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Desalination of the brackish water using a passive solar still with a heat energy storage system

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HIGHLIGHTS

- Phase change materials (PCMs) are used to store the thermal energy.
- The choice of the PCM depends on the maximum water temperature.
- Energy storage allows the improvement of the solar still performance.

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ABSTRACT

Desalination of the brackish water using a passive solar still with a heat energy storage system put under the basin liner of the distillation device is dealt with the help of transient mathematical models. Phase change materials (PCMs) are used to store energy in the process of changing the aggregate state from solid to liquid. The energy balance equations for the various elements of the still as well as for the PCM are formulated and numerically solved. In meteorological conditions taken on 15th of June 2011 at the Errachidia city (Latitude: 31°58′N, Longitude: 4°20′W), Morocco, numerical calculations have been carried out for three kinds of PCMs which have different melting temperatures. To validate the simulation results, the brackish water temperature is compared with the analytical expression and the existing results in the literature. The obtained results show that the excess energy produced during sunshine times is stored in a PCM for use later during the night. Moreover, it is highlighted that the choice of the phase change material (PCM) depends closely on the maximum of the brackish water temperature that can reach by the brackish water in the basin.

1. Introduction

In 1872, the fundamental installation of a single basin solar still was built in Chile at Las Salinas in a desert area [1,2]. After that, several searchers around the world have participated to the improvement of solar stills [3–10] by acting on the factors affecting the performance of those solar stills.

In view of this, a lot of research works are undertaken to improve the productivity of the solar still and since the publications on this topic are very abundant in the literature, we content ourselves to quote here a few more recent anterior works. So, over the past years, a set of papers have been published by Tiwari and his different collaborators [7,11–15]. Generally, these various studies both theoretical and experimental have practically included some influencing parameters on the solar distillation such as: Climatic conditions, condensing cover material, solar still slope,…

In 2005, Tiwari et al. presented in reference [11] a regression analysis based on the experimental data obtained from rigorous indoor experimentation with a constant temperature bath over three different inclinations of a flat glass condensing cover. It has essentially been deduced that the values gotten at higher operating temperatures for the convective and evaporative heat transfer coefficients by Dunkle's [16] relation did not agree with the experimental results obtained by the authors. As for the article [15], it undertook a hybrid (PV-T) solar still which is a combination of solar still and flat plate collector (FPC) integrated with glass–glass photovoltaic module. In this last citation, the authors used two analytical methods to establish characteristic equation of hybrid (PV-T) active solar still based on annual experimental observations. The comparative performance of these two methods has also been estimated in terms of root mean square percentage (RMS) error.

According to this full literature review and despite all efforts in the field of research to improve the efficiency of solar stills, it is recognized

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that their productivity is much lower than other desalination thermal processes. This can be partially explained by the intermittent nature of solar energy because it is not available after sunset and during cloudy periods. The thermal energy storage appears to be a very promising technical solution to overcome the mismatches between energy supply and energy demand that are caused by irregularity variations of solar radiation energy. Indeed, to improve the productivity of solar stills, two thermal storage systems could be used: either sensible or latent heat system. Due to its capability of storing thermal energy and almost constant temperature for charging and discharging, the latent heat thermal energy storage (LHTES) technique has received significant attention [17]. Phase change materials (PCMs) are latent heat thermal storage materials which are used to store energy in the process of changing the aggregate state from solid to liquid. Nowadays, relatively few papers have used the phase change materials (PCMs) as storage media in solar stills [18–20]. Radhawan [18] examined the transient performance of a stepped solar still with built-in latent heat thermal energy storage. This solar still was intended for heating and humidification of agriculture greenhouses in remote areas. It is composed of five stepped basins with an inclined glass cover and is insulated on the bottom. The basin was placed on a slab filled with a layer of the phase change material (paraffin wax) which serves as a latent heat thermal energy storage system (LHTESS). The results were remarkable in comparison with the case of solar still without LHTESS. For a selected design and operational parameters, the still was able to provide heat an agriculture greenhouse for 24 h a day. In reference [19], El-Sebaii and his co-authors presented the transient mathematical models for a single slope-single basin solar still with and without phase change material (PCM) under the basin liner of the still. Analytical expressions for temperatures of the still elements and the PCM have been obtained. The still performance has been investigated by computer simulation. Numerical calculations have been carried out, using stearic acid as a PCM, on typical summer and winter days in Jeddah, Saudi Arabia. It is showed that during discharging of the PCM, the convective heat transfer coefficient from the basin liner to basin water is doubled; thus, the evaporative heat transfer coefficient is increased by 27% on using 3.3 cm of stearic acid beneath the basin liner. As for Dashtban and Tabrizi [20], they theoretically studied a weir-type cascade solar still, integrated with latent heat thermal energy storage system. It was designed with the view of enhancing productivity. In this research investigation, the paraffin wax was used as a heat storage system which keeps the operating temperature of the still high enough to produce distillated water during the lack of sunshine, particularly at night. On the other hand, the internal convective heat transfer coefficient calculated from the experimental data of the still without PCM was applied for the calculations since the common relation proposed by Dunkle [16] could not follow the still performance. Moreover, important parameters affecting the performance of the still, such as water level on the absorber plate and distance between water and glass surfaces, were theoretically investigated. The performance of the still with and without PCM was also studied on a typical day in Iranian Zahedan city.

The main aim of this paper is to highlight the effects of the heat energy storage on the desalination of the brackish water by using a passive solar still with an integrated phase change material (PCM) under the basin liner. Furthermore, it is also intended for designers in order to choose the right material of the heat storage to improve the performance of this distillation device. The energy balance equations for the various elements of the still as well as for the PCM are formulated and numerically solved. In meteorological conditions taken on 15th of June 2011 at the Errachidia city (Latitude: 31°58′N, Longitude: 4°20′ W), Morocco, numerical calculations have been carried out for three kinds of PCMs which have different melting temperatures. To validate the simulation results, the brackish water temperature is compared with the analytical expression and the existing results in the literature. Results such as: brackish water temperatures, PCM medium temperature, powers of charge and discharge, the daily productivity,… are respectively presented for the considered day and for two successive days.

2. System description

A schematic diagram of a passive solar still with built-in phase change material (PCM) is shown in Fig. 1. The system of one square meter of surface area, is consisted of several elements numbered and listed in the same figure. Thus, the basin (3) of this desalination device is fed by a brackish water reservoir (10) through a non-return valve (7) and this water is heated by solar radiations received by the solar still through the condensing glass cover (1). A large temperature difference between the brackish water surface and the inner glass cover surface causes an increase in water evaporation process, hence the water gets condensed at the inner surface of the glass cover and it is collected by the outlet (8) put at the base of the condensing cover of the solar still. A storage medium (5) with e_{PCM} thickness is incorporated under the absorber plate (4) and it is filled by a type of paraffin as a phase change material (PCM) that serves as a latent heat thermal energy storage system (LHTESS). The still is insulated to minimize any heat loss from the bottom and sides of the unit (6).

3. Mathematical and thermal analyses

To evaluate the temperature of the condensing glass cover, water, absorber plate and PCM medium, the energy balance equations are written under the following hypotheses:

- Heat losses from the sides of the solar still are negligible.
- Water layer has a constant thickness of water.
- Water layer is assumed to be stagnant and its temperature is supposed to be homogeneous on the absorber surface.
- Within the PCM, the thermal convection is negligible.
- The PCM is in perfect contact with the absorber.
- There is no temperature gradient through the thickness of the PCM and it has an average temperature during the melting and solidification processes.

It is necessary to point out that almost all the physical and geometrical quantities which appear in the thermal energy balance equations are listed in the nomenclature.

3.1. Thermal energy balance of the condensing glass cover

In the condensing glass cover the absorbed fraction of the incident heat faux density P_g is equally shared between the external and the internal faces. Thus, the thermal energy balance equations are as follows:

3.1.1. External face of the condensing glass cover

$$\frac{m_g Cp_g}{2A_g}\frac{dT_{e,g}}{dt} = Q_{cond/glass} - Q_{rad/glass/sky} - Q_{conv/glass/ambient} + \frac{P_g}{2} \quad (1)$$

where

- $Q_{cond/glass} = \frac{\lambda_g}{e_g}(T_{i,g} - T_{e,g})$ is the conductive heat flux density between internal and external glass surfaces;
- $Q_{rad/glass/sky} = h_{rad/glass/sky}\ (T_{e,g} - T_{sky})$ is the radiative heat flux density between the external glass and the sky. Its expression is given by formula (A.13a);
- $Q_{conv/glass/ambient} = h_{conv/glass/ambient}\ (T_{e,g} - T_a)$ is the convective heat flux density between the external glass and the ambient air;
- and P_g is the absorbed fraction of the incident heat flux density on the glass cover of the solar still.