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Technical Note

Enhancement of cascade solar still productivity with sloping absorber plate

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Abstract: A step-type solar still with a sloping absorber plate was developed. The productivity index was investigated experimentally in two types of solar still, namely the modified and the ordinary stills, under identical operating conditions. A mathematical model was developed to calculate the theoretical amount of solar radiation emitted to the absorber plate in the ordinary and modified solar stills. An evaluation of the theoretical model showed that the amount of absorbed solar radiation in the new design of absorber plate was 36% higher than that in the ordinary still on a sunny day. The daily efficiency of 42.3% was calculated for the ordinary still with a total productivity of 4.46 kg/m^2.day, while the total productivity of the modified still reached 5.19 kg/m^2.day, corresponding to an efficiency of 49.2% on a sunny day. The results also demonstrated a 16% productivity increase with the modified cascade solar still on a sunny day, while there was no significant difference in productivity between the two evaluated stills on a cold day.

Keywords: sloping absorber plate, cascade solar still, step-type solar still

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INTRODUCTION

The lack of access to adequate, safe and clean drinking water in many areas of the world is a longstanding problem. Supplying the required amount of potable water has already been a problem in many developing countries. Water scarcity problem is generally observed in warm and arid middle-eastern and northern African countries, which causes socioeconomic problems. In contrast, abundant solar energy is available, along with large amounts of sea or underground saline water in these regions. Therefore, it should be economically possible to produce fresh water from sea or underground saline water using solar energy (i.e. solar desalination). The increased fresh water demand can then be partially solved by solar desalination technologies, which can meet a small-scale water demand and are easy to be integrated into a solar still [1].

Delyannis [2] presented a historic background of desalination and renewable energies. Various technologies are being utilised for desalination, such as multi-stage flash, multiple-effect, vapour compression, reverse osmosis, ion exchange, electrodialysis and solvent extraction [3]. However, these technologies are costly, especially when a large amount of fresh water production is not desirable. Besides, using conventional energy sources (hydrocarbon fuels) to drive these systems has harmful environmental impacts. A solar still of a desalination plant is considered to have the lowest thermal efficiency and productivity among the other techniques. However, this could be improved by various passive and active methods.

In order to improve the performance of solar collectors and conventional solar stills, several designs have been developed. For example, Khodadadi et al. [4] conducted an experimental study on water inlet and outlet positions in a solar collector reservoir. In this study they obtained the best location for maximum temperature range. Gorji et al. [5] and Ghsemi et al. [6] presented mathematical models of solar air heaters. They used analytical methods to obtain the solar collector's efficiency. Al-Karaghouli and Alnaser [7] conducted an experimental study on two solar stills (single and double basins). El-Sebaii [8] developed a transient mathematical model for the multi-basin type. In some other studies Minasian and Al-Karaghouli [9] designed a wick-basin type in order to increase the productivity, and Shukla and Sorayan [10] developed a computer model for single- and double-slope multi-wick solar stills. Mathioulakis and Belessiotis [11] have investigated an integration of the solar still in a multi-source and multi-use environment. Effects of several parameters on the annual performance of an active solar still have been studied [12]. Moreover, effects of the heat exchanger length, mass flow rate of fluid in the heat exchanger loop and water depth in the basin on the performance of an active solar still have been examined [13]. The influence of using black rubber and black gravel for augmenting productivity of the solar still has been studied [13–15].

The design of the cascade solar still is the result of an attempt to tilt the water tray towards the transparent cover without loss of distillation. The cascade still is a basin-type still offering a better orientation of water with respect to the transparent cover and a minimum air gap between them [16]. This results in a better performance, as has been reported by many authors. The cascade still has many designs. The first design, suggested by Achilov et al. [17], has a basin divided by transverse sections and provides a superior output in comparison with the ordinary types. Headly and Sweeny [18] built and tested two cascade stills inclined at 3.5° and 10°. Monem and Bassuoni [16] presented the design, analysis and performance of ordinary and newly modified cascade solar stills. Tabrizi et al. [19] investigated two cascade solar stills, which had been constructed with and without a latent-heat thermal-energy storage system. Kabeel et al. [20] designed a step-type basin to improve the performance of the solar still. They carried out an experimental and theoretical investigation, and studied the influence of depth and width of trays on the performance of the step-type solar still. Montazeri et al. [21] designed a type of absorber plate and investigated its effect on the productivity theoretically and experimentally.

