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Examination of a solar desalination system equipped with an air bubble column humidifier, evacuated tube collectors and thermosyphon heat pipes

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HIGHLIGHTS

- The performance of a novel HDH system is investigated experimentally.
- Effect of initial water depth in the humidifier and air flow rate is studied.
- Adding oil in the space between ETCs and HPs increases productivity significantly.
- The maximum daily productivity and daily efficiency are 6.275 kg/day·m^2 and 65%.
- The estimated cost of the fresh water produced is 0.028 $/L.

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ABSTRACT

In this paper, the performance of a novel HDH solar desalination system equipped with a combination of heat pipe (HP), evacuated tube collector (ETC) and air bubble column humidifier is experimentally investigated. This novel HDH system uses advantages of ETC-HP as a highly efficient thermal absorption and conductor device, and at the same time employs the advantages of an air bubble column humidifier, i.e. high interface area and effective mixing in order to heat the water and humidify the air, respectively. The effects of various parameters including incoming air flow rate into the humidifier, initial depth of water in the humidifier, and adding fluids such as oil and water in the space between the ETCs and heat pipes on the system performance were investigated. Results indicate that by adding oil in the space between the ETCs and heat pipes, daily fresh water productivity and daily efficiency increase significantly and reached 6.275 kg/day·m^2 and 65%, respectively. In addition, the optimum initial water depth in the humidifier is the same as the length of the heat pipe's condenser section in the humidifier. Moreover, daily production slightly increases as the air flow rate increases. The estimated cost of fresh water produced through the HDH system designed is 0.028 $/L.

1. Introduction

It is expected that by the year 2025 more than 60% of the world's population will be faced with water shortage problems [1]. One of the most popular methods to produce potable water is "desalination". Among the different common desalination processes, multi-stage flash (MSF), multiple-effect distillation (MED), vapor compression (VC), and reverse osmosis (RO) processes are commonly practiced to supply drinking water. Due to the high energy consumption and high maintenance costs of these technologies, producing drinking water on a small scale is not economical. Moreover, these technologies have destructive environmental effects due to the use of fossil fuels [2,3]. One of the simplest and most efficient desalination processes for small-scale, decentralized demand is the humidification-dehumidification (HDH) process, which has distinctive advantages including a simple structure, low operating temperature and the ability to use solar energy [4–6]. The HDH unit has three main sections: the humidifier, dehumidifier, and heat source. In the humidifier, air and water, one or both which have been heated by an external heat source, are in contact and a certain amount of vapor is extracted by the air. Hot and humid air leaves the humidifier and enters the dehumidifier. In this section, water vapor is distilled by bringing the humid air in contact with a cooled surface which enables condensation of the vapor in the air and production of fresh water. Heretofore spray towers and bubble columns have been used more to humidify air in the HDH process. The principle of operation for these devices is same. When water is brought into contact with air that is not saturated with water vapor, water diffuses into the air and

