Desalination 347 (2014) 66–76

Contents lists available at ScienceDirect

Desalination

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

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

Tze-Ling Chong [b], Bin-Juine Huang [a,*], Po-Hsien Wu [a], Yeong-Chuan Kao [b]

[a] Department of Mechanical Engineering, National Taiwan University, Taipei 106, Taiwan
[b] Department of Physics, National Taiwan University, Taipei 106, Taiwan

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.

ARTICLE INFO

Article history:
Received 21 March 2014
Received in revised form 13 May 2014
Accepted 17 May 2014
Available online xxxx

Keywords:
Solar desalination
Solar distillation
Solar still
Multiple-effect diffusion solar still

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

* Corresponding author. Tel.: +886 918291621.
E-mail address: bjhuang@seed.net.tw (B.-J. Huang).

http://dx.doi.org/10.1016/j.desal.2014.05.023
0011-9164/

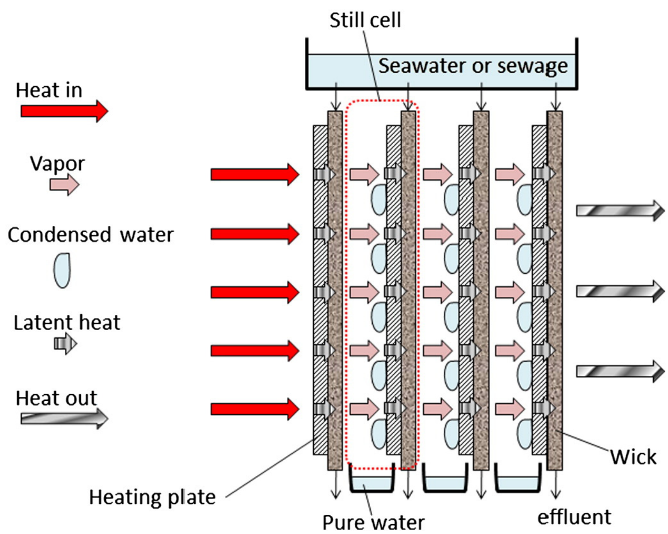

Fig. 1. Distillation process inside the multiple-effect diffusion unit (MDU).

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

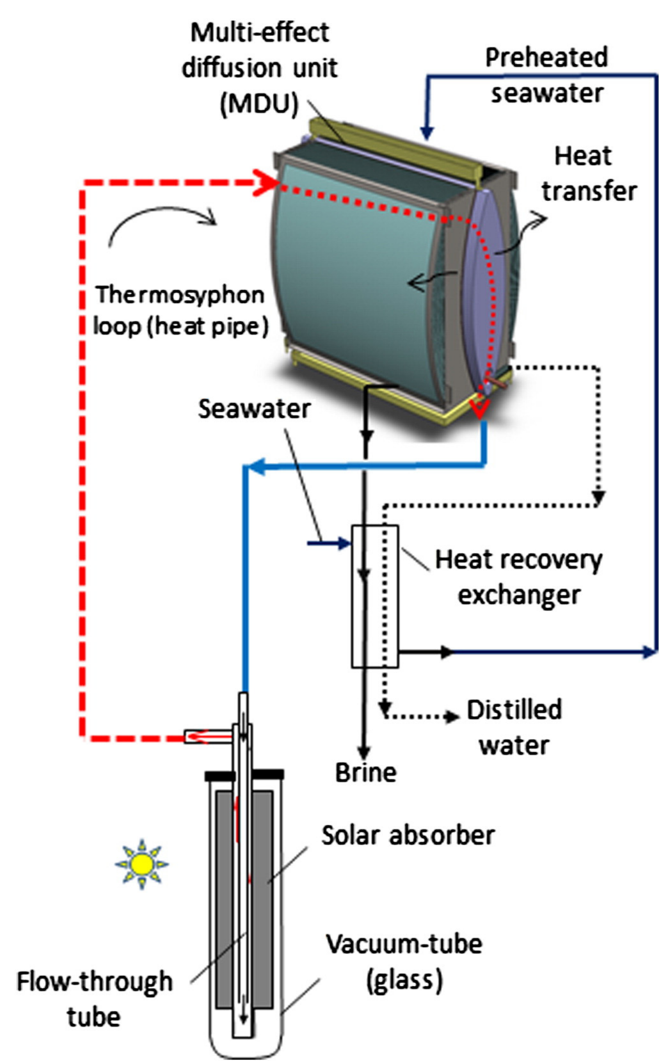

Fig. 2. Schematic diagram of MEDS.

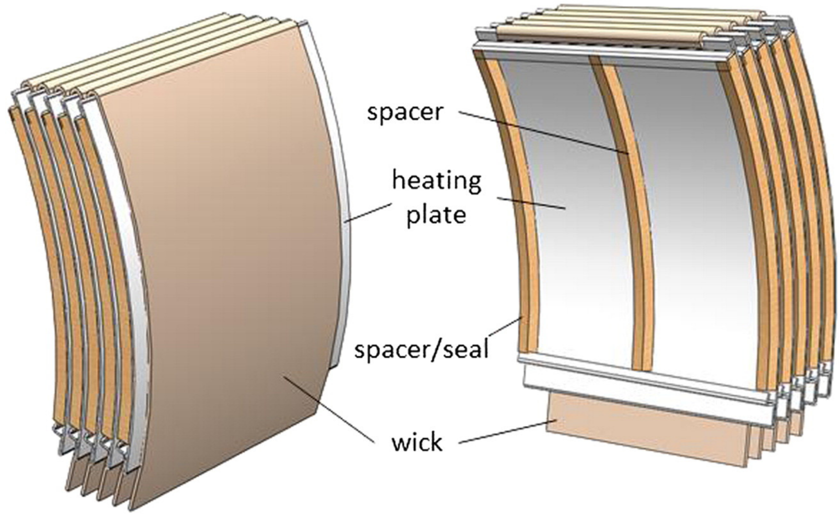

Fig. 3. Schematic diagram of the bended plate and wick.

solar heat from a flow-through type 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 seawater feed.

