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Development and performance evaluation of an active solar distillation system integrated with a vacuum-type heat exchanger

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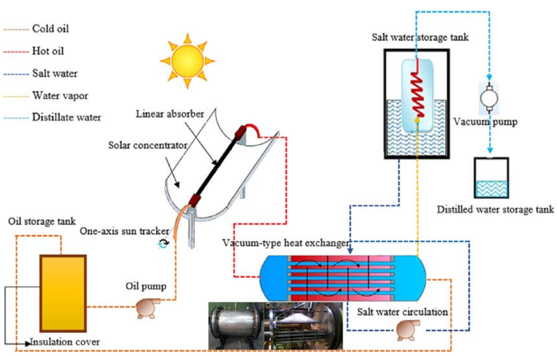
GRAPHICAL ABSTRACT



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ABSTRACT

Industrialization and growth in the world's population have increased the demand for fresh water. Solar desalination systems are energy consuming and therefore using solar stills in the remote locations is more feasible and affordable. In the present study, a solar distillation system integrated with a solar parabolic trough concentrator and a vacuum-type heat exchanger with falling film technique has been developed and experimentally evaluated during five sunny days in October 2015 between 10 am to 2.30 pm. During the evaluation period, the environmental parameters of solar radiation, air temperature, and wind speed were recorded in every 15 min. Then, the effect of these environmental parameters on the daily productivity of the distillation system through the performance evaluation of both solar concentrator and heat exchanger. Then, the energy and exergy efficiencies of the heat exchanger, as the central part of the system, were calculated based on the recorded environmental and operational parameters during the experiments. The obtained results showed that the solar radiation has the dominant effect on the thermal performance of the concentrator which delivers hot oil to the heat exchanger. Moreover, it has been investigated that the vacuum pressure of the heat exchanger has a significant effect on the vapor productivity of the system. The maximum distillate production of the distillation device was recorded to be 1.5 kg/m^2/day with the average solar radiation of 1227.68 W/m^2 under the heat exchanger vacuum pressure of 0.5 bar. According to the results obtained from the energy and exergy analysis, the highest energy and exergy efficiencies were obtained as 60.98% and 56.80% respectively.

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1. Introduction

Water is one of the essential constituents for the sustenance of humankind and as a critical material for human life. It is useful for many purposes like agriculture, irrigation and domestic uses like cooking and so on. Freshwater is the most critical issues of health hazard in today's world. More than two-thirds of the earth's surface has been covered with water of which around 97% is salty, 2.6% is presented as icebergs, and therefore, only less than 1% of the fresh water is within the human reach [1]. The demand for freshwater is growing continuously due to the population growth and its rapid use in agriculture and industry. It is essential to minimize the gap between the demand and supply of fresh water by developing alternative technologies for water purification to overcome the challenge of water shortage. It is becoming a challenge to avail of low-cost potable water to humanity. Solar distillation has been known as one of the most promising, simple, and economic methodology for salt and brackish water purification by utilizing solar energy as a renewable energy source [2].

Industrial desalination technologies are divided into two main categories of phase-change/thermal and membrane processes. All desalination technologies require a chemical pretreatment of raw seawater to avoid scaling, foaming, corrosion, biological growth, and fouling and also need a chemical post-treatment [3]. One of the evolving desalination methods is solar distillation. Solar stills are divided into two categories of passive and active systems. In active solar stills, additional thermal energy can be given to the passive solar still using an external source to increase the evaporation rate. In contrast, passive systems use no external power source [4]. Kumar et al. [1] have discussed a detailed review of different types of solar stills, including passive and active systems.

Badran et al. [5] studied the effects of integrating a flat plate solar collector on the efficiency of a solar distillation system. Results showed that solar still outlet could reach to the highest value for the lowest water depth of 2 cm in the basin. Also, the total efficiency reduced by increasing the depth of water in the basin. Chaouchi et al. [6] developed a solar desalination unit equipped with a parabolic concentrator. The results showed that there is a relative error between the experimental results and the theoretical analyses with an average value of 42% for the distillate flow rate. The higher percentage of error refers to the imperfections in the geometry of the parabolic mirror, the sun manual following up and the system's tilt variation throughout the day. Kumar and Tiwari [7] developed a hybrid (PV/T) active solar still with the efficiency of 5.5 times more than a passive solar distillation system. The results indicated that for the depth of 0.05 m of saline water in the basin, energy transmission coefficient for passive and active distillation systems is 0.78 and 2.41 $W/m^2 \cdot K$ respectively.