In this study two cascade solar stills, one with a newly modified structure and the other with an ordinary structure, were designed based on the optimum inclination (35.67° N lat.) for Tehran, Iran. The thermal performance and productivity of the stills were evaluated and theoretical analyses were made by solving energy balance equations. The aim of the present paper is to conduct experimental work for the two types of solar still under the Iranian climate. The new solar still with a different absorber plate design is proposed to improve productivity. Furthermore, in order to demonstrate the effect of absorber plate shape on the productivity, the two solar stills are experimentally compared.

MATERIALS AND METHODS

Experimental Procedures

Experimental tests were carried out during July 2011 at Tarbiat Modares University, Tehran (35.67° N lat. and 51.42° E long.), Iran. Schematic diagrams of the ordinary and modified cascade stills are shown in Figures 1 and 2 respectively. Aluminum sheet was used for constructing the absorber plate in both types of cascade solar still because of its high thermal conductance coefficient, better resistance to corrosion in low and medium temperatures, low weight and easy formation.

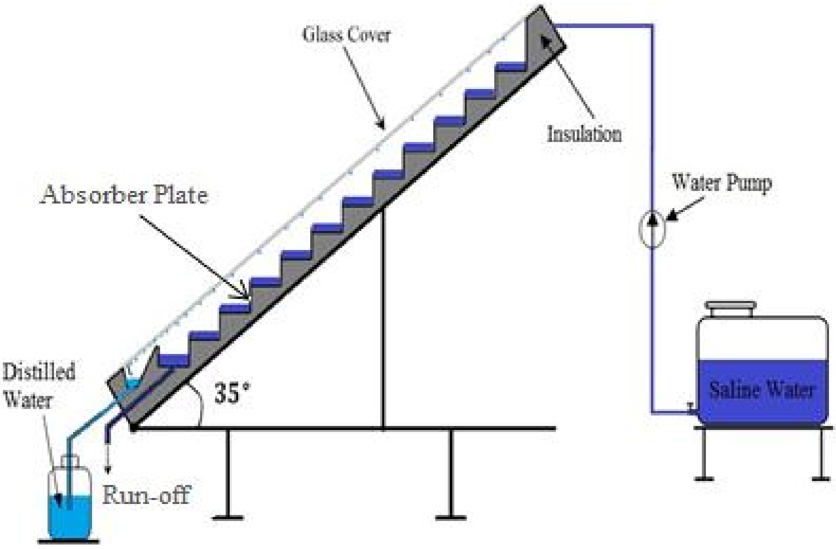
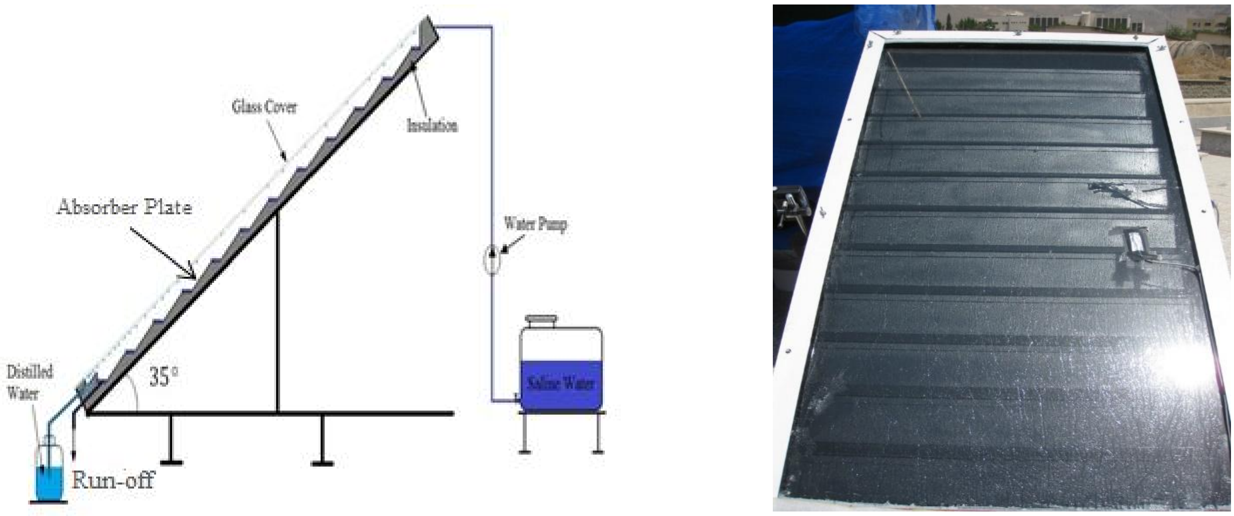