2.1. Design of multiple-effect diffusion unit (MDU)

To avoid contamination of distilled water and blockage of heat conduction path caused by deformation of the heating plate and peel-off of wick material, the wick-plate is designed in bended shape as shown in Fig. 3. A silicone rubber spacer is sandwiched between two plates vertically to create the gap of diffusion cell. By bending the plate, the wick material can be stretched to create a tensile force for tight contact with the plate.

The bending structure increases the strength even when using plastic material as the heating plate, such as polycarbonate (PC) used in the present study. However, thermal deformation may occur at a high temperature and cause wick peel-off and contamination problem. A test shows that thermal deformation of bended PC plate (0.5 mm) with a radius of curvature of 500 mm is negligible at 100 °C if the width is shorter than 300 mm. For wider heating plate, more spacers are needed to avoid thermal deformation.

Fig. 4 shows the flow path of pure water and brine. The inlet water was distributed evenly to all wick layers through a 5 cm thick pulp sponge attached on the top of the wicks as shown in Fig. 4 (left-hand side figure). A cotton rope is placed inside the ditch at the bottom which is formed by bending the heating plate. The ditch collects the distilled pure water flowing down from one side of the heating plate (bare surface). The rope then transports the pure water from the ditch to a pure water collector by capillary effect. The wick material attached on the bended plate is made in one continuous sheet spread all the way from the top (inlet tank) to the bottom (outlet brine collector) through the heating plate where evaporation takes place as shown in Fig. 4 (right-hand side figure). Therefore, the pure water and brine can be separated effectively by the present design.

The wick material is in contact with the heating plate by the bending structure. However, the dissolved gas in water such as oxygen may be evolved and produce bubbles which may cause wick peel-off problem. The water flow rate through the wick needs to be controlled to avoid wick dry-out and bubble formation in the wick. A test of the wick material used in present study shows that, the bubble problem at 100 °C can be avoided if the ratio of pure water flow to brine or effluent flow is in the range 0.3–2.0 or the ratio of inlet water flow to pure water flow is in the range 1.3–3.0.

In order to reduce the heat loss, the MDU is designed in two parts symmetric to the heat source (condenser of heat pipe) located in the middle as shown in Fig. 5. Seawater feed is preheated by the heat

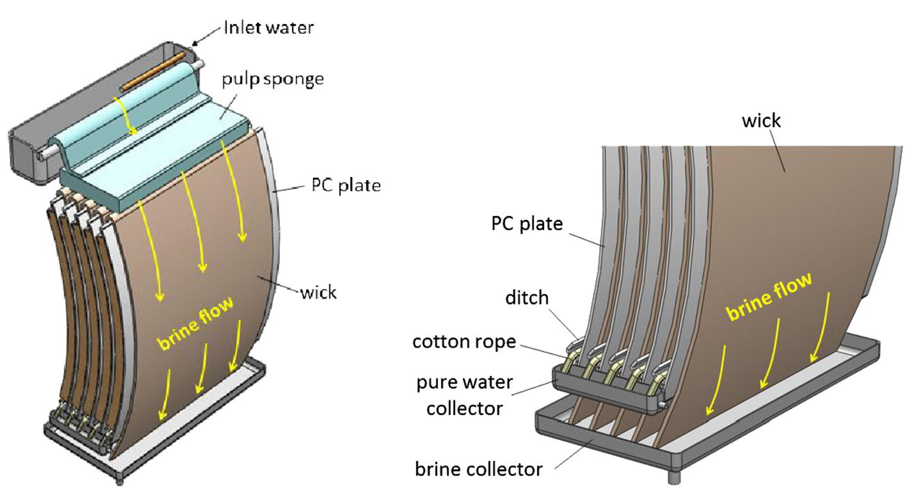

Fig. 4. Flow path of pure water and brine in MDU.

