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Modeling and analysis the productivity of solar desalination units with phase change materials

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ABSTRACT

Water scarcity in several parts of the world is a matter of concern for human beings. Solar stills are capable of producing fresh water during day hours and the production becomes zero after sunset. In this study detailed modeling of water desalination involving PCM that stores energy during day time and emits it during night time is theoretically investigated. The effect of various parameters such as the PCM type through its melting point, PCM quantity, feed-water flow rate, and solar irradiation on the productivity of the unit expressed as the amount of fresh water produced per day is theoretically investigated. The results showed that the presence of PCM with 40 °C melting point maintains higher water temperatures after sunset but negatively affects the productivity. Decreasing the feed flow rate from 10 L/hr to 1 L/hr improved the fresh water productivity by 49%. When the maximum solar intensity increased from 400 to 1000 W/m^2, the fresh water productivity increased from 0.75 L/day to 2.1 L/day. In the presence of PCM and at certain solar irradiation intensity the productivity can be improved by using PCM of higher melting point and reducing water feed flow rate.

1. Introduction

Industrialization and heavy use of vehicles by humans soon after the industrial revolution (in year 1750) have increased the concertation of atmospheric CO_2 from 280 ppm to 400 ppm in 2015 [1,2]. An estimation in the recent literature publications indicate that if rate of emission of greenhouse gases continues at the present rate, it may harm ecosystem, biodiversity, water availability and livelihood of living culture [3,4]. Thus it is necessary to increase social awareness towards savings of energy worldwide. The increased temperature has created new concepts of solar cookers [5], solar water heaters [6], solar lights [7], etc. in the recent past.

In many countries, often, water sources are either brackish or containing harmful bacteria. It cannot be used for drinking in its natural form especially on coastal areas where there is a scarcity of potable water. A portable solar desalination still has attracted the attention of various researchers in the recent past. Al-Kharabsheh, and Goswami [8] used passive vacuum method to innovate the solar desalination technique using a system consisting of an evaporator, a condenser, and injection, withdrawal and discharge pipes. In their study, the effect of heat source temperature was significant compared to the effects of withdrawal rate and the depth of water in the evaporator. Tiwari et al. [9] studied three different inclinations of a flat glass condensing cover and presented experimental data obtained from rigorous indoor experimentation with a constant temperature bath using detailed regression analysis approach.

Recently Elango and Murugavel [10] enhanced the productivity of the solar still by introducing single and double glass solar stills having same area of basin. Water depths were varied from 1 to 5 cm under both insulated and un-insulated conditions. The production rate was found to be improved even at lowest water flow rate. They concluded that though fabrication of the double basin increased the manufacturing cost, high yield of the distillate made it a better one during the cooling period.

Gude et al. [11] designed the low temperature desalination process to utilize solar energy harvested from flat plate solar collectors. They majorly focus on thermodynamic aspect of thermal energy storage (TES) including the entropy generation aspect. They concluded that by means of excess area of the solar system, collectors help the TES to store the additional energy which can be stored and supplied on a cloudy day or low solar insolation day.

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Arunkumar et al. [12] reported a concept of solar still water desalination unit with a hemispherical top cover. Two different cases were experimentally investigated for water desalination: with and without flowing water over the cover. They concluded that the efficiency was increased by 8%–42% with the top cover cooling effect. Santos et al. [13] used artificial neural network (ANN) modeling approach to model the solar still system using local weather data. The ANN model successfully predicted the performance of the solar still using several experimental data. The predicted data using ANN ranges between 31 and 78% within 10% of actual yield. El-Ghonemy [14] presented a review and comparative study on technology and economics aspects (including water sources, demand, availability of potable water and purification methods) of renewable energy sources based water desalination systems. Chen et al. [15] presented design and testing of four-stage distillation unit with triple-effect regeneration considering the mechanism of falling film evaporation condensation in China. Detailed review of specific studies on solar cell, active solar distillation, etc. focusing on productivity of solar cell units is also widely published [14,16–18]. Various country specific studies considering the advantage of solar system is also reported by various authors [15,19–24]. Several studies on solar desalination having advancement of various dependent parameters are reported in the literature [25–28]. In the developing oil and gas countries like Oman, lot of importance is given to solar energy to extract oil [29]. The use of phase change materials has also gained lot of popularity in the recent past due to its ability of retaining heat during the night hours [30].