Figure1. Cross-sectional view of ordinary cascade solar still



(A) **(B)**

Figure 2. (A) Cross-sectional view of modified cascade solar still; (B) Photograph of modified cascade solar still

The ordinary still, a vertical cascade solar still (VCSS), consisted of the step-type absorber plate with 12 steps of 70-cm width and horizontal and vertical surfaces with widths of 5 and 3.5 cm respectively. The areas of the absorber plate and evaporation surface were about 0.69 and 0.42 m^2 respectively (Figure. 1). The modified still, a sloping cascade solar still (SCSS), had horizontal and sloping surfaces with an angle of 135° between the two surfaces, The SCSS consisted of step-type absorber plate with 12 steps of 70-cm width and horizontal and sloping surfaces of 3 and 10 cm in width respectively. Thus, the absorbing and evaporation areas were equal to 1.02 and 0.25 m^2 respectively (Figure 2).

In both the cascade solar stills, the absorber plate was placed inside a galvanised iron steel box and covered with 4-mm inclined transparent glass on the top. The whole experimental set-up was aligned in the north-south direction and the top glass cover was inclined at an angle of 35° facing the south-latitude of Tehran. All the experiments were carried out between 8 a.m. - 7 p.m. local time with a water flow rate of 0.2 kg/min. The solar intensity was measured using a solar power meter (TES-1333R, TES Electrical Electronic Corp., Taiwan) with an accuracy of $\pm 10\ \mathrm{W/m^2}$, which was placed parallel to the surface of the glass cover towards the upper side of the still. For measurement of temperatures of air, inlet and outlet water of the still, glass cover, vapour and absorber plate, digital temperature transmitters (TM-1201, TIKA Eng. Co., Iran) with an accuracy of ± 0.7°C were used. Finally, an electronic weighing device recorded the amount of distilled water hourly.

Thermal Analysis

In the following equations, T_w, T_g and T_a, all in terms of K, are the average basin water, glass cover and ambient temperatures respectively. The still receives solar radiation per unit area of $I\ (W/m^2)$. The following assumptions were used in the mathematical models: (1) there is no leakage of saturated air from the still; (2) the heat loss from the still sides are negligible; (3) the water layer is assumed to be stagnant and has constant thickness; and (4) the temperature of stagnant water layer is homogeneous on the absorber surface.

The performance of solar desalination system is governed by the following heat balance equations.