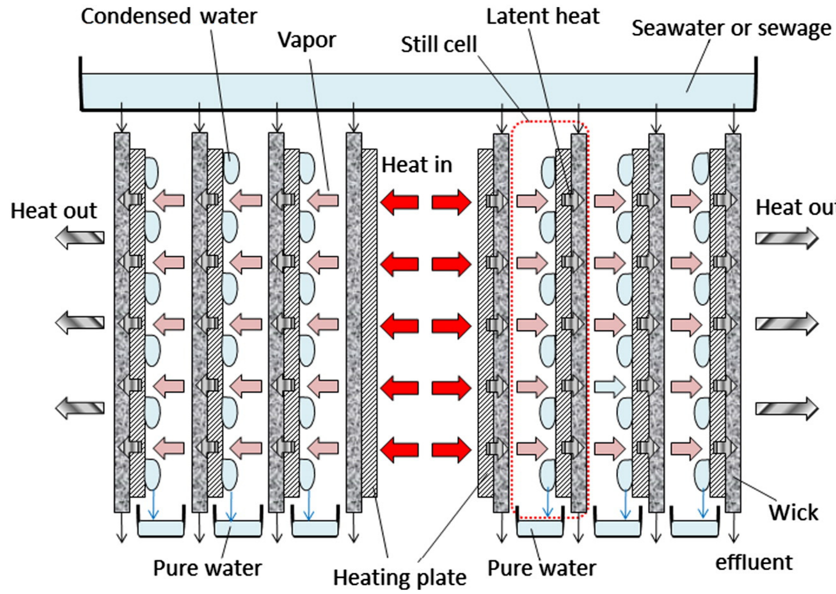

Fig. 5. Schematic diagram of distillation process inside a symmetric MDU.

recovery exchanger and fed into MDU from the top. The pure water and effluent are collected separately at the bottom.

The design specification of MDU is shown in Table 1. The overall configuration of MDU is shown in Fig. 6. On the front and back of MDU, a cover with openings is added to block sunlight. The front cover also reflects sunlight onto the vacuum-tube solar collector, while its openings provide cooling by air ventilation for heat dissipation of the last cell. Fig. 7 shows the manufactured bended plates and wicks.

Fig. 8 shows the condenser design of the thermosyphon connected to the first heating plate of MDU. Fig. 9 shows the prototype of MEDS-1L.

Table 1
Design specifications of MDU.

Shape	Bended-plate, symmetrical
Cell dimension	W610x H520, gap 6 mm; two symmetric parts
Cell material	Plate: polycarbonate (PC), thickness 0.5 mm Wick: nonwoven 100% wooden fiber (used in coffee maker), thickness 0.225 mm, size 580 × 480 mm Spacer: silicone rubber
No. of multiple effects	18
Total evaporating surface area, m^2	580 mm × 480 mm × 18 × 2parts = 10 m^2

2.2. Vacuum-tube solar collector

A flow-through vacuum-tube solar collector module (EZL 100-6) made by Viessmann Heating Technology Beijing Co., Ltd. was used in MEDS-1L. EZL 100-6 has 6 tubes with a total absorber area of 1.08 m^2. The solar absorber is made from a selective surface with high solar absorption coefficient (0.95) and low infrared emissivity (<0.05). The measured solar energy collection efficiency with glycol water is shown in Fig. 10. The test result shows that the solar energy collection efficiency is 0.6 at an inlet temperature of 100 °C. A test for steam generation (100 °C) was carried out outdoors using sunlight. Fig. 11 shows the steam generation efficiency measurement of the vacuum-tube solar collector. The solar collector efficiency is around 0.6–0.7 at steam generation temperature (100 °C).

The high-quality vacuum-tube solar collector is shown to be able to provide heating temperatures of up to 100 °C to MDU to create a high temperature gradient to improve its performance (Table 2).

2.3. Thermosyphon (heat pipe)

The solar energy collected by the vacuum-tube collector is delivered to MDU through a thermosyphon loop (heat pipe). The solar energy absorbed by the metallic absorber (fin) is conducted to the working

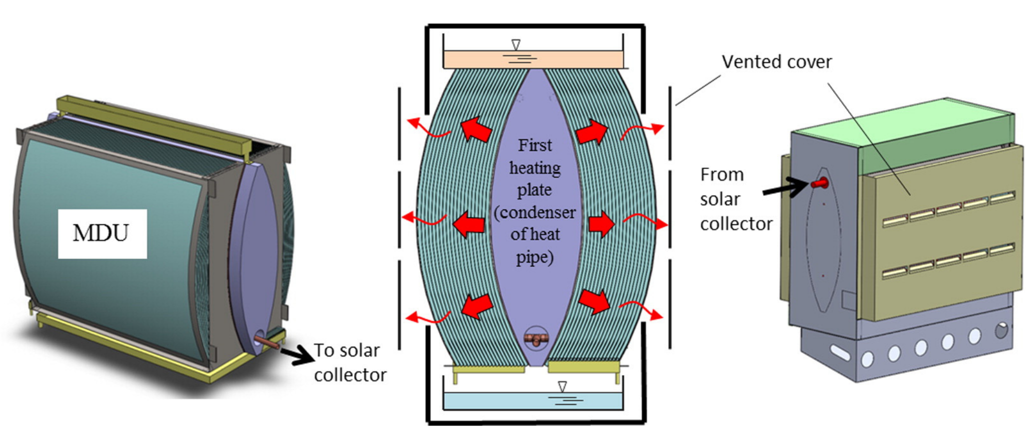

Fig. 6. Configuration of bended-plate MDU design.

Fig. 7. Bended plates and wicks.

fluid inside the flow-through tube and causes evaporation. The vapor flows to the MDU through the pipe and enters the condenser pipe attached on the first heating plate of MDU (Fig. 8). Condensation heat of the working fluid is released to the heating plate and conducted to the liquid-saturated wick adhered on the other side to create evaporation and the subsequent diffusion processes. The condensate of the heat pipe flows back to the evaporator (solar collector) by gravitational force. This completes a heat transport cycle. The working fluid of the thermosyphon is acetone which is charged to the thermosyphon loop after evacuation.

