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Experimental investigations on the performance of an air heated humidification–dehumidification desalination system

Mohamed A. Antar*, Mostafa H. Sharqawy

Mechanical Engineering Department, King Fahd University of Petroleum and Minerals, Dhahran, Saudi Arabia
Emails: antar@kfupm.edu.sa, mhamed@kfupm.edu.sa

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ABSTRACT

Experiments on a single- and two-stage air-heated humidification–dehumidification desalination system (HDD) driven by solar energy are conducted. The system is built on the seashore of Dhahran, Eastern Province of the Kingdom of Saudi Arabia. In this harsh climate, natural water sources are absent. Currently, Saudi Arabia uses desalination to augment its water supply. It is ranked the first worldwide in water desalination. However, the current large-scale desalination plants are fossil-fuel-driven and consume large amount of energy. Since there is abundance of solar energy in the region, attempts are made to utilize the solar energy to produce fresh water on a small scale for remote areas. The HDD systems have received considerable attention as an effective way to produce fresh water in remote areas where receiving water through pipelines is a challenge. The system used in this study is a solar air heated, closed-water closed-air cycle that can be adjusted to operate in a single-stage or two-stage mode. In this system, evacuated tube solar heaters are used to heat the air. The heated air is humidified by passing it over a spray of seawater in a countercurrent direction inside a humidifier. Additional heating and humidification processes follow in case of operating the two-stage system mode. The humidified air is then dehumidified inside a water-cooled dehumidifier (condenser). Air leaving the dehumidifier is circulated again to the solar heaters. Due to the relatively elevated temperature of incoming water to the dehumidifier, the water cycle is divided into two. In the first cycle, water leaving the cooling water tank flows to the condenser and then returns back to a tank. In the other one, water leaves a small tank and is then distributed to the humidifiers where it is sprayed. The rejected brine returns to the tank. The reason for using a small tank is to keep the water in the cycle warm due to its interaction with hot air in the humidifiers. A make-up tank is connected to this tank through a float valve to compensate for the evaporated water. Measuring sensors are connected to various locations within the system to measure dry- and wet-bulb temperatures, flow rates, and solar radiation flux. Data acquisition system is used to record the reading every 10 min. Results show the effect of the main controlling parameters on the system performance in terms of produced distillate.

Keywords: Desalination; HDH; Solar energy; Experiments

*Corresponding author.

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1. Introduction

Widely used desalination technologies such as multi-stage flash (MSF), multi-effect distillation (MED), and reverse osmosis (RO) are suitable only for large-scale water production. Desalination plants that use these technologies are centralized plants where large amount of desalinated water is produced and pumped to urban areas. These plants are fossil-fuel driven and consumes large amount of energies. However, decentralized water production is important for regions that have neither the infrastructure nor the economic resources to run MSF or RO plants and that are sufficiently distant from large-scale production facilities where pipeline distribution is prohibitive. The humidification–dehumidification desalination system (HDD) cycles have received ongoing attention in recent years due to its operational simplicity and higher productivity at small to medium scale as compared with solar stills. The most prohibitive drawback of a solar still is its low efficiency (and productivity), which is primarily the result of the immediate loss of the latent heat of condensation through the glass cover of the still. A basic solar HDD cycle consists of three components: (a) solar collector, (b) humidifier, and (c) dehumidifier. In these cycles, air is humidified by evaporation of water from any impure water source (e.g. seawater or brackish water) in a humidifier. The humidified air is then passed through a dehumidifier, where the pure water is condensed out of the air.

A state-of-the-art literature review [1,2] on the existing HDD cycles has shown that the gain output ratio (GOR) of these cycles is lower than the conventional desalination methods (GOR < 3). This requires large solar collector areas in order to heat the air and/or the water. However, HDD cycle has other advantages for small-scale decentralized water production. These advantages include much simpler brine pre-treatment and disposal requirements and simplified operation and maintenance. On the other hand, a recent publication [3] conducted a detailed thermodynamic analysis of such systems. These analyses proposed many high-performance variations on those cycles that have higher GOR values and can compete with the conventional desalination methods.