Glass cover

The equations of thermal energy balance of glass cover are given as:

$$I(t)\alpha_g + q_{ig} = q_{lg} \tag{1}$$

$$q_{ig} = q_{c,wg} + q_{e,wg} + q_{r,wg} \tag{2}$$

$$q_{lg} = q_{c,ga} + q_{r,ga} \quad , \tag{3}$$

where α_g is the coefficient of glass absorption, q_{lg} is the sum of heat loss from glass to surrounding (W/m^2) and q_{ig} is the input thermal energy from water surface to glass cover (W/m^2). The rest of the variables, $q_{c,wg}$, $q_{e,wg}$, $q_{r,wg}$, $q_{c,ga}$ and $q_{r,ga}$, are convective heat transfer rate, evaporative heat transfer, radiative heat transfer, heat loss by convection and heat loss by radiation, which are calculated by (4), (6), (8), (11) and (13) respectively.

Variable $q_{c,wg}$ is the convective heat transfer rate between the saline water and inner glass cover unit (W/m^2), and is calculated by the following formula:

$$q_{c,wg} = h_{c,wg} \times (T_w - T_g)\,, \tag{4}$$

where T_w and T_g are saline water and inner glass temperatures respectively and $h_{c,wg}$ is an important parameter in still modelling (*W/m^2.K*). The Dunkle's correlation for calculating the heat transfer from water surface to glass cover in conventional solar stills is given by the following expression, adopted from Tiwari and Tiwari [22]:

$$h_{c,wg} = 0.884 \times \left[(T_w - T_g) + \left(\frac{(P_w - P_g)(T_w)}{268.9 \times 10^3 - P_w}\right)\right]^{1/3}, \tag{5}$$

where P_w is the vapour pressure (*N/m^2*) of water at water surface temperature and P_g is the vapour pressure (*N/m^2*) of water at glass cover temperature. Variable $q_{e,wg}$ is the evaporative heat transfer between water and glass (*W/m^2*) and is calculated from the following equation:

$$q_{e,wg} = h_{e,wg} \times (T_w - T_g)\ , \tag{6}$$

the evaporative heat transfer coefficient $h_{e,wg}$ (*W/m^2.K*) being calculated by Tiwari [23]:

$$h_{e,wg} = 16.276 \times 10^{-3} \times h_{c,wg} \times (P_w - P_g)/(T_w - T_g)\ , \tag{7}$$

where P_w and P_g are the partial vapour pressures (*N/m^2*) at water and glass temperatures respectively. Variable $q_{r,wg}$ is the radiative heat transfer between water and glass (*W/m^2*), which is determined by Zurigat and Abu-Arabi [24]:

$$q_{r,wg} = h_{r,wg} \times (T_w - T_g)\ , \tag{8}$$

the radiative heat transfer coefficient between water and glass, $h_{r,wg}$ (*W/m^2.K*) being given as:

$$h_{r,wg} = \varepsilon_{ef} \times \sigma \times \left[(T_w)^2 + (T_g)^2\right] \times (T_w + T_g)\ , \tag{9}$$

where

$$\varepsilon_{ef} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1\right)^{-1} . \tag{10}$$

Variable $q_{c,ga}$ is the heat loss by convection between glass cover and surrounding (*W/m^2*), which are obtained as:

$$q_{c,ga} = h_{c,ga} \times \left(T_g - T_a\right)\ , \tag{11}$$

the heat transfer coefficient from glass cover to surrounding, $h_{c,ga}$ (*W/m^2.K*), being calculated from Zurigat and Abu-Arabi [24]:

$$h_{c,g-a} = 2.8 + 3 \times V\ , \tag{12}$$

where V (*m/s*) is the wind speed. Variable $q_{r,ga}$ is the heat loss by radiation between glass cover and surrounding (*W/m^2*), calculated by:

$$q_{r,ga} = \varepsilon_g \times \sigma \times \left({T_g}^4 - {T_{sky}}^4\right), \tag{13}$$

where ε_g is the glass emissivity and σ is Stefan Boltzmann constant, which equals 5.67×10^{-8} *W/m^{2}K^4*. The radiation to sky depends on the effective sky temperature, T_{sky} (*K*), which is calculated from Zurigat and Abu-Arabi [24]:

$$T_{sky} = T_a - 6\ . \tag{14}$$

Brackish water

The total amount of energy received by brackish water in the still (from sun and absorber plate) is equal to the sum of energy lost by: convective heat transfer between water and glass ($q_{c,wg}$), evaporative heat transfer between water and glass ($q_{e,wg}$), and radiative heat transfer between water and glass ($q_{r,wg}$), and energy gained by brackish water. The thermal energy of brackish water is calculated from equation (15).