Phase change materials (PCMs) also called latent heat storage materials are capable of storing the energy during process of heat transfer and phase change from solid to liquid. Various attempts were made to enhance solar desalination units using PCM [31–34]. Radhawan [32] examined the unsteady state response of a stepped solar still (five stepped basins with an inclined glass cover and insulated on bottom) with built-in PCM. Radhwan carried out this study considering the benefits of obtaining heat and moisture for greenhouse based agricultural products in remote areas. The PCM which serves as a latent heat thermal energy storage system (LHTESS) was placed as a slab in the basin. The results were remarkable in comparison with the case of solar still without LHTESS. IT was observed that for their studied design the desalination still was able to provide 24 h supply of heat and water in greenhouse based agricultural project. Another unsteady state modeling and simulation approach 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 under the basin liner [33]. They used stearic acid as PCM and used computer based simulation procedure to obtain a better insight of temperatures of the still elements and the PCM. The data was correlated using summer and winter day's temperature data in Jeddah, Saudi Arabia. It was observed that during phase change (liquid to solid) of 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% upon using 3.3 cm layer of stearic acid beneath the basin liner. Dashtban [34] used paraffin wax as PCM in their theoretical study of PCM based weir-type cascade solar still. It was expected to obtain an enhanced productivity by using PCM which helps in keeping the temperature of basin high enough to produce the distilled water without interruption especially after sunset.

In this study, water desalination and hot water production using solar still involving PCM is theoretically investigated. Numerical approach is presented to study the performance of desalination units -with and -without phase change materials. The effect of the PCM on the productivity expressed as amount of water produced is theoretically studied. The effect of various parameters such as the type of the PCM and hence its melting point, its quantity along other parameters such as water feed flow rate, solar irradiation is theoretically investigated. It is hoped to determine the optimum parameter that will result in the higher unit productivity.

2. Theoretical development

Consider a solar still as shown in Fig. 1 where a black plate receives solar energy at a rate of q_s W/m^2. Accordingly the plate gets heated and it transfers some of its heat to the water in the basin, M_w, above the plate and to the phase change material (PCM) placed beneath it. The PCM gets heated and melts when its temperature reaches its melting point, T_m, and when the melting process is complete its temperature continues to rise based on the length of the day and the solar radiation intensity. In this process the energy is stored in the PCM which is released back after sunsets. Most of the released energy is transferred to the water and some of it is lost based on how good the unit is insulated. Therefore the water in the basin gets heated during the day and the night times and some of it evaporates and condenses on the glass cover. The condensed water vapor is withdrawn as fresh water, $\dot{M}_D$. Hot water is also withdrawn from the system based on one needs and it is assumed that it is withdrawn at a constant rate equals $\dot{m}_h$. The amount of water in the basin is kept constant by feeding the unit with water at a rate of $\dot{m}_F$ such that $\dot{m}_F = \dot{m}_h + \dot{M}_D$. To estimate the amount of fresh water produced by such system energy balance is performed at its important components namely; the black plate, the PCM, the glass cover, and the water in the basin. The energy equations are presented below:

2.1. Water in the basin

$$\frac{dT_{w,b}}{dt} = \frac{\left[Aq_{c,p-w} + \dot{m}_F C_{p,w}(T_F - T_0) + q_s a_w A\right] - \left[q_{evap} + \dot{m}_h C_{p,w}(T_{w,b}(t) - T_0) + Aq_{r,w-g}\right]}{m_{w,b} C_{p,w}} \quad (1)$$

where A is the surface area, $C_{p,w}$ is the heat capacity of water, T_F is the feed water temperature, T_0 is the reference temperature = 0 °C, $q_{c,p-w}$ is the convective heat transfer rate per unit area from the black plate to the water in the basin given by

$$q_{c,p-w} = h_{c,p-w}\left[T_p(t) - T_{w,b}(t)\right] \quad (2)$$

where $h_{c,p-w}$ is the convective heat transfer coefficient from the plate to the water, T_p and $T_{w,b}$ are the temperatures of the plate and the water in the basin respectively, $q_{r,w-g}$ is the radiation energy from the water in the basin to the glass cover given by