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An experimental investigation of a parabolic concentrator solar tracking system integrated with a tubular solar still

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HIGHLIGHTS

- Tubular solar still is combined with parabolic concentrator solar tracking system (PCST-TSS).
- PCST-TSS system was able to increase TSS daily yield by 676%.
- Cost per liter (CPL) is reduced by 45.5%.
- PCST-TSS is promising for small communities in remote areas.

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ABSTRACT

This study describes the performance of three different experiments under the climatic conditions of Hail city (27.5°N, 41.7°E) in Saudi Arabia by using a tubular solar still (TSS) with a rectangular trough filled with a black cloth and saturated by raw water in the first experiment; a TSS with a half cylindrical trough without clothing in the second experiment, while in the third experiment TSS of the second experiment was integrated with a parabolic concentrator-solar tracking system (PCST-TSS). Results show a high potential of using PCST-TSS compared to conventional TSS. The obtained yields were 0.28, 0.214 and 1.66 L/day for 0.059 m^2 TSS area (4.71, 3.6 and 3.53 L/m^2day) for the three experiments with daily efficiencies of 36.5%, 30.5% and 28.5% respectively. The PCST-TSS yield was increased by 676% with 45.5% cost reduction per liter (CPL). This promising technique is suitable for house roofs and small communities located in remote areas.

1. Introduction

1.1. General back ground

Natural water resources come from the natural evaporation of earth's water surfaces (oceans and seas). This resource is fixed as there are no other natural resources in earth. Moreover the world population is growing fast causing an increase in water demand especially in countries with no rivers like Saudi Arabia. The common solution for such a problem is sea water desalination by using the conventional fossil fuel which has a damaging impact on the environment. Saudi Arabia heavily depends on the red sea and the Arabian Gulf coasts and brackish water desalination. The three main techniques used in water desalination are Multi Stage Flash (MSF, 88%) Reverse Osmosis (RO, 10%) and Multi Effect Desalination (MED, 2%).

As the challenge to secure drinking water increases worldwide, the attention is turned to the solar energy as a magic solution and a source of sustainable energy needs in the twenty-first century. The worldwide demand for water desalination is expected around 54 billion cubic meters a year by 2020 [1–3]. Saudi Arabia alone produces around 20% of the water desalination market worldwide [4]. This huge amount of water desalination (8 million tons per day) requires a substantial amount of energy that has a negative impact on the environment. Therefore, finding new sustainable and renewable energy resources is a strategic priority in Saudi Arabia. A number of researchers have evaluated and compared the available solar water desalination technologies including [4,5].

1.2. Solar stills

The solar still is the oldest and most common way employed to desalinate water by solar energy. There exists a substantial number of studies on solar stills with many of these focusing on the single-basin

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single-slope performance including experimental studies [6,7], theoretical and numerical studies [8,9], tilt angle of the class cover [6,10]. Other studies focused on the double-slope basin [11,12]. Many other parameters were also considered by researchers including inverted trickle and absorber solar stills [13–16], vertical solar still [17–20], active solar stills [21–23], wick and tilted wick types [24,25], hybrid P.V./thermal (PV/T) solar stills [26,27]. Attention was also given solar stills integrated with a greenhouse for agriculture self-irrigation systems [28–30]. Another useful utilization of solar stills is water extraction from humid air using chemical materials (normally $CaCl_2$) which absorb water vapor during night hours and regenerate it through the evaporation-condensation process during day hours [31–33]. The integration of phase change material (PCM) with solar stills enables the continuation of water production during night hours. Paraffin wax is commonly used as PCM because of its uniform melting, safety and relative low cost. Some studies [34,35] introduced theoretical analysis for solar stills with PCM and others performed an experimental studies [36,37]. Recently a detailed review study about the factors affecting solar still productivity for several solar still types including tubular solar still (TSS) was performed [38,39].

1.3. Tubular solar stills (TSS)

A tubular solar still (TSS) is a very old technique [40,41] which employs the same distillation principle of the conventional basin solar still type, but differs in shape (cylindrical).

