Desalination and Water Treatment
www.deswater.com
16 (2010) 17–28
April

doi: 10.5004/dwt.2010.1083

Performance characteristics of a solar humidification dehumidification unit using packed bed of screens as the humidifier

A.H. EL-Shazly[a,*], M.M. EL-Gohary[b], M.E. Ossman[c]

[a]*Faculty of Engineering, Chemical Engineering Department, Alex University, Egypt*
email: Elshazly_a@yahoo.com
[b]*Faculty of Engineering, Marine Engineering Department, Alex University, Egypt*
[c]*Mubarak city for scientific research and technological applications (IRI), Alex, Egypt*

Received 29 November 2008; Accepted 9 December 2009

ABSTRACT

The aim of the present work is to investigate the main factors affecting the performance improvement of a solar humidification-dehumidification unit (HD), using a packed bed of screens as the humidifier. The HD unit consists mainly of a flat plate solar collector, humidification section and dehumidification exchanger. The investigation was divided into three main parts which are

Part 1: investigation of the main variables affecting the solar collector performance. It was found that the efficiency of solar collector increased by increasing the collector angle of inclination up to 45°, increasing the area of solar collector, and decreasing the inlet water flow rate.

Part 2: investigation of the humidification-dehumidification unit separated from the solar collector and using external source of heating. It was found that, the productivity of the unit increased by increasing the saline water inlet temperature, saline water flow rate, and thickness of screen packing.

Part 3: the overall system components were assembled, and investigated under different conditions, the results show that, the unit productivity increased by increasing inlet saline water flow rate up to 5 L/min and then it is decreased by increasing the inlet flow rate beyond this value, and increased by increasing the thickness of packed bed up to 40 cm and then decreased by increasing the thickness above this value. Recycling of the hot brine out of the humidification section was found to increase the unit productivity by a factor of 214% than the system without recycling. The average unit productivity per day was about 9 L per m^2 of collector area

Keywords: Desalination; Solar collector; Humidification-dehumidification process; Packed bed Screen packing, Productivity of humidification dehumidification unit; Efficiency of solar collector

1. Introduction

Desalination has been found to be the most suitable solution for supplying the Egyptian desert with fresh water, due to the increasing demand for the Nile water in the Nile valley. The areas suitable for development are those along the Red and Mediterranean Sea shores [1]. The standard techniques like multi-stage flash (MSF), multi-effect (ME), vapor compression (VC) and reverse osmosis (RO) are only feasible for large capacity ranges of 100–50,000 m^3/day of fresh water production [2]. These technologies are expensive for small amounts of fresh water, and they cannot be used in locations where there are limited maintenance facilities and energy supply. Development and use of new technologies for small capacity plants is highly desirable. On the other hand solar energy is the most important renewable source of energy in Egypt, which receives more than 5.0 kW/m^2

*Corresponding author.

per day [3]. Solar desalination is a suitable solution to supply some remote regions in Egypt with fresh water. Solar desalination processes are a future promising technology because solar energy is environmentally friendly [4]. The solar desalination can be either direct or indirect [5]. One of the well known indirect solar desalination systems is the humidification–dehumidification (HD) process. The humidification dehumidification desalination process is viewed as a promising technique for small capacity production plants. The process has several attractive features, which include operation at low temperature, ability to utilize sustainable energy sources, i.e. solar and geothermal, and requirements of low technology level. There is a number of configurations for HD desalinating processes which have been developed. Al-Hallaj et al. [6] used humidification-dehumidification, where the air was circulated in a closed loop using a blower. The humid air was partially condensed in a large surface condenser where most of the latent heat from water condensation was used to preheat the saline water. Daily production of 12 l/m^2 of solar collector area was achieved. Moreover, Farid and Al-Hallaj [7] improved the solar desalination unit where the circulated air by natural or forced convection was heated and humidified by the hot water obtained either from a flat-plate solar collector or from an electrical heater. A simulation program to optimize the unit performance was developed by Nawayesh *et al*. [8–10], they found that in natural draft operation, the air circulation rate is increased with the rate of water flow. Farid *et al*. [11] modified the numerical simulation in, where the model allows the proper choice of the feed water flow rate to the unit. In addition Parekh *et al*., [12] discussed the methods to improve system performance and efficiency that paves the way towards possible commercialization of such units in the future. Further, Bourouni *et al*. [13] presented a state of the art of the desalination technology using solar and geothermal energy. While, Ben-Bacha [14] presented simulation and experimental validation of the distillation module of a desalination unit in Sfax, Tunisia. The plant was supplied with water heated either by solar energy or by geothermal water. It was shown that the developed model is able to predict accurately the trends of the heat and mass characteristics of the evaporation and condensation chambers. Garg *et al*. [15] investigated the possibility of using humidification–dehumidification (HD) techniques in the coastal regions of India where many industries using seawater as coolant were implemented. This water, when ejected at a temperature of about 55°C, can be used for appreciable recovery of fresh water. With this recovery a contribution of 28% of the total cost can be achieved. Heating the air inside the evaporation–condensation unit may be able to raise the distilled water productivity. Nafey *et al*. [16] investigated numerically a HD system that consists mainly of a concentrating solar water collector, flat-plate solar air collector, humidifying tower and dehumidifying exchanger. Two separate circulating loops constitute the HD system, the first for heating the feed water and the second for heating air. The results of the developed mathematical model are in good agreement with the corresponding experimental results and other published works. In another research Nafey *et al*. [17] validated experimentally the numerical model at the weather conditions of Suez City, Egypt. Orfi *et al*. [18] suggested that HD system can be used in an open or closed cycle for air circulation inside the unit. The theoretical results show that there is an optimum mass flow rate ratio corresponding to maximum fresh water produced. It is normally based on the weather conditions of the system location. Ben Amara *et al*. [19] investigated experimentally the principal operating parameters of the desalination process working with an air multiple-effect HD method. They found that the ratio of water to dry air mass flow rates was optimized, precisely 45%. Dai *et al*. [20] presented a mathematical model, which was experimentally validated. The effect of some of the operating conditions such as flow rates, temperatures of feed water, air and cooling water, etc., was studied in detail by Dai and Zhang [21] who suggested that their experiments worked perfectly and the thermal efficiency was above 80%. Al-Sahali and Ettouney [22] in their study found that, modeling results for variations in the humidifier height, heat transfer area of the condenser, flow rate of cooling water, performance ratio (defined as kg of product water per 1 kg of heating steam), and flow rates of the air and water streams, need further system optimization through experimental measurements and mathematical modeling to determine the design and operating conditions that provides the lowest unit product cost. Yamali and Solmus [23] in an experimental study showed that: (i) under certain operating conditions, the HD system productivity decreases about 15% if double-pass solar air heater is not used; (ii) significant improvement on the productivity of the system is achieved by increasing the initial water temperature inside the storage tank; (iii) productivity of the system increases with increasing the feed water mass flow rate and quantity of water inside the storage tank, but remains approximately the same when the air mass flow rate is increased; (iv) increasing the cooling water mass flow rate results in the improvement on the productivity of the system. Finally, they compared their results with the theoretical study and a good agreement between them was observed. Abdel Dayem [24] represented experimentally and numerically the performance of a simple solar distillation unit that is based on the multiple condensation–evaporation cycle. The pilot plant was designed, fabricated, tested and simulated at the solar energy laboratory, Mattarria Faculty of Engineering, Cairo, Egypt. It is well known that the capacity of air for carrying water vapour is limited to the operating