HDD cycles are classified into water-heated and air-heated cycles with open or closed circulation of both streams. The performance of the system depends greatly on whether the air or water is heated. While there are several works in the literature done on water-heated HDD cycles [4–13], relatively little work has been done on the solar collectors for air heating [1], such as [14–22]. Therefore, this study is focusing on the air-heated HDD cycles and provides our experience on the design, operation, and testing of such cycles. The cycle studied in this article is an air-heated cycle in which vacuum tube solar collectors are used to heat the air to a temperature of 80–90˚C. The air is then sent to a humidifier. In the humidifier, the air is cooled and saturated. It is then dehumidified and cooled in the dehumidifier and exited as cooled saturated air. Using solar air heater is preferred because of less fouling and corrosion problems than in water solar heaters.

A major disadvantage of the air-heated cycle is that the absolute humidity of air that can be achieved at these temperatures is very low (<6% by weight). This impedes the water productivity of the cycle, and therefore, less work has been conducted on this type of HDD cycles. Chafik [14,15] reported a method to address this problem. He used a multi-stage heating and humidification cycle. The air after getting heated in the solar collector and humidified in the evaporator is fed to another solar collector for further heating and then to another humidifier to attain a higher value of absolute humidity. Many such stages can be arranged to attain absolute humidity values of 15% and beyond. The main disadvantage of this air-heated cycle is the high temperature that has to be reached in a single-stage cycle to attain the same humidity as a 3-stage cycle. This higher temperature has substantial disadvantages for the solar collectors. However, from an energy efficiency point of view, there is not much of an advantage to multi-staging, as the higher water production comes with a higher energy input as compared to single-stage systems.

Al-Enzi et al. [16] used flat plate air solar collector to heat the air in a forced circulation. The authors have studied the variation of production in kg/day and heat and mass transfer coefficients with respect to variation in cooling water temperature, hot water supply temperature, air flow rate, and water flow rate. They concluded that the highest production rates are obtained at high hot water temperature, low cooling water temperature, high air flow rate, and low hot water flow rate. The variation in parameters the authors have considered is very limited, and hence, these conclusions are true only in that range. Dai et al. [17,18] used forced air circulation in a closed-water open-air cycle. It was found that the performance of the system was strongly dependent on the temperature of inlet salt water to the humidifier, the mass flow rate of salt water, and the mass flow rate of the process air. The authors reported that there is an optimal air velocity for a given top temperature of water. The top water temperature has a strong effect on the production of fresh water.

Khedr [19] used a direct contact condenser with air heated before the humidifier. The author reported the GOR for their system as 0.8, which shows that heat recovery is limited and the performance of this air-heated cycles is low. Houcine et al. [20] studied a multi-stage system that consists of 5 stages of flat plate solar collectors and air-forced circulation. The system was built and tested for 6 months; however, water production cost was very expensive (28.65 €/m^3). Ben-Amara et al. [21] used Four-Fold-Web-Plate air solar collectors in air-heated HDD cycle. Variation of performance with respect to variation in wind velocity, inlet air temperature and humidity, solar irradiation, and air mass flow rate was studied. Endurance test of the polycarbonate material showed it could not withstand the peak temperatures of summer and it melted. Hence, a blower or forced air circulation is necessary. In addition, it was found that at minimum wind velocity, the collector efficiency is maximized. Hermosillo et al. [22] studied an air-heated HDD system in which a treated cellulose paper substratum is used as a packing material in the humidifier through which water flows. The condenser unit is a liquid–gas heat exchanger, where water vapor is condensed and the enthalpy of condensation is recovered to pre-heat the water. The experimental values of GOR of their system were 0.5 – 0.85.

The main objective of this study is to investigate experimentally the air-heated HDD cycle for single- and two-stage systems. The experience of 2 years of design, building, and operation of these cycles is presented. The performance of the system investigated is also presented.

2. Experimental setup

2.1. System description

A closed system, air-heated, one- and two-stage humidification–dehumidification system was designed and erected to utilize solar energy for desalinating seawater. The system as shown in Fig. 1 is composed of solar collectors, humidifiers, a dehumidifier, pumps, and fans. In the current setup, air is heated in two evacuated tube solar collectors (SC3 and SC4) connected in series to increase the air temperature significantly before it is allowed to enter a humidifier (H2) where it flows in counterflow arrangement with sprayed seawater (raw water). Colder and humid air leaves the humidifier to a dehumidifier (condenser) where water vapor condenses on the outer side of the condenser tubes. Then the condensate is collected as desalinated water. Fans are used to circulate air within the cycle, whereas two water pumps are used, one to circulate water from a small water tank to the humidifiers and another one to circulate cold water