$$I(t)(\alpha\tau)_w + q_{c,bw} = q_{c,wg} + q_{e,wg} + q_{r,wg} + \left(\left(mc_p\right)_w / A_w\right)\frac{dT_w}{dt} \;. \tag{15}$$

The first term of the above equation is the energy received by brackish water from the sun, and $q_{c,bw}$ is the heat transfer from the absorber plate to brackish water, which is obtained as follows:

$$q_{c,bw} = h_{c,bw} \times (T_b - T_w) \;, \tag{16}$$

where $h_{c,bw}$ is the convective heat transfer coefficient between the basin (absorber plate) and water, and is equal to 135 W/m^2K [24].

Absorber plate

The heat loss from basin base to ground ($q_{l,ba}$) can be calculated by:

$$q_{l,ba} = h_{l,ba} \times (T_b - T_a) \;, \tag{17}$$

where $h_{l,ba}$ ($W/m^2.K$) is the convective heat transfer coefficient of the basin base and is a function of thermal conductivity and thickness of insulating material, which can be calculated as follows:

$$h_{l,ba} = k_i / X_i \;, \tag{18}$$

where k_i and X_i are thermal conductivity ($W/m.K$) and thickness of insulating material (m) respectively.

Productivity and efficiency of solar still

The hourly productivity of the solar still, $\dot{m}_w$ (kg/hr), was calculated from the following relationship:

$$\dot{m}_w = \frac{\dot{Q}_{e,wg}}{h_{fg}} = 16.276 \times 10^{-3} \times h_{c,wg} \times A_b \times (P_w - P_g / h_{fg}) \;, \tag{19}$$

where h_{fg} is the latent heat of vaporisation of water ($J/\,kg$) and $\dot{Q}_{e,wg}$ is the evaporation heat transfer from water surface to glass cover (W). The overall thermal efficiency of the distillate output for a passive solar still can be written as equation (20):

$$\eta_{passive} = \frac{\sum \dot{m}_w h_{fg}}{A_b \int I_T \, dt} \times 100 \tag{20}$$

where dt is the time interval during determination of solar radiation intensity. The efficiency of the system is the ratio of the amount of distilled water obtained per day to the total solar energy received by absorber plate.

RESULTS AND DISCUSSION

Figures 3A and 3B show the hourly variation of solar radiation absorbed on the absorber plate for the VCSS and SCSS on July 15, 2012 and December 10, 2012 respectively. As can be seen, the absorbed solar intensity on July 15 in the SCSS was approximately 36% higher than that in the VCSS. However, on December 10, there was no significant difference in the absorbed solar intensity between the VCSS and SCSS. This is because the declination angle of the sun is higher in July than in December (Figure 4). Hence the sloping surfaces of the absorber plate in the SCSS has an effective role in trapping the solar radiation.