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raises the humidity of the air. With the aim of improving the efficiency of spray humidifiers, various packing materials are used to increase the contact area of water drops with the air and transfer of heat and mass. Different packing materials such as wood [7,8], plastic [8,9], and cellulose papers [10] have been evaluated by performance analysis of the common HDH desalination processes. Amer et al. [8] showed numerically and experimentally that the use of wood as a packing material leads to higher fresh water productivity compared to plastic. Kabeel et al. [10] experimentally investigated the use of two types of cellulose papers (5 mm and 7 mm). Their results showed that the use of 5-mm cellulose brings higher fresh water productivity. Sharqawy et al. [11] numerically studied two HDH cycles, namely water-heated and air-heated cycles. It was shown that an optimum value for water to air mass flow ratio results in maximum efficiency for each cycle. Moreover, it was also demonstrated that increasing the temperature of the water entering the humidifier reduces GOR for the water-heated cycle, whereas it increases for the air-heated cycle. Ashrafizedeh et al. [12] investigated the exergy of different HDH processes, which were used spray humidifiers based on sink and source model. The results showed that 80 to 90% of exergy losses are related to the heater section. Yildirim et al. [13] numerically studied the influence of different parameters on the performance of conventional HDH systems. A flat plate solar water heater and a flat plate double pass solar air heater were used to heat water and air. The results showed that the impact of water heating is much more than air heating on desalinated water productivity. Another method for air humidification is applying bubble columns. In this method gas is injected into a column filled with liquid which then ascends in the form of bubbles. The same phenomena can be applied to improve the humidification process in the HDH process. Zhang et al. [14] experimentally investigated the influence of different parameters on the performance of solar bubbling humidification desalination units. Results showed that when the humidifying temperature increased, GOR increased, while electric power consumption of unit freshwater output and freshwater production costs decreased. Zhang et al. [15] also experimentally studied the bubble humidification process. The results showed that increasing humidifying temperature by 10 °C, increased the humidification capacity about 80%. It was shown that air is easily to be humidified to the saturated state by bubbling humidification on a single stage sieve plate. El-Agouz [16] evaluated the productivity of the system by using the technique of air injection into hot water in a HDH process. In this system electrical heaters were used to heat water and a compressor was utilized to blow air into the water. Due to the considerable cost of the compressor and high electricity consumption, the reported cost of desalinated water was quite high. Ghazal et al. [17] investigated the effect of using a direct contact bubbling humidification method on the production rate of a HDH process. In this system, air is blown by a compressor into the water inside the solar collector. Results showed that the outlet air of a solar collector was saturated, and by applying a reflector mirror absolute humidity increased by 32%. Recently, Khalil et al. [18] performed an experimental study on a solar HDH system in which an air bubble column humidifier was used. The impact of water temperature, air flow rate, and the sieve's hole diameter on the performance of the system were surveyed. It was shown that the daily efficiency reached 63%. It was concluded that air bubble column humidifier systems had a higher performance than conventional humidifier systems. Considering the low operating temperature of HDH processes, the use of solar energy in these systems reduce energy consumption, which is desirable. In many of the previous studies, different solar collectors or photovoltaic plates were used to supply the required energy for air or water heating in the HDH processes. Zamen et al. [19] experimentally studied a two-stage solar HDH system which used flat plate collectors for water heating. The desired system was evaluated on both hot and cold days of the year, and it was shown that the daily fresh water productivity in the winter was less than half of the daily fresh water productivity in the summer. It was shown that the performance of conventional flat plate collectors is highly dependent on the weather conditions, so on cloudy and cold days their performance was significantly reduced. Evacuated tube collectors, which have the two advantages of evacuated space and proper shape, have higher performances than flat plate collectors. Due to the evacuated space in these collectors, convection and conduction losses are reduced resulting in better thermal performance of these collectors at higher temperatures. Meanwhile, a heat pipe as a highly efficient thermal conductor in the evacuated tube collector can transfer significant amount of heat from the heat source to the heat sink. A heat pipe is an evacuated tube which is filled with the proper amount of working fluid. Several studies have been undertaken to investigate the effect of using different working fluids on the heat pipes performance [20,21]. A heat pipe consists of three parts namely: an evaporation section, an adiabatic section and a condensation section. When the evaporation section is in contact with a heat source (evacuated tube) the heat pipe's working fluid absorbs heat through the wall, it then evaporates and, due to the difference of pressure in the tube, moves to the opposite end or the condensation zone where it loses its heat to the cold fluid (saline water). The resulting condensate returns to the evaporation section by a wick or gravity and the cycle repeats again. Ayompe et al. [22] studied the use of flat plate collectors (FPC), heat pipe and evacuated tube collectors (HP-ETC) in a domestic water heating system. Results showed that the annual heat generation rate per unit area of collectors for FPC and HP-ETC is 496 kW h$\cdot$m^{-2} and 681 kW h$\cdot$m^{-2}, respectively. Jahangiri et al. [23] studied the performance of a solar still in which thermosyphon heat pipes and evacuated tube collectors were used to heat the water. The comparison of the production of the mentioned system with some of the previous studies indicated that fresh water productivity increased significantly. Jafari et al. [24] introduced a new solar still system which used a thermosyphon heat pipe, an evacuated tube collector, and parabolic through collector. Different tests were carried out to evaluate the performance of the system. The fresh water productivity was significantly higher than that of the previous study [23], but the reported cost of desalinated water increased.

The aim of this paper is to investigate the performance of a novel HDH solar system experimentally in terms of its productivity. The proposed system is an integration of an air bubble column humidifier to humidify the air and also evacuated tube collector and heat pipe (ETC-HP) to heat the water inside the humidifier. This system is manufactured to exploit the advantages of air bubble column humidifiers to conventional humidifiers such as high interface area and effective mixing and other significant features such as a lower rate of heat loss in an evacuated tube collectors and high performance of heat pipes in heat transfer. Unlike other common solar HDH processes which use pumps to circulate water to collectors, in this study solar energy is absorbed by ETCs and is directly transferred to the humidifier using heat pipes. Due to the aforesaid advantages and removal of the pump, we expected to achieve a higher rate of desalinated water and a lower desalinated water cost. In order to find the best system performance, the effects of different parameters such as incoming air flow rates into the humidifier, initial depth of water in the humidifier, and adding fluid in the space between the collectors and heat pipes on the system performance were investigated.

2. Experimental setup and procedure

All tests have been conducted in Tehran, Iran (latitude: 35°42′ ; longitude: 51°35′ and altitude of 1172 m above mean sea level). Figs. 1 and 2 show a schematic diagram and a photo of the experimental setup. The main components of the system are a humidifier, dehumidifier, and solar water heater (ETCs and HPs). In this system, air is streamed in a closed cycle between the humidifier and dehumidifier. In the humidifier, air is injected in the water chamber through an air stone and is dispersed as small-diameter bubbles to make a large area of heat and mass transfer with water. The air stone has dimensions of 2 cm × 80 cm and generates very tiny bubbles along the humidifier