A new TSS design was proposed by Ahsan et al. [42] to enhance the design, maintenance and economy. The new design has a frame assembled with six galvanized iron (GI) pipes (longitudinal) six GI rings (transverse) to hold a polythene film as a transparent cover of the TSS instead of the old vinyl chloride rigid sheet cover. Results show reduction in productivity because of the pipe's geometry which obstructed the way of some droplets. In further research effort, Ahsan et al. [43] developed his new design by using GI wire that is spirally coiled on a two GI pipes. Although the developed design had no impact on productivity it significantly simplified the design and lowered cost. TSS could be also designed as a multi-effect tubular solar still; the most important advantage of a multi-effect TSS is that it allows for a multiple reuse of the latent heat and increases the condensation area. Zheng et al. [44] performed an experiment to compare single, double and triple-effect TSSs. The performance ratio (PR) of the three experiments were 0.75, 1.4 and 1.7 respectively. Recently Xie et al. [45] proposed a five-effect modular MED system (86 L/day capacity) composed of arrayed TSS on a matrix. Results showed more than 70% energy utilization efficiency, Chang et al. [46] analyzed the performance of a triple-effect vertical concentric tubular solar still. Arunkumar et al. [47,48] tested the potential of cooling the TSS surface by air and water. Results show an increase in water productivity by 49% for air cooling and 144% for water cooling compared to non-cooled TSS under the climatic conditions of Coimbatore city, India.

The TSS geometry enables it to be integrated easily with the parabolic concentrator by placing it coaxially. Results of a research shows a yield increase of 54% when using a compound parabolic concentrator–tubular solar still (CPC-TSS) supported by PCM [49]. The integration of CPC-TSS with conventional solar stills was tested by Arunkumar et al. [50,51], with a single slope solar still using PCM [50] and with two types of solar still for comparison (Pyramid and single slop) [51]. Results show a significant efficiency increase for the active solar still especially for the pyramid type. Arunkumar et al. [52] introduced an experimental comparison study on different solar still types. The maximum yield was obtained by the CPC-assisted TSS. Several correlations, CFD and theoretical models for tubular solar stills were introduced and developed through many studies including [53–57].

This study presents an experimental investigation on parabolic concentrator equipped with a manually controlled solar tracking system and integrated with tubular solar still (PCST-TSS). The productivity, efficiency and cost analysis are introduced and compared to other TSS results. PCST-TSS is expected to increase significantly the TSS yield introducing a simple and compact device suitable for easy use and maintenance in small communities in remote and isolated areas.

2. Experimental setup

Fig. 1 shows a test-rig pictorial view of the parabolic concentrator with solar tracking system (PCST) assembled with the tubular solar still (TSS) forming PCST-TSS.

Fig. 2 shows a schematic diagram of the TSS configuration consisting of a transparent tube, a co-axial aluminum trough manufactured as half-cylinder painted black on both the inside and outside surfaces and a distillation hole connected to a collecting bottle. Pyranometer ($\pm 1\%$) was used to measure the horizontal solar radiations, 3K-type thermocouples connected to thermometers ($\pm 0.2\%$) were used to measure the temperatures of the trough and 2-points on the inner tube surface to measure the inner transparent tube temperatures. Solar tracking was manually controlled by changing the angle of the concentrator every 1 h, the mechanism used for controlling the concentrator is shown in Fig. 1.

3. Theoretical analysis of TSS

Theoretical analysis of the tubular solar still (TSS) is performed under the following conditions:

- Absence of any vapor leakage from the TSS.
- Vapor at saline water surface is saturated.

3.1. Mass balance

According to Islam and Fukuhara [54]. evaporation and condensation mass fluxes, $\dot{m}_e$ and $\dot{m}_c$, (kg/m^{2}s) of TSS can be determined by Eqs. (1) and (2).

$$\dot{m}_e = h_e(\rho_{vw} - \rho_{vha}) \quad (1)$$

$$\dot{m}_c = h_c(\rho_{vha} - \rho_{vrr}) \quad (2)$$

where

$h_e = 0.00586 + 0.000065(T_w - T_{tt})$ and $h_c = 0.00155 + 0.0000197(T_w - T_{tt})$where h_e and h_c [56] are the evaporation and condensation mass transfer coefficients (m/s) between water and TSS transparent tube surface respectively and T_w and T_{tt} are the temperatures of the water and TSS transparent tube surface respectively.

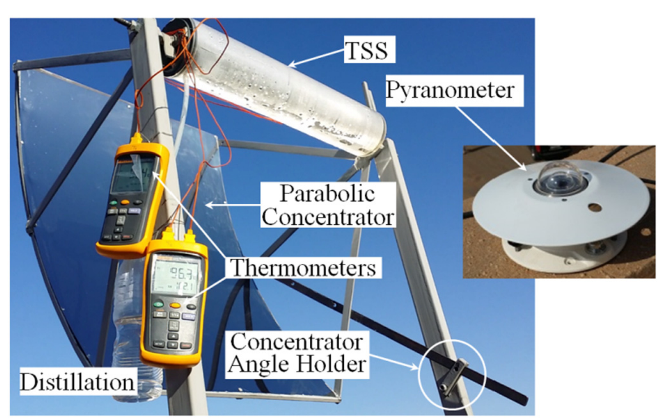

Fig. 1. Photograph of the PCST-TSS test rig.