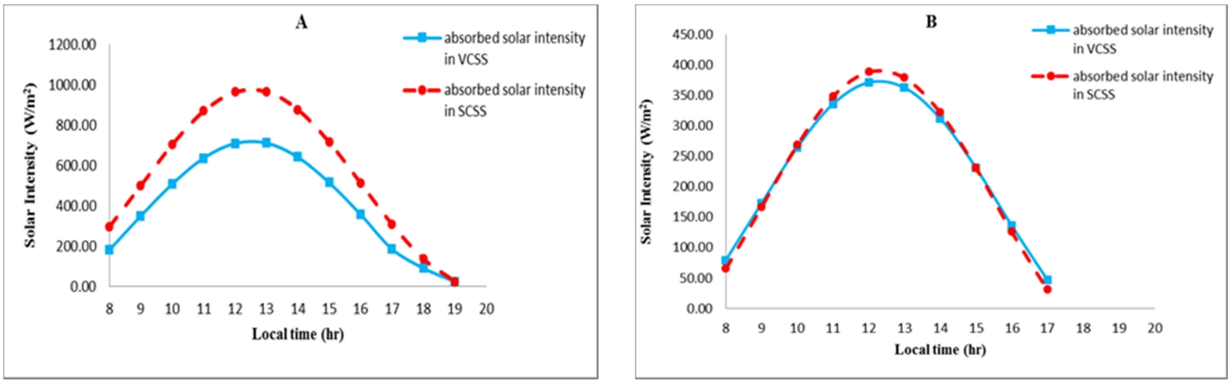


Figure 3. Variation of solar intensity with time for the cascade still in (A) summer and (B) winter

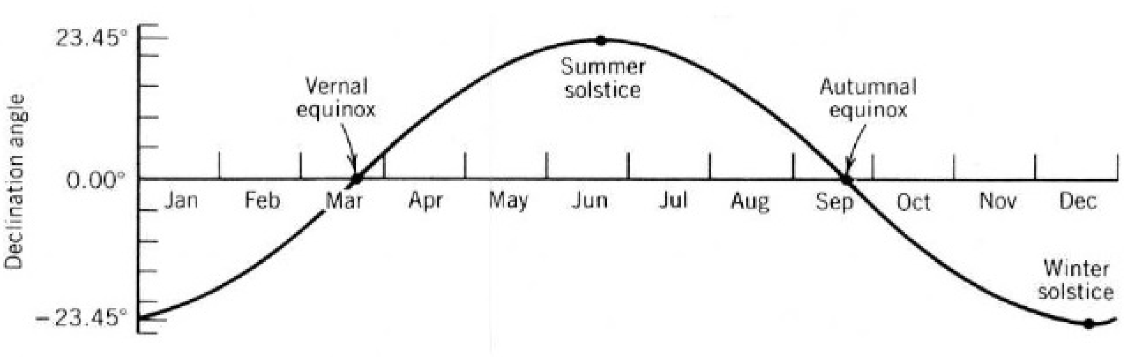


Figure 4. Variation of the declination angle of the sun [25]

Figures 5A and 5B show the temperature variation of the absorber plate in the two types of still for a selected day in July and December respectively. In Figure 5A the maximum temperatures of the absorber plate in July are approximately 77°C and 67°C for the SCSS and VCSS respectively and there is a significant difference between the SCSS and VCSS in terms of the absorber plate temperature. The same result was achieved by El-Agouz [27]. However, in December the maximum temperature values are about 31°C and 30°C for the SCSS and VCSS repectively (Figure 5B), and the difference in the absorber plate temperature between the SCSS and VCSS is insignificant.

