Desalination 407 (2017) 61–74

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Heat transfer coefficients and yield analysis of a double-slope solar still hybrid with rubber scrapers: An experimental and theoretical study

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HIGHLIGHTS

- A new double-slope solar still hybrid with rubber scrapers is designed.
- It has a small slope of the condensing cover of the solar still.
- It allows more solar radiation to enter the still.
- It avoids falling down of the condensation drops back to basin water.
- The productivity of this new model is increased by 63%.

ARTICLE INFO

Article history:
Received 20 September 2016
Received in revised form 22 December 2016
Accepted 23 December 2016
Available online xxxx

Keywords:
Double-slope
Rubber scrapers
Hybrid solar still
Heat transfer coefficient
Yields

ABSTRACT

In this study, a new double-slope solar still hybrid with rubber scrapers (DSSSHS) and a double-slope solar still (DSSS) were designed, manufactured and tested. The proposed design of DSSSHS makes use of the advantages of using a small slope of the condensing cover of the still that allows higher solar radiation to enter into the still. Disadvantages resulting from using the small slope are overcome by using the rubber scrapers. No researcher has yet used the scrapers in solar still. Experimental measurements and results were used to calculate the theoretical values of convective and evaporative heat transfer coefficients, in addition to the theoretical values of the yields. Results of the two models were compared to evaluate the advantages of using rubber scrapers in the new model. Using rubber scrapers in DSSSHS model enhanced the total internal heat transfer coefficient (h_1) as well as the productivity. The maximum recorded value of the total internal heat transfer coefficient for the DSSSHS is found as 38.754 W/m^2 °C and the daily yield as 4.24 L/m^2 day with productivity improvement of 63%, for the case when the inclination angle of the glass cover is quite small (about 3.0°).

1. Introduction

In the last four decades, solving fresh water shortage problem has become a great challenge to many nations around the globe. Potable water is vital for our existence; however, non-potable water is also important to meet agricultural and industrial demands. Despite that more than three quarters of the earth is covered with water, only 0.014% is potable. Conversely, sea water constitutes 97.5% of global water; this water can be purified by distillation to be suitable for human use [1]. Many countries suffer from shortage of natural fresh water. Increasing amounts of fresh water will be required in the future as a result of the rise in population and higher living standard, as well the expansion of industrial and agricultural activities [2].

Therefore, finding sustainable, safe, cheap, and environment-friendly techniques to produce potable water from salty water is necessary. The best solution to this problem is solar distillation; this process is safer for the environment and uses only sustainable energy [3]. Solar distillation is a desalination method with many advantages, including the ability to reduce or solve the problem of potable water shortage in the future, especially in arid, coastal, remote, and rugged areas. Thus, in the last three decades, many researchers and scientists have conducted studies to improve fresh water production and/or efficiency of a conventional solar still, which simply works based on the principles of evaporation and condensation. These improvements increase the effectiveness of solar distillation technique in solving potable water shortage.

Many researchers have investigated various types of solar stills, such as weir type [4], simple single basin [5], active double slope [6], tubular

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http://dx.doi.org/10.1016/j.desal.2016.12.017
0011-9164/

solar still [7] and portable thermoelectric solar still [8]. Tests were also conducted to increase the productivity of solar stills by using the following designs: double-glass glaze where brine flows between them [9], utilizing water and air flow [10,11], sponge cubes of different sizes in the still basin [12], a built-in sandy heat reservoir [13], increasing condensation area [14,15], parabolic concentrator with focal pipe and heat exchanger [16], solar collector with water sprinkling system and thermoelectric cooling device [17], tubular and triangular still [18–22], fin at the basin of the still [23–25], parabolic concentrator tubular solar stills [26–28], internal and external reflectors [29–31], vinyl chloride sheet and polythene film transparent tubular covers [32], thermoelectric cooler [33], low cost technique [34–36], forced convection inside the solar still [37,38], optimized position and size partition inside a single slope solar still [39] and nanomaterials with and without a vacuum fan [40]. The parameters affecting the performance of solar stills were studied to improve the yield [41–43]. Theoretical and numerical studies were also reported for estimating the productivity and the convective heat transfer coefficient in solar stills [44–47].

The best inclination of the condensing cover to give the highest yield through receiving maximum solar radiation varies from season-to-season. However, it should be optimized from the annual yield perspective. Many researchers reported that the best cover inclination angle is near [48–50] or nearly equivalent [5,51–57] to the latitude angle. Some other researchers concluded that this angle should be far from the latitude angle [58–62]. Data and results from previous studies were obtained [57] for different locations, climate conditions, and solar still shapes; a trend for the variation between the latitude and optimum inclination angles for the cover was established. That is, when the latitude angle for the experiment location is increased, the inclination angle of the condensing cover should also increase. In addition, the trend showed that the best inclination angle for the condensing cover is close to the latitude angle of the experiment's location. The minimum inclination of the glass cover should be at least 10° to avoid falling and/or slowing down the condensate [63].