2.4. Experimental setup

MEDS-1L was tested outdoors with solar radiation. For automation in measuring the pure water production rate and operating conditions, an automatic measuring system was developed (Fig. 12) for the long-term experiment. A weight measuring device was designed using weighing method. The pure water and the brine water were drained from MDU into two tanks separately and the weight was measured by a digital weighing scale. A solenoid valve was installed at the bottom of each tank to empty the water at night. The instantaneous and accumulated water outflow can be measured automatically. Temperatures at solar collector exit (T_h), first plate of MDU (T_{p1}), and ambient (T_a) were measured using thermocouples. Solar radiation was measured using a pyrometer. The whole measurement is automatic and all the data are recorded by a recorder. All the measuring processes are controlled by PC. The sampling time interval is set at 1 min.

3. Test results

3.1. Daily performance of MEDS-1L under different weather conditions

MEDS-1L was installed on a building rooftop in Taipei. Measurement was started since early 2012. To simplify the experiment without frequent replacement of wick material (MDU), the inlet water used in the experiment was tap water from a reservoir on the rooftop of the building.

The feeding rate of MEDS-1L was regulated by a valve and set at 120–130 g/min, about twice the maximum production rate of the still, to avoid bubble formation and peer-off of wick material as described in Section 2.1. That is, the flow ratio of inlet water to pure water is in the range 1.3–3.0.

Fig. 13 shows the test result of MEDS-1L in sunny weather (2012/5/07). It is seen that the solar collector supply temperature T_h reaches 100 °C at solar radiation higher than 800 W m^{-2}, which is able to drive MDU in high productivity. T_h was 70 °C at solar radiation of 400 W m^{-2} in the early morning when MDU is still cold but at the same solar radiation intensity in the afternoon when MDU is hot, it became 80 °C. This is due to the effect of thermal mass of MDU. The daily-total pure water production (D_W) is 27.68 kg d^{-1}.

The test result of MEDS-1L in cloudy weather (2012/2/02) is shown in Fig. 14. The solar collector supply temperature T_h is always below 60 °C and pure water production (M_w) is low (1.19 kg d^{-1}).

The test result of MEDS-1L in sunny day with clouds (2012/3/01) is shown in Fig. 15. The first-plate temperature in MDU reaches 100 °C at

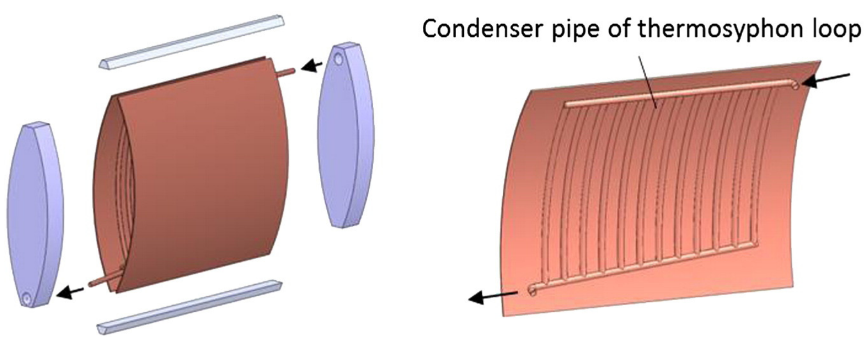

Fig. 8. Condenser of thermosyphon heat pipe connected to the first heating plate of MDU.

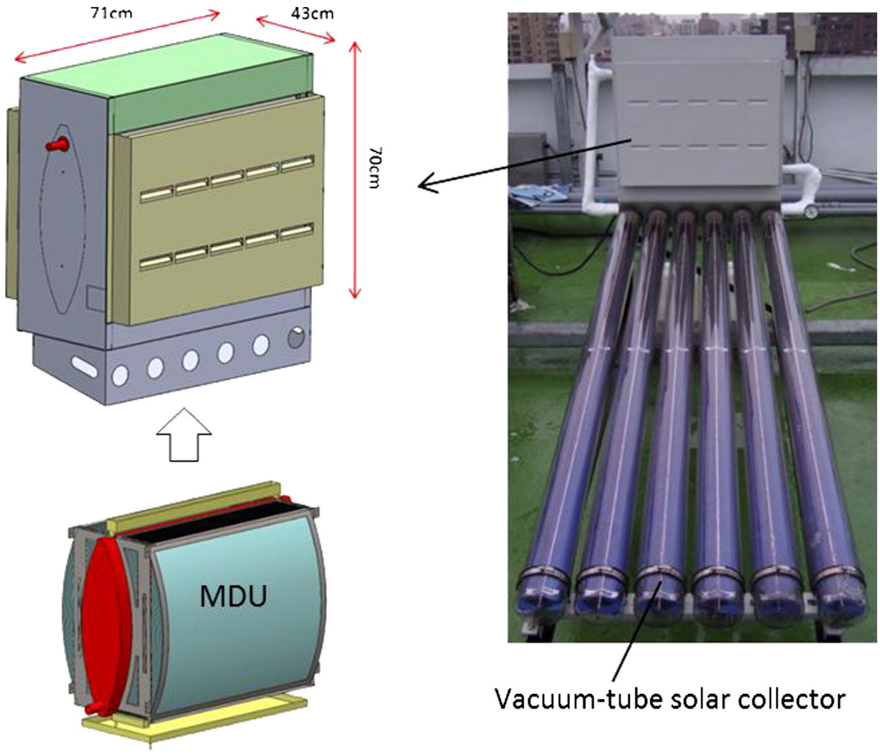

Fig. 9. Prototype of MEDS-1L.

high solar radiation which is able to drive MDU in high productivity. The daily-total pure water production (M_w) is 20.18 kg d^{-2}.

