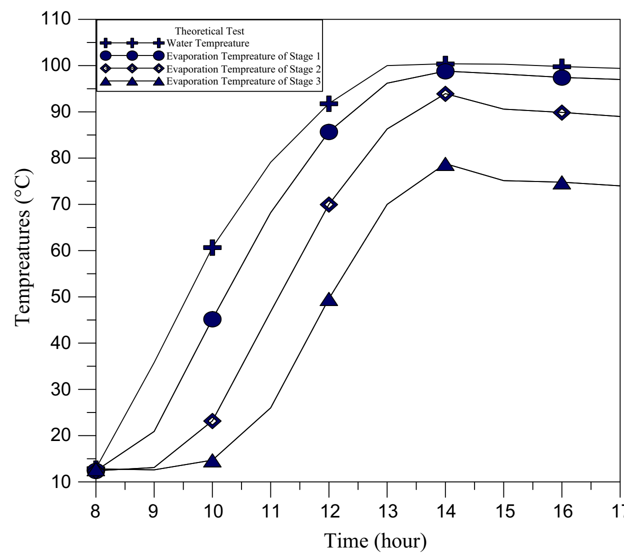

Fig. 6 Theoretical test of water temperature and evaporation temperatures to three stages with time

Figure 6 shows the variation of water and evaporation temperature stages. From this figure, the results showed that the water temperature is higher than those obtained by the evaporation of the three stages. Figure 7 shows the profile of the condensation temperature, while the variation in the values of condensation and evaporation temperature at each stage is shown in Figs. 8 and 9.

Also, the deviations of the results in both experimental and theoretical work are shown in Fig. 10. From this figure, the percentage of the variance is about 11.3% of the experiments of the evaporation temperature. The results recorded by thermocouples showed that the temperature of

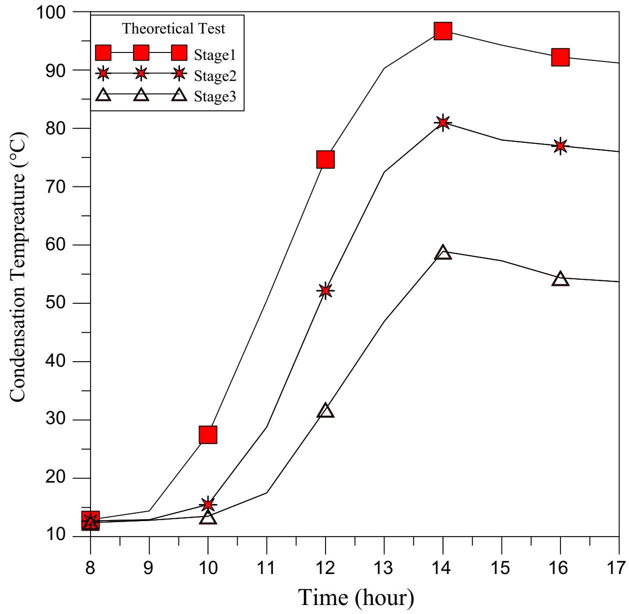

Fig. 7 Theoretical test of condensation evaporation temperatures of temperatures of three stages with time

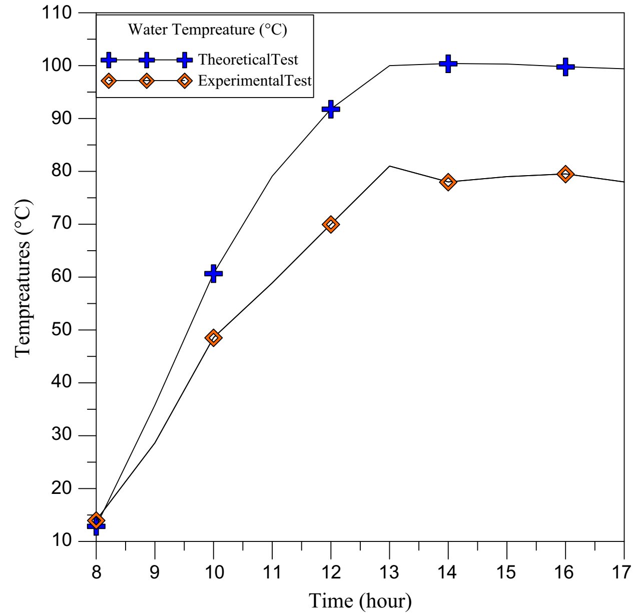

Fig. 9 Theoretical and experimental tests evaporation of water temperature with time

