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A modified solar desalination system using evacuated tube collector

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HIGHLIGHTS

- A modified desalination uses an evacuated tube collector to directly heat water.
- A quasi-steady state theoretical model is presented for this desalination system.
- Adding stainless steel wool enhances the heat transfer and increases the yield.
- The yield and efficiency reach up to 1.01 kg/(m^2·hr) and 65.6%, respectively.

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ABSTRACT

Solar energy is turning to one of the important types of clean energies, due to its availability, and its potential for wide range of applications. In this work, a new passive solar desalination system is introduced, which benefits from excellences of twin-glass evacuated tube collectors. For the first time, the evacuated tube collector is not only used as the solar thermal collector, but also as a basin to heat the water. Hence, the thermal resistance between the collector and basin is virtually eliminated. Results show a considerable increase in the rate of desalinated water production and the maximum production reaches up to 0.83 kg/(m^2·h). It was observed that the maximum rate of the production occurs when the tube is in inclination angle of 35°, and filled 80% with water. Moreover, it is seen that filling the tube with a stainless steel wool can enhance the production rate up to 1.01 kg/(m^2·h). It was observed that optimum inclination angle is 35°, which is the latitude of location of the experiments. Moreover, a theoretical model is presented in order to evaluate the system's efficiency in quasi-steady state conditions.

1. Introduction

Fresh water is a vital substance for mankind. Approximately 97% of the available water in the earth is in the oceans. The Polar Regions contain around 2% of the world's water, and only about 1% of the remaining water is fresh water and can be used by humans, animals and plants [1]. Nowadays, scarcity of clean drinking water is one of the main concerns of many countries, especially those in arid areas. In order to supply fresh water in dry regions, several technologies have been developed. Among these developments, Reverse Osmosis (RO), Vapor Compression (VP) and Electrodialysis (ED) are the most common methods [2]. Fossil fuels can be used for this purpose as well. However, air and water pollution, and limitation of fossil fuel sources are drawbacks that highlight undeniable importance of the renewable energy technologies in the future.

A complete review of solar technologies was presented by Thirugnanasambandam et al. [3]. The solar distillation is a simple and economical technology. Operation of a solar still is based on the cycle of water evaporation and steam condensation. Sun rays transport the radiation heat transfer to the still and water evaporates while all of the pollutions and impurities sediment in the basin. To gain the pure water, a condensation process is required after collecting the evaporated steam. Many factors affect the rate of production and efficiency of a still, such as location (and latitude), climate (ambient temperature, wind speed and etc.), inclination of the collectors, depth of water in the basin, solar radiation intensity, thickness and material of the glass cover, wind velocity and heat capacity of still [4]. It is observed that the inclination angle of the collector should be adjusted based on the latitude of a location to obtain a higher rate of production [5].

Solar distillation systems are in two main categories: Passive solar stills and Active solar stills. In a passive solar still, solar radiation is the only source of energy for raising the temperature of the water in the basin, while in an active system, additional sources of thermal energy enhance the rate of evaporation and consequently the rate of productivity of the system increases [2]. Many new methods have been introduced to increase the rate of production and efficiency in solar stills. Flat plate collector, which was proposed by Rai and Tiwari [6] improved

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the production by increasing the amount of thermal energy received by basin of the solar still. Badran and Al-Tahaineh [7] experimentally investigated a solar still coupled with a flat plate solar collector and concluded that the coupling increase the productivity by 36%. Sanjeev Kumar and Tiwari [8,9] suggested the optimum number of flat plate collectors and water depth in the basin for maximum annual performance and also the optimum collector inclination and glass cover inclination. Singh and Tiwari [10] evaluated the thermal performance of a regenerative active solar still (in which water is preheated by passing over the glass cover) and concluded that there is a significant improvement in overall performance due to water flow over the glass cover. Kumar and Tiwari [11] designed a solar still coupled with a photovoltaic system and showed the efficiency of the system is 20% higher than their passive solar still.