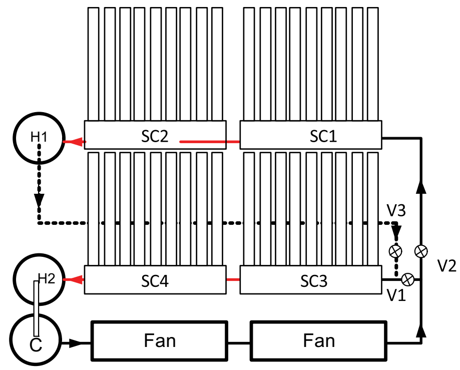

Fig. 1. Schematic diagram of the experimental setup.

used for condensation from a large tank (heat sink) to the condenser.

The system shown in Fig. 1 can be operated as a two-stage system through the control valves (V1, V2, and V3). When V1 is open, while valves V2 and V3 are closed, the single-stage cycle described above is operating. On the other hand, closing valve V1 and opening V2 and V3 result in changing the cycle to a two-stage cycle where air drawn from the fans is driven to pass by the solar collectors (SC1 and SC2) and then to the humidifier H1. Humid air then leaves the humidifier H1 to another stage that starts reheating the air in solar collectors (SC3 and SC4), humidifying it. Then finally air passes by the condenser C before the cycle is repeated again. A photograph of the system is shown in Fig. 2. Detailed pressure drop calculations in air side in the solar collectors, humidifiers, dehumidifier, pipes, and fittings in addition to the water flow rates were used to size the system components; fans, humidifiers, and dehumidifier are not included here due to space limitation. It is important to mention that the shell of both humidifier H2 and the dehumidifier were made of plexiglass in order to monitor the evaporation and condensation in both components visually.

Fig. 2. Photograph of the last system modifications.

2.2. Instrumentation

2.2.1. Thermocouples

Calibrated K-type thermocouples were installed to record temperatures in the following locations: solar collectors inlet and exit, humidifier (1) inlet and exit conditions (both dry bulb and wet bulb), and condenser inlet and exit conditions (both dry and wet bulb). Water temperature at inlet and exit of H1, H2, and C was also recorded.

2.2.2. Flow meters

Inline flow meters, Omega FL-510, are installed at the water line into the humidifiers.

2.2.3. Pyranometer

A pyranometer (self-powered, unamplified model SP-110 by Apogee) measuring shortwave radiation was connected at the same collector slope to read solar radiation flux (W/m^2) on the inclined surface.

2.2.4. Pressure gauges and manometers

Air flow rate was measured using a pitot-static tube connected to both a U-tube and an inclined manometer for results confirmation.

2.2.5. Data logging

To prepare the unit for the experiment, the instruments installed in the unit were connected to a data acquisition system (DAS) (NI SCXI-1000 12 Slot Chassis) so that readings were obtained for three inlet air temperature values and three exit air temperature values, in addition to readings of the temperature of the absorber plate at different locations along the length and across the width. These readings were made through the use of T-type thermocouples as indicated earlier. The thermocouples were connected to the DAS through a thermocouple amplifier/terminal block arrangement (SCXI 1102 32-channel thermocouple amplifier, signal conditioning module for thermocouples along with SCXI 1303 32-channel isothermal terminal block). In addition, another T-type thermocouple was connected to measure the ambient air temperature. The pyranometer was connected to the DAS, and its output reading was converted into a heat flux using the calibration relation provided by the manufacturer. The calibrated air velocity sensor was connected to the DAS through SCXI-1338 8 channel Current Input Terminal Block. It connects current inputs to the SCXI 1120 Module to be connected to the velocity sensor. The DAS is operated using a LabView program that was prepared for recording the measured temperatures, solar radiation flux, and air speed at an interval of 10 min.

3. Results and discussion

It is important to state that air-heated cycles, where air flows in long pipes, experience significant pressure drop that results from long pipe connections, fittings that include expansion in pipe diameters in addition to valves. A setup was made earlier but then abandoned due to the existence of a long pipe where significant temperature drop was monitored, see Fig. 3. When hot air leaving the solar collectors passes through long pipe connections and fittings, the pressure drop and heat loss result in a significant temperature drop. Therefore, the humidification process in the humidifier becomes inefficient because the temperature difference between the hot air and the sprayed water is small. Consequently, the amount of water evaporated into the air steam, and hence the productivity of the system, is reduced.

