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Experimental performance evaluation of a stand-alone point-focus parabolic solar still

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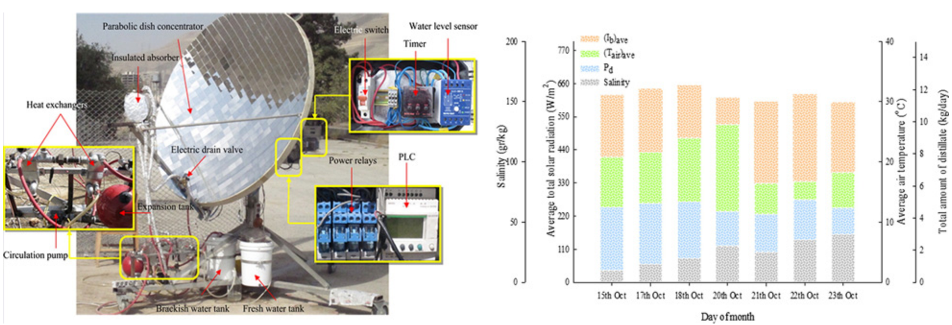
GRAPHICAL ABSTRACT



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ABSTRACT

A stand-alone point-focus parabolic solar still (PPSS) was designed and fabricated for desalination of seawater or brackish water and purification of non-potable water. The system consists of a parabolic dish concentrator; a two axis sun tracker based on programmable logic controllers (PLCs) and two plate heat exchangers (PHEs) to pre-heat the salt water before entering the absorber located at the focal point as well as condense the generating steam. Distillate productivity of the PPSS was measured along with evaluation of the effects of environmental and operational parameters that includes: beam solar insolation, wind speed, air temperature, absorber wall temperature and raw water salinity under the climatic conditions of Tehran during October. The maximum productivity of 5.12 kg within 7 h in a day was measured with the maximum average solar insolation of 626.8 W/m^2 and the absorber wall temperature of 150.7 °C. However, no significant effect of air temperature, wind speed, and water salinity on the productivity was observed. The maximum daily efficiency of 36.7% was calculated with a maximum hourly output of 1.5 kg/h. The quality of lab-prepared salt water samples was analyzed before and after desalination and the results comply with the WHO guidelines for drinking water quality.

1. Introduction

Water which is essential to life on earth is the constituent of the environment. Out of the total water on earth, about 96.54% is salt water and only 2.53% is fresh water. However, just less than 0.36% of the fresh water is directly available to humans. Over two thirds of the fresh water is frozen in glaciers and polar ice caps and the remaining unfrozen fresh water is found mainly as groundwater, with only a small fraction present above the ground or in the air [1–4]. The water crisis is the biggest problem that humanity will be facing in the next few decades. Worldwide population expansion and industrial development have resulted in an enormous demand for fresh water [5–7].

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The term "desalination" refers to any process that removes some amount of salt and other minerals from saline water and is the most popular treatment solution throughout the world today. Solar distillation is the best suited solution for water purification in areas where plenty of solar energy is available, but the quality of water is not suitable for drinking. A solar still is a primitive yet effective device for desalination of non-potable water [4]. The solar stills do not need fossil fuels and can be used for low capacity and self-reliance water supplying systems. They are cheap with low maintenance cost, though their major problem is low productivity [8,9].

Radhwan [10] performed a transient performance analysis of a stepped solar still with built-in latent heat thermal energy storage. The still performance parameters were analyzed and the results showed that, decreasing the air flow rate has an insignificant effect on the still yield. Tanaka et al. [11] performed a theoretical parametric investigation for a developed vertical multiple-effect diffusion-type solar still coupled with a heat-pipe solar collector. It was found that productivity increases with an increase in the partition numbers and the feeding saline water temperature and reducing the solar collector area compared to the thickness of gaps between partitions. The performance of a single-basin solar still with different absorbing materials was analyzed by Nijmeh et al. [12]. A significant increase was obtained by using absorbing materials with high absorptivity. Tiwari and Tripathi [13] found out that the distillate output decreased significantly with the increase of water depth in the basin of the solar still. Esteban et al. [14] designed and constructed a basin-type solar still coupled with a solar collector to enhance the productivity. The results showed that the enhancement of the daily productivity was approximately 70%. Tanaka and Nakatake [15] presented a numerical analysis to investigate the effect of vertical flat plate external reflector on the productivity of a tilted wick solar still. Abdallah and Badran [16] deployed a sun tracking system for enhancing the solar still productivity. The results showed the increase of productivity to be around 22%. Velmurugan et al. [17] integrated a basin-type solar still with fins to increase the distillate production rate. The results showed the evaporation rate augmentation of about 45.5%.

