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Spiral multiple-effect diffusion solar still coupled with vacuum-tube collector and heat pipe

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HIGHLIGHTS

- A spiral multiple-effect diffusion solar still is developed.
- The measured water productivity is higher than the published results.
- The manufacture of spiral solar is easier and cheaper.

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ABSTRACT

A novel solar still with spiral-shape multiple-effect diffusion unit is developed in the present study. The test results of a 14-effect unit coupled with vacuum-tube solar collector (absorber area 1.08 m^2) show that the highest daily pure water production is 40.6 kg d^{-1}. The measured highest productivity based on the area of glass cover, solar absorber, and evaporating surface is 34.7, 40.6, and 7.96 kg m^{-2} d^{-1}, respectively, which are much higher than the published results. The measured solar distillation efficiency is 2.0–3.5. The performance enhancement results mainly from the lateral diffusion process in the spiraled still cell. The vapor flow generated by heat input can flow freely and laterally through the spiral channel down to the end when solar heat input is high. Besides, the larger evaporating and condensing area at the outer cell may increase heat and mass transfer at the outer cell.

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1. Introduction

Many researches have proved that multiple-effect diffusion solar still (MEDS) has high productivity [1–14]. MEDS consists of a multiple-effect diffusion unit (MDU), a solar collector, a heat recovery exchanger, and a heat transfer device to connect solar collector and MDU. The conventional MDU (Fig. 1) is made of a number of closely packed vertical still cells. Each cell is made of a heating plate and a thin wick (porous) material which is attached on one side of the heating plate. The seawater or sewage water is supplied to the wick from the top. The heating plate absorbs heat from vapor condensation (latent heat) and conducts the heat through the plate to the liquid-saturated wick at the other side to evaporate the water. The vapor diffuses and condenses on the heating plate of the next cell. The processes repeat until the last cell and finally discharge the heat to the ambient. The water collector under the heating plates collects the pure water. The effluent from sewage water is collected in another collector. Heat is applied to the heating plate in the first cell. The heat source of MEDS is from the solar collector.

The configuration of MEDS may be different. Dunkle [4] built a solar distillation system consisting of a MDU and a storage tank which is connected to a solar collector. Cooper and Appleyard [5] simplified Dunkle's design by combining the solar collector and the MDU into one such that the first plate of MDU acts as the solar absorber. It was found that the productivity is significantly improved by narrowing the diffusion gaps between the parallel plates [7–10].

Tanaka et al. [11] further designed a basin-type MEDS consisting of a MDU coupled with a basin-type distillation section, called "MEDS-Basin". The measured productivity was the highest in literature in the 2000's. Tanaka et al. [15–17] showed theoretically that the productivity of MEDS can be higher.

Chong et al. [18,19] designed a similar MEDS of Tanaka et al. [15–17] but using a bended-plate MDU coupled with a vacuum-tube solar collector. The bended-plate MDU solves the problem of wick peel-off from the heating plate and pure water contamination. The vacuum-tube solar collector creates a higher temperature gradient in MDU to increase the productivity. The outdoor test of a MEDS prototype (MEDS-

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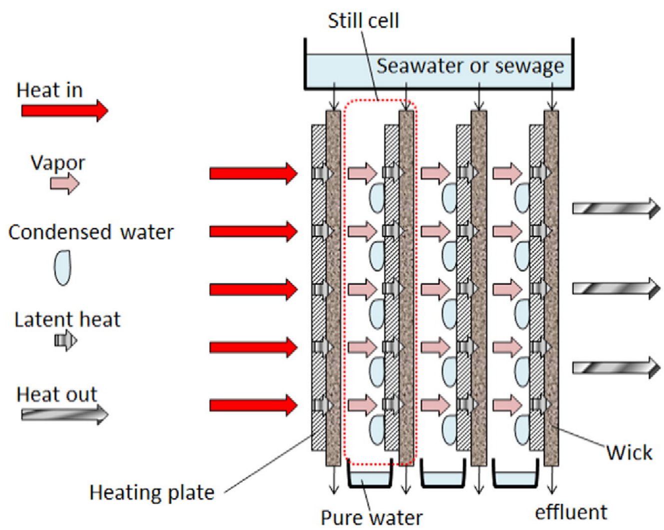

Fig. 1. Distillation process inside multiple-effect diffusion unit (MDU) [18].

1L) [18] shows that the productivity is much higher than the test results of MEDS-Basin [11] and the theoretical calculation of MEDS-FHP [17].

The long-term outdoor test results of MEDS-1L show that the average daily pure water production is higher than the basin-type MEDS [11,18]. The solar distillation efficiency R_{cov} (COP) is 23% higher than the basin-type MEDS [11].

The bended-plate MDU of Chong et al. [18,19] is designed in a laminated-structure in which the bended plates/wicks are laminated piece by piece with a silicone rubber spacer in between to seal each diffusion gap. The heat path is in outward direction perpendicular to the plate. The diffusion gaps are sealed in each still cell. Hence, the resistance of heat transfer and diffusion process becomes higher if the number of multiple-effect cells is high. Besides, the manufacturing process for laminated-structure and bended-plate of MDU is not very simple because the plate and wick are in piecewise form and need a bonding process to make a good sealing at the edge.

