Desalination 358 (2015) 9–17

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Mathematical and experimental investigation of a solar humidification–dehumidification desalination unit

Mofreh H. Hamed [a], A. E. Kabeel [b,*], Z. M. Omara [a], S. W. Sharshir [a,c]

[a] *Mechanical Engineering Department, Faculty of Engineering, Kafrelsheikh University, Kafrelsheikh, Egypt*
[b] *Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt*
[c] *School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*

HIGHLIGHTS

- A desalination system based on air humidification–dehumidification is investigated theoretically and experimentally.
- The average productivity of HDH unit is 22 L/day (11 L/day·m^2 of collector).
- A comparison between experimental and theoretical results shows a good agreement.

ARTICLE INFO

Article history:
Received 9 July 2014
Received in revised form 4 December 2014
Accepted 6 December 2014
Available online xxxx

Keywords:
Desalination
Humidification
Dehumidification
Solar energy
Simulation

ABSTRACT

In this paper, performance of a proposed desalination system based on air humidification–dehumidification (HDH) is investigated theoretically and experimentally. To evaluate the performance and productivity of the proposed solar humidification–dehumidification desalination unit, a theoretical simulation model is developed in which the energy equations of each component are considered. Productivity of the proposed system at different operating times during the day is calculated in two periods. First one starts at 9 am and ends at 17 pm, while the second starts after preheating before entering the humidifier at 13 pm to 17 pm. The results show that the highest fresh water productivity is found to be in the second period. A comparison between experimental and theoretical results shows a good agreement and gives evidence that the proposed model is valid to be used under different boundary conditions. The results also show that when the system operates 4 h in a day with preheating before it gives higher productivity of about 22 L/day (11 L/day·m^2 of collector) as a result of stored energy in the system since sunrise. The total cost per 1 l for the unit is 0.0578$.

1. Introduction

Desalination of sea water and brackish water has been given high priority as a source of water for domestic, industrial and agricultural applications [1]. Abdel Dayem and Fatouh [2] installed and tested a multi-effect HDH solar desalination system. The system consists of two loops, a solar loop and a water desalination loop. Three systems were compared experimentally and numerically. It was found that the solar open system with natural circulation is more efficient regardless of practical difficulties where the closed system using an auxiliary heater has the highest distilled water production. Nafey et al. [3] also investigated a HDH desalination facility where both the water and air use solar heating in Suez City, Egypt. A fresh water production rate of 10.7 L/day was achieved in July, and the production rate dropped to 5 L/day in November. While all of these prior investigations have made significant contributions toward the development of solar driven HDH desalination, the electric specific energy consumption was not reported. Orfi et al. [4] studied a solar HDH desalination system theoretically and experimentally. In order to improve the productivity of the system, they utilized the latent heat of condensate water vapor in the condenser to preheat the feed water. Prakash et al. [5] conducted a comprehensive review of the state-of-the-art in solar-driven humidification dehumidification (HDH) desalination units. Particular attention was given to solar air heaters, for which design data was limited; and direct air heating was compared to direct water heating in the cycle assessments. Alternative processes based on the HDH concept were also reviewed and compared. It was concluded that HDH technology has great promise for decentralized small-scale water production applications, although additional researches and developments are needed for improving system efficiency and reducing capital cost. Chafik [6] presented a new type of seawater desalination plant using solar energy. The process consisted of several steps for air heating, each followed by a humidification stage. Design and analysis of different HDH processes have been considered by Ettouney [7]. He gave practical equations for the design of a HDD

---

[*] Corresponding author.
E-mail addresses: mofrehhh@yahoo.com (M.H. Hamed), kabeel6@hotmail.com (A.E. Kabeel).

http://dx.doi.org/10.1016/j.desal.2014.12.005

process and a performance summary of the system as a function of outlet air temperature from the humidifier. He discussed a drawback of the HDD process that was mainly due to the presence of a large amount of air together with the water vapor product. This large amount of air that must be dried during the dehumidification step reduces the process efficiency. El-Agouz [8] investigated experimentally the performance of a single stage bubble column using air bubbles passing through seawater. The results showed that the productivity of the system increases with the increase of the water temperature and the decrease of the airflow rate. The maximum productivity of the system reached to 8.22 kg/h at 86 °C for water temperature and airflow rate of 14 kg/h. A detailed review of performance parameters which enables the comparison of the various versions of the HDH cycle has been defined and evaluated by Parekh et al. [9]. Zhani [10] studied a new generation of water desalination unit by solar energy using the humidification and dehumidification (HDH) principle which was constructed at the National Engineering School of Sfax, Tunisia. The good quality of distilled water obtained by this new concept favors its use for producing water for drinking and irrigation. The thermal performance was evaluated by the gained output ratio (GOR) and the efficiency of the water solar collector. Series of experiments were conducted and compared with the simulation results to validate the developed models. As a result, the proposed model can be used for sizing and testing the behavior of such a type of desalination unit. Abdel-Dayem [11] investigated theoretically and experimentally the influence of a pioneer system of solar water desalination on the productivity of a solar desalination system using HD process at the weather conditions of Cairo, Egypt. The salt water is heated by either solar energy or/and auxiliary heater before injection inside an insulated desalination chamber using an air atomizer. The system was successfully tested using either solar or/and auxiliary energies. It can produce about 36 l daily of purified water while the use of solar energy alone can obtain about 12 l on clear days.

