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Multiple-effect diffusion solar still coupled with a vacuum-tube collector and heat pipe

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HIGHLIGHTS

- We design a multiple-effect diffusion solar still with a bended shape.
- A vacuum-tube solar collector is used to produce high temperature for distillation.
- A heat pipe is used to transfer solar heat for distillation.
- A prototype MEDS-1L was built and tested outdoors.
- MEDS-1L performs very well compared to other designs.

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ABSTRACT

The present study develops a multiple-effect diffusion solar still (MEDS) with a bended-plate design in multiple-effect diffusion unit (MDU) to solve the peel-off problem of wick material. The MDU is coupled with a vacuum-tube solar collector to produce a high temperature gradient for high productivity. A heat pipe is used to transfer the solar heat to the MDU. A prototype MEDS-1L was built and tested outdoors. Four performance indexes are proposed for the performance evaluation of MEDS, including daily pure water production per unit area of glass cover, solar absorber, and evaporating surface (M_{cov}, M_{sol}, M_{evp}, respectively), and solar distillation efficiency R_{cov}. The outdoor test results of MEDS-1L show that the solar collector supply temperature T_h reaches 100 °C at solar radiation 800 W m^{-2}. The highest M_{cov} is 23.9 kg m^{-2} d^{-1} which is about 29% higher than the basin-type MEDS [11]. The highest value is 25.9 kg m^{-2} d^{-1} for M_{sol} and 2.79 kg m^{-2} d^{-1} for M_{evp}. The measured R_{cov} is 1.5–2.44, higher than the basin-type MEDS (1.45–1.88). The M_{cov}, M_{sol}, M_{evp} and R_{cov} of MEDS-1L are all higher than the theoretical calculation of a MEDS with a flat-plate solar collector coupled with a heat pipe (MEDS-FHP) [17].

1. Introduction

Various kinds of solar stills have been studied since the 1960's by Malik et al. [1], Tanaka [2,3] etc. Among them, multiple-effect diffusion solar still (MEDS) is recognized to have high productivity. MEDS usually consists of a multiple-effect diffusion unit (MDU), a solar collector, a heat recovery exchanger, and a heat transfer device from the solar collector to MDU. As shown in Fig. 1, the MDU consists of a series of vertical still cells, which are closely spaced. 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 environment. The water collector under the heating plates collects the pure water. The effluent from sewage water is collected in another collector. The original heat source is supplied to the heating plate in the first cell. The heat source is from the solar collector.

MEDS was first studied in 1961 by Dunkle [4] who constructed a solar distillation system consisting of a MDU and a storage tank connected to a solar collector. The hot water was supplied to the first plate of MDU to heat the plate and create evaporation from the wick attached on the other side. The vapor diffuses through the gap to the next plate and the latent heat of condensation released on the next plate surface was conducted to the wick on the other side of the plate and induces another evaporation. The distillation process includes evaporation, vapor diffusion, and condensation, which occurred in gaps between the plates. Dunkle [4] found that the distillation rate is increased by narrowing the gaps between plates and by replacing the air in the gaps with hydrogen

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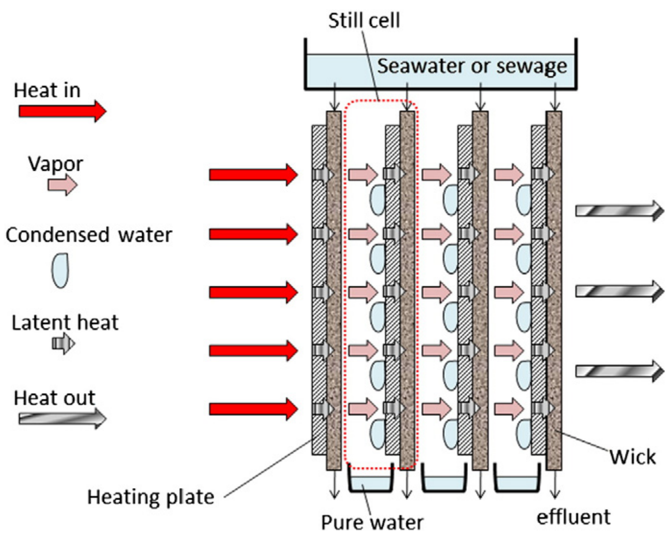

Fig. 1. Distillation process inside the multiple-effect diffusion unit (MDU).

which increases the diffusivity or reduce vapor diffusion resistance in the gaps.

Cooper and Appleyard [5] simplified the MEDS by combining the solar collector and the MDU into one. They constructed a multiple-effect diffusion solar still (MEDS) equipped with a glass cover parallel to the first plate. Solar radiation transmitted through the glass cover was directly absorbed at the first plate to induce evaporation. The hot water storage tank and the separated solar collector were thus not necessary.

Elsayed et al. [6] experimentally tested a three-effect diffusion still of the same structure as Dunkle's and found that the distillation rate per unit amount of heat supplied to the still increases with a decrease in feed rates of saline water.