The test result of MEDS-1L in partly-cloudy weather (2012/5/14) is shown in Fig. 16. The solar collector supply temperature T_h exceeds 90 °C most of the time. The daily-total pure water production (M_w) is 25.96 kg d^{-2}.

3.2. Methods of long-term performance evaluation

The water productivity of a MEDS is related to the solar energy received by MEDS through the glass cover (larger glass cover receives more solar energy and increases productivity), the solar energy absorbed by the solar absorber (larger absorber area absorbs more solar energy and increases the productivity), and the evaporation rate from the evaporating surface of MDU (related to the efficiency of multiple-effect diffusion process of MDU). Therefore, we defined four kinds of performance indexes for the performance evaluation of MEDS.

First, following the method of Tanaka et al. [11], the measured daily pure water production (D_W) is converted into daily pure water production per unit area of glass cover (A_{cov}), M_{cov}, as shown in Eq. (1). M_{cov} represents the water productivity based on solar energy incident on MEDS at collector opening (aperture).

$$M_{cov} = D_W / A_{cov} \tag{1}$$

Since MEDS can be designed in variable configuration, the solar absorber area may be different from the sunlight aperture area, such as the basin-type MEDS of Tanaka et al. [11]. We define the daily pure water production per unit area of solar absorber, M_{sol}, as shown in Eq. (2). M_{sol} represents water productivity based on the solar energy absorbed (related to solar collector efficiency).

$$M_{sol} = D_W / A_{sol} \tag{2}$$

Since the multiple-effect diffusion efficiency of MEDS as well as the cost of MDU is related to the evaporation rate from the evaporating surface, we define the daily pure water production per unit area of

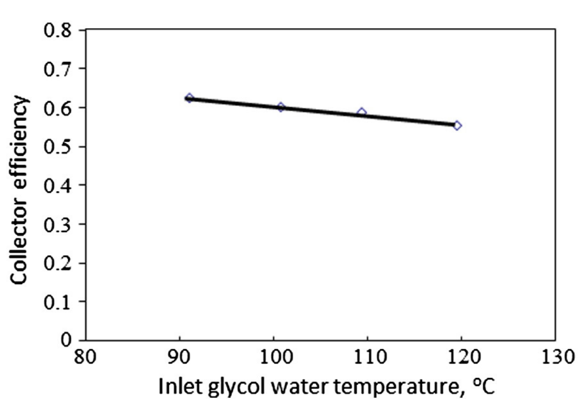

Fig. 10. Measured solar collector efficiency.

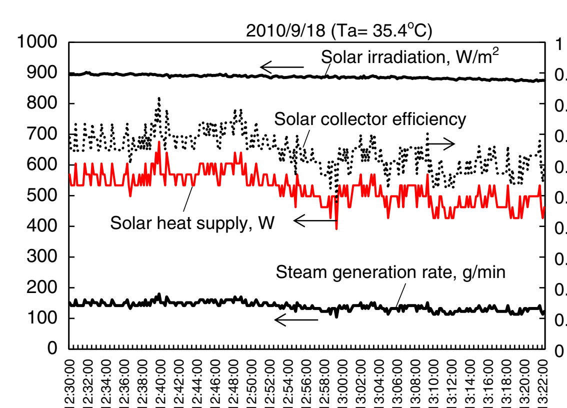

Fig. 11. Steam generation efficiency measurement of the vacuum-tube solar collector.

Table 2
Specification of the vacuum-tube solar collector used in MEDS-1L.

Model	EZL 100-6
Total absorber area	1.08 m^2 per module
No. of vacuum tubes	6
Collector tube dimensions	Φ100 × 2000 mm
Collector efficiency	0.615 at 120 °C

evaporating surface (A_{evp}), M_{evp}, as shown in Eq. (3). A_{evp} is the total area of evaporating surface such as wicks or solar pond. A_{evp} is also an index reflecting the cost.

$$M_{evp} = D_W / A_{evp} \tag{3}$$

In addition to the above three kinds of performance indexes of MEDS, we also defined the solar distillation efficiency of MEDS based on incident solar energy on the glass cover R_{cov}:

$$R_{cov} = h_{fg} D_W / (H_T A_{cov}) = h_{fg} M_{cov} / H_T \tag{4}$$

where h_{fg} is the latent heat of water; H_T is daily-total solar radiation incident upon glass cover of MEDS. R_{cov} is defined as the ratio of total energy required to produce the pure water to the total solar incident energy which is also called "the coefficient of performance (COP) of MEDS". M_{cov}, M_{sol}, M_{evp} and R_{cov} can be used to evaluate the performance of MEDS-1L and compare with the published results.

3.3. Long-term performance evaluation of MEDS-1L

The long-term performance test of MEDS-1L was started from January 2012. The daily-total pure water and brine water production were measured automatically using the measuring system described in Section 2.4. The data of daily pure water production were converted into M_{cov}, M_{sol}, M_{evp} and R_{cov} to compare with the published data of Tanaka et al. [11,17].