Most of previous studies have shown that the best productivity is achieved when the condensing cover slope is the same as the latitude angle of the experiment location. However, problems that result from the reduction in productivity when the condensate water stays on the inner surface of a small inclination condensing cover for a relatively long time before collection were not resolved. Productivity reduction occurs when the condensate film decreases the total amount of solar radiation that enters the solar still or when this condensate fall toward the basin because of gravitational force or re-evaporate when exposure to solar radiation.

In this study, a double-slope solar still hybrid with rubber scrapers (DSSSHS) is designed for the first time with a 3.0° slope condensing cover, which is equal to the latitude angle of the experiment location (latitude N 3° 0′ 27.71″, longitude E 101° 43′ 15.24″ and 45 m height from sea level). The main aim is to obtain maximum fresh water yield during daytime using the DSSSHS. The proposed design makes use of the advantages of using the small slope of the condensing cover of the still. This allows higher solar radiation to enter into the still. Disadvantages resulting from using the small slope are solved by using the rubber scrapers. No researcher has used the scrapers in solar still till to-date. These rubber scrapers have water guides (made of aluminum) with a suitable slope and are fixed to collect scraped water during movement of the rubber scrapers without allowing the fall of water drops toward the basin of the still.

2. Methodology

2.1. Experimental setup

In the current study, two solar stills are designed, manufactured, and tested to study and compare their effectiveness. The first one is a double-slope solar still (DSSS) and the second one is DSSSHS. Both stills are installed in a fixed east–west orientation. The movements of rubber scrapers of DSSSHS are achieved by using two 12 V DC motors, which are operated using DC current supplied from two 12 V, 150 Ah DC batteries. The DC batteries are powered by a charger, which obtains its power from a 12 V, 200 W/h DC solar photovoltaic panel. The system also consists of a feeding tank of saline water. All six faces of this tank are made of aluminum which is non-transparent. All external faces of this tank, except the one facing the sun, are insulated from the ambient air using 19 mm-thick nitrite foam (insulation sheet). Its thermal conductivity equals to 0.038 W/m K and density equals to 70 kg/m^3. The external face opposite to the sun is blackened with paint to increase its solar radiation absorptivity, which in turn increasing the water temperature inside this tank because of conductive heat transfer from the tank to the water.

Two PVC water hoses are insulated from the ambient air with 10-mm-thick nitrite foam (insulation pipes). Its thermal conductivity equals to 0.038 W/m K and density equals to 70 kg/m^3. Then, they are connected to the main feeding tank to supply the two solar stills with saline water via floating valves. Two colored rulers are fixed on the opposite sides of each basin base of the stills to ensure depth adjustment of saline water in both solar stills. Thermocouples (K-type model, Omega Engineering, USA) are fixed in different locations, inside and outside the solar stills, to measure the basin, saline water, air inside the solar stills, and glass temperatures. The thermocouples are linked with a data logger (model GL 800, Graphtec Corporation, Yokohama Japan) to record temperatures every 5 min. Fig. 1 illustrates the experimental setup.

Fig. 2 shows the schematic diagram of DSSSHS. This still consists of an aluminum rectangular base. The still dimensions are as follows: each of the basin length and width is 1000 mm; basin height is 30 mm; glass sides are 1000 mm in length; two opposite ones are of fixed height, which is 100 mm; while the other two opposite ones are of height that starts from 100 mm at the edges, reaching 126.2 mm in the middle of their lengths; and basin area is 1 m^2. The inner faces of the basin are painted with food grade, black paint to increase its solar absorptivity. The thickness, thermal conductivity and density of the basin are 3 mm, 222 W/m K and 2710 kg/m^3, respectively. The base and all sides of the basin are insulated from the outside by using 19-mm-thick nitrite foam (insulation sheets). Its thermal conductivity equals to 0.038 W/m K and density equals to 70 kg/m^3.

Four inclined collecting channels are used to collect the condensed water into two 3-L-capacity containers. The condensing still cover is a 2.6-mm-thick clear glass. Its thermal conductivity equals to 0.96 W/m K and density equals to 2500 kg/m^3. The cover is fixed on the edges of the still sides with a 3.0° angle with horizontal plane, which is the latitude of the experiment location, maximizing the solar radiation intensity that enters the still. Two rubber scrapers are used to scrape the condensed water on the inner side of the condensing surface toward the PVC collecting channels, which lead the collected condensed water toward the collecting containers.

The movements of the rubber scrapers are achieved by using two 12 V DC motors, which are operated using DC current supplied from two 12 V, 150 Ah DC batteries. The batteries are powered by a charger, which obtains its power from a 12 V, 200 W/h DC solar photovoltaic panel. This model is mounted on a hollow iron post with 100 mm diameter and 1100 mm length, which can be rotated 360° in a horizontal plane. Speed, direction, and time interval of movements of the rubber scrapers are controlled by electrical control boards. In this study the rubber scrapers are moving in 15 min intervals at 0.2 m/s speed. The control boards consist mainly of DC 12 V delay relay timers, general purpose relays, micro basic switch of rotary roller hinge lever, resistances, and wiring system. These boards are operated using DC current, supplied by two 12 V, 150 Ah DC batteries. To prevent any losses of collected water while scraping the condensed water, aluminum water guides are fixed under each scraper. These guides have a suitable slope that directs any amount of collected water through their open sides toward