A detailed review of performance parameters which enables the comparison of the various versions of the HDH cycle has been defined and evaluated by Prakash et al. [5], Parekh [9] and Kabeel et al. [12]. The principal components of the HDH system were also reviewed and compared, including the humidifier, solar heaters, and dehumidifiers.

The objective of this paper is to present the results of a study on a new HDH system, with the air working in a closed loop and the evaporator made of treated cellulose paper substratum. The new system is designed to improve the heat recovery in the condenser. The purpose of the system is to desalinize water by recovering the heat released by vapor condensation. Thus, it is interesting to find the best time operating on the system to give high productivity. Therefore, in the present study a mathematical model is developed to simulate the proposed system and experimental test rig is built up to investigate the effect of different parameters on the system performance.

2. Description of the physical model

The proposed solar humidification and dehumidification HDH unit consists essentially of three main components named “humidifier (evaporator), dehumidifier (condenser) and solar water heater (evacuated tube solar collector)”. The system is based on an open cycle for water and closed cycle for the air stream. The air closed cycle is achieved through connecting the evaporator and the condenser from both the upper and lower ends by connecting duct. The unit is operated in a forced draft mode using an electrical fan installed at the bottom. A copper coil is used in the condenser for better heat transfer, while cellulose paper (packing material) with 5 mm opening holes is used in the evaporator for efficient humidification of the air. The HDH system consists of two loops for the water (one for hot brackish water and the other for cold brackish water). Firstly, the saline water at the condenser inlet from cooled water tank is fed to the condenser to condense partially the water vapor from the air leaving the evaporator and entering the condenser top. The latent heat of condensation of water vapor is used to preheat the feed water when flowing to the condenser exit. The air finally becomes dry at the bottom of the condenser. Then, the saline water at the condenser exit is further heated in an evacuated tube solar collector. Finally, the hot water leaving the evacuated tube solar collector is sprayed over the cellulose packing in the evaporator. The air is continuously heated and humidified. The desalinated water is collected from the bottom of the condenser, while the brine water is rejected from the bottom of the evaporator. A photograph and sketch of a solar desalination process of the humidification–dehumidification are shown in Figs. 1 and 2 respectively.

3. Experimental setup and measuring devices

Experimental system was built to study the heat and mass transfer properties of the system as shown in Figs. 1 and 2. The experimental setup consists of five main parts namely humidifier, dehumidifier, vacuum tube, pumps and fans and water storage tank.

3.1. Experimental setup

The first part of the experimental setup named humidifier consists of various parts (humidifier shell, swing door and packing material). The humidifier shell is made of 1.5 mm thickness galvanized steel with a rectangular cross sectional area of 50×80 cm^2 and a height of 200 cm. The base of the humidifier has a gradual slope to permit the highly concentrated salt water to be blown down out of the humidifier. A built-in swing door is added to the humidifier to facilitate the changeability of humidifier's packing material, which is installed inside. Cellulous papers have approximately honey comb shape used as packing material. This packing material consists of 12 slabs each one has dimensions of $80 \times 50 \times 10$ cm^3 with openings in the form of equilateral triangle, which has a side length of 5 mm (cellulose 5 mm). The total surface area of all these triangles in this group is approximately 10 m^2. While the dehumidifier consists of two parts. The first one is a dehumidifier shell of cylindrical shape galvanized steel with 40 cm diameter and 200 cm height. The second part is the coiled copper tube of 15 m length, 1.5 mm thickness and 1.27 cm outer diameter and mounted by copper corrugated fins. The lowest end of the dehumidifier has a conical shape for collecting condensate (desalinated) water. The evacuated solar water heater consists of collector, water tank, expansion vessel and frame. The solar collector consists of 20 vacuum tubes. A cylindrical stainless steel water tank, insulated with 5.5 cm polyurethane foam having 200 liter capacity and projected area of 2 m^2, is used to feed the humidifier with brackish hot water through insulated tube. Two centrifugal pumps of 373 W each are used, one for hot water pipeline and the other for cold water pipeline. A 15 W electric fan is used to circulate the air through the unit (forced draft). Fan can be fixed at the bottom of the dehumidifier duct according to the experiment need. A group of valves is used to separate each part of the saline water loop from the system when it is necessary. The water storage tank (cold water tank) having a volume of 220 l is constructed of 2 mm thick and it is made from PVC. The water storage tank is supported on an iron stand. The height of the stand is 2 m above the ground which helps to maintain a constant water flow rate. The system components are insulated using glass-wool thermal insulation of low thermal conductivity of .047 kW/m·K in order to reduce the heat loss to the surrounding as much as possible.

3.2. Measurement devices

During the experiments, several parameters are measured in order to evaluate the system performance such as, flow rates of air and water streams, temperatures of air and water at the inlet and exit of each tower, temperature of water at inlet and exit of the storage tank, relative humidity of air at inlet and exit of each tower and the productivity of the unit. To measure either cold or hot water flow rate; two