On the other hand, a portion of water vapor in the humid air condenses in the inner walls of the equipment and tubes that experience heat losses leading to a decrease in the condensate collected in the dehumidifier. For example, as air passes through the humidifier, since the humidifier walls are not insulated, condensation occurs both in the humidifier inner wall surface and in the pipe connecting the humidifier to the dehumidifier. Therefore, in the modified design, the length of pipe has been minimized, see Fig. 2. Traces of condensation on the outer walls of the condenser tubes and inner surface of condenser shell as well as humidifier shell can be seen in Fig. 4a and 4b, respectively.

Fig. 3. Previous set up with long pipe connections.

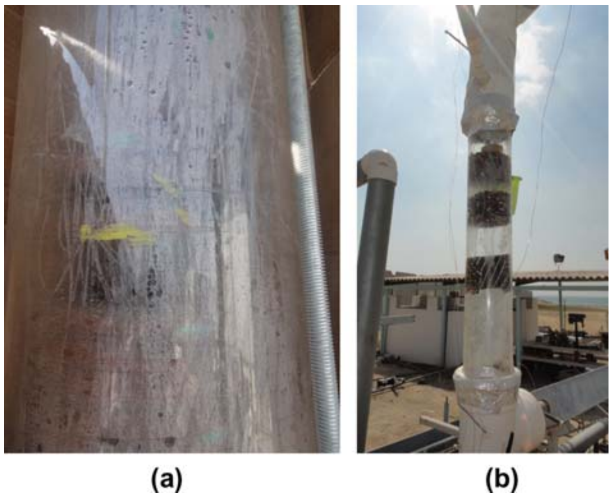

Fig. 4. Condensation of humid air at the inner shell surface in both a) dehumidifier and b) humidifier.

Fig. 5 shows the solar radiation flux and values of the temperature at various locations in the cycle. The solar radiation flux starts at a low value in the morning. Then, it increases till a peak value is reached (noon) and then it decreases till sunset. Temperatures follow a similar profile. Connecting two solar collectors in series allows the air to reach a high temperature that exceeds 90˚C for a longer period. That was needed since a significant decrease in temperature is expected across the humidifier as shown in Fig. 6. The line showing the inlet temperature for the first collector represents air leaving the condenser (dehumidifier) flowing through the fans and directed to the solar heater to complete the cycle. This explains why it is not directly affected by the solar heat flux.

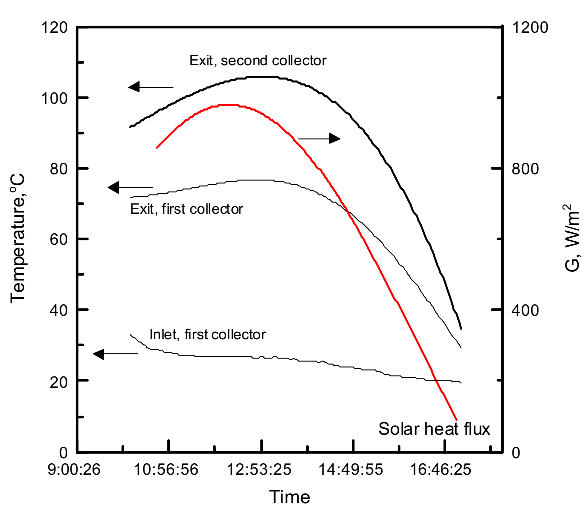

Fig. 5. Profiles of air temperature and solar heat flux.

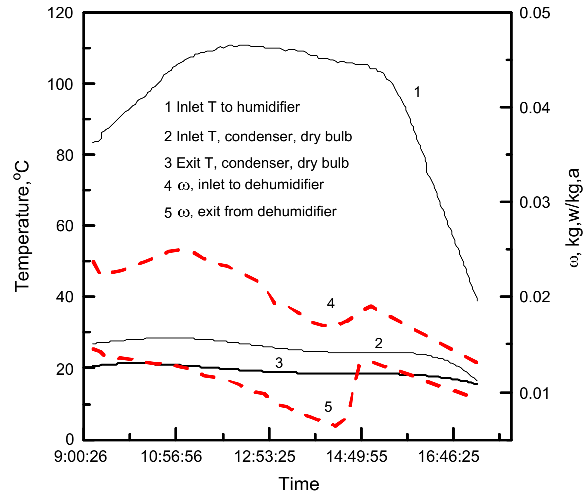

Fig. 6. Temperature and humidity ratio profiles.