Abdallah et al. [18] developed a modified conventional solar still, with reflecting mirrors, step-wise basin, and a sun tracker. The inclusion of internal mirrors improved the system's thermal performance up to 30%, while step-wise basin enhanced the performance up to 180% and finally the coupling of the step-wise basin with sun tracking system gave the maximum average thermal performance of 380%. Kumar and Bai [19] designed and built a basin-type solar still integrated with an improved condensation technique to enhance the efficiency. An integrated basin solar still with a built-in sandy heat reservoir was investigated experimentally by Tabrizi and Sharak [5]. The integrated heat reservoir causes a significantly higher productivity during nights and cloudy days. Eldalil [20] presented a new concept of active vibratory solar still. The productivity was increased to be about 5.8 l/m^2 due to added backed helical wires at the bottom of the basin. El-Zahaby et al. [21] designed a new stepped solar still with flashing chamber. It was found that the productivity of the system is significantly dependent on both inlet feeding water temperature and the power consumed. Omara and Eltawil [22] presented a design and installation of solar dish concentrator, simple solar collector and modified boiler for brackish water desalination. A mini single slope-air tight solar still was installed at the focus of dish concentrator as a boiler. The increase in distillate production for solar dish concentrator was about 244% and 347% higher than that of conventional type without and with preheating, respectively.

Arunkumar et al. [23] developed a basin solar still coupled with hemispherical concentrator and phase change material to augment the efficiency and distillate yield. The experimental results indicated that the productivity increases by using PCM. Riffat and Mayere [24] presented a working principle and thermal performance of a v-trough solar concentrator. The obtained results showed that the collector system can have a thermal efficiency up to 38%. A detailed review of different designs of active solar stills was also made by Sampathkumar et al. [7].

It is noticeable in the literature that most of the studies have focused on enhancing the productivity of the basin-type solar stills and improving their efficiency via modifying their basic structure or integrating the basins with the other equipment which increase the costs of construction. However, too little attention has been paid to the design and development of solar distillation systems in the form of stand-alone units which employ concentrators especially point focusing types. Point-focus solar collectors have some important advantages over other solar collectors. They are the most efficient due to the continuous sun tracking system and highly efficient at thermal power conversion systems because of minimum thermal losses [22,25]. Desalination of brackish water by means of these solar collector types make it possible to reach high temperatures to boil the salt water in the absorber which leads to further evaporation rates [26].

The current research work is intended to design and fabricate a stand-alone point-focus parabolic solar still (PPSS) for the desalination of brackish water and purification of non-potable water. The effect of environmental and operational parameters on the productivity of the developed solar still was investigated during experimental work. Finally, the most important water quality parameters of the feeding water before and after desalination as well as the brine were analyzed. A cost analysis was also conducted to assess the cost effectiveness of the desalination plant and determine the unit cost of the produced fresh water.

2. Materials and methods

2.1. Experimental setup

The experiments were carried out in the National Bioenergy Research Center of Tarbiat Modares University, Tehran, Iran. The location lies at 35.68° N latitude and 51.42° E longitude during the seven sunny, relatively cloudy and dusty days in October 2013 from 8:00 am to 3:00 pm. A schematic diagram of the designed and constructed point-focus parabolic solar still is shown in Fig. 1, whereas Fig. 2 is a photograph of the still.

The developed PPSS consists of a parabolic dish concentrator, a two-axis sun tracking system comprising of a PLC-based control unit; an evaporation chamber (absorber) positioned at a focal point of the concentrator with an inlet linked to a brackish water tank; two plate heat exchangers (PHEs) which condense the water vapor existing in the absorber as well as increase the temperature of the brackish water before entering the absorber; and a control unit for level controlling of the brackish water in the absorber. All of the items are supported on a stand. The parabolic reflector has the aperture diameter of 2 m and the focal length of 0.693 m which is covered with highly reflective silver-backed glass segments with 0.002 m thick and creates the reflecting area of 3.142 m^2. The absorber, mounted at the focal point, was made of CK45 steel alloy which has a receiving surface of 0.031 m^2 and a geometric concentration of 100. The outer surface of the absorber was completely insulated with rock wool of 0.02 m thick, except the part lit by the concentrated solar rays. The bottom side of the absorber was coated with the black chrome to increase the absorptivity. The absorber was mounted with an air-vent, a pressure relief valve and a moisture separator. The air-vent and pressure relief valve were mounted on the absorber at the highest point. The valve has a provision to set operating pressure at which it should open and release the steam generated. It is opened only at a set pressure (about 4.5 bar) and hence it is possible to maintain the desired pressure inside the absorber. The air-vent was provided to remove the air/dissolved gases in the water during initial heating. A moisture separator was installed between the pressure relief valve and the absorber to avoid carry-over of liquid droplet from the steam relief valve.