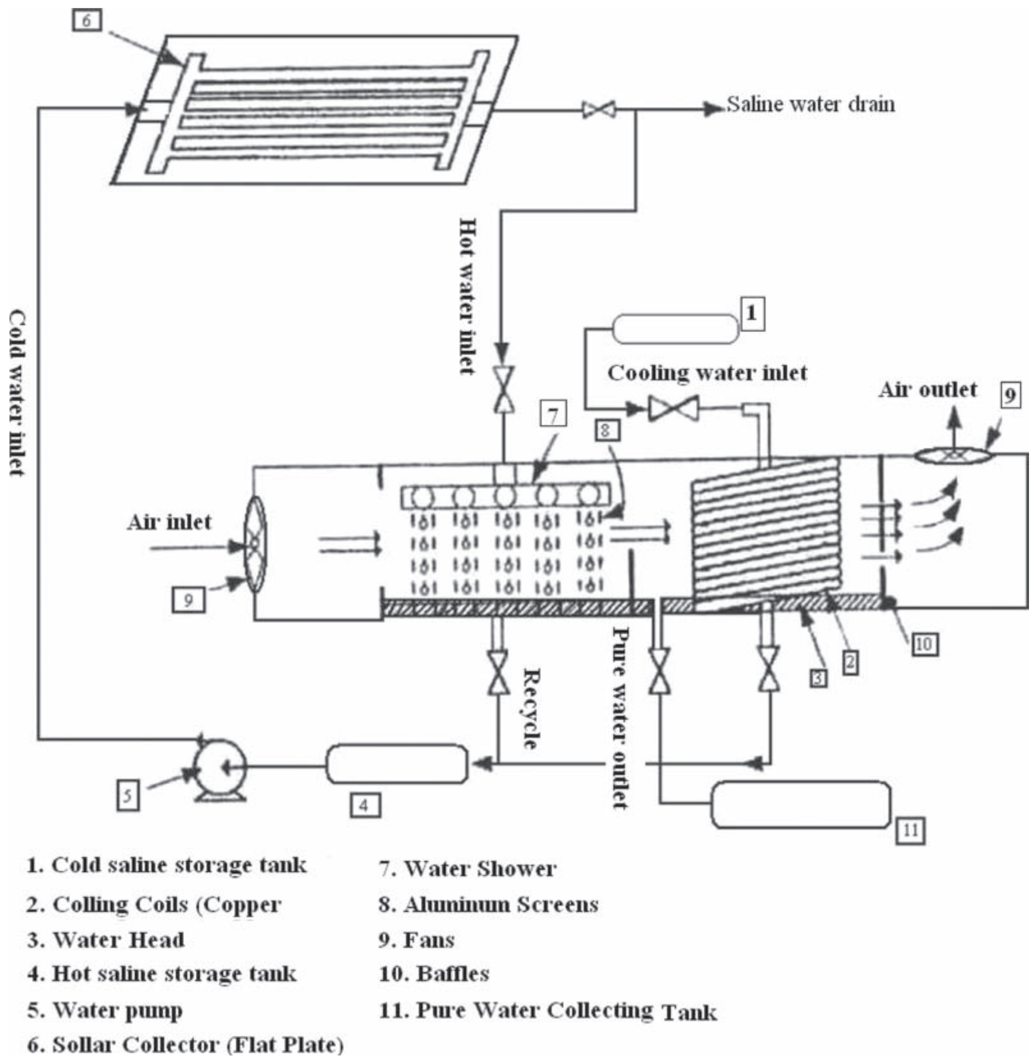

Fig. 1. Schematic diagram of saline water desalination system by humidification dehumidification process using solar energy.

conditions such as temperature and humidity. Increasing the contact area between air and water vapour can increase the water productivity from the HD unit. Using fixed bed of screens will increase the contact area between hot water and solid screens, which in turn increase possibility of water evaporation. The evaporated water can be easily carried on by the flowing air. The humid air can be dehumidified in the dehumidification section where pure water can be collected as the product.

The main objective of this investigation was to examine experimentally the solar HD system using fixed bed of plastic screens with different lengths. The system was established in Alexandria- Egypt. The unit was examined at different real weather and operating conditions. In addition, the main parameters affecting the efficiency of the solar collector and the productivity of the HD unit were examined. Finally, correlations for predicting the unit performance as a function of operating conditions were deduced.

2. Experimental setup and procedure

2.1. Experimental setup

Fig. 1. shows a schematic diagram of the desalination unit established in Alexandria, Egypt. The unit consists of three main parts: (i) solar collector where saline water is heated using the solar energy; (ii) humidification part where an air current driven by fans is to be humidified by the hot saline water coming from the solar collector; and (iii) the dehumidification part where fresh water is

condensed from the humidified air and collected as the final product.

2.1.1. The solar heater

The collector dimensions were about 100 cm wide, 160 cm long and 10 cm high. It consisted (Fig. 2a) of an iron sheet base of 3 mm thickness; a glass wool layer of 3 cm thickness; a corrugated iron sheet; a glass cover 3 mm thick and a 0.5 inch schedule 40 iron tube. The iron tube was 9 m long with five tube passes Fig. 2b, for increasing residence time inside the heater. All iron sheets and tubes were painted with black dye. The solar heater was positioned facing south at different tilt angles ranging from 0° to 45°.

