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Examination of a novel solar still equipped with evacuated tube collectors and thermoelectric modules

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HIGHLIGHTS

- The performance of a novel solar still equipped with evacuated tube collectors and thermoelectric modules was examined.
- This study involves conversion of vapor latent heat to electrical energy using the thermoelectric modules.
- The effect of creating a forced convection inside the condensation chamber was examined by using the electricity generated.
- The maximum yield and efficiency of the system were respectively equal to 1.11 kg/m^{2}hr and 68%.

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ABSTRACT

In this article, a novel solar still which is equipped with thermoelectric modules to utilize the heat of vapor condensation is experimentally investigated. The use of thermoelectric modules as devices for generating electricity from the temperature difference between two environments (hot vapor steam and cold ambient air) as well as taking outstanding advantages of evacuated tubes as collectors with high performances in adverse climatic conditions, led to utilizing of the energy dissipated due to vapor condensation and a considerable increase in the performance of the system. The effect of using the generated electricity to operate a small propeller fan for inducing forced convection was examined. The results indicated that, by generating a forced convection, the water yield and hourly efficiency of the system increase and reach respectively to the maximum values of 1.11 kg/m^2/h and 68%. In addition, the effect of two different depths for the water inside the evacuated tubes underwent experiments and it was observed that by filling the evacuated tubes, the output increases by 27% compared with the half-full case.

1. Introduction

Water is one of the most abundant resources on Earth which covers three fourths of its surface. Approximately 97% of the water is in the form of saline waters in the seas and only 3% of the water is in the form of fresh water. Moreover, a great portion of this water is in the form of ice in the poles and lakes and only less than 1% of it is within the reach of human beings [1]. Inasmuch as the sea water contains dissolved salts and harmful bacteria, it cannot be directly consumed and must be desalinated. From the various methods of desalination, solar stills have received considerable attention since they do not create environmental pollution, do not need fossil fuels, and are simple and inexpensive to manufacture [2]. The operation basis of all solar stills is the absorption of solar energy by the saline water, evaporation and condensation of water and then collection of water as the fresh water.

The solar stills are in general divided into two categories of active and passive systems. In active systems, in contrary to passive systems, an external source besides the solar energy is necessary. The external source can be a solar collector, solar pond, parabolic concentrator or whatever device that can be used to increase the water temperature [3]. Since solar stills have low productivity [4], a substantial number of studies have been conducted by the researchers to increase the efficiency of these systems and enhance their geometric and operational parameters. Manokar et al. [5] presented a complete review of the studies conducted to improve the parameters affecting the evaporation and condensation rate in passive systems. In addition, a comprehensive review on the active solar stills was conducted by Sampathkumar et al. [6]. Apart from experimental efforts, there are also some numerical and theoretical attempts to study the effect of different parameters such as solar intensity and wind velocity on efficiency of the solar stills [7–13]. The rate of production of a solar still mainly depend on location, intensity of solar radiation, depth of water in basin and inclination angle of glass [14]. An equation for determining the effect of the orientation

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angle of glass on the amount of water generated was presented by Khalifa [15]. The results of their experiments demonstrated that the optimum orientation angle of the glass was the latitude of the experiment location. The effect of the depth of water inside the basin is examined by several researchers. The results reflect a decrease in the efficiency by an increase in the water depth [16–19]. The use of multi-stage solar stills is one of the methods to maintain minimum water depth in basin. Kabeel et al. [20] presented a review of the works carried out to enhance the performance of multi-stage solar stills. The main disadvantage of these systems is their need for a larger area. Several studies have been conducted into decreasing the area and at the same time, increasing the water yield of the system by using solar collectors. Many articles focus on adding flat plate collector to the solar stills [21–25]. The results show an increase in the water production after the use of flat plate collectors. Kargar Sharif Abad et al. [26] used flat plate collectors and pulsating heat pipes in conjunction with the solar still and achieved the maximum yield of 0.875 l/m^2 h. Feilizadeh et al. [27] investigated the effect of the number of flat collectors on multi-stage solar stills. 96% and 48% increase in the summer and winter production was observed by adding the second collector. In addition, the water yield increased by 23% by adding the third collector. Flat plate collectors have two disadvantages: heat dissipation from the upper section of the collector, and non-normal radiation of the sun except at midday. Evacuated tube collectors have less heat waste due to the existence of vacuum between two glass tubes and demonstrate higher performance in adverse climatic conditions. Moreover, due to the cylindrical structure, these collectors do not need sun tracking systems, and therefore, have attracted the researchers. However, Jafari Mosleh et al. [28] have recently used a combination of evacuated tubes and parabolic collectors in conjunction with a sun tracking system and achieved the highest efficiency of 62.5%. The thermal modeling of solar still with evacuated tubes in thermosyphon mode has been conducted by Singh et al. [29]. Their results point to the optimum number of ten evacuated tubes for 52.2 kg water with the depth of 0.03 m in the basin. Kumar et al. [30] reported the optimum energy and exergy efficiency for a solar still with evacuated tubes with the forced motion of the fluid as 33.8% and 2.6% respectively. Jahangiri et al. [31] experimentally evaluated the performance of a single basin solar still with evacuated tubes with the heat pipe inside them and achieved the efficiency of 22.9%. They also reported the optimum depth of water as the length of the heat pipe condenser.

