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Performance of a two-stage multi-effect desalination system based on humidification–dehumidification process

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HIGHLIGHTS

- Two-stage multi-effect desalination system is proposed.
- Desalination system is based on the humidification–dehumidification process.
- Condensation latent heat and residual heat in the brine are recycled and reutilized.
- Mathematical model in each component of the system is developed.
- Principles and functionality are demonstrated through simulation and experimentation.

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ABSTRACT

This paper presents a two-stage multi-effect desalination system based on humidification–dehumidification process. The sketch of two-stage multi-effect humidification–dehumidification desalination process is given. The good quality of distilled water obtained by this novel concept favors its use for producing water for drinking and irrigation. A mathematical model based on mass and energy balances in each component of the system is developed. The numerical model is used to investigate the performance of this kind of installation exposed to a variation of the control parameters. The fresh water production can reach 72.6 kg/h and the gained output ratio (GOR) can reach 2.44, because it recycles and reutilizes latent heat of condensation and the residual heat in the brine. A series of experiments was conducted and compared with the simulation results to validate the developed models. As a result, the proposed models can be used for describing the behavior of such a type of desalination system.

1. Introduction

In many places, drinkable water is already a scarce goods and its lack will rise dramatically in the future. About 80 countries in the world are confronted with the problem of severe freshwater scarce [1]. The solar desalination systems based on the humidification–dehumidification principle are considered as the most viable among solar desalination systems [2]. Compared with other desalination systems [3–7], it is an innovative technology with promising diffusion and application due to its flexibility, simplified design, low maintenance, extended life time for over twenty years, low capital cost, construction and adaptation for use in rural areas to produce fresh water for drinking and irrigation [8–10].

The humidification–dehumidification (HD) process is an interesting technique that has been widely adapted for water desalination. There are a number of studies on the humidification–dehumidification desalination (HDD) process most of which focus on performance evaluation and efficiency improvement in order to optimize the fresh water production of solar desalination systems and to reduce their costs.

Bacha et al. [9] presented the concept of the multi-effect humidification dehumidification (MEH) process, the mathematical model of the desalination systems, and some simulated and experimental results. The obtained results are then compared against the experimental results. The good quality of distilled water obtained by this concept favors its use for producing water.

Nawayseh et al. [11,12] have done much research on the MEH process. These include the method of evaluating the heat and mass transfer coefficients in the evaporator, simulation, and so on. Solar desalination with a HD process has proven to be an efficient means of utilizing solar energy for the production of fresh water from saline or sea water.

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Arabi et al. [13] evaluated the performance for HDD processes with different carrier gases through modeling and simulation techniques. Different carrier gases besides air were used in the performance evaluation: hydrogen, helium, neon, nitrogen, oxygen, argon and carbon dioxide. It was found that hydrogen and helium give much better heat flux than air, while argon and carbon dioxide give much better mass flux. Carbon dioxide is recommended as a carrier gas in desalination systems that are based on the humidification–dehumidification principle taking into account both the heat and mass fluxes evaluated in them.

Nafey et al. [14,15] presented a numerical and experimental investigation of a HDD process using solar energy at the weather conditions of Suez City, Egypt. Both tested and numerical results showed that the productivity of the system is strongly affected by the saline water temperature at the inlet to the evaporator. The condenser cooling water flow rate, air flow rate and solar intensity and the wind speed and ambient temperature variation have a very small effect on the system productivity.

Soufari et al. [16] optimized a HD desalination process with three objective functions using mathematical programming. Results reveal that the water to air mass flow rate ratio is the most effective parameter and has an optimum value. The upper temperature results in more productivity and a smaller heat transfer area. But minimum specific thermal energy consumption of the system occurs at an optimum temperature. The specific thermal energy consumption can be decreased more through recycling of the outlet evaporator water into the condenser.

Morteza and Majid [17] developed a model and a structured procedure to optimize the shape and structure of a MEH system. The results showed that the inlet cold and hot water temperatures and the column heights play important roles in the construct design of a MEH system, especially as the total volume increases. Moreover, the tube diameters and the number of condenser tubes should be suitably selected based on the values of the condenser, the humidifier inlet water temperatures and the column heights.

Yuan et al. [18] constructed a 1000 L/day solar HDD system. This system was composed of a solar air heater field, a solar water collector, a HD system, a pretreatment and other subsystem. Performance of the solar air heater field and the evaporator was investigated by experimental tests. The results showed that water production of the system could reach 1200 L/day under the average intensity of solar radiation got to 550 W/m^2.