The present study further develops a MEDS with a novel design of MDU in which the plate/wick and the diffusion gap are in spiral shape. The plate and the wick are in one single sheet. A continuous manufacturing process is employed by rolling the plate/wick sheet with seal/spacer placed at two edges.

In the spiral design, the still cell gap is a single spiraled continuous cell from the first heating section (from solar heat) to the last heat sink section (to ambient). Beside the vapor diffusion in the direction perpendicular to the plate, vapor can also flow freely and laterally down to the end of the still cell to enhance the mass transfer. This may create a better thermal and mass transfer process at high heat input (high solar radiation). In addition, the MDU is coupled with a vacuum-tube solar collector which can produce a higher temperature gradient in MDU for high productivity. A thermosyphon heat pipe is used to connect the MDU and solar collector to effectively transfer the solar heat to the MDU.

2. Design of multiple-effect diffusion solar still with spiral cell (MEDS-sp)

Fig. 2 shows the schematic diagram of multiple-effect diffusion solar still (MEDS-sp). It consists of a spiral-type multiple-diffusion unit (sMDU) which is heated by solar heat from a vacuum-tube solar collector via a heat pipe (thermosyphon). A heat recovery exchanger is used to recover the heat of hot brine and distilled water to preheat the feed water.

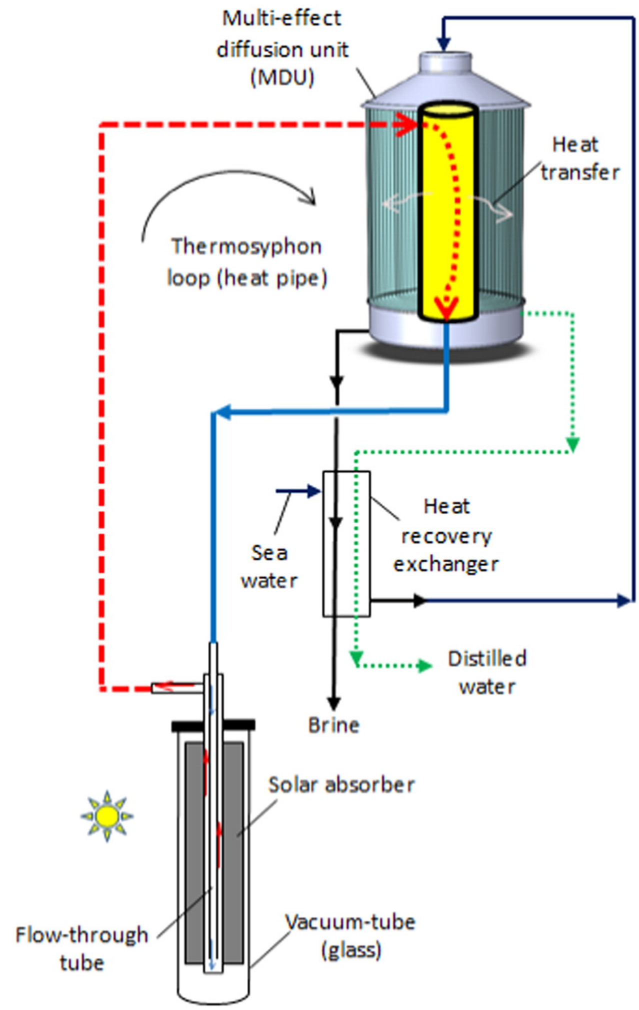

Fig. 2. Schematic diagram of MEDS-sp.

2.1. Design of spiral-shape multiple-effect diffusion unit (sMDU)

The design concept of spiral-shape MDU is shown in Fig. 3. The heating plate (polycarbonate) and the wick are spiraled together with seal/spacer placed at two edges. During the process of rolling the plate, the wick material is stretched on the curved heating plate to create a tensile force for tight contact with the plate. Wick peel-off problem can then be solved.

Two silicone rubber spacer/seals at the top and bottom edges were used. The top spacer/seal is in a rectangular shape in cross section. The bottom spacer/seal (called “ditch component” in Fig. 3(a)) also acts as a ditch for pure water collection. Both spacer/seals are made from extrusion of silicone rubber. Silicone rubber pipes for feed water flow are placed inside the ditch to recover the heat of pure water and inside the brine collector to recover the heat of brine.

In the spiral MDU, there is only one still cell which is in spiral shape. Besides the vapor diffusion across the gap in the outward direction perpendicular to the plate (radial diffusion), lateral diffusion along the circumference down to the end of the spiral cell may occur, see Fig. 3(b). The lateral diffusion may induce an additional mass transfer effect which increases vaporization of water in the wick and condensation of vapor on the bare side of heating plate.

Fig. 4 shows the schematic diagram of the design of spiral multiple-effect diffusion unit (sMDU). The feed water first flows down and is heated in the heat recovery pipes of pure water and brine at the bottom and then flows up and is fed to a pulp sponge (at the top) which

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