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Theoretical study on hybrid desalination system coupled with nano-fluid solar heater for arid states

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HIGHLIGHTS

- A two-stage solar desalination system is given out.
- The daily water production up to 112.5 kg/day.
- The gained output ratio (GOR) can reach about 7.5.
- The cost of the potable water is calculated as 6.43 US$/m^3.
- Specific work consumption is 2.32 kWh/m^3.

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ABSTRACT

This paper introduces a hybrid desalination system coupled with nano-fluid solar heater for small scale needs. The hybrid desalination system consisting of a two stagehumidification–dehumidification unit and single stage flashing evaporation unit (MSH–SSF) configured by a (Al_2O_3/H_2O) nano-fluid solar water heater is tested under the climatological conditions of Tanta city, Egypt. This system was designed and modeled using the finite deferral scheme in quasi-steady-state conditions. The main parameters that have influence on the system productivity are studied such as feed water mass flow rate of SSF unit, feed water mass flow rate of HDH units, cooling water mass flow rate of SSF unit, cooling water mass flow rate of HDH units, air mass flow rate, inlet cooling water temperature and nano-particle volume fraction. The economic analysis was to show both the economic benefits and the feasibility measurement. The results showed that, the considered MSH–SSF desalination system gives daily water production up to 112.5 kg/day. The gained output ratio (GOR) of the system reaches 7.5. The solar water heater efficiency is affected by the nano-particle volume fraction by increasing the freshwater production and decreasing cost. Solar water heater efficiency is about 49.4%. The estimated cost of the generated potable water was 6.43 US$/m^3.

1. Introduction

The worldwide demand for freshwater is escalating due to the population growth and ever-increasing industrialization of our society. The rest exists in lakes, rivers and underground reservoirs. Natural resources cannot satisfy the growing demand for low-salinity water. This is because of industrial development, together with the increasing worldwide demand for supplies of safe drinking water. This has forced mankind to search for other sources of water. In addition, the limited fossil fuel resources, it is expected that their price continues to rise dramatically in the future. On the other hand climate change obliges humanity to react accordingly. Renewable energy is the favorable alternative to fossil fuels. Solar energy can be used for saline water desalination either by producing the required thermal energy by using direct solar collection systems. Wu et al. [1] investigated mathematically and experimentally a new multi-effect solar desalination system based on humidification and dehumidification process. The warm saline water is sprayed upon the porous ball humidifiers, which is simple and effective for enhancing the evaporation process. The results indicated that the maximum performance ratio and freshwater productivity of the system can reach up to about 2.65 and 182.47 kg/h respectively. Giwa et al. [2] investigated a technical feasibility and environmental friendliness of an air-cooled PV system integrated with ambient seawater inflow into a Humidification–dehumidification desalination system. Their results

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showed that the heat recovered from the PV resulted in the production of a daily average of 2.28 L of freshwater per m^2 of PV. Elminshawy et al. [3] investigated analytically and experimentally the effect of using an induced atmospheric air, water heaters, external reflector and weather condition on the performance augmentation of humidification–dehumidification system. The experimental results showed that the daily productivity has improved when using both water heaters and reflector. The estimated cost of freshwater produced is 0.035 USD/L and the peak efficiency is 0.77. Nada et al. [4] investigated an experimental study of the performance of a hybrid humidification–dehumidification water desalination and air conditioning system using vapor compression refrigeration cycle. The results showed the enhancement of the freshwater production rate with increasing air specific humidity and air mass flow rate. Kang et al. [5] presented numerically experimentally a two-stage multi-effect desalination system based on humidification–dehumidification process. The results showed that the freshwater 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. Nafey et al. [6] investigated theoretically and experimentally a small unit for water desalination by solar energy and a flash evaporation process. The average accumulative productivity of the system was between 1.04 and 1.45 kg/day/m^2 in winter and between 4.2 and 7 kg/day/m^2 in summer. Junjie et al. [7] studied experimentally the heat and mass transfer properties of static/circulatory flash evaporation, i.e., non-equilibrium fraction (NEF), evaporated mass and heat transfer coefficient. The heat transfer coefficient was redefined as average heat flux released from unit volume of water film under unit superheat. Results suggested that this coefficient was a time-dependent function and a peak value existed in its evolution versus time. Saad et al. [8] investigated experimentally a new desalination system for converting seawater into freshwater utilizing the waste heat of internal combustion engines. The desalination process is based on the evaporation of seawater under a very low pressure (vacuum). They found that decreasing the vacuum pressure causes a significant increase in the yield of freshwater. They also found that decreasing the condenser temperature, or increasing the evaporator temperature both lead to an increase in the yield of freshwater. Moreover, increasing the condenser flow rate tends to increase the yield of freshwater. Narayan et al. [9] analyzed the thermodynamic performance of various humidification and dehumidification cycles by way of a theoretical cycle analysis.

