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Experimental study on a parabolic concentrator assisted solar desalting system

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This paper presents a modification of parabolic concentrator (PC) – solar still with continuous water circulation using a storage tank to enhance the productivity. Four modes of operation were studied experimentally: (i) PC-solar still without top cover cooling; (ii) PC-solar still with top cover cooling, PC-solar still integrated with phase change material (PCM) without top cover cooling and PC-solar still integrated PCM with cooling. The experiments were carried out for the cooling water flow rates of 40 ml/min; 50 ml/min, 60 ml/min, 80 ml/min and 100 ml/min. Diurnal variations of water temperature (T_w), ambient air temperature (T_a), top cover temperature (T_{oc}) and production rate are measured with frequent time intervals. Water cooling was not cost effective, but adding PCM was.

1. Introduction

By 2050, the demand for energy could double or even triple, as the global population rises and developing countries expand their economies. All life on Earth depends on energy and the cycling of carbon. Energy is essential for economic and social development but also poses an environmental challenge. We must explore all aspects of energy production and consumption including energy efficiency, renewable energy, nuclear energy, carbon capture and storage, and the global carbon cycle, as well as their relationship to climate and natural resource issues [1]. Today the world is challenged to provide sufficient pure water resources for human needs. A recent report shows that the ground water levels and rainfall are in decline [2–4]. In the future, with population and per capita consumption growth, the situation will become even more difficult. But desalinization is one class of solutions that holds significant promise. An example of distillation is a solar still, which is a simple device that can be used to convert saline or brackish water into drinking water [5]. Karimi Estahbanati et al. [6] analysed the effect of number stages of evaporation and condensation on the performance of multi-effect solar stills and their effects on productivity. They concluded that with more stages, the production enhancement is more in the continuous mode compared to the non-continuous mode. Ahsan et al. [7] studied the low cost triangular solar still to be used in rural and coastal areas for converting saline water into potable water using solar energy.

Many researchers have analysed the impact of cooling of the condensation surface of solar stills. Somwanshi and Tiwari [8] found that the distillate output increases slightly with an increase in water flow rate over the top cover. Arunkumar et al. [9] analysed the effect of water flow over a tubular solar still. They concluded that the water flow over the cover increases the distillate productivity. Suneesh et al. [10] investigated a 'V' type solar still with cotton gauze cooling. They concluded that water flowing over the condensation surface increases the productivity. Tiwari and Bapeshwara Rao [11] evaluated the performance of a solar still with water flow over the glass cover. Tiwari et al. [12] incorporated the flow of waste hot water in the basin along with water flow over the glass cover and obtained an increase in distillate output commensurate with the increase in inlet water temperature in the basin. Lawrence et al. [13] validated their model by incorporating the effects of water flow over the cover and heat capacity of water in the basin. They found an increase of 7–10% in efficiency of the solar still due to water flow over the glass cover. Abu-Hijleh [14]

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theoretically investigated the effectiveness of film cooling under different operating characteristics; his results indicated that the proper use of the film cooling parameters can increase the still efficiency by 6% but poor parameters can reduce still efficiency. Abu-Hijleh and Mousa [15] extended the earlier work and included the evaporation effect of a water film flowing over the glass cover. Water flowing over the condensing cover [16–35] has been studied by many authors working in the field of desalination.

Nowadays concentrators are used in various applications. Many innovative research activities have been performed on concentrator systems, e.g. photovoltaic systems [36–38], buildings [39], air conditionings [40] and cooling-heating [41]. Concentrator powered solar distillation systems play a significant role in producing de-salted water. Presently many researchers are involved in these activities to accumulate high quality de-salted water through concentrator-assisted systems. Chaochi et al. [42] designed and built a small solar desalination unit equipped with a parabolic concentrator. The experimental and theoretical study concluded with an average relative error of 42% for the distillate flow rate. Many authors have performed the distillation process with concentrator-assisted techniques [43–56].

