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Experimental study of a cascade solar still coupled with a humidification–dehumidification system

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ABSTRACT

In this study, coupling of a cascade solar still with a humidification–dehumidification system was investigated experimentally under the climatological conditions of Zahedan (Latitude: 29.49, Longitude: 60.87), Iran. The inclined solar stills produce distillated and hot water simultaneously. In addition, the effects of different operating conditions and configurations on thermal performance and productivity of the solar system were studied. The effect of feed water and air flow rates on the daily productivity of HD system in different conditions such as feed water temperature has been investigated. The daily productivity of cascade solar still with and without HD system at different flow rates is investigated. Moreover, the end result of assembling the HD system with a cascade solar still was studied. The daily productivity of the system increases from 28% to 141% in the presence of humidification–dehumidifica tion system. It also improves the thermal efficiency from 9% to 20% after using 40–150 ml/min of flow rate, respectively. The maximum productivity and efficiency were 5.4 kg/m^2 day and 39% for minimum flow rate.

1. Introduction

Nearly 97 percent of the water resources on the Earth is salt water and held in the oceans. Also, about 2% of the world's water supply is frozen in polar caps and glaciers [1]. Hence, only 1% of available sources are useable for drinking and domestic usages. However, it is disproportionately spread on the earth and many countries suffer from water shortage problem. Naturally, water scarcity occurs in warm regions with high solar radiation. Therefore, solar desalination is one of the best choice to produce fresh water. Solar energy can be used for desalination in two direct and indirect procedures. In the direct method, distilled water is produced directly in solar collectors. In other words, evaporation and condensation chambers are integrated, which is called a solar still. In the indirect case, solar collectors supply energy for conventional desalination such as multi-stage flash, vapor compression and reverse osmosis [2]. Much research has been done to improve the daily productivity and thermal efficiency of the basin and inclined solar still types. The performance of the basin type solar still have been developed by Rahim [3,4], Bahadori and Edlin [5] and Tiwari et al. [6]. El-Sebaii has investigated theoretically and experimentally a shallow solar-pond integrated with a baffle plate [7]. Velmurugan et al. has integrated fins at the basin of the still and compared it with other types and reported that daily productivity has increased from 1.88 to 2.80 kg/m^2 around 45.5% [8]. Aybar et al. [9] tested an inclined solar still with and without wicks. The results showed that the wicks increase the distilled water generation by two or three times that of bare plate. It is noteworthy that our previous study (Tabrizi and Sharak [10]) had experimentally studied a basin solar still with a built-in sandy heat reservoir and concluded that usage of heat reservoir increased the productivity especially after sunset. Sadineni et al. [11] designed a weir-type inclined solar still and showed that the productivity of the weir type still was approximately 20% higher than basin type. Also, they stated that a glass cover has a significant influence on the productivity of the system so that the productivity decreases from 5.51 to 2.20 l/m^2 day for single- and double-pane glass covers, respectively. The experiment of Ziabari et al. [12] on the modified cascade solar still portrayed the average fresh water production around 6.70 l/m^2 day, which shows that there is 26% growth in comparison to the prior cascade. In addition to that, they used a weir on each step of the stills to increase the residence time of water on the absorber surface in order to increase the evaporation. Hansen et al. [13] experimentally investigated the performance of an inclined solar still by using different wick materials

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Nomenclature

A_p	area of evaporative surface (m^2)	T	temperature (°C)
CSS	cascade solar still		
HD	humidification–dehumidification	*Subscripts*	
h_{fg}	latent heat of vaporization (J/kg)	*ao*	air outlet
I	solar intensity (W/m^2)		
m_{CSS}	daily productivity of cascade solar still (kg)	*Greek*	
m_{HD}	daily productivity of humidification–dehumidification system (kg)	η	overall thermal efficiency
n	number of desalination hours		