Fig. 6 shows the air temperature at the inlet of the humidifier (leaving the second solar collector), the temperature at the exit from the humidifier (inlet to dehumidifier), and the exit temperature from the dehumidifier. A significant decrease in the temperature within the humidifier is due to spraying water that absorbs heat from the hot air to heat and evaporate a portion of water flow. The decrease within the condenser is due to heat rejection in the shell side to cooling water coming from the cold water tank (flowing inside the tubes) to condense water vapor in humid air and hence obtain desalinated water. Water flowrate within the dehumidifier is adjusted to keep a temperature difference of about 10˚C between inlet and exit conditions as a potential for condensation. The plot area occupied by the experimental setup is about 7.5 m^2 for the single-stage system, whereas the two-stage system occupies 10 m^2. Moreover, it has been observed that the productivity of a single stage was about 3.5 L/day, whereas the two-stage system yields 6 L/day.

It is important to indicate that the productivity of the system does not only depend on the solar radiation flux during the day, but also on the dehumidifier cooling water temperature that is responsible for the condensation effectiveness. Fig. 7 shows the hourly condensed water vapor in the dehumidifier when the system was operating in two typical days of different weather conditions. The major difference between these days was the ambient temperature (accordingly the temperature of cooling water in the tank that feeds the condenser. The solar radiation flux variation between both days was not significantly different. One run was operating in December 2011 (Run 1), whereas the second run was conducted in April 2012 (Run 2). The

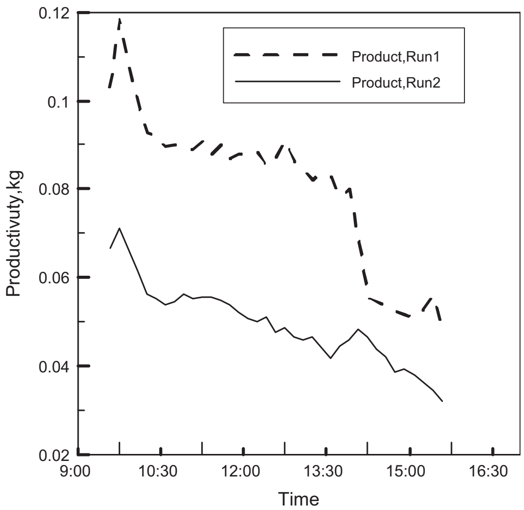

Fig. 7. Hourly water productivity rate at a typical day on December 2011 (Run 1) and April 2012 (Run 2).

condenser water temperature in the tank was considerably lower in December, resulting in more effective condensation. During morning hours, high rate of evaporation is due to high temperature, higher solar radiation, and clear sky. In the afternoon, the temperature dropped and accordingly the evaporation rate in the humidifier is reduced. That explains the reduction in the evaporated water vapor in the humidifier and hence the condensate in the condenser (dehumidifier). It is important to note here that the effectiveness of the dehumidifier plays a key role in the productivity rate of the system. Since the unit is located outdoors, the cooling water in the condenser is affected by the ambient conditions. More condensate was obtained when the inlet cooling water temperature in the condenser was lower since it provided more potential for vapor condensation.

4. Conclusion

An experimental setup for air-heated, single- and two-stage HDD desalination system was designed, built, and tested. Several modifications were made to the system to reduce the temperature drop of air due to pressure drop and heat losses. Avoiding long pipe connections and use of proper insulating materials are required in order to utilize the solar energy in this cycle efficiently. Pressure drop and heat loss in pipelines and fittings result in air side temperature drop that affects the air-heated HDD cycle significantly. The temperature profile follows the solar radiation flux falling onto the solar collectors showing an increase from early morning till the irradiation reaches a peak value at noon time, then temperature falls again until the sunset where the solar radiation diminished. Water productivity follows the same trend. Productivity of 3.5 and 6 L/day was obtained from the single-stage and two-stage systems, respectively. The system is modular and can be expanded for higher productivity through increasing the number of solar collectors, well-insulated humidifiers, dehumidifier, and connecting pipes.

