



Experimental Analysis of a Vertical, Double-Effect Diffusion Solar Still

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Abstract: In this study, a vertical, double-effect diffusion solar still has been built and tested during a three-month time in summer. The device operates in a distillation cycle in two consecutive steps, in which the saline water evaporates within the wick applied on vertical surfaces. Compared with conventional desalination it has a higher efficiency and a simple geometrical structure. In the current research, a working prototype of this solar still has been designed, built and tested during the months of September, October and November 2015. The study aimed to evaluate the thermal efficiency of the system and the amount of fresh water produced by the solar still. It was found that the maximum amount of distilled water produced from the experimental double-effect vertical diffusion solar still is quite compatible with the overall daily productivity of similar type of work found in the literature. The results indicate that the developed solar still has a high efficiency with simple structure and is suitable for water production in developing countries.

Keywords: solar energy, desalination, multi-effect distillation, thermal efficiency, vertical diffusion solar still.

تحلیل تجربی عملکرد یک آب شیرین کن خورشیدی پخشی قائم دو اثره

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چکیده: در این تحقیق، یک سیستم آب شیرین کن خورشیدی قائم از نوع پخشی دو اثره ساخته و در مدت زمان سه ماه تابستان مورد آزمایش قرار گرفته است. دستگاه در یک سیکل تقطیر و در دو مرحله متوالی، که در آن آب شور در داخل پد اعمال شده در روی صفحات قائم تبخیر گردیده عمل می نماید. در مقایسه با سیستم های نمک زدای رایج، دستگاه ساخته شده دارای راندمان بالاتر و ساختار هندسی ساده تری می باشد. در تحقیق فعلی، یک دستگاه از این آب شیرین کن طراحی، ساخته و در ماه های سپتامبر، اکتبر و نوامبر ۲۰۱۵ مورد آزمایش قرار گرفت. هدف ارزیابی راندمان گرمایی سیستم و مقدار آب شیرین تولید شده توسط آب شیرین کن می باشد. مشخص گردید که مقدار بیشینه آب مقطر به دست آمده از دستگاه تجربی فوق با میزان محصول تولیدی متوسط روزانه توسط دستگاه مشابه انجام شده از سوی سایر پژوهشگران همساز می باشد. نتایج همچنین نشان می دهد که دستگاه ساخته شده دارای راندمان بالا و ساختاری ساده و مناسب جهت تولید آب شیرین در کشورهای در حال توسعه می باشد.

واژه های کلیدی: انرژی خورشیدی، نمک زدائی، نمک زدائی چند اثره، راندمان گرمایی، آب شیرین کن خورشیدی قائم پخشی.

1. Introduction

Given the importance of renewable energy in drinking water supply from non-potable water sources such as sea water, application of solar desalination systems seems to be quite attractive. Vertical multiple-effect diffusion solar still with a simple structure and high efficiency requires low maintenance and is a suitable choice for potable water production in dry regions that face water shortages. Much research work has been conducted in the case of vertical diffusion solar still, the most important of which belongs to Hiroshi Tanaka and Yasuhito Nakatake [1, 2]. They developed a solar still and tested it from July to November 2005 at Kurume, Japan, following the production of a geometrical model to describe the performance of the device. They obtained good agreement between their theoretical and experimental results. In fact, the results of their experiments showed seven percent error when compared with their theoretical daily fresh water production. This indicated that the absorption of direct, diffuse, and reflected solar radiation within the first effect of the solar still closely matched with the geometrical model calculations. It is notable that the still made by Tanaka and Nakatake actually was a single effect of a multi-effect vertical diffusion solar still, which had a glass plate instead of its last copper plate. This would enable to check the situation of the wick and the sediments accumulated in it.