Tanaka et al. [11] built a basin-type, multiple-effect, diffusion-coupled solar still and measured the outdoor performance. The basin-type MEDS with 5-mm diffusion gaps and 11-effect (called "MEDS-Basin") produces 14.8–18.7 kg d^{-1} pure water per unit area of the glass cover at 20.9–22.4 MJ m^{-2} d^{-1} solar radiation incident on the glass cover. In the basin-type design, the evaporating surface for distillation process includes all the plates of 11-effect MDU and the basin (solar pond).

Tanaka et al. [15–17] proposed another MEDS design using a vertical MDU coupled with a heat-pipe and a flat-plate solar collector (called "MEDS-FHP"), which is similar to the present MEDS-1L. Tanaka and Nakatake [15] developed a theoretical model, including calculation of

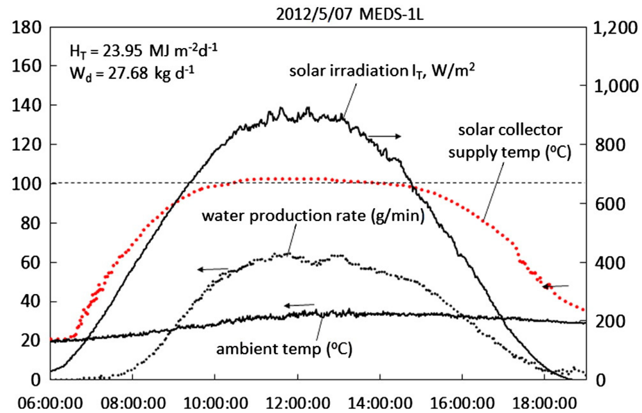

Fig. 13. Test result of MEDS-1L in sunny day (2012/5/07).

incident solar radiation intensity on a solar collector slope, to predict the performance of MEDS-FHP, which was later verified by an indoor experiment [16]. Using the theoretical model [15], Tanaka et al. [17] further carried out a parametric study for the performance at different design and operating conditions. On the summer solstice, the calculation of Tanaka et al. [17] shows that a MEDS-FHP with 11-effect and 5-mm diffusion gap produces 20.2 kg m^{-2} d^{-1} pure water with 27.4 MJ m^{-2} d^{-1} incident solar radiation at optimal collector angle (10°). At the fixed collector angle (26°) which is the latitude of the MEDS location, MEDS-FHP produces 18.5 kg m^{-2} d^{-1} pure water with 24.8 MJ m^{-2} d^{-1} incident solar radiation.

The test results of MEDS-Basin [11] and the theoretical calculation of MEDS-FHP [17], both obtained by Tanaka et al., are compared with the present outdoor test results.

3.3.1. Long-term performance evaluation based on M_{cov}

Fig. 17 shows the daily pure water production per unit area of glass cover M_{cov}. It is seen that the highest M_{cov} of MEDS-1L is 23.9 kg m^{-2} d^{-1} at H_T = 22.1 MJ m^{-2} d^{-1} which is about 29% higher than the test result of MEDS-Basin [11] (18.7 kg m^{-2} d^{-1} at H_T = 22.4 MJ m^{-2} d^{-1}) with 11-effect MDU. If the linear regression lines of test data were used to compare the performance difference, M_{cov} of MEDS-1L is 31% higher than that of MEDS-Basin [11] at H_T = 15.2 MJ m^{-2} d^{-1} and 13% higher at H_T = 22.4 MJ m^{-2} d^{-1}. Overall, M_{cov} of MEDS-1L is 19% higher than that of MEDS-Basin [11], as can be seen from Table 3 in which the regression lines of test data are used in the MEDS performance evaluation.

Table 3 also summarizes the performance comparison of MEDS-FHP [17] and MEDS-1L. It shows that the measured M_{cov} of MEDS-1L is higher than the calculation of MEDS-FHP [17] by 26%–29%.

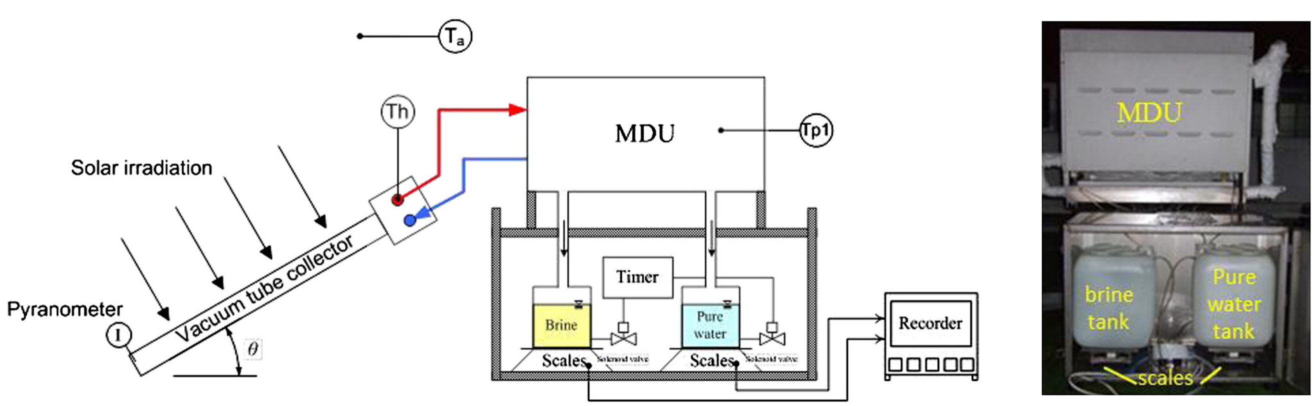

Fig. 12. Automatic measuring system for long-term performance of MEDS-1L.