El-Sebaii [57,58] studied the performance of single slope solar still with phase change material. Gude [59] reviewed energy storage for desalination processes with waste heat sources. A single basin double slope solar still with different energy storing materials has been studied by Kalidasa Murugavel et al. [60]. They found that quartzite rock is the more effective in increasing production per day. Sodha et al. [61] presented the effect of dye on the solar still performance. They concluded that black and violet dyes were found more effective than other dyes. A step type solar still with built-in latent heat thermal energy storage has been investigated by Radhwan [62]. They concluded that the still's efficiency is 57% compared to 61% for the still without phase change material. An experimental study on a regenerative solar still with thermal energy storage medium has been studied by Sakthivel et al. [63]. This modification was low cost as the jute cloth is very cheap and readily available. Arjunan et al. [64] investigated the performance of a simple solar still with different energy storage materials like black granite gravels, pebbles, blue stone, and paraffin wax. A simple solar still with different coloured sponge liners on the inner wall surfaces was investigated by Arjunan et al. [65]. They concluded that the 5 mm thickness sponge liner gives 35.2% higher yield than the conventional still and a black sponge gives more yield than the others, which is 43.5% higher than the conventional still. The effects of heat storage bed and water depth are studied by Omara and Kabeel [66]. They showed that storage bed (sandy layer) enhanced the solar still productivity. Experimental analysis of a solar still with phase change material has been studied by Sathyamurthy et al. [67]. They found that the efficiency of the solar still improved by 14% with PCM. A solar still with a semi-circular trough absorber has been analysed by Sathyamurthy et al. [68]. They concluded that the baffles enhanced the productivity by 16.7%. Sathyamurthy et al. [69] presented a pyramid shaped solar still with phase change material. They found that the distillate productivity was enhanced by 35% with the latent heat thermal energy storage system. A multistage active solar still with solar energy collectors have been analysed by Feilzadeh et al. [70]. They found that the productivity increased by 48% with the effect of collectors. El-Sebaii et al. [71] studied the effect of a fin on the solar still performance. The overall distillation increased by 13.7% with the effect of the fin in the solar still. El-Agouz et al. [72] studied the effect of a fin in an inclined solar still. They found that the daily distillate yield improved by 57.2% with top cover cooling over the condensing cover. Tiwari and Suneja [73] developed an inverted reflector solar still for distillation. They concluded that the productivity was doubled. El-Sebaii [74] presented a vertical design of new solar desalting system. The experimental results showed that the efficiency of the system increased by 29%. El-Sebaii et al. [75] studied the effect of baffle absorbers in the single slope solar still. They concluded that the daily distillate yield improved by 20% relative to a conventional solar still. El-Agouz [76] studied the water flow over a stepped solar still. The author concluded that the efficiency of the proposed solar still was 20% greater than conventional solar stills. A solar still with built-in internal and external reflectors has been studied by Omara et al. [77]. They found that the productivity enhancement was 125% due to the effect of reflectors. A solar still with sponge cubes has been experimentally analysed by Abu-Hijleh and Rababa'h [78]. They concluded that the distillate yield increased by 18–273% with the effect of sponge cubes in the solar still basin.

2. Methodology

In this work, a parabolic concentrator-solar still has been fabricated that is different from all previous works because it couples a parabolic concentrator with top cover cooling. Testing for the present study was carried out for Coimbatore India climatic conditions during March–July, 2014. Also, the basin of the solar still is made as hemispherical bowl, where the solar radiation is focused to a point to increase the temperature of the water inside the still. To increase the condensation of water on the inner surface, cover cooling is invoked. The experiment involved different flow rates over the top cover. In order to improve the overnight productivity, paraffin wax phase change material (PCM) loaded copper balls were placed in the still basin.

3. Materials

The PC solar still consists of a spherical section collector (roughly parabolic) and a hemispherical absorber. The hemispherical part was separately designed and attached to the basin bottom part of the still. This entire hemispherical absorber volume acts as water storage for the still. The absorber is composed of copper with 4 mm thickness. The diameter of the hemispherical base is 0.22 m. The inner and outer surfaces were painted black and a ¼ in. inlet pipe served as a water inlet. The six copper balls are hollow. The paraffin wax is filled with the hole provided at the top. 25 g of PCM was used in the balls. If more were used, since the volume of the PCM increases upon melting, it would cause leakage. A pyranometer is used to monitor the solar radiation. The water temperature, air temperature, ambient temperature, inner cover temperature and PCM ball temperatures are measured by K-type thermocouples. The uncertainty of the measuring devices are in Table 1. Table 2 summarizes the thermo-physical properties of commercial-grade paraffin wax PCM. The heat extracted water was collected and it is used in the same solar still for distillation purpose for the next day.

The top surface of the still is a cover of area 0.25 m × 0.25 m. The top cover is composed of transparent glass 2 mm thick. The top cover was placed over the grooves with uniform resting slope of 11° from the horizontal. A water collection segment was also provided at the appropriate place. The segment has a length of

Table 1
Accuracies and error for various measuring instruments [9].

Sl. No.	Instrument	Accuracy	Range	% Error
1	Pyranometer	±30 W/m^2	0–1750 W/m^2	3
2	Digital thermometer	±1 °C	0–100 °C	1
3	Thermocouple	±1 °C	0–100 °C	1
4	Measuring jar	±10 ml	0–1000 ml	1