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Effects of amount and mode of input energy on the performance of a multi-stage solar still: An experimental study

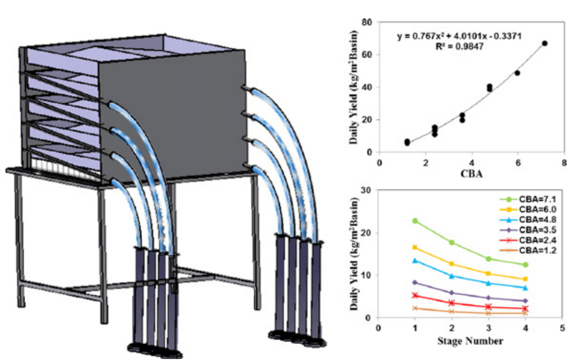
Mehrzad Feilizadeh [a], M.R. Karimi Estahbanati [a], Ahmad Seddigh Ardekani [b], S. Mohammad Esmaeil Zakeri [c], Khosrow Jafarpur [d,*]

[a] *Department of Chemical and Petroleum Engineering, Sharif University of Technology, Tehran, Iran*
[b] *Department of Chemical Engineering, School of Chemical and Petroleum Engineering, Shiraz University, Shiraz, Iran*
[c] *Department of Engineering, University of Kashan, Kashan, Iran*
[d] *School of Mechanical Engineering, Shiraz University, Shiraz, Iran*

HIGHLIGHTS

- Indoor experiments were performed on two multi-stage active solar stills.
- Effects of the amount and mode of energy input were studied.
- Distillate production was a quadratic function of collector over basin area ratio.
- Impulsive energy input mode increased distillate production by only 5–10%.

GRAPHICAL ABSTRACT



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ABSTRACT

Effects of the amount and mode of input energy to an active multi-stage solar still were investigated in this work. To control the input energy, an electrical heater controlled by a PLC was utilized to simulate the energy absorbed by solar collectors. The study of the amount of input energy indicated that the freshwater production was a quadratic function of the collector over basin area (CBA) ratio. It was also found that stages 1 to 4 produced about 36%, 26%, 20% and 18% of the overall yield, respectively. Moreover, the effect of employing a thermal energy storage (TES) on the system performance was studied by comparing the mode of feeding energy according to the daily solar radiation pattern with the impulsive pattern (feed all of the energy at the beginning of the experiment). The current results showed that using TES increased the still's production by merely 5–10%. Thus, TES is suggested to be employed only if the CBA ratio is high and the system is not capable of operating at high temperatures.

* Corresponding author.
E-mail address: kjafarme@shirazu.ac.ir (K. Jafarpur).

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1. Introduction

Solar stills can be classified into passive and active as well as single and multi-stage categories based on different applications. Passive systems [1–4] are those which receive no energy form non-solar energy sources while active systems [5–9] receive some energy from an external source in addition to the common solar energy to raise the temperature and consequently the evaporation rate of undistilled water. This external energy can be supplied by solar collectors [10–13] or the thermal energy wasted in industrial units [14]. Conventional single stage solar stills [15–17] utilize the system's energy input only once. However, multi-stage systems [18–22] are specifically designed to use the heat of condensation of the vapor again, so that this energy can be used for evaporation a couple of times.

A review on previous studies on different basin-type multi-stage active solar stills is presented on Table 1. As it is obvious, although most of research was performed theoretically, experimental investigations were also done recently. However, it can be seen that earlier researchers did not measure the amount of distilled water hourly during whole experiment.

Both of indoor and outdoor approaches were followed in the past research (see Table 1). The indoor experiments have the advantage of precisely controlled environmental variables and prevent the effect of unpredictable incidents such as wind speed variation or cloudy weather on the results. However, exact simulation of solar radiation as the input energy is not simple. In order to examine the performance of a 4-stage solar still, Mahkamov and Akhatov [23] used a solar simulator with hydrogen lamps to simulate solar radiation in a laboratory environment. They employed a transformer to produce variable radiation according to solar irradiances. Shatat and Mahkamov [24] utilized a similar system for the simulation of solar radiation. Additionally, Kalbasi and Nasr Esfahani [25] used an electric heater for indoor experiments using constant heat flux.