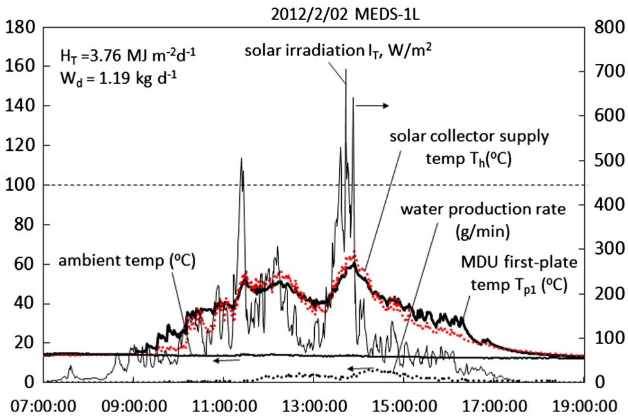

Fig. 14. Test result of MEDS-1L in cloudy weather (2012/2/02).

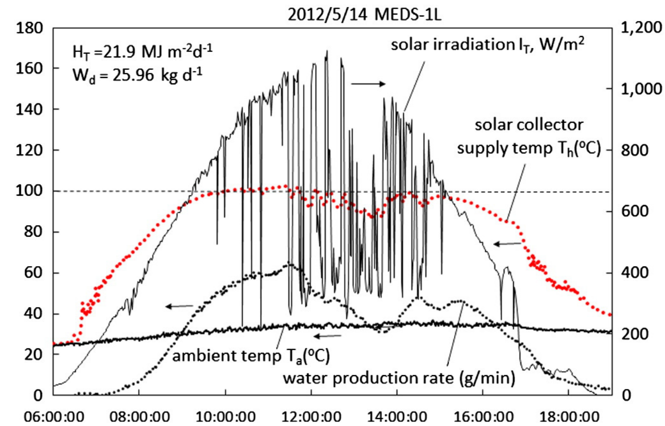

Fig. 16. Test result of MEDS-1L in partly-cloudy weather (2012/5/14).

3.3.2. Long-term performance evaluation based on M_{sol}

The water productivity per unit area of solar absorber, M_{sol}, is shown in Fig. 18. M_{sol} of MEDS-1L is much larger than that of MEDS-Basin [11]. The highest M_{sol} of MEDS-1L is 25.9 kg m^{-2} d^{-1} at $H_T = 22.1$ MJ m^{-2} d^{-1} which is about 102% higher than MEDS-Basin [11] (12.8 kg m^{-2} d^{-1} at $H_T = 22.4$ MJ m^{-2} d^{-1} with total solar absorber area of 2.25 m^2). The total solar absorber area of MEDS-1L is only 1.08 m^2 but MEDS-1L is more efficient in solar energy absorption because of the vacuum-tube solar collector. In overall average, M_{sol} of MEDS-1L is 89% higher than that of MEDS-Basin [11], as can be seen from Table 3.

It can be seen from Table 3 that the measured M_{sol} of MEDS-1L is higher than the calculation of MEDS-FHP [17] by 37%–40%.

3.3.3. Long-term performance evaluation based on M_{evp}

The water productivity per unit area of the evaporating surface, M_{evp}, is shown in Fig. 19. The highest M_{evp} of MEDS-1L is 2.79 kg m^{-2} d^{-1} at $H_T = 22.1$ MJ m^{-2} d^{-1} which is about 38% higher than the test result of MEDS-Basin [11] (2.02 kg m^{-2} d^{-1} at $H_T = 22.4$ MJ m^{-2} d^{-1}) with total evaporating surface area of 14.25 m^2 in the 11-effect MDU. The total evaporating surface of MEDS-1L is 10.02 m^2. This indicates that MEDS-1L is more efficient in the multiple-diffusion and evaporating process in still cell due to the higher temperature gradient. Overall, M_{evp} of MEDS-1L is 29% higher than that of MEDS-Basin [11], as can be seen from Table 3.

Table 3 also summarizes the performance comparison of MEDS-FHP [17] and MEDS-1L. It shows that the measured M_{evp} of MEDS-1L is higher than MEDS-FHP [17] by 63%–66%.

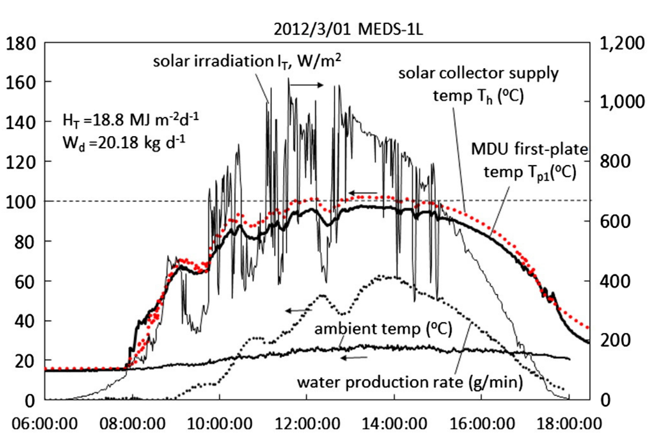

Fig. 15. Test result of MEDS-1L in sunny with cloudy weather (2012/3/01).

