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Experimental evaluation of hybrid solar still using waste heat

Chang-Dae Park [a,*], Byung-Ju Lim [a], Kyung-Yul Chung [a], Sung-Soo Lee [a], Young-Man Kim [b]

[a] Environmental and Energy Systems Research Division, Korea Institute of Machinery and Materials, 156 Gajeongbuk-Ro, Yuseong-Gu, Daejeon 305-343, Republic of Korea
[b] PROSAVE CO., LTD., 185 Gomo-Ro 324beon-gil, Jillye-Myeon, Gimhae-Si, Gyeongsangnam-Do, Republic of Korea

HIGHLIGHTS

- Structural design of some components of the hybrid MED solar still was improved.
- Performance of the still proposed depends more on the MED section than the basin section.
- Larger feeding flow rate shows better performance for the still with an insufficient plate number.
- Maximum performance of the still achieved at the maximum productivity condition of the 2nd plate.
- Productivity of the still increases linearly with heat input, recording 18.02 kg/m^2 at 22.37 MJ/d.

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ABSTRACT

Solar stills are cost-competitive compared to other renewable desalination technologies especially for very small-scale desalination devices. The commercialization of advanced solar stills, which can largely increase productivity, may require simpler design to increase their reliability and maintainability. In this paper, we have designed a multiple-effect diffusion (MED) hybrid solar still with simpler seawater feeding device and dual heat sources of solar thermal energy and waste heat. Performance tests with waste heat were performed with three operational parameters: the amount of heat inputted into the hybrid still, the seawater flow rate to the wick, and the seawater level in the basin. Experimental results show that the productivity of the hybrid still increases linearly with increasing heat input, recording 18.02 kg/m^2 at 22.37 MJ/d. The maximum productivity of distillate was obtained at the lowest seawater level even in the case of the experiment with waste heat source. The maximum performance of the MED solar still is achieved at the operation condition obtaining maximum productivity at the second effect plate, indicating that the MED section of the hybrid solar still plays a more important role than the basin section in the entire performance of the hybrid still.

1. Introduction

Generally, the major desalination technologies at present are reverse osmosis, multi-effect distillation, and multi-stage flash distillation. These technologies have been developed mainly in the scale of desalination plant larger than the capacity of 10,000 m^3/d, because the scale-up of plant capacity is a general method of decreasing the costs of water production. Nonetheless, there are still many regions worldwide where this large-scale desalination plant is not appropriate. Places such as remote areas, islands, and developing countries do not have electricity infrastructure and water grid, and they cannot afford the high initial construction cost, operation and maintenance cost, and/or skills. The desalination technology suitable for these situations may be considered a distributed-type small facility utilizing renewable energy such as solar energy.

Various renewable energy systems such as solar thermal desalination facility generally require a back-up system such as thermal reservoir due to its characteristics of intermittent and low-density energy. Thus, recent trends in renewable energy systems point to hybrid between the systems and energies, compensating each other's demerits and increasing their own availabilities. Fortunately, heat engines such as diesel generator have been widely used to generate electricity in remote areas. The temperature of the exhaust gas from the engines is typically larger than about 300 °C and the gas can be used as heat source for the evaporation of seawater [1–3], even though its utilization through the heat exchanger may deteriorate the performance of the engine itself due to the pressure drop in the heat exchanger.

Solar energy desalination is generally classified as direct evaporation technology such as solar stills and indirect technologies using solar thermal collectors or photovoltaic cells. Fig. 1 shows that the water costs incurred by these desalination technologies are still high compared to the fossil fuel desalination cost. In contrast, solar stills are cost-competitive compared to other renewable desalination technologies and even to the

* Corresponding author.
E-mail address: parkcdae@kimm.re.kr (C.-D. Park).

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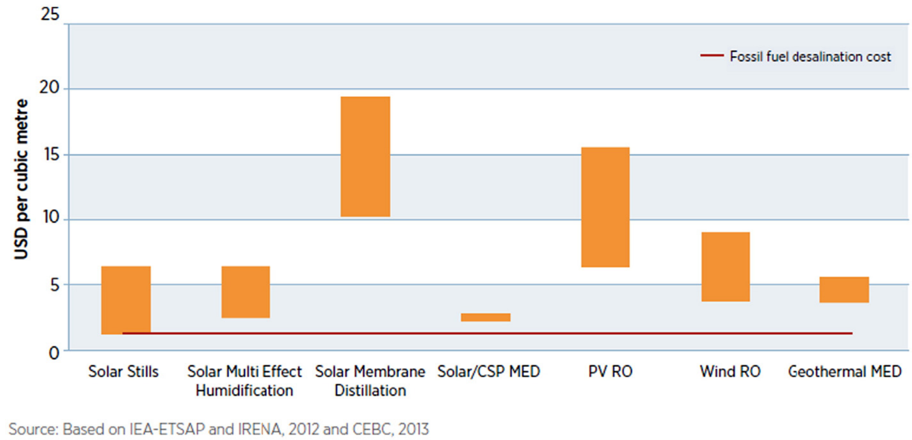

Fig. 1. Cost comparison of renewable energy desalination technologies with fossil fuel-based plants.

fossil fuel desalination cost. This is quite a fascinating fact for very small-scale desalination devices. The solar distillation method is the oldest and most conventional technology. In 1872, the first big desalination plant with capacity of about 23 m^3/d was constructed and successfully operated using solar still technology in North Chile. The low construction cost and high maintainability due mainly to its structural simplicity make it viable even nowadays. Nonetheless, solar stills have the disadvantage of low productivity; typically less than 4 kg/(m^2·d) [4], so the installation area required largely increases as production capacity increases compared to other desalination technologies. Therefore, many research studies have been widely performed to increase the performance of the solar stills, and some papers with good reviews were published [5–8].

Among the various types of solar stills, multiple-effect diffusion (MED) solar stills have great potential based on their benefits of high productivity and structural simplicity [9–24]. The MED solar stills consist of a series of closely spaced parallel plates in contact with saline-soaked wicks. Solar thermal energy is used to evaporate saline water flowing through the wick of the first plate. The water vapor diffuses through the humid air layer between plates and condenses on the facing second plate. The latent heat from condensation contributes to further evaporation from the wick of the second plate. This way, the evaporation, vapor diffusion, and condensation process is repeated on all plates to increase distillate productivity in the still. Such MED solar stills with glass covers have been extensively studied theoretically and experimentally. Tanaka et al. [19] showed experimentally that a still with 11 effects produces 14.8–18.7 kg/(m^2·d) distillate at 20.9–22.4 MJ/(m^2·d) solar radiation and 19–30 °C ambient air temperature. In another study [20], they showed theoretically that the MED solar still coupled with heat-pipe solar collector produces 18.5 kg/(m^2·d) of the overall daily production at 24.8 MJ/(m^2·d) solar radiation and 11.4 kg/(m^2·d) at 20.2 MJ/(m^2·d) solar radiation.

Most previous studies on solar stills have focused on productivity improvement by changing its structure or operation parameters. These kinds of advanced solar stills have definitely improved their productivities in comparison with 4 kg/(m^2·d) of a simple solar still. Note, however, that these advanced stills have a fairly complicated structure especially the feeding device of the saline water into the wick, which is not easy to make; it is also difficult to control the flow rate to the wick. Moreover, they did not adopt a backup system such as a subsidiary heating system that can increase the feasibility of solar stills. Structural simplicity that can generally increase the reliability of the stills and backup system are very important from a commercial point of view because the remote areas commonly lack operation and maintenance skills.

This research has tried to improve further the performance of the MED solar still by modifying its structure and to enhance its feasibility by simplifying the structure and incorporating a backup system. Experimental results include the performance of a simplified MED still using waste heat from the exhaust gas of a small electric generator and its optimum operation conditions.

2. Hybrid MED solar still

Fig.2(a) shows the schematic diagram of the hybrid MED solar still, which largely consists of basin section and MED section. The basin section is a kind of typical solar still but has a heat exchanger tube added in the basin. The heat exchanger tube is 6 m length of stainless steel to protect the seawater scaling and its schematic diagram is depicted in Fig. 2(b). The exhaust gas from the engine of the electric generator flows into the tube submerged in the basin seawater and transfers heat into the basin seawater, and then flows out of the hybrid solar still. This waste heat, together with solar radiation, evaporates the basin seawater, and vapors condense on the glass cover. Therefore, the distiller has a hybrid heat source consisting of solar heat and waste heat recovered from the exhaust gas of the generator.

The MED section consists of wicks, plates, feeding distributor of saline water, seawater pockets, and distillate pockets. Each wick (cotton flannel) is attached to the rear surface of the vertical stainless steel plate, feeding the seawater from the seawater pocket by capillary force. The direct solar-insolated heat and latent heat of the condensed water on the front surface of the first plate transfer to the seawater flowing down through the wick. The evaporated vapors diffuse across the gap between the neighboring plates, and then condense on the front surface of the second plate. At this time, the latent heat of the condensation works as heat source of the evaporation on the wick surface of the second plate. In this manner, evaporation, vapor diffusion, and condensation are repeated at the subsequent plates by the effect numbers. Condensed water on the front surface of each plate flows down and gets collected in the distillate pockets. Therefore, the thermal efficiency of this MED solar still is very high because of the repetitive use of heat that used to be supplied to the distiller. The concentrated seawater flows down out of the distiller at the bottom of each wick.

3. Experiment

Fig. 2(c) shows a picture of the experimental apparatus of the hybrid solar still with electric generator. The glass cover has effective area of 1 m^2 and 45° angle from the horizontal surface. The tilt angle of the glass cover of the simple solar still is generally set to the latitude where the still is located [25]. Nonetheless, this angle was set to be 45° larger than its latitude (36.5°) because, at fixed length of the glass cover, larger angle leads to larger area of evaporation in the MED section and to smaller installation area of the distiller. In addition, the amount of