Vertical multiple-effect diffusion solar still consists of three main parts: distillation part, flat plate reflector, and the tank of saline water supply. The distillation part contains of a series of vertical parallel plates or partitions, located at a small distance from each other and make up a desalination effect. The first effect includes a glass cover followed by a metal plate painted black with a selective coating to absorb the maximum solar energy. Solar radiation passes through the glass cover and is absorbed by the

black surface of the first effect. A wick, made of water-absorbent fabric with capillary effect, is attached to the rear surface of the metal plate, through which the saline water flows from the overhead tank. Vaporization takes place inside the wick in the first effect, which results in the water vapor condensation on the front surface of the vertical plate of the next effect. The latent heat released on this surface is used to evaporate the saline water within the wick of the second effect, while the condensate of the first effect is collected in the channels located at the bottom of the plates and directed into the fresh water tank. Impurities and salt from the saline water flow down the wick to the bottom of the solar still and is collected in the saline water tank. The efficiency of a multi-effect device depends on the number of effects included in the desalination process. In fact there is a temperature gradient between the first and the final effect of the solar still, where the remainder heat of condensation will be transferred to the environment.

Figure (1) shows a single effect vertical diffusion solar still. It has a flat plate reflector connected to the base of the solar still with an adjustable angle measured from the horizontal surface. The reflector is a glass mirror that reflects the maximum sunrays into the front surface of the glass cover. The absorber plate receives the direct and diffuse radiation plus the reflected sunrays from the mirror. In contrast to the conventional basin type solar still, which has absorber plate inclined to the latitude of the location, inclination of the absorber plate of a vertical diffusion solar still would result in the mixing of saline and distilled water, which should be avoided. Furthermore, it would produce a film of air between the plate surface and the wick that reduces the heat transfer and as a result reduces the efficiency of the device. An adjustment of the angle of the flat plate reflector made at the recommended amount

given in the literature, can compensate much of the radiation loss and give a favorite radiation on the front of the absorber plate [1,5, 9]. Another part of the vertical multiple-effect diffusion solar still is the saline water storage tank that is placed at the upper part of the device. Saline water flows from the tank by gravity into the feeding channels at the top of the solar still and through the tubes and regulating valves and finally through the wick by the capillary action. In order to put the still in line with the direct normal radiation of the sun it can be rotated around manually or by an automatic sun tracker. In this study, however, only manual operation has been used.

2. Description of the system

Figure (2) shows the double-effect vertical diffusion solar still designed and built in this study using the SOLID WORK software. The principal part of the system is the distillation units, which include the glass cover, aluminium absorber plate and the partitions, which are separated from each other by a 10 mm air gap. The dimensions of the plates are 500 x 500 mm, which is the useful surface area for the absorber plate and the partitions. Water vapour produced over the wick of the absorber plate diffuses within the thin layer of the moist air between the first and the second partition. This results in the vapour to condense over the front face of the second partition. In the case of a double effect diffusion solar still, latent heat of condensation in the first effect causes the brine to evaporate over the wick attached to the rear surface of the second partition. The evaporation and condensation processes would continue in a multi-effect diffusion system, which would increase the production rate of the distilled water and at the same time increase the efficiency of the devise.

To increase the efficiency of the system, a flat plate reflector is used, which is a glass mirror with the dimensions of 500 × 500 mm. It

is coupled to the device with some support and can be rotated and adjusted according to the season, in which the experiment is conducted. The angle of the mirror is the recommended amount suggested by Tanaka [1, 6]. To further increase the efficiency, the device can also be coupled with a vacuum-tube or heat pipe collector [7, 10].

To rotate the solar still around its vertical axis on the ground a rail system has been designed. By adding a servo motor, the system can be programmed for sun tracking, which would result in the still having a high efficiency. However, due to rather high expenses involved in employing an automatic sun-tracking system, the sun tracking operation in this study has only been performed manually in the experiments.

The other main part of the solar still is a saline storage tank located on a stand above the desalination unit, so that the saline can flow into the unit by gravity. Between the storage tank and the feed channels there are connecting tubes and regulating valves. These are used to adjust the flow of saline water entering the desalination unit. In the prototype built in this study, there are two feed channels with a single spare tube used in critical conditions to avoid halting of the flow. Figure 3 shows the basic design of a double-effect vertical diffusion solar still developed by the SOLIDWORK software.