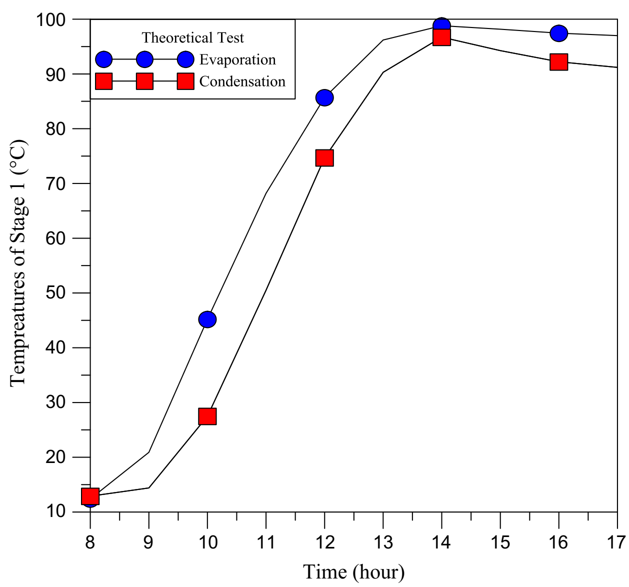

Fig. 8 Theoretical test of condensation and first stage with time

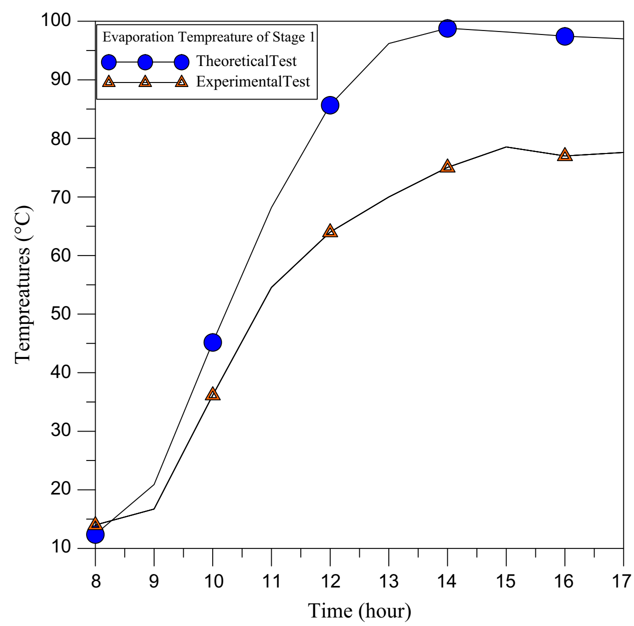

Fig. 10 Theoretical and experimental tests to temperature of first stage

condensation in all stages is less than the temperature obtained by the evaporation. Figure 6 shows the variation of water and the condensation temperatures of the three stages. An example of the condensation temperature recorded is 60.1, 44.0 and 31.9 °C in the first, second and third stages, respectively. The results of the test indicated that the productivity of the freshwater is highly affected by the variation of evaporation and condensation changes. As much as the productivity increases with the increase in the solar radiation intensity and with reducing the heat losses. Also, it is higher at the first stage; then, such values were reduced in the other stages owing to decreasing the energy evaporation phase. Such values were reported to be 0.86, 0.46 and 0.24 kg for the first, second and third stages, respectively. Note that the theoretical productivity of the purest water in the first stage has started at 10:30 a.m. to be

0.11 kg and the experimental productivity of the water has started at 11:00 with 0.10 kg. At the same time, the second stage and the third stage did not get involved in any distillation process because the temperatures of the evaporation and condensation are small. Also, of the time 13, it has been noted that an increase in the theoretical productivity of the water. The first phase is reported to be 0.25 kg, and the experiment is at 0.23 kg while in the second stage the theoretical productivity is at 0.12 kg and the experimental is 0.10 kg while the third stage has not been obtained in distilled water. Lastly, the comparison of the experimental productivities of the four months tested shows that the productivity of the months May, June, July and August were 0.87 kg, 1.14 kg, 1.2 kg and 1.56 kg respectively.