2.1.2. The humidifier

Fig. 1. shows a general view of the humidifier, which consisted of a fixed bed of plastic screens, mounted vertically and supported by means of up and down wall supports. The total bed length was about 20–50 cm; each screen has a thickness of 1mm. At the top of the humidifier, there is a liquid sprayer, which sprays hot saline water coming from the solar collector, onto the packed screens. At the bottom of the humidifier there is a water storage tank, for collecting drained brine. Part of this water is recycled back to the solar collector and the other part is drained off, for keeping water salinity below certain level, decrease scales formation and corrosion rate. Thus, the hot water flows downward, while air passes in a cross-flow direction through the openings of the screens. The air is humidified as it contacts water vapour at the hot wetted surface of the packed screens. Presence of screens helps air humidity to increase up to its saturation limits at the studied temperature range (up to 70°C).

2.1.3. The condenser (the dehumidifier)

The condenser was composed of copper cooling coil with total surface area of about 50 cm². A constant liquid level of fresh water was kept at the bottom of the condensation section by using an over flow weir for collecting condensed pure water at pure water tank. At the end of the dehumidification unit air has to pass through a Plexiglas screen, with 1 mm hole diameter and 2 mm hole spacing, arranged in-line. This screen is used for increasing the amount of water condensed from exit air by obstructing the humid air pass.

2.2. Procedure

The saline water was pumped from the saline water storage tank (4) through the flat plate solar collector by

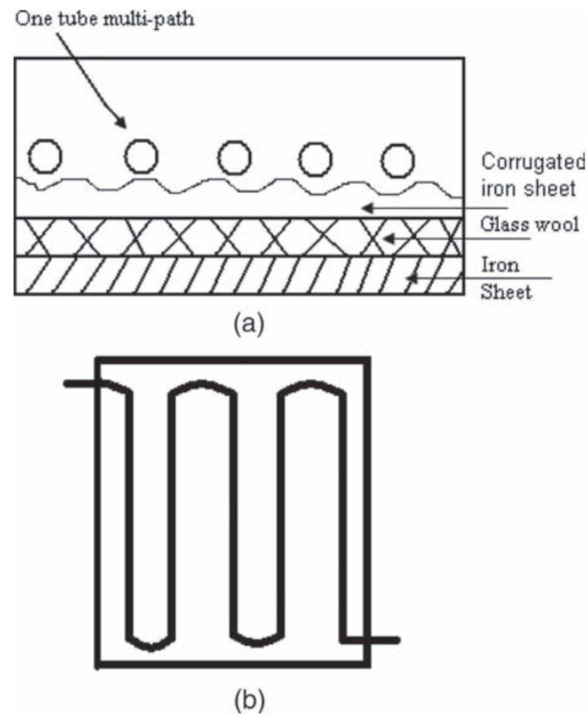

Fig. 2. Details of the solar collector used in the desalination units: (a) sketch of flat plate solar collector; (b) sketch of the pathway in the solar collector.

using a plastic head (0.25 hp) centrifugal pump, where it is heated up to certain temperature depending on atmospheric conditions. The heated water was sprayed over the fixed bed of plastic screens mounted vertically in the humidification section; at the same time air was forced through the humidification section, in cross flow to the sprayed water by means of an air fan (1/3 hp). Air leaving the humidification section carrying the water vapour was transferred to the dehumidification section where it exchanged heat with the cold fresh saline water coming from tank (1). The condensed water was collected at the bottom of the condensation section where it drained to the pure water collection tank (11). The preheated saline water drained at the bottom of the condensation section was transferred to the saline water storage tank (4) to combine with the drained hot water down the humidification section to be recycled back to the flat plate solar collector. Part of this water was drained off at different time intervals in order to control the salinity increase. Salinity of water was measured using conductivity meter and a calibration curve. The unit operation lasts for 8 h from (9 am up to 5 pm). The work is divided into three main parts. First is the study of the main variables affecting the performance of the solar collector such as area of solar collector, tilt angle of the collector and saline water feed rate

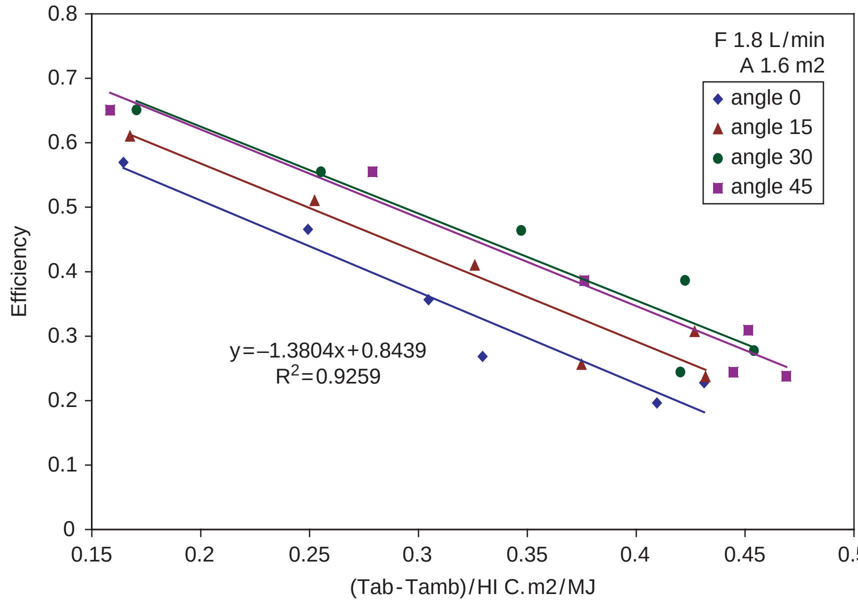

Fig. 3. Efficiency of the solar collector at different angles of inclination.

to the collector; second is the investigation of the main variables affecting the productivity of the humidification unit such as thickness of packed bed in the humidification section, water flow rate and inlet water temperature to the humidification section. For this part of investigating the HD unit only (using external source of heating instead of using the collector), the total time of operation was only 2 h. Finally the unit parts were assembled together and the overall performance of the unit was investigated under different conditions such as inlet water flow rate, packed bed thickness and effect of recycling the brine solution from the humidification unit to the solar collector.