3.3.4. Solar distillation efficiency (coefficient of performance COP) R_{cov}

The energy efficiency of a MEDS can be represented by solar distillation efficiency R_{cov} which is "the coefficient of performance (COP) of MEDS" as defined in Eq. (4). It is seen from Fig. 20 that the highest R_{cov} of MEDS-1L is 2.44 at $H_T = 22.1$ MJ m^{-2} d^{-1} which is about 30% higher than the test result of MEDS-Basin [11] (1.88 at $H_T = 22.4$ MJ m^{-2} d^{-1}). R_{cov} of MEDS-1L is in the range 1.5–2.5, while the MEDS of MEDS-Basin [11] is 1.45–1.88 at higher solar radiation. In overall average, R_{cov} of MEDS-1L is 23% higher than that of MEDS-Basin [11], as can be seen from Table 3. This indicates that the higher temperature gradient produced by the vacuum-tube solar collector enhances the multiple-diffusion process in MDU.

It is seen from Table 3 that the measured R_{cov} of MEDS-1L is higher than the calculation of MEDS-FHP [17] by 45%–56%. Although the area of solar absorber and evaporating surface used in MEDS-1L is about half of MEDS-FHP, the solar distillation efficiency R_{cov} is 50% higher than MEDS-FHP.

4. Discussion

The MEDS made for outdoor test by Tanaka et al. [11] is a basin-type design integrated with an 11-effect MDU (MEDS-Basin). Solar energy is absorbed by the basin and the first vertical plate of MDU. No heat pipe was used. The outdoor test result of MEDS-Basin [11] was compared with MEDS-1L.

Another design (MEDS-FHP) proposed by Tanaka et al. [15–17] used a vertical MDU coupled with a heat-pipe and a flat-plate solar collector, which is similar to the present MEDS-1L. Using the theoretical model

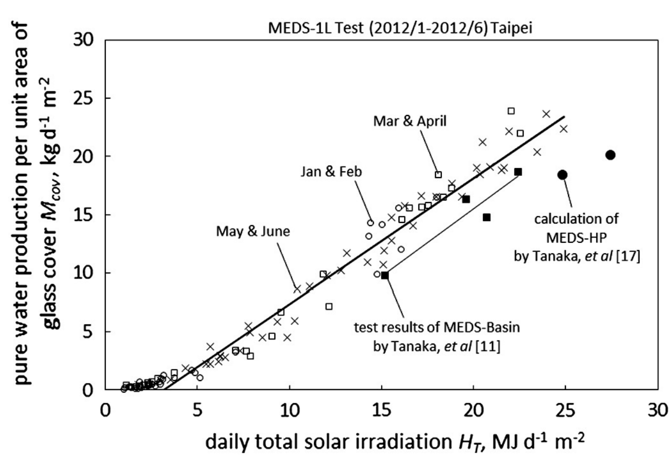

Fig. 17. Comparison of water productivity per unit area of glass cover.

Table 3
Performance comparison of MEDS-1L, MEDS-Basin [11], and MEDS-FHP [17].

	MEDS-Basin built by Tanaka et al. [11]	MEDS-FHP proposed by Tanaka et al. [17]	MEDS-1L built in the present study
Design parameters			
Glass cover area A_{cov}, m^2	1.54	2.0	1.17
Solar absorber area A_{sol}, m^2	2.25 [1.2(first plate);1.05(basin)]	2.0	1.08
Wick area per layer, m^2	1.2	2.0	0.278 (580mm x 480mm)
Still cell gap, mm	5	5	6
Number of effects	11	11	18
Total evaporating surface area A_{evp}, m^2	14.25 [13.2(wick);1.05(basin)]	22	10.02

Daily-total solar irradiation on glass cover H_T, MJ m^{-2} d^{-1}	Water productivity D_w, kg d^{-1}	Daily water productivity per unit area, kg m^{-2}d^{-1} M_{cov}	M_{sol}	M_{evp}	Solar distillation efficiency R_{cov}	Water productivity D_w, kg d^{-1}	Daily water productivity per unit area, kg m^{-2} d^{-1} M_{cov}	M_{sol}	M_{evp}	Solar distillation efficiency R_{cov}
Comparison between MEDS-Basin [11] and MEDS-1L both from the regression lines of test data										
15.2	15.3	9.93	6.80	1.07	1.48	15.4	12.98 (+31%)	14.06 (+107%)	1.52 (42%)	1.81 (+22%)
19.6	23.2	15.05	10.30	1.63	1.71	20.7	17.73 (+18%)	19.20 (+86%)	2.09 (+28%)	2.11 (+23%)
20.7	25.1	16.33	11.17	1.76	1.77	22.0	18.91 (+16%)	20.49 (+83%)	2.21 (+25%)	2.18 (+23%)
22.4	28.2	18.30	12.53	1.98	1.86	24.1	20.75 (+13%)	22.48 (+79%)	2.43 (+23%)	2.29 (+23%)
						Average improvement	+19%	+89%	+29%	+23%
Comparison between MEDS-FHP [17] (theoretical result) and MEDS-1L (from the regression lines of test data)										
24.8 (Summer solstice) (fixed collector angle 26°)	37.0	18.5	18.5	1.68	1.68	27.0	23.34 (26%)	25.28 (+37%)	2.73 (+63%)	2.43 (+45%)
27.4 (Summer solstice) (optimal collector angle 10°)	40.4	20.2	20.2	1.84	1.66	30.1	26.14 (29%)	28.32 (+40%)	3.06 (+66%)	2.59 (+56%)

[15], