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Analysis of heat and mass transferring mechanism of multi-stage stacked-tray solar seawater desalination still and experimental research on its performance

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ABSTRACT

In this paper, a multi-stage stacked-tray solar seawater desalination still was designed and used to assess heat and mass transfer mechanisms and test water production performance in both transient and steady states. A mathematical model of heat and mass transfer was developed and used to calculate the heat transfer velocity equation at each stage, the heat and mass transfer equation at the highest stage, and determine the performance coefficient of the still. The running of the still only needs the solar energy. It is showed that the water production rate became stable after 3 h and higher temperatures resulted in higher water production rates. Both the performance coefficient in steady state and performance coefficient were above 1 when the temperature above 70 °C. Under the practical weather, the smaller the seawater depth was, the bigger the accumulative water production and performance coefficient were. The total production was 8.1 kg/m^2·d and the performance coefficient was 1.12 when the depth of seawater was 2 cm. The good agreement between the model predictions and experimental data shows the validity of the model.

1. Introduction

Among various types of solar energy desalination stills, the tray-type still is widely used due to its simple structure, convenient construction from raw materials, and easy maintenance, particularly in remote island areas with limited energy and freshwater resources and technical expertise. The conventional tray-type solar energy still has some disadvantages, including no recycling of latent heat from condensation, lower heat transfer coefficient, high thermal capacity, and a relatively low driving force during the evaporation. There has been extensive research into enhancing the heat and mass transfer properties of tray-type stills.

Murugavel et al. enhanced the water production rate of tray-type stills by utilizing core materials derived from cotton (light cotton, jute fibre cloth, and 2 mm-thick sponge) and water-absorptive materials (washed natural rocks and quartz sands). Their experimental results showed that black light cotton produced the most water (Murugavel et al., 2008). Srivastava and Agrawal designed a type of suspended carrier able to float on the surface of water and covered with a black cloth on the top, so as to enhance the absorption of solar energy and increase the evaporation area. Simulation results showed that the water production per day for these stills in fine weather was 68% higher compared with conventional tray-type stills (Srivastava and Agrawal, 2013). Khalifa et al. found that the water depth played an important role in water production from desalination stills. When the depth of seawater decreased from 10 cm to 1 cm, the water production was observed to increase by 48% (Khalifa and Hamood, 2009). In another study, researchers designed a grid-fin type of absorption tray covered with black sponge cloth to increase the evaporation area and found that the water production per day was 48% higher than that of a conventional tray-type still (Srivastava and Agrawal, 2013). Hiroshi Tanaka added an external reflector to a traditional tray-type desalination still, and, compared with a traditional desalination still, daily water production increased by 29%, 43%, and 67% at glass cover inclination angles of 10°, 30°, and 50° respectively (Tanaka, 2010). Velmurugan et al. used a small-scale solar pond to evaluate the impact of salinity on water production and internal temperature distribution and found that the water

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production rate of the still with the solar pond was 20% higher than that without the pond (Velmurugan and SritharTiwari, 2007).

These previous studies primarily focused on single-effect tray-type stills, which can directly release latent heat to the outside environment after the condensation of water vapor during evaporation. Since the quantity of solar radiation per unit is fixed, the fraction of solar energy that can be used to heat the seawater is limited. Thus, it is important to determine how to most effectively harness solar energy for desalination. Multi-effect structures can recycle the latent heat released during condensation to heat seawater, so as to harness a greater fraction of solar energy and enhance the water production rate.

Suneja and Tiwari (2013, 1999a,b, 1998) designed single-effect, two-effect, three-effect and multi-effect trayed desalination still and drew from the relevant experiments a conclusion that the water yield of the newly designed still is much higher than that of conventional ones. The increase of effects helps enhance the water yield, but when the number of effect is more than seven, the increase of effects has a limited impact on the water yield. The depth of seawater in each effect has an impact on the water yield. For example, the relatively small amount of seawater in the secondary effect in a two-effect still is helpful to increase water yield. Tiwari et al. (2015), Kumar et al. (2014), Tiwari and Sahota (2017) also studied those stills driven by different types of solar energy collectors and made an analysis of their corresponding performances. El-Sebaii constructed a three-effect device and developed a water production prediction model (El-Sebaii, 2005). Schwarzer et al. designed a five-to-seven-effect desalination unit (Schwarzer et al., 2009). Rajaseenivasan et al. designed a two-effect dual-slope tray desalination device and studied the impact of seawater quality on the water production rate. Their results showed that with the same available surface area and operating parameters the water production of a two-effect tray-type still was 85% higher than that of a single-effect still (Rajaseenivasan and Murugavel, 2013). Panchal added black granite fillers to a two-effect tray still to reduce the thermal capacity of the seawater and studied the impact of different sizes of fillers on the average water production. They found that the application of fillers of 30 mm, 20 mm and 10 mm resulted in an in-crease of 11%, 7%, and 3 in water production, respectively (Panchal, 2015). Hiroshi Tanaka added vertical multi-effect evaporation units to the flank of a two-effect tray structure and reflectors to the outside of the still in order to increase the energy input (Tanaka, 2009; Tanaka, 2015).