3. Result and discussion

3.1. For flat plate solar collector

The collector efficiency was calculated as a function of the ambient temperature, water inlet temperature, and solar radiation, as reported by Farid *et al*. [11], who used the following equation for determining the collector efficiency:

$$\eta = a - b\left(T_{ab} - T_{amb}\right)/\,H_I$$

where η is the solar collector efficiency, T_{ab} and T_{amb} are absolute and ambient temperatures respectively. Absolute temperature was taken as the average between inlet and outlet temperature of saline water $(T_{in} + T_{out})/2$. H_I is the solar radiation intensity received by the collector (W/m^2), while a and b are constants depending on the conditions affecting the performance of the collector such as insolation rate, angle of inclination and the collector geometry. The above efficiency includes the heat losses through the pipes connecting the desalination unit with the solar collector. The value of H_I was taken as the average solar radiation rate in Alexandria, Egypt (Ave Egypt 2171 kWh/m^2/nominal annual insolation) [25]. Values of a and b for present collector were investigated under different conditions as follows:

3.1.1. Effect of changing angle of inclination of solar collector

Figs. 3 and 4 show the effect of changing the angle of inclination of the solar collector on the efficiency of solar collector. The tilt angle ranged from 0° up to 45°. It is obvious that the collector efficiency increased by increasing the angle of inclination. Constants a and b for different angles were found according to the following equations:

For horizontal collector:

with $$\eta = 0.7944 - 1.4202\left[\frac{T_{ab} - T_{amb}}{H_I}\right] \quad (1)$$

The efficiency of solar collector with 15° angle of inclination:

with $$\eta = 0.8404 - 1.4456\left[\frac{T_{ab} - T_{amb}}{H_I}\right] \quad (2)$$

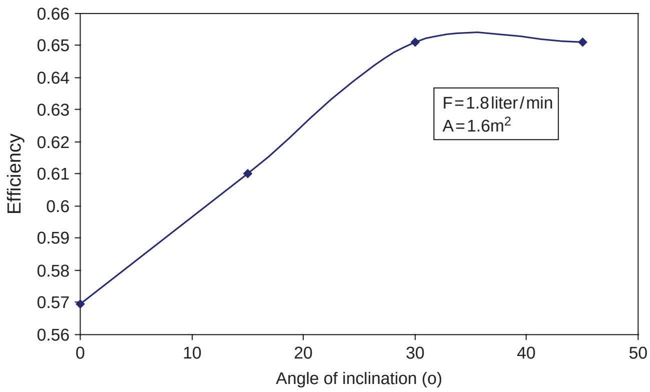

Fig. 4. Effect of changing the angle of inclination on the efficiency of the solar collector.

The efficiency of solar collector with 30° angle of inclination:

with $$\eta = 0.7944 - 1.4202\left[\frac{T_{ab} - T_{amb}}{H_I}\right] \quad (3)$$

The efficiency of solar collector with 45° angle of inclination:

with $$\eta = 0.8404 - 1.4456\left[\frac{T_{ab} - T_{amb}}{H_I}\right] \quad (4)$$

The above results show good agreement with the literature [26, 27]; the optimum angle of inclination for solar collector to obtain maximum energy collection is coincident with the latitude of the location ±10°. In practice, most energy is collected by a surface with angle 30–35 ° to the horizontal. Angles greater than the optimum will cause a reduction in the efficiency of the collector and an angle of more than 45° is not recommended (this may reduce the amount of energy captured by up to 10%). The collector efficiency may reach up to 90% especially when the term (T_{ab} – T_{amb}/H_I) equals zero, this is the case when T_{ab}= $T_{amb.}$ A reasonable similarity was obtained between the present experimental results and the results of Hahne and Ristoiu [26, 27].

3.1.2. Effect of changing area of collector

Figures 5 and 6 show the effect of changing the area of solar collector on its efficiency. The total area of the collector (1.6 m^2) was divided into four main parts (each part is 25% of the total area), three layers of carton were used as the insulation by covering the unused area. The efficiency of each part was calculated as before.

From Fig. 5. it is obvious that the efficiency of solar collector at 75%, 50% and 25% of its total surface area can be calculated according to the following correlations respectively:

with $$\eta = 0.8599 - 1.3903\left[\frac{T_{ab} - T_{amb}}{H_I}\right] \quad (4)$$

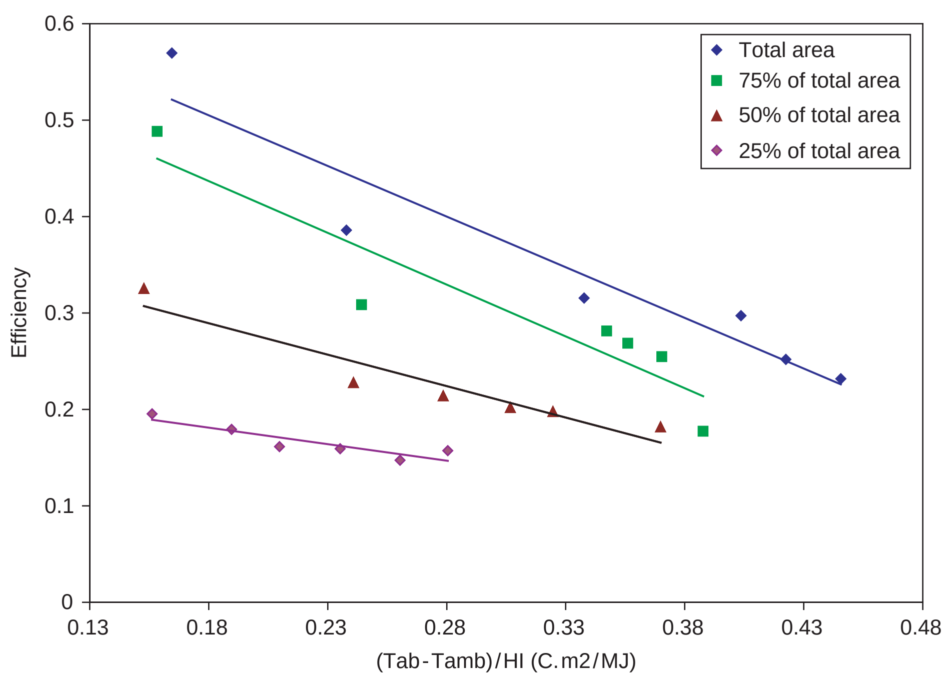

Fig. 5. Efficiency of the solar collector at different surface area of the collector.

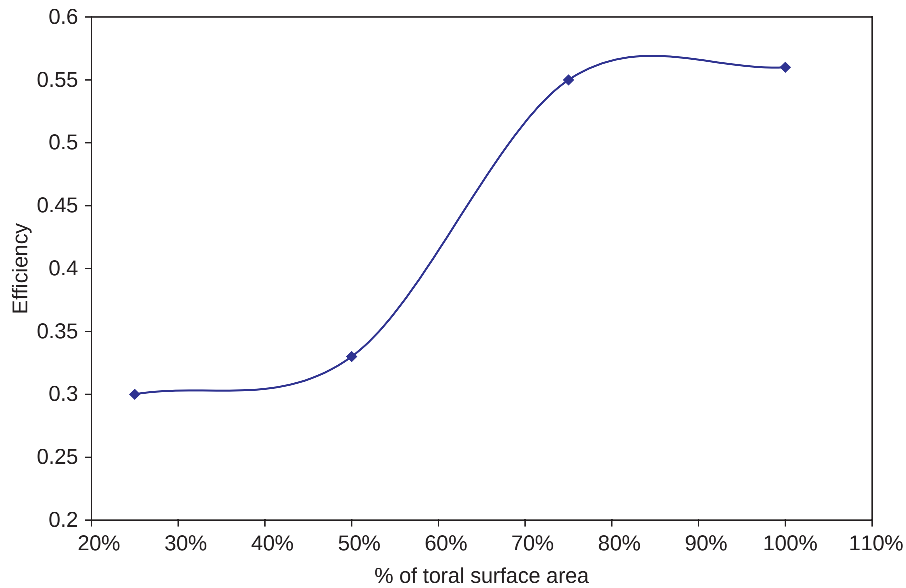

Fig. 6. Effect of changing the area of the solar collector on its efficiency.

The efficiency of solar collector at area = 50% of total solar collector.

with $$\eta = 0.8947 - 1.37\left[\frac{T_{ab} - T_{amb}}{H_I}\right] \tag{5}$$

The efficiency of solar collector at area = 25% of total solar collector.

with $$\eta = 0.6301 - 1.0741\left[\frac{T_{ab} - T_{amb}}{H_I}\right] \tag{6}$$

As shown in Fig. 6. it was found that the efficiency of solar collector decreased by decreasing its area. The reduction in collector efficiency due to reduction of collector area may be ascribed to the short path traveled by the flowing saline water due to the reduction in the collector length, which will decrease both the residence time and the total amount of heat absorbed by the flowing water. On the other hand, it is clear that the percentage reduction in the collector efficiency due to decreasing the solar collector area from 100% to 75% of its total surface area is not so high about 5%, which indicates that economic optimization for the optimum required area of solar collector, will be essential. The above result indicates that the path of water inside the solar collector has to be optimized, as the solar energy is not efficient in heating water above certain level.

3.1.3. Effect of changing flow rate of inlet saline water

Figures 7 and 8 show the effect of changing the flow rate of saline water entering the collector. It was found that the efficiency of solar collector decreases by increasing the water flow rate and this shows good agreement with the literature [23]. This result may be attributed to the short path traveled by water through the solar collector, which results in a reduction both on residence time and on heat transferred to the flowing saline water. Thus reduced output temperatures and reduced efficiencies are obtained.

3.2. Humidification dehumidification unit

The performance of the HD unit was investigated under different conditions, such as saline water flow rate, inlet water temperature, and thickness of packed bed used. The productivity of the system is defined by the amount of water collected from the unit (liter). For investigation of the HD unit a separate storage tank was used as a reservoir for the saline water, which was passed through a heater and a temperature control thermocouple. In addition a centrifugal pump with regulation valve was used for controlling flow rate. The operation of the unit lasted for only 2 h for each experiment.

3.2.1. Effect of inlet saline water flow rate on the productivity of the HD unit

Saline water from storage tank was introduced into the humidification unit, and distributed well over

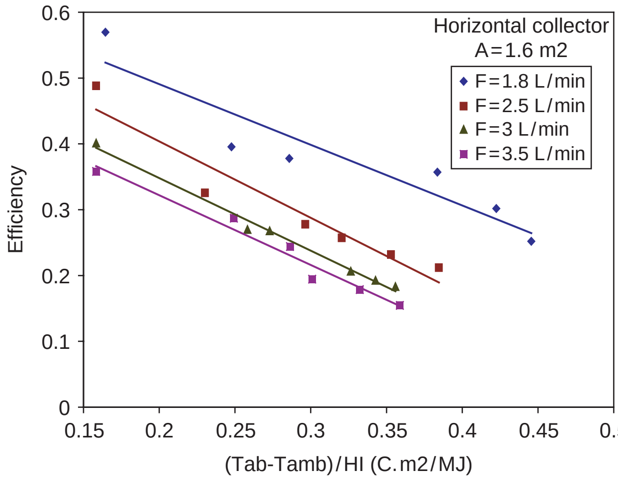

Fig. 7. Efficiency of the solar collector at different saline water flow rates.

the plastic screen packing, with a volumetric flow rate ranging from 1.5 to 5 L/min. The effect of saline water flow rate was investigated under different conditions of saline water temperatures ranging from 40 to 70°C. As shown in Fig. 9, the amount of pure water collected was increased by increasing the inlet saline water flow rate, which can be ascribed to the fact that, increasing the water flow rate increases both the amount of water vapor produced in the humidification section and the contact area between air and hot water which, enhances the rate of mass transfer between the two phases and increase the unit productivity. In addition, the presence of plastic screens packing can maintain isothermal conditions inside the humidification unit that can overcome the effect of short residence time of higher rate conditions, which also increases the absolute humidity of the air leaving the humidification unit, and therefore the unit productivity.

3.2.2. Effect of saline water inlet temperature on the productivity of the HD unit

The amount of pure water collected was increased by increasing the saline water inlet temperature, as shown in Fig. 10. This result may be attributed to the increased amount of vapour produced due to the temperature elevation in the humidification section. In addition higher temperature combined with higher evaporation rate maintain saturation conditions in the humidification section, which ensure saturation condition for leaving air with higher absolute humidity that increases the unit productivity.

3.2.3. Effect of packed bed thickness on the productivity of the HD unit

It was found that the unit productivity was increased by increasing the packing material thickness, as shown in Fig. 11. This result may be attributed to the fact that, the presence of plastic packing screens provides higher surface area of mass transfer between water vapor and air. In addition, the lower heat transfer coefficient of the plastic packing maintains the temperature of the humidifier at a reasonable higher value, which ensures

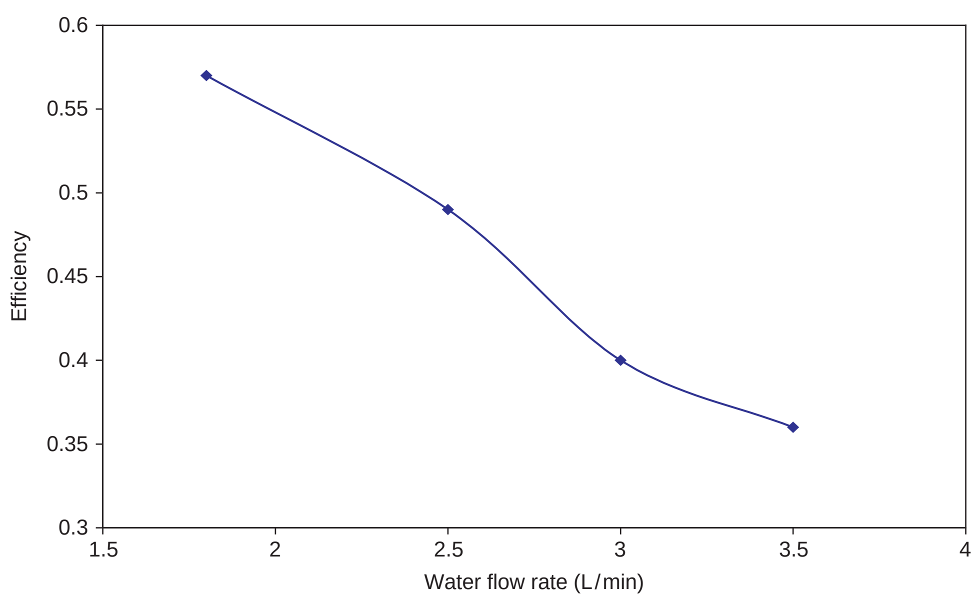

Fig. 8. Effect of changing the water flow rate on the efficiency of the solar collector in the HD unit.

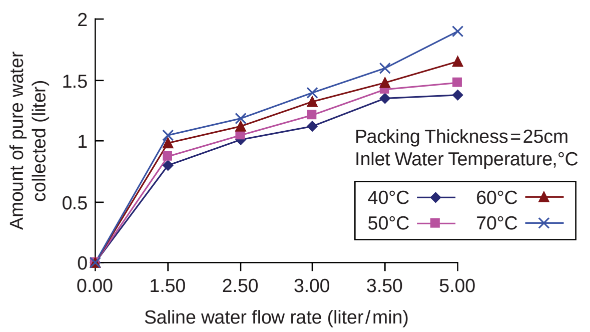

Fig. 9. Amount of pure water collected versus saline water flow rate for different inlet water temperatures.

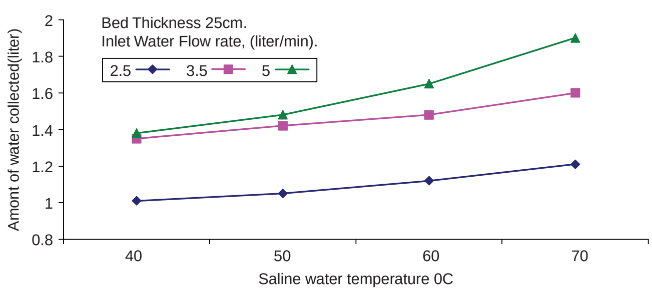

Fig. 10. Amount of water collected versus saline water inlet temperature at different inlet water flow rates.

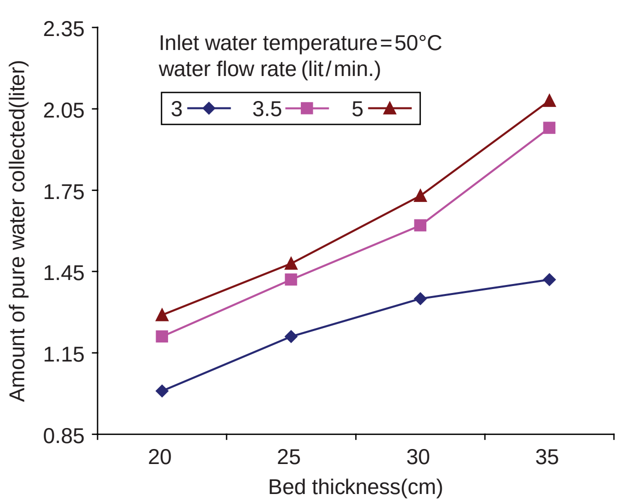

Fig. 11. Amount of pure water collected versus Bed thickness at different inlet water flow rates.

saturation conditions in the humidifier and higher air capacity that increases the unit productivity.

3.3. Unit integration and operation

The unit parts were assembled together and examined at real atmospheric conditions, 8 h per day (from 9 am up to 5 pm) under different conditions of inlet saline water flow rate , packed bed thickness, in addition the effect of preventing the recycle of the hot brine from the humidification unit to the collector was investigated. The inlet water temperature to the condenser was about 16°C, and a total area of the collector 1.6 m^2 were used. The average daily productivity of the unit was about 9 liter per m^2 of collector area.

3.3.1. Effect of inlet saline water flow rate

As shown in Figs. 12 and 13 the total amount of water collected at the end of the day (8 h) was increased by increasing inlet saline water flow rate up to 5 L/min, increasing the inlet water flow rate beyond this value decreased the total amount of collected water. The above results can be ascribed to the fact that, there are two opposing effect for the increased flow rate on the performance of solar collector and humidification unit respectively. Increasing inlet saline water flow rate will reduce the efficiency of the solar collector as shown in Fig. 8. and thus reduces the exit temperature of water leaving to the humidifier and the unit productivity as well. On the other hand increasing the inlet water flow rate to the humidification chamber can improve the performance of unit as shown in Fig. 9. These two opposing effects are now added together by connecting the unit (solar collector and the HD unit) up to 5 L/min the enhancing effect on the humidification unit is predominant while for higher flow rates the reduction effect on the collector efficiency will be the dominant effect. It has to be mentioned that as shown in Fig. 14. the productivity of the unit was the maximum within the period from 11 am to 3 pm. This result may be ascribed to the increase in the atmospheric temperature and average solar radiation rate at this period of the day. In addition it is clear that as shown in Fig. 12. flow rates above 2.5 L/min approximately have the same effect on the unit productivity especially at the period from 11 am to 3 pm, which can be explained by the fact that at this period of the day all the unit components (solar collector, humidification and dehumidification units) have reached the steady state conditions and thus the effect of higher flow rates have been reduced.

3.3.2. Effect of the packed bed thickness

As shown in Fig. 15. different bed thicknesses in the range from 20 to 50 cm were investigated for its effect on the unit performance, the results show that the unit productivity increased by increasing the bed thickness up to 40 cm, while increasing the bed thickness above this value approximately has no effect on the unit performance. This can be ascribed to fact that saturation conditions inside the humidification unit has a maximum limit which is more related to air and water temperature than to packing thickness.