Feasibility studies have been performed on the extension of the construction methods for the production of a solar still prototype similar to the one developed by Tanaka [1]. Further research has also been conducted on the possibility of improving the structure of the solar still for more efficient performance.

Due to the lack of adequate drafts and literature about how to build and design the solar still, reverse engineering process has been selected for the production of a prototype. The process is performed according to the article related to construction of a vertical diffusion

solar still by Tanaka [1]. A number of parameters including the amount of some areas have also been identified in the article. Other parameters based on design constraints and technical limitations have been considered, which indicates that the prototype developed is, to some extent, different from the Japanese one. The solar still is then installed at a suitable location according to the method of installation, and prepared for conducting the experiments.

3. Experimental Procedure

Before starting the experiments, it is important to test the device for a steady state operation in the absence of solar energy and ensure that there is a steady flow of saline water from the saline water storage tank through the channels and wicks and that the saline water is finally flown out of the device and collected inside the brine tank. At such a condition, vaporization and condensation do not occur and as a result no distilled water is collected at the exit and, therefore, validation of the still operation is guaranteed.

Following the validation and smooth operation of the system, the solar still was exposed to the sun and the experiments were conducted in the city of Qazvin, latitude of $36^{\circ} 15'$ during the months of September, October and November 2015. The time of experiments was the local time from sunrise to sunset. Orientation of the solar still, γ , was regularly selected as follows: 60° in the south-east at 7 a.m., 30° in the south-east at 10 a.m., 0° in the south at local noon, 30° in the south-west at 2 p.m. and 60° in the south-west at 5 p.m. These values of γ are approximately similar to the sun-track angles, which are different from Tanaka's experiment. Based on Tanaka's recommendation the angle of the flat plate reflector has been selected as 0° [1,2]. In each of the above cases the output of the still, which includes the temperature of the first and second vertical plates and the amount of distilled and

brine water at the exit of the still are measured and recorded.

4. Results of the Experiments

The still test results obtained on 23rd September and 6th October 2015 are as follows (see Figs. (4) and (5)).

Temperature of the absorber plate vs. time for the first and second effects are also measured and the results are given in Figs. (6) and (7).

It can be seen from these figures that the maximum amount of desalination, as well as the maximum temperature are approximately related to 8-10 a.m. and 2-4 p.m. The above amounts are shown in Table 1 for 23rd September and 6th October 2015, respectively.

The experiment conducted on the solar still on 30th of September 2015 indicates that compared with the above two experiments, the maximum amount of temperature and distilled water have, in fact, been obtained on this date, which are 81°C and $5.22 \text{ kg/m}^2\text{-day}$, respectively. These are shown in Figs. (8) and (9).

The maximum amount of distilled water produced from the experimental double-effect vertical diffusion solar still developed in this study can be compared with the overall daily productivity from the solar still investigated by Tanaka and Nakatake [4] in Fig. 10. As shown in the figure the amount of fresh water produced from the two effects is slightly more than $5 \text{ kg/m}^2\text{-day}$, which is compatible with the amount obtained in this study.

As can be seen from Figure 10 for the multiple-effect vertical diffusion solar still with 10 effects, the amount of fresh water produced per square meter per day is 25 to 35 kg. The daily distillate production obtained from the double-effect solar still in Qazvin has been quite consistent with the productivity shown in Figure 10. This indicates that the solar still

developed in this study has a high efficiency and a simple structure and suitable for potable water production in developing countries.

5. Conclusions

A vertical, double-effect diffusion solar still has been built and tested in this study. It was found that the maximum amount of distilled water produced from the solar still was 5.22 kg/m²-day, which is quite compatible with the overall daily productivity of similar type of work found in the literature. The daily distillate production obtained from the double-effect solar still in Qazvin has been quite consistent with a multiple-effect vertical diffusion solar still with 10 effects, which can produce 25 to 35 kg/m²-day of distilled water. The results indicate that the developed solar still has a high efficiency with simple structure and is suitable for water production in developing countries.