on different absorber plate configurations. They used wood pulp paper wick, wicking water coral fleece fabric, and polystyrene sponge on every flat absorber and stepped absorber, with and without wire mesh. They achieved the maximum productivity of 4.28 l/day for coral fleece fabric with wire mesh-stepped absorber plate. Another still was designed, built and evaluated by El-Zahaby et al. [14], to study the performance of the step-wise water basin coupled with a spray water system using two air heaters. The thermal efficiency and daily productivity of this system were about 50% and 54.48 l/m^2, respectively. Park et al. [15] designed a simple multiple-effect diffusion (MED) hybrid distiller which used solar heat and waste heat recovered from the generator concurrently to evaporate seawater. The maximum productivity of that system was 18.02 kg/m^2. They have reported that the performance of the system depends more on the MED section than the basin section. Saeedi et al. [16] have analytically optimized the energy efficiency of photovoltaic/thermal (PV/T) active solar still. Their results showed a good agreement with previous experimental research. They showed that by increasing the speed and the area of basin or reducing the mass inside the water basin, the energy efficiency of the PV/T active solar still increases. EL-Agouz et al. [17] theoretically studied the performance of an inclined solar still desalination system with and without a water close loop. They showed the inclined solar still with a make-up water improves the productivity by 57.2% compared to conventional basin-type solar still. They also mentioned that water film thickness plays an important role in the productivity as well as the efficiency of the system.

One of the indirect solar desalination systems is the humidification–dehumidification (HD) process [18]. During direct contact between water and air, water evaporates into the air and humidifies the air. The energy for evaporation can be supplied by hot water or air. Clearly, hot air consists of more vapor content. During the air dehumidification in the condenser, distilled water is produced by condensing the vapor. The HD process is worked at atmosphere pressure, but the high temperature in the evaporation process is not necessary, therefore the required energy of this process can be provided by solar energy. Many researchers have conducted their studies in this field. For example, Nafey et al. [18] investigated the influence of different environmental and operating conditions on the productivity of a HD process using a solar system. Experimental systems consist of a concentrating solar water heater, flat plate solar heater, humidifying tower, and dehumidifying exchanger. Their results showed that the productivity of the system is strongly affected by the inlet water temperature, flow rate of cooling water and air, and also depends on solar intensity conversely. The wind speed and ambient temperature have insignificant effects on the productivity. Summers et al. [19] used an air heating solar collector in HD desalination process. They built a phase change material (PCM) storage below the absorber plate of collector to produce a constant air temperature throughout the day or night. This method could help to provide constant productivity. Orfi et al. [20] presented an experimental and theoretical study on a solar HD desalination process. Their system included two solar collectors (water and air), a horizontal evaporator, and a condenser, where results indicated that the global efficiency of the unit depends on the efficiency of each component. Hermosillo et al. [21] presented a mathematical model to calculate the rate of distillate production and temperature of a HD system. The results showed that there isn't a significant difference between their mathematical modeling results and experimental data. A high thermal efficiency value of 85% was reported for a solar HD system by Dai and Zhang [22]. In their system, an open air cycle and a closed water cycle were implemented. The system consisted of a solar air heater, humidifier and condenser. However, water vapor with a high temperature and pressure generated by a boiler was used as the heat source instead of solar energy. Zheng et al. [23] investigated a two-stage desalination system based on the HD process and developed a mathematical model for each component of the system. Kabeel et al. [24] investigated a desalination system theoretically and experimentally based on air humidification–dehumidification. They used an evacuated solar collector to preheat inlet humidifier water in order to increase the system productivity. Yıldırım and Solmuş [25] mathematically investigated a coupling system of flat plate water heater and HD system by using a double pass solar air heater. They observed that water heating has a critical effect on the distilled water production.

In the present study, a cascade solar still, which was designed and built before in the University of Sistan and Baluchestan [26], was coupled with an HD system and experimentally investigated. In other words, it was a direct solar still system combined with an indirect one. In the mathematical investigation of Yıldırım et al., distilled water was produced by condensing in the dehumidifier, however, in the present experimental system, the distilled water was obtained by cascade solar still and dehumidifier simultaneously. Furthermore, there is a closed air loop instead of the open one in the new system. The main objective of this study is to improve the cascade solar still productivity because the unusable outlet of the cascade system, which is loosed in common systems can be used also by HD system. Many studies sought to improve efficiency of the cascade solar still, but there is no reported study to couple a cascade system and an HD system with each other. If the outlet water is returned to the cascade system again, the overall efficiency reduces because salt from outlet water covers the surface of absorber. This is a good reason to use an HD system instead of return water to cascade system. Furthermore, the effect of different operating conditions and configurations on thermal performance and productivity are simultaneously investigated.

2. Experiment

2.1. Experimental set up and methods

A schematic diagram of the investigated weir cascade solar still with the main parts of the humidification tower and condenser is