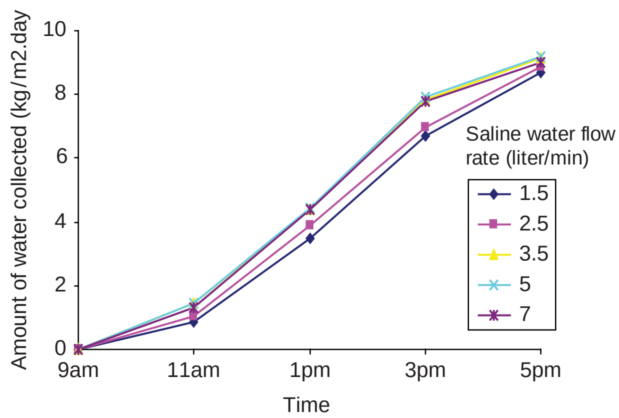

Fig. 12. Amount of water collected distributed from 9 am up to 5 pm for different inlet saline water flow rates.

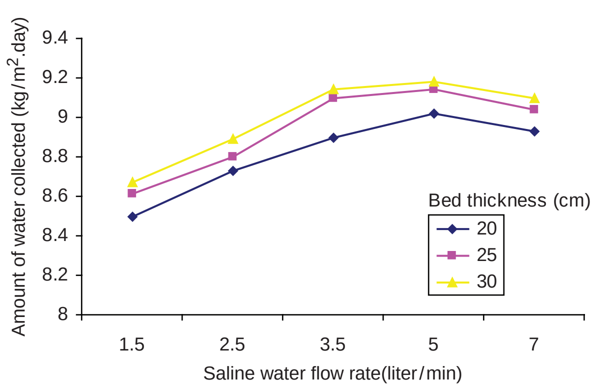

Fig. 13. Amount of water collected versus inlet saline water flow rate for different bed thickness.

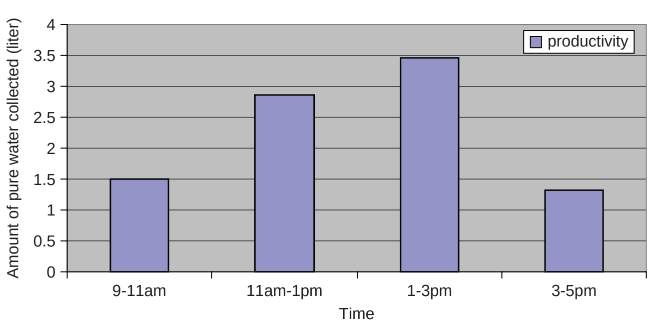

Fig. 14. The unit productivity distribution a long the day from 9 am up to 5 pm.

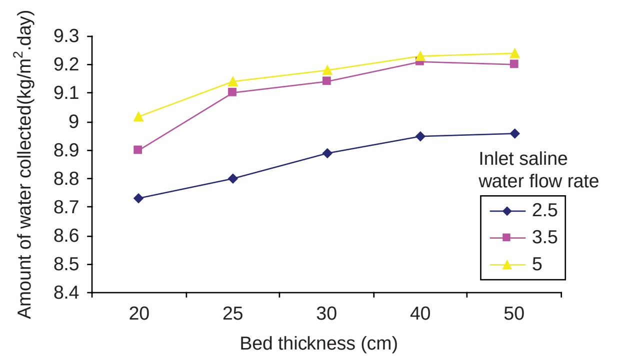

Fig. 15. Amount of water collected versus bed thickness for different inlet saline water flow rates.

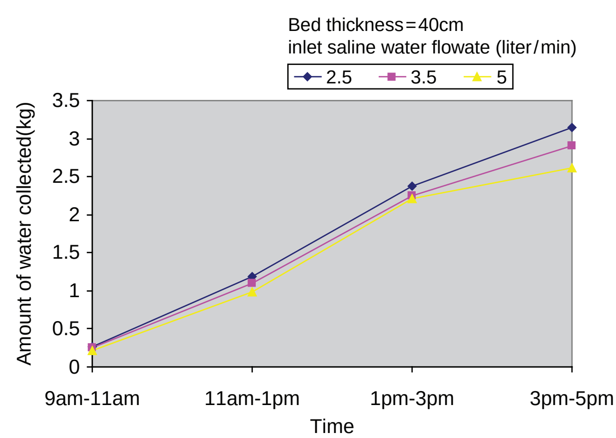

Fig. 16. Amount of pure water collected versus time for different inlet saline water flow rates without exit brine recycling.

3.3.3 Effect of recycling the hot brine exit from humidification unit to the collector

For all the above examinations the exit hot brine from the humidification unit was recycled back to the solar collector, now the unit was investigated without recycling the brine, it was drained off**.** As shown in Fig. 16. the maximum amount of pure water collected ranged from 2.3 to 3.15 L/day depending on the inlet saline water flow rate. The results show that increasing the inlet saline water flow rate without recycling decrease the unit productivity which can ascribed to the short pass traveled by water inside the collector and due to energy losses of exit brine solution. Fig. 17. shows that brine recycling increased the unit productivity from 2.9 to 9.15 L/day with a percentage increase of about 214.5%. This result can be ascribed to the saving in energy due to brine recycling.

4. Conclusion

The performance characteristics of a solar powered humidification-dehumidification unit were analyzed at different operating condition. It was found that the efficiency of solar collector was increased by increasing the

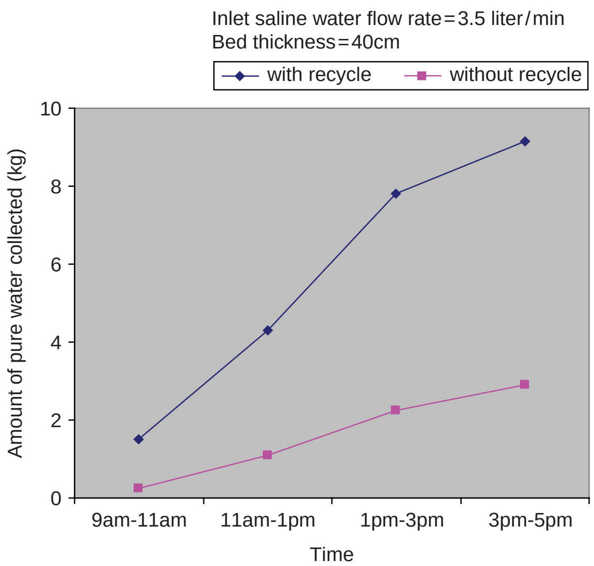

Fig. 17. Amount of pure water collected versus time with and without exit brine recycling