8. References

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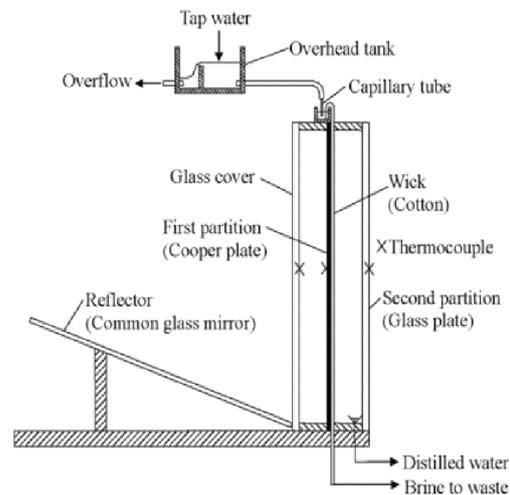


Fig. (1): Vertical single-effect diffusion solar still.



Fig. (2): Double-effect vertical diffusion solar still built in this study.

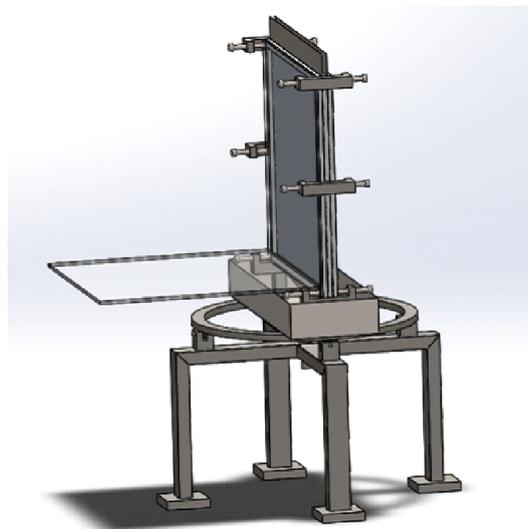


Fig. (3): SOLIDWORK modeling of the double-effect vertical diffusion solar still.

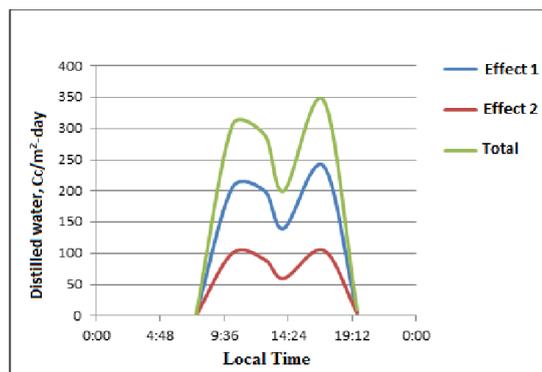


Fig. (4): Distilled water production vs. time on 23rd September 2015.

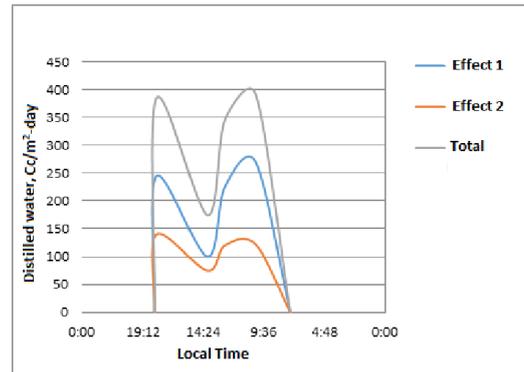


Fig. (5): Distilled water production vs. time on 6th October 2015.

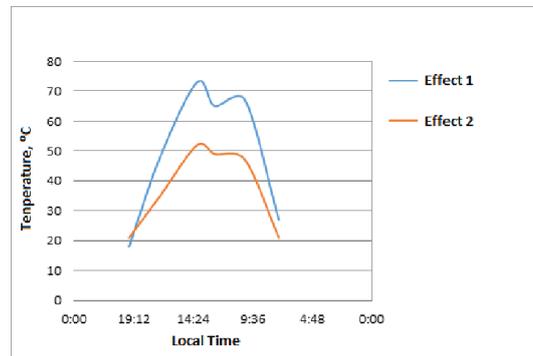


Fig. (6): Temperature of the absorber plate vs. time on 23rd September 2015.