The MEDS developed by Cooper and Appleyard has been studied by many researchers such as Toyama et al. [7,8], Yeh et al. [9], and Bouchekima et al. [10]. It was found that the productivity is significantly improved by narrowing the diffusion gaps between the parallel plates. Tanaka et al. [11] designed and built a basin-type, multiple effect diffusion solar still, consisting of a MDU coupled with a basin-type distillation section. The 11-effect still with 5-mm diffusion gap produces 14.8–18.7 kg d^{-1} distillate per unit area of the glass cover at 20.9–22.4 MJ m^{-2} d^{-1} solar radiation incident upon the glass cover and at ambient temperatures of 19–30 °C. Another MEDS design proposed by Tanaka et al. [15–17] used a vertical MDU coupled with a heat-pipe (thermosyphon) and a flat-plate solar collector. The theoretical analysis [15] shows that an 11-effect still with 5-mm diffusion gap produces 19.2 kg m^{-2} d^{-1} distillate per unit area of glass cover at 24.4 MJ m^{-2} d^{-1} solar radiation and an ambient temperature of 30 °C. The indoor experiment verifies the theoretical prediction [16].

The theoretical calculation of Nosoko et al. [12] shows that the MEDS with 19 layers of wicks with 1 m by 2 m evaporating areas, 5 mm gap and 80% heat recovery, produces 12 kg distillate per kg steam (100 °C) consumption at 26.4 kg/h distillate production rate.

It is understood that the water productivity of a MEDS is significantly improved by narrowing the diffusion gap between the parallel plates. However, narrowing the diffusion gap causes serious contamination of condensate water with saline water. Tsumura et al. (referred in [13]) reported that the contamination often occurred in tilted solar stills with 7 mm diffusion gap. The contamination is caused by deformation of the plate due to gravity and thermal stress and by fiber (wick material) protruding to touch the condensing surface of the next plate. The fiber absorbed saline water to become heavier and then gradually expanded toward the condensing surface.

In addition, the tight attachment between the wick material and the heating plate is very important in keeping good heat conduction from the heating plate to the liquid-saturated wick attached on the other side. The peel off of wick material from the heating plate may block the heat conduction path. The peel off of wick material may result from the deformation of the plate due to manufacture defect or thermal effect in operation and weak contact due to stress release.

The latent heat in the last stage of MDU has to be dumped to ambient air. The higher the temperature gradient between the heat source (solar collector) and the heat sink (ambient) in MDU, the higher is the productivity. The MEDS designed in the abovementioned researches [1–14] uses a flat-plate solar collector to supply heat which cannot reach higher temperatures. The productivity is thus limited.

The present study develops a MEDS with a new design of MDU to solve the problem of heating plate deformation and peel off of wick material from the plate. 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 collector heat to the MDU.

2. Design of multiple-effect diffusion solar still (MEDS)

The schematic diagram of multiple-effect diffusion solar still (MEDS) developed in the present study is shown in Fig. 2. MDU is heated by

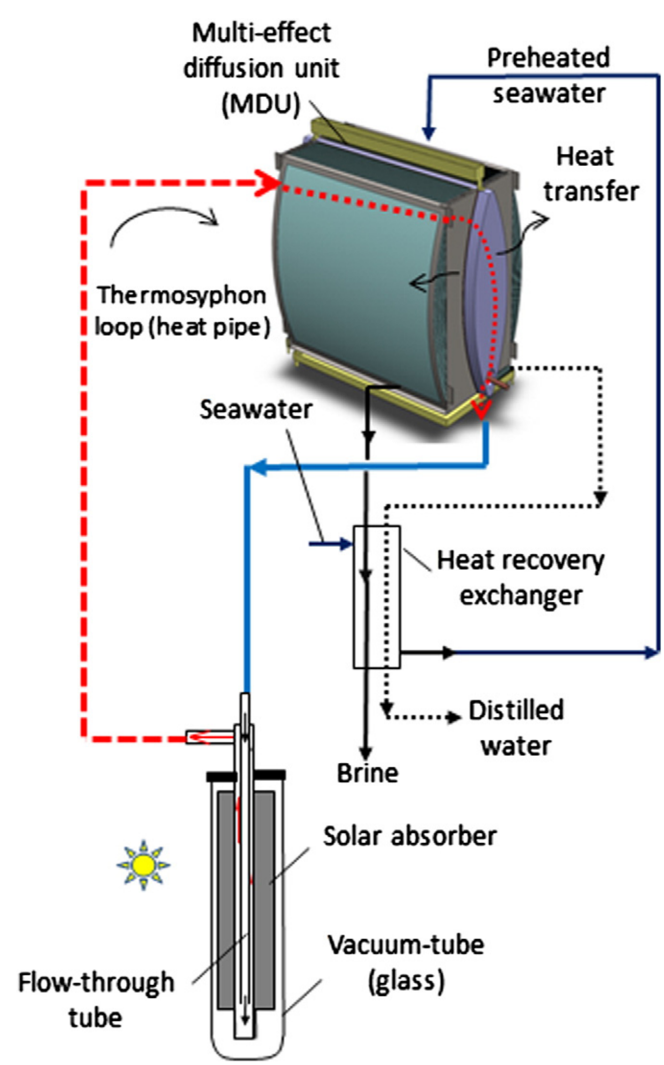

Fig. 2. Schematic diagram of MEDS.