Dwivedi and Tiwari [8] developed an active solar still with double-slope through natural circulation. Results showed that active type has 51% more efficiency in comparison with the passive one. Kabeel and El-Agouz [9] reviewed the single-effect solar stills and solar stills coupled with different devices such as sun tracker and phase-change materials. They demonstrated that using the sun tracker is more efficient and can enhance the total productivity. Kargarsharifabad et al. [10] experimentally investigated the performance of a flat plate solar collector, enhanced by the use of a closed loop pulsating heat pipe. The results indicated that the use of solar heat pipes could increase the performance of the solar systems.

Gorjian et al. [11] developed a stand-alone point-focus parabolic solar still which was experimentally evaluated during seven sunny, slightly cloudy and dusty days in October. The effect of environmental variables such as direct solar radiation, wind speed, air temperature and inlet water's salinity on the system production rate was examined. Results showed that the most critical factors affect the production rate of the system are direct solar radiation and absorber surface temperature. A maximum production rate of 5.12 kg per 5 h in a day was reported with the average solar radiation of 628.8 W/m^2 and the maximum average value of the absorber's surface temperature of 150.7°C. The average daily efficiency of the system was also reported to be %34.69 with a maximum production rate of 1.5 kg/h.

Jafari Mosleh et al. [4] designed a new desalination system using a combination of the heat pipe collector, evacuated tube collector, and parabolic trough concentrator. With using aluminum conducting foils in the space between the heat pipe and the twin-glass evacuated tube collector, the production rate was recorded to be 0.27 kg/m^2.h. The efficiency of the desalination system was also obtained about 22%. This is while that using oil as a heat transfer working fluid flowing through the heat pipe and the twin-glass evacuated tube collector, increased the production rate and the efficiency of the system to 0.933 kg/m^2.h and 65.2%, respectively.

Moh'd [12] designed a solar still along with a porous evaporator and an internal condenser. The results showed that the distillation rate and efficiency of the solar still increase by increasing the basin's temperature. Also, the efficiency rate was increased by decreasing the wind speed and condensation temperature. The results showed that the solar radiation is the most effective parameter on the total efficiency of the system.

Elashmawy [13] examined the performance of the three different solar still set-up. This solar still has been experimented in three modes. In the first experiment, tubular solar still (TSS) with a rectangular trough filled was tested. A TSS with a half cylindrical trough without clothing in the second experiment was tested. Eventually in the third experiment, TSS of the second experiment was integrated with a parabolic concentrator-solar tracking system (PCST-TSS) was tested. Results show a high potential of using PCST-TSS compared to conventional TSS. The production of fresh water in these three experiments was 4.71, 3.6 and 3.53 L/m^2 day, respectively.

In well-known conventional desalination systems such as MED and MSF, falling film evaporation and condensation techniques have been widely used [14,15]. Zhang et al. [16] designed a horizontal tube falling film evaporation system and closed circulation solar desalination plant. The thermal performance of the system was significantly improved because of the falling film evaporation technology used. As a result, the yield was to be about two to three times more than that of a conventional single basin type solar still under the same conditions. Aybar et al. [17] investigated experimentally, an inclined solar water distillation unit. Three absorber plate surfaces were used; a bare plate, a plate covered with a black-cloth wick and with a black-fleece wick. The results showed that coating the plate with black-fleece wick increase the system productivity.

Abu-Arabi et al. [18] experimentally investigated the effect of various parameters on the productivity of such a desalination unit. The effects of feed water flow rate, ambient temperature, water salinity and cooling the outer glass surface of the basin were investigated. The results showed that about 0.6 L/m^2 h of water is produced during the hot months.

In the present study, a solar distillation system integrated with a vacuum-type heat exchanger, which will act as a vaporizer, has been developed. Creating vacuum along with using the falling film technique in the proposed design of the heat exchanger increase the productivity of the heat exchanger and therefore, improve the total performance of the distillation system. Using a heat exchanger with the proposed design can be a novel solution for utility-scale solar stills to achieve this goal. The performance of the developed solar distillation system has been evaluated by investigating the effects of the environmental and operational parameters on the productivity of the whole system. Also, the thermal performance of the heat exchanger has been evaluated by carrying out an energy and exergy analysis.

2. Materials and methods

A solar distillation system integrated with a parabolic dish concentrator and a vacuum-type heat exchanger was designed and