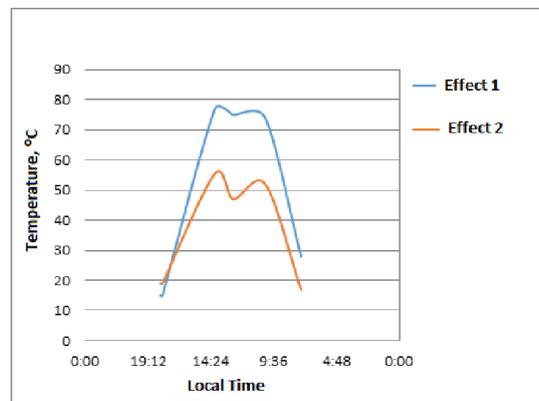


Fig. (7): Temperature of the absorber plate vs. time on 6th October 2015.

Table (1): Maximum amount of temperature and distilled water produced by the solar still on 23rd Sept. and 6th Oct. 2015.

Date of the experiment	Maximum temperature	Maximum amount of distilled water* CC/m ² day
23 rd September 2015	73° centigrade	4600
6 th October 2015	77° centigrade	5188

* The actual surface area of the absorber plate is 0.25 m², so the amount of distilled water obtained is one-fourth of these values

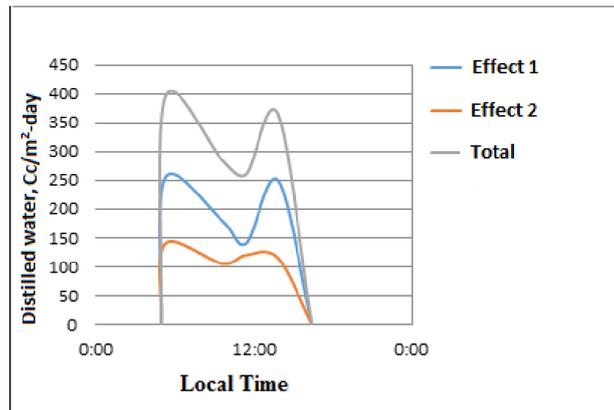


Fig. (8): Distilled water production vs. time on 30th Sept. 2015.

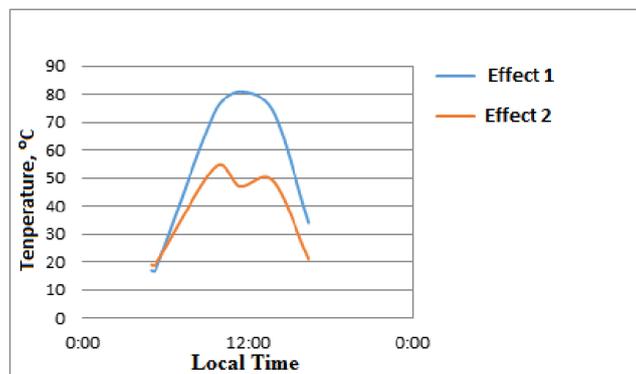


Fig. (9): Temperature of the absorber plate vs. time on 30th Sept. 2015.

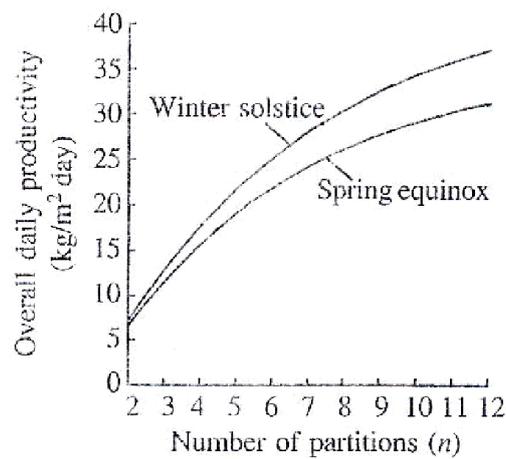


Fig. (10): Overall daily productivity vs. number of partitions (effects) with 10 mm air gap. (Tanaka and Nakatake 2005)