Many articles focus on improving the efficiency of solar stills by using external condensers as well as thermoelectric modules, in order to increase the rate of evaporation and condensation along with preventing the loss of latent heat of condensation to ambient. Monowe et al. [32] prevented the heat dissipation from the condensation of vapor by using a heat exchanger to preheat the input saline water by the vapor leaving the system and achieved the efficiency of 85%. Madhlopa and Johnstone [33] proposed a passive solar still with an external condenser. By providing the latent heat of condensation to second and third basin inside condenser, 62% higher theoretical productivity than a conventional solar still was reported. Sathyamurthy et al. studied a solar still in which the evaporation and condensation chambers were separated by phase change materials (PCM). By releasing the latent heat of vapor to the PCM, the productivity of the system increased by 52% in which more than 34% of production was associated with the time after sunset [34].

Rahbar and Esfahani [35] experimentally studied a novel type of solar still by using the heat pipes and thermoelectric modules. In the system they studied, the cold side of the thermoelectric module was located at the upper section of the glass on its outer surface and the hot section of the module was cooled down by heat pipes using a fan blowing ambient air. By supplying electricity to the module, the temperature of the cold side of the module reduces and as a result, temperature difference between evaporating and condensing zones as well as efficiency of the system increases. Simultaneous use of thermoelectric module for enhancing the condensation process, water dispersion system for enhancing the evaporation process, and solar collector for greater energy absorption was assessed by Esfahani et al. for a portable solar still [36]. Dehghan et al. conducted thermal modeling and exergy analysis for a solar still equipped with thermoelectric modules. Their results show that by elevating the temperature difference between evaporating and condensing zones by providing electricity to thermoelectric modules, the energy efficiency increases compared to the simple solar stills, while the exergy efficiency is still low due to high drop in modules [37]. In the previous studies, by providing the thermoelectric module with electrical energy, temperature difference was produced at the two ends of the thermoelectric module, and as a result, the condensation rate was raised. The disadvantage of these systems is their need for electricity to create temperature difference at the two ends of the thermoelectric modules. So far, the reverse of this phenomenon, i.e. generating electricity from the temperature difference between vapor as the hot side and the ambient air as the cold side of the thermoelectric module, has not been studied. Further details toward recent development and application of thermoelectric generator and thermoelectric cooler can be found in [38].

The aim of the present study is to retrieve the wasted latent heat in the condensation process using thermoelectric modules. The temperature difference between the vapor as the hot side of the thermoelectric and outside environment as the cold side is exploited and the energy produced from the condensation is recycled as electrical current to run a propeller fan inside the condensation chamber to increase forced convection heat transfer. In this research, the effects of increasing water temperature by evacuated tubes, recycling of condensation waste heat by thermoelectric modules, and using a propeller fan to increase forced convection heat transfer on the production rate of the solar still will be examined.

2. Experimental setup

All experiments were performed in Tehran (latitude: 35.42, longitude: 51.35, and elevation: 1172 m above sea level). The experimental setup has two evacuated tubes as solar collectors. A schematic of the experimental setup is shown in Fig. 1a. First the saline water is directly injected inside the evacuated tubes. The direct placement of water inside the collectors causes its temperature to increase as much as possible. In Table 1 further details on the equipment used is presented. By absorbing the solar energy, the water starts to evaporate and resulting vapor enters a chamber made of galvanized sheet with the thickness of 1.5 mm, so that it could get distilled and its heat can be recycled. The release of latent heat of condensation causes the wall temperature to increase and hence a temperature difference between the chamber wall and the outside environment is created. The thermoelectric modules are used to employ this temperature difference for generating electricity. In fact, by using the modules, the energy from the vapor condensation is recycled and converted to the electrical energy. Due to inexpensiveness of the thermoelectric coolers in comparison with thermoelectric generators (approximately 1/5 of TEG price), thermoelectric coolers, which have a structure similar to the thermoelectric generators, are utilized. This thermoelectric effect is reversible so that both module types can act as a cooler or a generator. Twenty modules are grouped in five and the modules in each group are connected in series. They are then placed on the ceiling and lateral walls of the chamber. These groups are themselves connected to each other in parallel and are located in a circuit with a small propeller fan. A heat sink is used on the outer surface of each module to draw the temperature around the cold side of the module close to the ambient temperature. To have a higher heat transfer between the heat sink surface and the cold side of the module and also between the condensation chamber and the hot surface of the module, silicon paste is placed between them. A schematic of the placement of the different components and various heat transfer processes are shown in Fig. 1b. The resulting electrical energy is used to