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A hybrid solar desalination system of air humidification, dehumidification and water flashing evaporation: Part II. Experimental investigation

A.E. Kabeel *, Emad M.S. El-Said

Mechanical Power Engineering Department, Faculty of Engineering, Tanta University, Tanta, Egypt

HIGHLIGHTS

- An experimental investigation of a solar hybrid desalination system was presented.
- The maximum productivity of the system reached 41.8 kg/day, according to operating conditions.
- The performance ratio of SSF unit is varied between 0.32 and 1.4.

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ABSTRACT

This paper describes laboratory experiments with a hybrid solar desalination system consisting of a humidification–dehumidification unit and single stage flashing evaporation unit configured by a (Al_2O_3/H_2O) nano-fluid solar water heater under the climatological conditions of Tanta City, Egypt. The laboratory work has been carried out in actual thermal environment in August 2013. The validation has an emphasis on the main parameters with impact on the water production capacity. These are the solar radiation, feed water mass flow rate, inlet cooling water temperature, mass flow rate of cooling water and nano-particle volume fraction. The main conclusion is that good agreement is obtained between simulated and measured variations of water production and performance ratio values for variations of these parameters. The performance ratio of SSF unit is varied between 0.32 and 1.4 and flashing ranges between 3 and 9 °C. The maximum productivity of the system reached 41.8 kg/day according to test and operation conditions. The solar water heater efficiency is affected by the nano-particle volume fraction. The humidifier efficiency is affected by increasing water mass flow rate more than the increasing air mass flow rate and reaches about 98%. Finally, collector's efficiencies are about 55% and 56% for solar water heater and solar air heater respectively.

1. Introduction

Water is essential for the survival of all living things. It is essential for agricultural and industrial growth, as well as for supporting growing populations who require a safe drinking water supply. In fact, 97% of all water in our planet exists in seas and oceans, and 2% in glaciers and ice caps. The rest exists in lakes, rivers and underground reservoirs. Natural resources cannot satisfy the growing demand for low-salinity water with 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 rapid reduction of subterranean aquifers and the increasing salinity of these nonrenewable sources will continue to exacerbate the international water shortage problems in many areas of the world. Desalination has already become an acceptable solution for shortages in conventional water resources. This is now acknowledged by reputable institutions such as the World Bank. Seawater desalination is being applied at 58% of installed capacity worldwide, followed by brackish water desalination accounting for 23% of installed capacity. Due to the limited fossil fuel resources, it is expected that their price will continue 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 by producing the thermal energy required to drive the phase-change processes by using direct solar collection systems. Garg et al. [1] presented an experimental design and computer simulation of multi-effect humidification–dehumidification solar desalination and the developed model which is useful in the estimation of the distillation plant output and optimized various components of the system like, solar water heater, humidification chamber, and condensation chamber. Dai and Zhang [2] experimentally conducted a solar desalination unit with humidification

* Corresponding author. Tel.: +20 1001543587.
E-mail addresses: kabeel6@hotmail.com (A.E. Kabeel), emad_mech@hotmail.com (E.M.S. El-Said).