Garcia Rodriguez and Gomez Camacho [12] used a distillation system coupled to a parabolic trough collector (PTC) and proposed the optimum axis height for a single collector. Hiroshi and Yasuhito [13] suggested a system including a heat pipe solar collector and a Vertical Multiple Effect Diffusion type (VMED) still and predicted to produce 21.8 kg/(m^2·day) which was shown to be 13% larger than that of the VMED still coupled with a basin type still. Dev et al. [14] used a system including concave reflectors with the water depth of 3 cm which led them to obtain 4.3 kg/(m^2·day) of fresh water. Kalidasa et al. [15] studied the influence of different wick materials on basin type double slope solar distillation systems. Nevertheless, several methods have been suggested to increase the daily yield of passive systems. Flat plate solar collectors, sun tracking systems, reflectors, condensers, coupling with sponge cubes, phase change materials and also the use of concave surfaces are some of the proposed improvements [4]. In 2012, Dev and Tiwari [16] investigated the annual performance of a solar still coupled with an Evacuated Tube Collectors (ETC), and reported an average thermal efficiency of 21.3% for the system. An ETC is a type of solar collector that uses evacuated tubes to insulate the inner pipes from the ambient. Sampathkumar et al. [17] also investigated the performance of a solar still coupled with an ETC and obtained higher production rate compared to the similar passive solar still. In 2013, Kargar Sharif Abad et al. [18] proposed a novel desalination system which employs pulsating heat pipe to transfer the heat from the collector to the basin. Moreover, Kargar Sharif Abad et al. [19] showed that the use of a closed-loop pulsating heat pipe in a water heater can enhance the performance of the system. In 2014, Jahangiri Mamouri et al. [20] introduced a solar still which uses a combination of thermosyphon heat pipes and ETCs. They concluded that the system can reach the maximum production rate of 1.02 kg/(m^2·h) and maximum efficiency of 22.9%. Evacuated tube solar collectors (ETC) are also observed to be more beneficial and efficient than flat plate collectors [21]. In 2014, Kumar et al. [22] introduced a solar still augmented with an ETC in forced mode water circulation in ETC. They reported the efficiency of 33.8% for that system. Sabiha et al. [23] presented the latest development and progresses in ETCs. They compared flat plate solar collectors and ETCs, and discussed on the economic considerations and challenges of using ETCs. In 2015, Jafari Mosleh et al. [24] proposed a new desalination system, which employs a heat pipe, ETC and a sun-tracking PTC. They showed that the production rate per total solar absorption and efficiency can increase to 0.933 kg/(m^2·h) and 65.2%, respectively.

In this study, a twin-glass evacuated tube collector (TETC) is employed as a basin. The present system can be classified as a passive solar desalination system. However, the conventional basin is eliminated from the setup and the TETC itself serves as a basins. The TETC absorbs the incoming solar radiation, converting it into heat at the inner absorbing surface, and transfers this heat directly to water inside it by means of natural convection and causes it to evaporate. Hence, there is no thermal resistance between the collector and the conventional basin as proposed by previous researchers. Therefore, a higher rate of production is expected. In order to enhance the thermal conductivity of the system, a Stainless Steel Wool (SSW) is also embedded in the tube and the change in the rate of production is measured. In addition, the effect of inclination angle on the rate of production is studied. Finally, a theoretical model is presented in order to evaluate the efficiency of the system without SSW for quasi-steady state conditions of midday hours.

2. Description of experimental setup

All the experiments were carried out in Tehran, Iran (latitude: 35° 42′; longitude: 51°35′ and altitude of 1172 m above mean sea level). The proposed desalination system is built of two main connected sections. The first section consists of a vacuum tube. The vacuum tube is a twin-glass evacuate tube collector of length 1820 mm. The inner and outer diameters of the glass tube are 47 mm and 57 mm, respectively. The space between the inner and outer surfaces of the glass tube is evacuated to prevent heat loss to the surroundings. Moreover, the inner surface of the glass tube is blackened to increase the absorption rate of the solar radiation. The tube is partially or fully filled by brackish water for different experiments. The second section is the condenser of the system, which is connected to the glass tube. It collects and condenses the water vapor produced by evaporation in the glass tube. The condenser consists of three different parts: a connector, a Steel tube, and a cap. The connector is made of plastic material Teflon polytetrafluoroethylene (PTFE) to provide a sealed connection between the glass tube and the steel tube. The steel tube is a heat-conductive tube of length 650 mm, diameter of 120 mm, and thickness of 2 mm. The water vapor loses the heat and condenses on the inner surface of the tube. So the purified water droplets appear on the inner wall and slide to reach the cap, the third part of the condenser. The cap is made of PTFE, and is sealed to avoid leakage of water vapor to the ambient. A picture of the experimental setup, a schematic of the tube collector, and a schematic of the system and attached measurement devices are shown in Fig. 1(a), (b), and (c) respectively.

3. Instrumentations

In Tehran, more than 80% of the solar heat is gained between 8:30 AM and 5:00 PM in summer. Hence, all the experiments are performed in this period of the time during summer 2014. Commonly used K-type thermocouples are employed for temperature measurements of the dry tube wall and the measured data were recorded by a Lutron BTM-4208SD with resolution of 0.01 °C. Simultaneously, a Pyranometer SP-110 apogee sensor recorded the intensity of solar radiation. The rate of the hourly production ($\dot{m}$) was measured using a graduated cylinder with resolution of 5 mL. The amount of the water was changing in the tubes, so to maintain the water level during the experiments, water was added manually by syringe in 15 min time intervals through the water inlet. A weight scale was placed under the system setup, in order to evaluate the mass losses of the system. Fig. 1(c) illustrates the schematic of the system and attached measurements devices. It should be noted that it does not provide details of fittings, and the schematic is not to scale.

Expanded uncertainties of the values of solar intensity, temperature and yield are calculated as 10.06 W/m^2, 1.006 °C and 5.8 mL, respectively [25]. The details of the uncertainty calculations are presented in "Appendix A" of a previous work [24].

4. Theoretical model

Several studies on theoretical modeling of evacuated tube collectors have been carried out [26–29]. In this section, a thermal analysis is performed to evaluate the system theoretically, according to recent studies and Kalogirou [30]. The vacuum tube is a twin-glass tube collector. Fig. 2(a) demonstrate the details of the radial system in evaporation