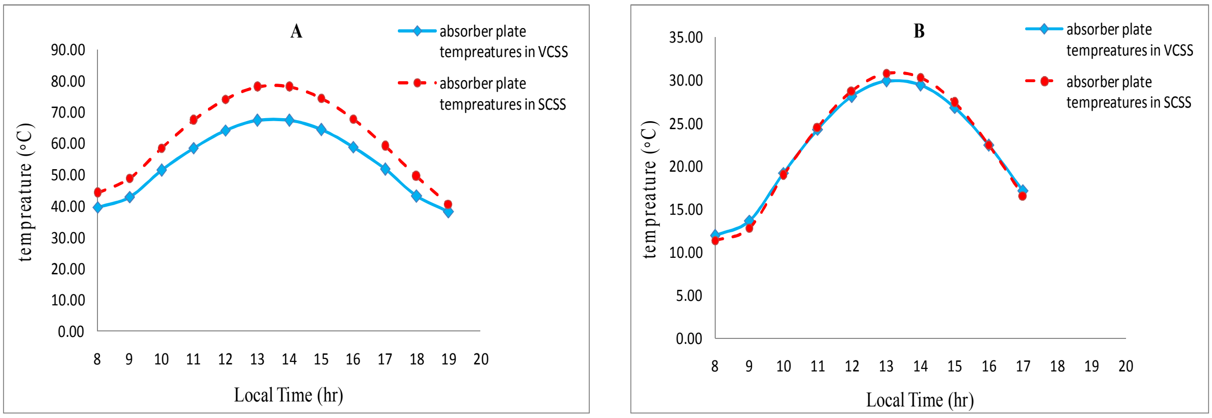


Figure 5. Variation of absorber plate temperature for the cascade still in (A) summer and (B) winter

Table 1 and Figure 6 show experimental results of the recorded variation of hourly productivity of the solar stills on July 15 and December 10 respectively. It was found that the total productivity of the VCSS reached 4.46 kg/m^2.day, on July 15, corresponding to an efficiency of 42.3%, while on the same day the total productivity of the SCSS reached 5.19 kg/m^2.day—an increase of 16%— corresponding to an efficiency of 49.2%. Monem and Bassuoni [16] reported the daily productivity and efficiency of an ordinary cascade solar still as 3.08 kg/m^2.day and 29.9% respectively for July, while Kabeel et al. [20] reported the daily productivity of a VCSS as 4.53 kg/m^2.day on July 20. However, no significant difference in the total productivity and efficiency was observed between the ordinary and modified cascade stills on the cold day (December 10, Figure 6B).

Table 1. Total productivity and efficiency of the cascade stills in summer and winter

Solar still	Winter		Summer	
	Efficiency (%)	Total productivity (kg/m^2.day)	Efficiency (%)	Total productivity (kg/m^2.day)
VCSS	13	0.74	42.3	4.46
SCSS	14.2	0.81	49.2	5.19

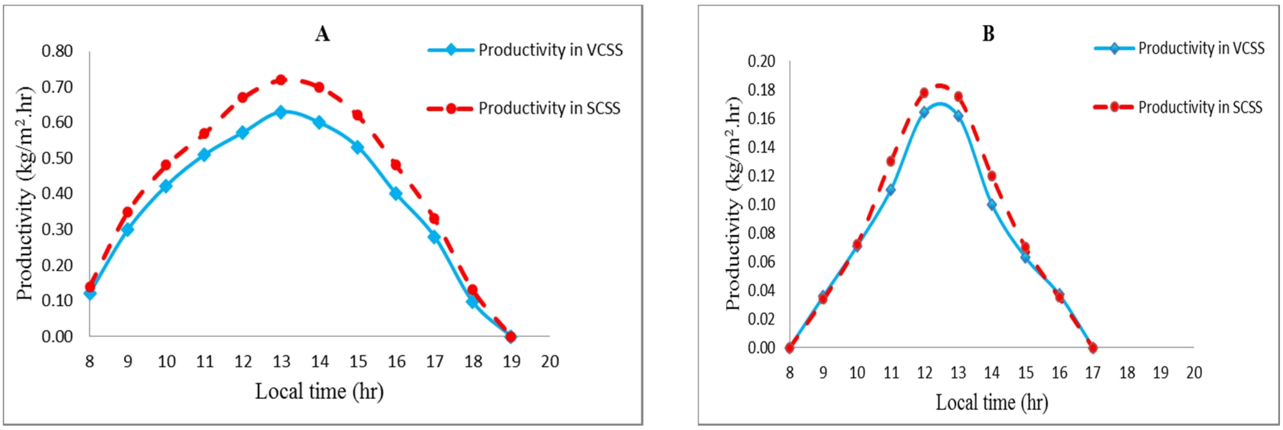


Figure 6. Variation of hourly productivity for the cascade stills in (A) summer and (B) winter

CONCLUSIONS

Compared with an ordinary type of cascade solar still, there is a significant improvement in the total productivity and efficiency of the cascade solar still with the proposed new sloping absorber plate design. However, this is the case only in the summertime.

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