angle of inclination, increasing the area of solar collector and decreasing the water flow rate. The optimum angle of inclination ranged from 30–45 for which the efficiency of the solar collector went up to 90% when $T_{ab}= T_{amb}$. Optimization of the collector length has to be considered, as increasing the collector length above certain value did not affect the efficiency of the collector, while it may increase the fixed cost of the unit. In addition, the productivity of the humidification-dehumidification unit was increased by increasing both the inlet saline water temperature and its flow rate. We have to mention that, these results inversed with the results obtained for the collector, as increasing the water flow rate within the collector did not increase the output temperature of the exit water to the HD unit. These results show that the collector length has to be optimized, in order to obtain a higher temperature with reasonable inlet water flow rate to the HD unit. Fig. 11. shows that the amount of pure water collected increased by increasing the thickness of the packed bed. The presence of packing ensures both higher temperature and higher contact area between air and the water vapour, and maintains suitable conditions for air saturation. Recycling the hot brine from the humidification unit to the solar collector was found to increase the unit productivity up to 214% than without recycling. The average unit productivity was about 9 liter per m^2 of collector area per day. This system is simple, cheap, and easy to operate therefore can be used for arid and remote areas.

References

[1] S.G. Serag El-din, M.A. Darwish and H.T. El-Dessouky, Interactions in a single-stage flash unit, Ind. Chem. Eng. Process Des. Dev., 174 (1978) 381–388.

[2] H.E.S. Fath, Desalination technology, the role of Egypt in region, IWTC, Alexandria, Egypt, 2000

[3] R.A. Abdelrassoul, Potential for economic solar desalination in the Middle East, In: 6th Arab International Solar Energy Conference, Muscat, Sultanate of Oman, 1998.

[4] H.E.S. Fath, Solar desalination promising alternative for fresh water production with free energy, simple technology and clean environmental, Desalination, 116 (1998) 45–56.

[5] M. Abdel-Monem, M. Abdel-Salam, E. Abdel-Waed, Theoretical and experimental studies of humidification–dehumidification desalination system, Ph.D. Thesis, Mechanical Engineering Department, Faculty of Engineering, Cairo, 1988.

[6] S. A1-Hallaj, M.M. Farid and A. Tamimi, Solar desalination with a humidification–dehumidification cycle: performance of the unit, Desalination, 120 (1998) 273–280.

[7] M. Farid and A. Al-Hajaj, Solar desalination with a humidification–dehumidification cycle, Desalination, 106 (1996) 427–429.

[8] K.N. Nawayseh, M.M. Farid, A. Omar, S. Al-Hallaj and A. Tamimi, A simulation study to improve the performance of a solar humidification–dehumidification desalination unit constructed in Jordan, Desalination, 109 (1997) 277–284.

[9] K.N. Nawayseh, M.M. Farid, S. Al-Hallaj and A. Al-Timimi, Solar desalination based on humidification process—I. Evaluating the heat, mass transfer coefficients, Energy Convers Manage, 40 (1999) 1423–1439.

[10] K.N. Nawayseh, M.M. Farid, A. Omar and A. Sabirin, Solar desalination based on humidification process—II. Computer simulation, Energy Convers Manage, 40 (1999) 1441–1461.

[11] M. Farid, S. Parekh, J.R. Selman and S. Al-Hallaj, Solar desalination with a humidification–dehumidification cycle: mathematical modeling of the unit, Desalination, 151 (2002) 153–164.

[12] S. Parekh, M.M. Farid, J.R. Selman and S. Al-Hallaj, Solar desalination with a humidification–dehumidification technique—a comprehensive technical review, Desalination, 160 (2004) 167–186.

[13] K. Bourouni, M.T. Chaibi and L. Tadrist, Water desalination by humidification, dehumidification of air: state of the art, Desalination, 137 (2001) 167–176.

[14] H. Ben Bacha, T. Damak, M. Bouzguend, A.Y. Maalej and H. Ben Dhia, A methodology to design predict operation of a solar collector for a solar-powered desalination unit using the SMCEC principle, Desalination, 156 (2003) 305–313.

[15] H.P. Garg, R.S. Adhikari and R. Kumar, Experimental design and computer simulation of multi-effect humidification (MEH)–dehumidification solar distillation, Desalination, 153 (2002) 81–86.

[16] S. Nafey, H.S. Fath, S.O. El-Helaby and A. Soliman, Solar desalination using humidification–dehumidification processes: Part II. An experimental investigation, Energy Convers Manage, 45 (2004) 1263–1277.

[17] S. Nafey, H.S. Fath, S.O. El-Helaby and A.M. Soliman, Solar desalination using humidification dehumidification processes: Part I. A numerical investigation, Energy Convers, Manage, 45 (2004) 1243–1261.

[18] J. Orfi, M. Laplante, H. Marmouch, N. Galanis, B. Benhamou and S. Ben Nasrallah, Experimental and theoretical study of a humidification–dehumidification water desalination system using solar energy, Desalination, 168 (2004) 151–159.

[19] M. Ben Amara, I. Houcine, A. Guizani and M. Mfialej, Experimental study of a multiple-effect humidification solar desalination technique, Desalination, 170 (2004) 209–221.

[20] Y.J. Dai, R.Z. Wang and H.F. Zhang, Parametric analysis to improve the performance of a solar desalination unit with humidification and dehumidification, Desalination, 142 (2002) 107–118.

[21] Y.J. Dai and H.F. Zhang, Experimental investigation of a solar desalination unit with humidification and dehumidification, Desalination, 130 (2000) 169–175.

[22] M. Al-Sahali, H. M. Ettouney, Humidification dehumidification desalination process: Design and performance evaluation, Chem. Eng. J., 143 (2008) 257–264.
[23] C.Yamali and I. Solmus, A solar desalination system using humidification– dehumidification process: experimental study and comparison with the theoretical results, Desalination, 220 (2008) 538–551.
[24] A.M. Abdel Dayem, Experimental and numerical performance of a multi-effect condensation–evaporation solar water distillation system, Energy, 31 (2006) 2710–2727.
[25] M.A.M. Shaltout, Solar hydrogen in Egypt as an alternative renewable clean energy for the future, hydrogen energy progress x, vol 1 (57–66), Florida, USA, 20–24 June, 1994.
[26] E. Hahne, U. Gross, The influence of the inclination angle on the performance of a closed two-phase thermosyphon, The Recovery Systems, 1 (1981) 267–274.
[27] D. Ristoiu, T. Ristoiu, C. Cosma and D. Cenan, Experimental investigation of inclination angle on the heat transfer characteristics of closed two-phase thermosyphon, BPU-5: Fifth General Conference of the Balkan Physical Union, Vrnjacka Banja, Serbia and Montenegro, August 25–29, 2003.V