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Year-round outdoor experiments on a multi-stage active solar still with different numbers of solar collectors

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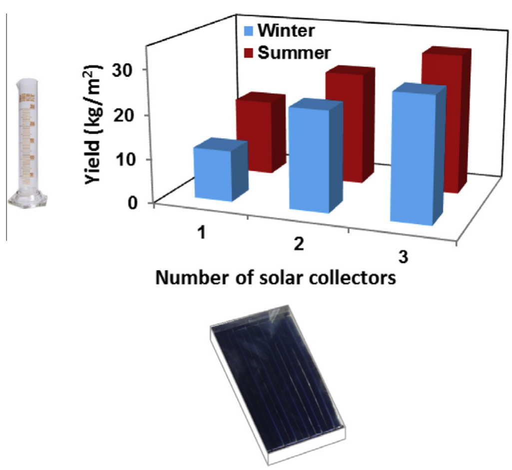
HIGHLIGHTS

- The researches on basin type multi-stage active solar still were reviewed.
- The outdoor performance of a multi-stage solar still was investigated.
- Some experiments were performed on the still in winter and summer.
- The effect of collector over basin area ratio was studied.
- Water production was measured every hour during the whole 24-h experiment.

GRAPHICAL ABSTRACT



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ABSTRACT

The present work investigated the outdoor performance of a basin type multi-stage solar still as well as the effect of collector over basin area (CBA) ratio on the distillate production. The effect of CBA was studied in outdoor experiments for the first time. The system consisted of a still coupled with one, two or three flat-plate solar collectors. In order to study the effect of CBA more accurately, the experiments were conducted in both winter and summer. In these experiments, the distilled water production of the multi-stage still was measured during the whole 24 h of a day on an hourly basis. The results revealed that in the winter, the basin coupled to one solar collector (CBA = 3.45) produced 11.56 kg of distillate. Adding a second collector (CBA = 6.90) to the system increased the production by 96%, whereas adding a third one (CBA = 10.35) increased it by only 23%. However, in the summer, 48% and 23% more productivity were obtained by adding the second and third collector, respectively.

1. Introduction

Water and energy are two inseparable commodities which continue to influence the growth of the human civilization. Energy is

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Nomenclature

A_{si}	area of the *i*th stage (m^2)
C_p	specific heat capacity (J kg^{-1} K^{-1})
h_{sci}	convective heat transfer coefficient in the *i*th stage (W m^{-2} °C)
h_{fgi}	latent heat of vaporization of water in the *i*th stage (J kg^{-1})
h^*_{fgi}	the refined value of Latent heat of vaporization of water in the *i*th stage (J kg^{-1})
$\dot{m}_{ei}$	evaporation rate of water in the *i*th stage (kg s^{-1})
M_{si}	mass of water in the *i*th stage (kg)
P_{Ci}	vapor pressure at the condensing surface in the *i*th stage (Pa)
P_{si}	vapor pressure at the surface of water in the *i*th stage (Pa)
$\dot{Q}_{eff}$	rate of effective energy input from the collector (J s^{-1})
t	time (s)
T_{ci}	condensing temperature in the *i*th stage (°C)
T_{si}	water temperature in the *i*th stage (°C)

required to supply quality water, and water is beneficial to produce energy in its useful form [1]. A sustainable alternative for the desalination process seems to be the solar energy. Therefore, solar stills can be used as one of the most suitable solar desalination units for low-capacity, low-cost, simple-to-operate and self-reliant water supply systems [2].

Various types of solar stills including single basin passive [3–5], single basin active [2,6–8], multi-basin passive [9], multi-basin active [10], tubular [11] and inverted absorber [12] were constructed and studied to date. Moreover, valuable reviews on solar stills can be found in the literature [13–15]. Taking advantage of most of these devices is difficult in practice due to technical problems, economic infeasibility or insignificant yield improvement. It seems that utilizing the latent heat from the condensed vapor and the evacuation of chamber play key roles in solar desalination devices in practice, as it can be seen in common industrial desalination processes such as Multi-Effect Distillation, Multi-Stage Flash and Vapor-Compression. Recovery of the condensed vapor's latent heat is the idea behind constructing multi-stage solar stills. Numerous researchers have dealt with the performance of multi-stage solar stills. Rajaseenivasan et al. [16] performed a review on different methods of enhancing the production of multi-stage solar stills. On the other hand, basin solar stills are the most frequently used devices [17]. Therefore, multi-stage basin solar stills seem to be appropriate to utilize the latent heat from condensed vapor. On the other hand, multi-stage solar stills coupled with solar collectors can be a reliable system in practice [18]. As a result, active multi-stage basin solar stills are proposed as a challenging solution [18]. A comprehensive review of the researches on basin type multi-stage active solar stills was done in this work and it was found that most of them have been performed theoretically.