In active solar stills which work with solar collectors, the number of collectors connected to the evaporation chamber can be optimized before fabrication. By increasing the number of solar collectors, the absorbed energy and consequently, the temperature of the brackish water increases, which results in the enhanced freshwater production [47]. On the other hand, heat loss rises with increased system temperature. Thus, the amount of input energy is one of the important parameters for the investigation of active solar stills. In a series of experiments on a double stage device, Kalbasi and Nasr Esfahani [25] maintained the input energy constant at 200, 500 and 800 W/m^2 and reported the water production at 6.85, 23.4 and 39.9 kg/m^2, respectively. Based on their results, as the input energy increased from 200 W/m^2 to 500 W/m^2 (150% increase) and 500 W/m^2 to 800 W/m^2 (60% increase), the production improved by about 240% and 70%, respectively. Jubran et al. [40] numerically investigated the effect of input energy variation on the water production of a triple-stage solar still with an evaporation area of 6.5 m^2. They predicted that water production (Kg) increases linearly with the slope of 0.0044 (Kg/W) according to heat input (W). To authors' knowledge, there is no publication on indoor investigation of the amount of energy input to multi-stage solar stills performance based on a realistic daily solar energy pattern. To fill this gap, the examination of effects of the amount of energy input is one of the objectives of the present research.

The daily solar radiation pattern is one of the most influential environmental parameters [7] which affects the stills' performance and yield. Fernandez and Chargoy [30] coupled a thermal energy storage (TES) to an active 4-stage solar still to change the energy input mode of the basin. In their device, the energy absorbed by the solar collector was stored in a TES and after the temperature of TES reached its maximum, the energy was fed to the evaporation chamber. It means that they used a TES to change the mode of the energy input from the solar energy pattern to the impulsive pattern (feeding all of the energy in the beginning of the experiment). Thereby, the comparison between

Table 1
Comparison between different researches on basin-type multi-stage active solar stills.

Authors	Year	No. of stages	Experimental/theoretical	Indoor/outdoor	Distillate production measurement period (hr.)	Source of energy	Specific characteristics
Tiwari [26]	1985	2	Theor.	–	–	–	–
Gupta et al. [27]	1988	2	Theor.	–	–	–	–
Yadav [28]	1989	2	Theor.	–	–	–	–
Yadav & Jha [29]	1989	2	Theor.	–	–	–	–
Fernandez & Chargoy [30]	1990	7	Exp. & theor.	Outdoor	17:00–21:00	Flat plate liquid collectors	With heat storage
Tiwari & Lawrence [31]	1992	2	Theor.	–	–	–	–
Adhikari, & Kumr [32]	1993	3	Theor.	–	–	–	–
Al Baharna et al. [33]	1993	3	Theor.	–	–	–	–
Adhikari et. al. [34]	1995	n	Exp. & theor.	Indoor	NA	Electric heater	–
Kumar & Tiwari [35]	1996	2	Exp.	–	–	–	–
Bhagwan & Tiwari [36]	1996	2	Theor.	–	–	–	–
Nishikawa et. Al [37]	1998	3	Exp.	Outdoor	NA	Evacuated collector	A specific design
Kumar & Tiwari [38]	1999	2	Theor.	–	–	–	–
Adhikari et al. [39]	2000	4	Theor.	–	–	–	–
Jubran et al. [40]	2000	3	Theor.	–	–	–	–
Schwarzer et al. [41]	2001	6	Theor.	–	–	–	–
Abu-Jabal et al. [42]	2001	3	Exp.	Outdoor	NA	Evacuated collector	An specific design
Avezov & Akhatov [43]	2007	4	Exp. & theor.	NA	NA	NA	Unknown system and method
Mahkamov & Akhatov [23]	2008	4	Exp.	Indoor	8:30–17:30	Heat pipe evacuated tube collector	Solar simulation by halogen lamps
Schwarzer et al. [44]	2009	5–7	Exp. & theor.	Outdoor	NA	Flat plate and evacuated tube collectors	The first stage does not produce distilled water
Ahmed et al. [45]	2009	3	Exp. & theor.	Outdoor	NA	NA	Evacuated basin chamber
Shatat & Mahkamov [24]	2010	4	Exp. & theor.	Indoor	8:00–20:00	Heat pipe evacuated tube collector	Solar simulation by halogen lamps
Kalbasi & Nasr Esfahani [25]	2010	2	Exp.	Indoor	10:00–2:00	Electric heater	Constant energy input
Reddy et al. [20]	2012	N	Theor.				Evacuated basin chamber
Xiong et al. [46]	2013	3	Exp. & theor.	Outdoor	8:00–19:00	Vacuum tube collector	Thermosiphon-utilizes an specific condenser
Karimi Estahbanati et al. [21]	2015	4	Exp.	Indoor	24 h	Electric heater	Number of collectors effect