Conclusion

A solar still was constructed and studied here under actual environmental conditions in Kirkuk, north of Iraq. A new promising technology of the solar water desalination system has been thoroughly studied via experimental investigation and theoretical analysis. A multistage solar still coupled with the solar collector panel was tested and simulated under several conditions of a typical midsummer day in the Middle East region. It was found that the capacity of the freshwater production of the system was 4.94 L/m^2/day at a distillation efficiency of 84%, which is higher than any other efficiency obtained from both conventional stills and stills coupled with flat plate collectors.

A mathematical model based on differential equations involving mass and energy conservations has been developed for transient numerical simulation and calibrated by the experimental results. Experimental validation of the model demonstrated indicated that there is an acceptable level of accuracy in the prediction of the performance of the system.

This mathematical model defines the relationship between the aperture area of the solar collector and that of the basin.

A rational design simulation analysis was carried out for parameters estimation, such as the number of stages and the evaporation area relative to the solar collector area for real dynamic variations in the solar insolation. It has been concluded that the evaporation area of the system should be increased by a factor of 2.

The simulation and the optimization results have also demonstrated that the performance of the system could be considerably improved and the production of the freshwater could reach as high as 11 kg/m^2 day. The advantage of the desalination system is that it is powered by completely environment-friendly and sustainable energy source. This advantage could, in itself, attract the international aid from countries interested in reducing climate change, especially if they were given credit for such aid by some of the carbon trading schemes under international discussion.

In practical terms, the recommendation would be to increase the evaporation area of the still. Also, the increase in the salt concentrations during the distillation process also should be studied. Finally, greater attention must be paid to reduce the heat losses from the system.

Acknowledgements We thank the staff of the mechanical engineering laboratory at Tikrit University. We extend our gratitude to the workshop team of the mechanical engineering of their useful comments and dedicated discussions and preparation of the manuscript.

References

Ahmed MI, Hrairi M, Ismail AF (2009) On the characteristics of multistage evacuated solar distillation. Renew Energy 34:1471–1478

Akash BA, Mohsen MS, Nayfeh W (2000) Experimental study of the basin type solar still under local climate conditions. Energy Convers Manag 41:883–890

AL-Karaghouli AA, ALnaser WE (2004) Performances of single and double basin solar-stills. Appl Energy 78:347–354

Attaseth T, Kirtikara K, Wibulswas P (1985) Vertical surface solar stills. TPA—KMITT, Bangkok

Bergman TL, Lavine AS, Incropera FP, DeWitt DP (2011) Fundamentals of heat and mass transfer (7th edn). Wiley, New York

Cooper P (1969) The absorption of radiation in solar stills. Sol Energy 12:333–346

Eames IW, Maidment GG, Lalzad AK (2007) A theoretical and experimental investigation of a small-scale solar-powered barometric desalination system. Appl Therm Eng 27:1951–1959

Fernández J, Chargoy N (1990) Multi-stage, indirectly heated solar still. Sol Energy 44:215–223

Grawand JS, Bhuyar LB, Deshmukh SJ (2013) Effect of depth of water on the performance of stepped type solar still. Int J Energy Eng (IJEE) 3:137–143

Khalifa AJN, Ibrahim HA (2010) Effect of inclination of the external reflector of simple solar still in winter: an experimental investigation for different cover angles. Desalination 264(1):129–133

Nijmeh S, Odeh S, Akash B (2005) Experimental and theoretical study of a single-basin solar sill in Jordan. Int Commun Heat Mass Transfer 32:565–572

Patel P, Solanki SA, Soni RU, Patel RA (2014) A review to increase the performance of solar still: make it multi-layer absorber. Int J Recent Innov Trends Comput Commun 2:173–177

Shatat MIM (2008) New and renewable energy and environmental engineering. Master Thesis in Solar Water Desalination, School of Engineering, Durham University (In Britain)

Tiwari GN (2002) Solar energy: fundamentals, design, modelling and applications. Alpha Science International, Limited, ISBN 1842651064, 9781842651063