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References

[1] G.P. Narayan, Mostafa H. Sharqawy, Edward K. Summers, John H. Lienhard, Syed M. Zubair, M.A. Antar, The potential of solar-driven humidification–dehumidification desalination for small-scale decentralized water production, Renew. Sustain. Energy Rev. 14(4) (2010) 1187–1201.
[2] G.P. Narayan, Ronan K. McGovern, Gregory P. Thiel, Jacob A. Miller, John H. Lienhard V., Mostafa H. Sharqawy, Syed M. Zubair, Mohammed A. Antar, Status of humidification dehumidification desalination technology, in: International Desalination Association World Water Congress, Perth, Australia, IDA, 2011.
[3] G.P. Narayan, M.H. Sharqawy, J.H. Lienhard V, S.M. Zubair, Thermodynamic analysis of humidification dehumanization desalination cycles, Desalin. Water Treat. 16 (2010) 339–353.
[4] S. Al-Hallaj, M.M. Farid, A.R. Tamimi, Solar desalination with humidification–dehumidification cycle: Performance of the unit, Desalin. Water Treat. 120 (1998) 273–280.
[5] H. Ben-Bacha, T. Damak, M. Bouzguenda, Experimental validation of the distillation module of a desalination station using the SMCEC principle, Renew. Energy 28 (2003) 2335–2354.
[6] M.M. Farid, A.W. Al-Hajaj, Solar desalination with humidification–dehumidification cycle, Desalin. Water Treat. 106 (1996) 427–429.
[7] H.P. Garg, R.S. Adhikari, R. Kumar, Experimental design and computer simulation of multi-effect humidification (MEH)-dehumidification solar distillation, Desalin. Water Treat. 153 (2002) 81–86.
[8] J.F. Klausner, R. Mei, Diffusion driven desalination apparatus and process, US Patent No. 6,919,000, US, 2005.
[9] J.F. Klausner, R. Mei, Y. Li, Innovative Fresh Water Production Process for Fossil Fuel Plants, DOE—Energy Information Administration annual report, US, 2003.
[10] H. Müller-Holst, Solar thermal desalination using the multiple effect humidification (MEH) method, in: Solar Desalination for the 21st Century, 2007, pp. 215–225.
[11] A.S. Nafey, HES Fath, SO El-Helaby, Solar desalination using humidification–dehumidification processes-Part II. An experimental investigation, Energy Convers. Manage. 45(7–8) (2004) 1263–1277.
[12] N.K. Nawayseh, MM Farid, S. AlHallaj, AR Tamimi, Solar desalination based on humidification process-Part I. Evaluating the heat and mass transfer coefficients, Energy Convers. Manage. 40 (1999) 1423–1439.
[13] M.A. Younis, M.A. Darwish, F. Juwayhel, Experimental and theoretical study of a humidification–dehumidification desalting system, Desalin. Water Treat. 94 (1993) 11–24.
[14] E. Chafik, A new type of seawater desalination plants using solar energy, Desalin. Water Treat. 156 (2003) 333–348.

[15] E. Chafik, Design of plants for solar desalination using the multi-stage heating/humidifying technique, Desalin. Water Treat. 168 (2004) 55–71.
[16] G. Al-Enezi, H.M. Ettouney, N. Fawzi, Low temperature humidification dehumidification desalination process, Energy Convers. Manage. 47 (2006) 470–484.
[17] Y.J. Dai, R.Z. Wang, H.F. Zhang, Parametric analysis to improve the performance of a solar desalination unit with humidification and dehumidification, Desalin. Water Treat. 142 (2002) 107–118.
[18] Y.J. Dai, H.F. Zhang, Experimental investigation of a solar desalination unit with humidification and dehumidification, Desalin. Water Treat. 130 (2000) 169–175.
[19] M. Khedr, Techno-economic investigation of an air humidification–dehumidification desalination process, Chem. Eng. Technol. 16 (1993) 270–274.
[20] I. Houcine, M. BenAmara, A. Guizani, M. Maâlej, Pilot plant testing of a new solar desalination process by a multiple-effect-humidification technique, Desalin. Water Treat. 196 (2006) 105–124.
[21] M. Ben-Amara, I. Houcine, A. Guizani, M. Mâalej, Experimental study of a multiple-effect humidification solar desalination technique, Desalin. Water Treat. 170 (2004) 209–221.
[22] J.J. Hermosillo, C.A. Arancibia-Bulnes, C.A. Estrada, Water desalination by air humidification: Mathematical model and experimental study, Solar Energy 86(4) (2012) 1070–1076.