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and dehumidification. 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 optimum rotation speed for the fan corresponds to an optimum mass flow rate of air with respect to both thermal efficiency and water production. The unit worked perfectly and the thermal efficiency was above 80%. Amer et al. [3] theoretically and experimentally investigated humidification–dehumidification desalination system. The system is based on an open cycle for water and a closed cycle for air stream. The air is circulated by either natural or forced circulation. Detailed experiments have been carried out at various operating conditions and using several packing materials. The heat and mass transfer coefficients have been experimentally obtained and fitted in forms of empirical correlations. The system productivity increases with the increase in the mass flow rate of water through the unit. Water temperature at condenser exit increases linearly with water temperature at humidifier inlet and it decreases as water flow rate increases. A maximum productivity of 5.8 l/h has been obtained using wooden slate packing and with forced air circulation. Nafey et al. [4,5] numerically and experimentally investigated a humidification–dehumidification desalination process using solar energy under different environmental and operating conditions. The comparison between theoretical and experimental results illustrated that the mathematical model is in good agreement with the experimental results. The productivity of the unit is strongly influenced by the air flow rate, cooling water flow rate and total solar energy incident through the day. The obtained results indicate that the solar water collector area strongly affects the system productivity, more so than the solar air collector area. Ben Amara et al. [6] experimentally and theoretically studied a pad humidifier used in a multi-stage solar desalination process in operation. The experimental operation of the humidifier is presented in terms of temperature, relative and absolute humidity, and the quantity of evaporated water for different climatic and working conditions. Dai et al. [7] mathematically and experimentally characterized that a solar desalination unit with humidification and dehumidification by reusing some of somewhat concentrated saline water after evaporation, recovering condensation heat, and forced air flow was expected to produce more freshwater. Parametric analysis was conducted in order to optimize the unit performance and to study the effect of some of the operating conditions such as flow rates, temperatures of feed water, and air and cooling water. The daily solar productivity corresponding to unit square meter of collector area is about 6 kg/day/m^2 with 20 MJ solar energy input a day under given conditions. El-Shazly et al. [8] took another way with humidification–dehumidification desalination method to enhance mass and heat transfer rates, and improve both process productivity and product quality by using pulsating liquid flow. An experimental investigation was performed in humidification–dehumidification desalination unit consisting of the main components (humidifier, dehumidifier, and solar water heater). The results showed that the unit productivity has been increased by increasing the off time i.e. decreasing the frequency of pulsed water flow up to certain levels, a frequency of 20/60 on/off time was found to have the highest productivity of the unit. Increasing the amplitude of water pulsation (water flow per pulse) was found to increase the unit productivity as well. Nafey et al. [9] theoretically and experimentally investigated a small unit for water desalination by solar energy and a flash evaporation process. The system consists of a solar water heater (flat plate solar collector) working as a brine heater and a vertical flash unit that is attached with a condenser/pre-heater unit. The average accumulative productivity of the system in November, December and January ranged between 1.04 and 1.45 kg/day/m^2. The average summer productivity ranged between 5.44 and 7 kg/day/m^2 in July and August and 4.2 to 5 kg/day/m^2 in June. Baig et al. [10] investigated the effect of various operating conditions on the performance ratio, brine temperature and salinity as it leaves the last flash stage in a once-through the multi-stage flash (MSF) distillation system. The numerical results obtained with the published data on similar plants were compared. The results show that both analytical solutions and experimental/field analysis are required to identify the most influential parameters that affect the performance and set proper plans for performance optimization. The accurate estimate of the variables related to the brine heater, selecting proper number of stages and the stage-to-stage temperature drop is of crucial importance. The thermal properties dependent on the operating conditions may affect the accuracy of numerical results. The salinity of the feed seawater has a significant effect on the plant characteristics. Junjie et al. [11] experimentally studied 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. Abutayeh [12] experimentally and theoretically simulated a new desalination process based on solar flash desalination process under a hydrostatically sustained vacuum and analyzed the flash temperature effect on system variables. The system consists of a saline water tank, a concentrated brine tank, and a freshwater tank placed on ground level plus an evaporator and a condenser located several meters above the ground. The vacuum is passively created and then maintained by the hydrostatic balance between pressure inside the elevated flash chamber and outdoor atmospheric pressure. The proposed desalination unit does not require high temperatures to perform the flash operation due to the vacuumed flash chamber. In addition, the vacuum is naturally produced by the hydrostatic forces without the need for vacuum pumps, which extends the efficiency of the unit. Saad et al. [13] proposed and designed a new desalination system for converting seawater into freshwater by utilizing the waste heat of internal combustion engines. The desalination process is based on the evaporation of seawater under a very low pressure (vacuum). The low pressure is achieved by using the suction side of a compressor rather than a commonly used vacuum pump. The evaporated water is then condensed to obtain freshwater. The effects of operational variables such as evaporator temperature, condenser temperature, vacuum pressure, and flow rate of both evaporator and condenser on the yield of freshwater are experimentally investigated. It is found that decreasing the vacuum pressure causes a significant increase in the yield of freshwater. It is 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. The same trend is attained by increasing the evaporator flow rate.

The solar collector is a convenient and common heater to be used as heat source for many applications such as domestic water heater and desalination purposes. However, the effectiveness of the present solar collector for low-capacity desalination units is low due to some reasons such as limited thermal conductivity of this working fluid and inefficiency and cost of solar radiation concentrators. Several years ago, 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 [14]. Yousefi et al. [15] experimentally investigated 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, absorption medium using the nano-fluids as working fluid increases the efficiency. For 0.2 wt.%, the increased efficiency was 28.3%.

The current work aims to experimentally study a pilot small-scale hybrid air humidification and dehumidification–water flashing evaporation (HDH–SSF) desalination system driven by solar thermal energy. The proposed system was designed, manufactured and tested to insure;

- studying the influence and performance of the different system operating conditions under actual climatological conditions,