Zhani [19] deals with modeling, simulation and experimental validation of a new generation of water desalination system by solar energy using a MEH process. The good quality of distilled water obtained by this concept favors its use for producing water for drinking and irrigation. A mathematical model based on heat and mass transfers in each component of the systems is developed. The numerical model is used to investigate the thermal performance of this kind of installation exposed to a variation of the control parameters. Experimental results were compared with the simulation results. It was shown that the developed models are able to predict accurately the trends of the heat and mass characteristics of the evaporation and condensation chambers and the solar collectors. As a result, the proposed models can be used for sizing and testing the behavior of such a type of desalination systems.

Hou [20] proposed the concept of a two-stage solar multi-effect HHD process. The two-stage solar multi-effect HDD process is plotted in two different temperature ranges according to pinch technology. The study shows that the two-stage solar multi-effect HHD process has a higher energy recover rate than the one stage does. In an extreme case, the minimum temperature difference at pinches is 1 °C, the energy recovery rate could reach 0.836.

As the HHD system developed from the one-effect to the multi-effect, the performance of the HHD system becomes well because of the recovery of the latent heat of condensation. However, there is some heat in the exhaust brine which should be recovered and utilized further. Additionally, most of those researches [8–19] focused on the one stage HHD system, and only a few [20] introduced the two-stage HHD system. The two-stage multi-effect proposed by Hou [20] doesn't recycle the latent heat of condensation or the residual heat in the brine. Thus, the novel structure, which can recycle both the latent heat of condensation and the residual heat in the brine, and the performance of the two-stage multi-effect HDD system are required further study.

This paper presented a novel two-stage multi-effect HDD system. Compared with the previous multi-effect HDD system, it not only recycles the latent heat of condensation but also successfully recycles the residual heat in the brine.

The present work deals with modeling, simulation and experimental validation of a novel generation of water desalination system. The main objectives of the present paper are:

(1) To describe the desalination process of a novel two-stage multi-effect HDD system.
(2) To present a steady state mathematical model of the different units of the system (higher temperature evaporation tower, higher temperature condensation tower, lower temperature evaporation tower, and lower temperature condensation tower).
(3) To present numerical and experimental data as an example of the validation process that has been carried out in order to assess the credibility of the numerical models.
(4) To investigate the performance of the desalination systems exposed to a variation of key operating parameters.

2. System process model

The two-stage multi-effect desalination system consists of two closed loops for air circulation as shown in Fig. 1. One is the higher stage, the high temperature circulation, and another is the lower stage, the lower temperature circulation. Four compartments constitute the installation: higher temperature evaporation tower (HET), higher temperature condensation tower (HCT), lower temperature evaporation tower (LET), and lower temperature condensation tower (LCT).

The developed system operates at atmospheric pressure using air as carrier for vapor. The circulation of the air in the evaporation tower may occur in forced convection with closed air circuit. The forced convection is insured by a helical fan fixed at the bottom of air channel.

The principle of functioning of this desalination process presented in this paper is as follows.

In the lower stage, the saline water is fed to the LCT to cool the water vapor from the LET. The saturated air condenses in contact with the cold condensation plates. The latent heat of condensation is used to preheat the feed water. Then the saline water is divided into two parts: one part is expelled from the system, and the other part enters into the HCT to be further heated in higher stage and cool the water vapor from the HET. Last, the saline water from the HCT is divided into two parts. The main part enters into the LET to spray, which is simple and effective for recovery of the latent heat of condensation. The other part enters into the HET to renew the circulating water, which can ensure the amount of hot water supply and the exhaust brine. The distilled water is collected from the bottom of the evaporation tower, while the warm brine is rejected from the bottom of the condensation tower.

In the higher stage, saline water is heated by the solar collectors. Then, the hot water is injected to the top of the HET. The spray nozzle with a special shape is used to assure a uniform pulverization of the hot water in all the sections of the tower. Hot water mist and saturated air mix with the rising air current toward the HCT. Due to the increasing temperature of the air, the saturation humidity in the evaporator increases, while the salt concentration of the hot water increases. The hot water with the temperature of T_7 is heated and then injected to the HET again. The water pumped into the solar collector is from the HET and the temperature of the water from HET is much higher than that of the exhaust brine from the LET. It not only reduces the heat load but also decreases the temperature of the exhaust brine.