Fernandez and Chargoy [18] examined the annual performance of a multi-stage indirectly-heated solar still. The still consisted of a chamber with 7 stages utilizing 32 flat plate collectors. The experiments were performed outdoors and the supplied energy was directed to the desalination chamber after the temperature of the heat storage reached its peak. As a result, the data was gathered and reported from 17:00 to 21:00 during the day. At the end, they concluded that the operation of multi-stage desalination of seawater is reliable and with a very simple manner of the ensuing apparatus. However, further effort must be made to determine a more successful sizing of the distillation unit in terms of collector area. The present article deals with this suggestion which has not been investigated to date.

Abu-Jabal et al. [19] experimentally examined a specifically-designed three-stage solar powered desalination system. The experiments were performed outdoors utilizing evacuated solar collectors. They reported that every square meter of this system had the maximum distillate production of 13 kg in July and August and the minimum distillate production of 3.5 kg in November.

Mahkamov and Akhatov [20] performed indoor experiments on a multi-stage solar thermal water desalination system. Their chamber consisted of 4 stages and vacuum tube solar collectors were employed to collect the radiation which was simulated by 110 halogen lamps. They concluded that by utilizing 2 m^2 of collector, their system can produce 8.4 kg of distillate.

Ahmed et al. [21] examined a three-stage evacuated solar distillation device both experimentally and theoretically. In outdoor experiments, they concluded that distillate production can increase significantly by evacuating stages. In a CFD analysis, they observed that decreasing the height of stages considerably enhances system production.

Shatat and Mahkamov [22] investigated a multi-stage solar water desalination still using transient mathematical modeling. They also conducted experiments on a 4-stage still that utilized a 1.7 m^2 heat pipe evacuated solar collector. The experiments were performed indoors and the solar radiation of a summer day was simulated by halogen lamps. The efficiency of the collector and also the overall efficiency of the system were calculated as 68% and 33%, respectively. Moreover, their system produced 9 kg of freshwater per day. Furthermore, their mathematical investigation indicated that a system with 4 or 5 stages is economically viable.

Xiong et al. [23] investigated a three-stage thermo siphon solar still both theoretically and experimentally. The third stage of the basin received direct solar energy. Moreover, the first stage utilized a 3 m^2 vacuum tube thermosiphon solar collector. The total production by all stages was reported up to 43.4 kg with a collector area of 3 m^2 and glass cover area of 1.28 m^2.

Indoor experiment benefits the advantage of the ability to control environmental parameters. However, this simulation is not reliable enough to be compared to real-life conditions. On the other hand, to the best of author's knowledge, none of the previous outdoor experiments have demonstrated the performance of a basic multi-stage active solar still. Fernandez and Chargoy's system [18] utilized heat storage and the energy input was impulsive; the design by Abu-Jabal et al. [19] was specific and completely different; the basin chamber by Ahmed et al. [21] was evacuated; and Xiong et al. [23] investigated a system with a thermosiphon collector and also employed a specific condenser. Therefore, one of the main objectives of this research is to investigate the outdoor performance of a basic active multi-stage solar still.

Previous research has illustrated that the distillate production of single-stage basin solar stills with high-depth brackish water is higher at nighttime [24]. The reason is the high heat capacity of these systems. Furthermore, since multi-stage solar stills contain a high amount of brackish water, they produce a significant amount of distillate at nighttime. Xiong [22] reported that 40% of the three stage basin's freshwater yield was produced at nighttime. Thus, in order to investigate the performance of multi-stage solar stills more accurately, it is essential to measure the distillate