The modification of tray-type stills has been shown to enhance the desalination efficiency and reduce costs; however the high thermal inertia, small condensation area, high resistance to convective mass transfer, and low water production rate still hinder its applicability and effectiveness. In this study, a multi-effect stacked-tray desalination still was designed and a theoretical model for heat and mass transfer was developed.

2. The structure and operation of a solar multi-stage stacked-tray still

2.1. Still structure

The structure and operating mechanism of a solar multi-stage stacked-tray still are illustrated in Fig. 1. The still consisted of a solar-energy heat collector, a heated water storage tank, water trays with reinforced condensation surfaces, a freshwater collecting trough, leveling pipes, a heated water output valve, and a freshwater output valve. The solar-energy heat collector was constructed of several tubular vacuum tubes connected with the heated water storage tank at one end. Multi-stage stacked trays

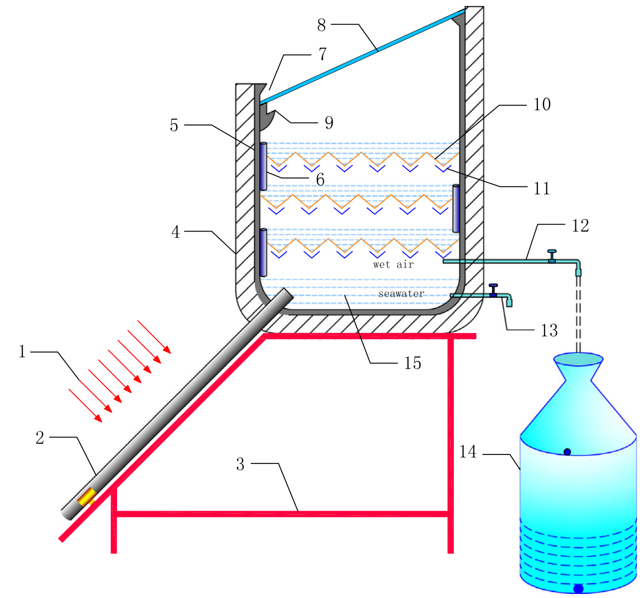

Fig. 1. The structure and operation of a solar multi-stage stacked-tray still. 1—Solar light; 2—Solar-energy heat collector; 3—Bracket; 4—Insulation layer; 5—Shell; 6—Leveling pipes; 7—Rain water collecting trough; 8—Glass cover plate; 9—Freshwater collecting trough; 10—A tray with a reinforced condensation surface; 11—Freshwater collecting trough; 12—Freshwater output pipe; 13—Strong brine output pipe; 14—Freshwater tank; 15—Heated water storage tank.

with a reinforced condensation surface at the top of the tank were interconnected through leveling pipes. The freshwater collecting trough at the back of each tray was used to collect freshwater. A glass cover plate at the top of the tank consisted of a brim equipped with a rain water collecting trough.

2.2. Still operation

The solar-energy heat collector was used to heat the raw water at the bottom of a heated water tank. The produced water vapor was condensed into freshwater at the back of the first-stage tray, and the heat released during the condensation was used to heat raw water at the top of the first-stage tray into water vapor, which was then condensed into freshwater at the back of the second-stage tray. The heat released from this stage was used to heat the raw water at the top of the second-stage tray, finally heating the raw water at the top-stage tray. A transparent glass cover plate set above the top-stage tray formed a distillation chamber similar to a conventional solar still. Water vapor was condensed at the back of the glass cover plate and converted into freshwater. Freshwater condensed at each stage was collected and delivered to users through collecting troughs. After a period of operation, there may appear fouling in the device. To solve this problem, the inflow volume can be raised to wash the water tray at each stage and the cleaning agent can be used when necessary. According to the actual situation, the glass cover shall be removed for thorough cleaning every half a year to one year.

3. Mathematical model

In order to determine the heat performance of the still and how to best improve water production, a mathematical model was established for each component and the whole system. This model allowed for prediction of still operating performance in different structures and conditions.