The solar collector is a convenient and common heater to be used as a heat source for many applications such as domestic water heater and desalination purposes. However, the effectiveness of presently solar collector for low-capacity desalination units is low. This is due to some reasons such as the limiting of the thermal conductivity of this working fluid and inefficiency and cost of solar radiation concentrators. Several years ago, the nano-fluid has been found to be an attractive heat transport fluid. It has exhibited a significant potential for heat transfer augmentation relative to the conventional pure fluids. It has been expected to be suitable for the solar water heating systems without severe problems in pipes and with little or no penalty in pressure drop [10]. Asirvatham et al. [11] studied experimentally of steady state convective heat transfer of de-ionized water with a low volume fraction (0.003% by volume) of copper oxide (CuO) nano-particles. The results have shown 8% enhancement of the convective heat transfer coefficient of the nano-fluid even with a low volume concentration of CuO nano-particles. The heat transfer enhancement was increased considerably as the Reynolds number increased. Yousefi et al. [12] investigated experimentally the effect of Al_2O_3/water nano-fluid, as working fluid, on the efficiency of a flat-plate solar collector. The weight fraction of nano-particles was 0.2% and 0.4%, and the particle dimension was 15 nm. The mass flow rate of nano-fluid varied from 1 to 3 l/min. The results showed that, in comparison with water as the absorption medium using the nano-fluids as working fluid increase the efficiency. For 0.2 wt.%, the increased efficiency was 28.3%.

The present study provides a theoretical simulation model for analysis of a hybrid two stage multi-effect air humidification and dehumidification–water flashing evaporation (MSH–SSF) desalination system coupled with nano-fluid solar heater for small scale needs. The system thermal performance, the freshwater productivity improvement and economical benefits will be presented.

2. Studied system

The system consists of two parts. One is the two stages of solar humidification–dehumidification unit (HDH), and another is a single-stage flashing evaporation (SSF) unit. A sketch of a hybrid solar desalination process of the two stages of humidification–dehumidification and the single stage flashing evaporation unit is shown in Fig. 1. Each of the solar humidification–dehumidification unit consists of humidifier, condenser (dehumidifier), and air heater solar collector for first stage only. The first stage of HDH is operated in a forced draft mode by using an air blower and with an open loop for air circulation. A packing is used in the humidifier for efficient humidification of the air. The feed water at (11) is sprayed over the packing in the humidifier. The fresh air at (12) is sucked from atmosphere to enter the humidifier and exit at (13). The brine at (14) is pumped to mixing tank (MT). The saline water at (27) is fed to the dehumidifier to condense the water vapor from the humid air at (13) by using dehumidifier (DE1) and exit at (15). The fresh desalinated water at (24) is collected from the bottom of the condenser. The second stage of HDH is operated in the same method of the first stage by using feeding and return water closed loop for heat recovery. The feed water at (22) is sprayed over the packing in the humidifier (H2). The air at (15) is discharged to air flat plate solar collector to heat in and exit at (16). The air at (16) is humidified in the humidifier (H2) and exit at (20). The brine at (22) is pumped as feed water again. The saline water at (21) is fed to the dehumidifier (DE2) to condense the water vapor from the air at (20). The fresh desalinated water at (25) is collected from the bottom of the condenser.

The solar SSF unit consists of flashing chamber and condenser. The warm saline water flowed from mixing tank at (5) is reheated in heat exchanger (HEx). This is done by the heat from a solar water heater flat plate solar collector (SWH) and desalinated in a single-stage flashing unit to distill water further. The water at (6) is pumped to flashing chamber to evaporate by flashing. The extracted water vapor on flashing chamber at (10) is flowed to the condenser (C). The saline water at (26) is fed to the flashing unit condenser to condense the water vapor and exit at (9). The desalinated water at (23) is collected from the bottom of the condenser tray, while is rejected from the bottom of the condenser tray. The flashing evaporation depends on the pressure reduction. So, the inside the condenser and flashing chamber is vacuumed by using a vacuum pump at (26)).

Then, the saline water exit from the condenser (C) at (9), is mixed with rejected brine water from the humidifier (H1) at (14), in mixing tank as well as is further preheated the feed water to (5) and (11) and the saline water exit from dehumidifiers (DE1) and (DE2) at (17) and (18) respectively are drained. A part of saline water in mixing tank (MT) is flawed to heat exchanger (HEx) to back up water in the closed loop of saline water flow between the flashing chamber and heat exchanger (HEx) at (5) while the rest is drained at (8). A part of saline water at (11) is flowed to backup water in the closed loop of saline water flow of humidifier (H22) at (26). As mentioned above; the mixing tank is used to improve the system performance due to its dual effect in energy saving for both HDH and SSF systems, where the heat recovery from the rejected hot water is increased. The humidification–dehumidification cycle is shown in Fig. 2 on the psychrometric chart for HDH unit. Fig. 3 shows the evaporation and condensation processes on T-s diagram for SSF unit.

According the heat transfer enhancements of nano-fluids, which have been mentioned in literature, relative to the conventional pure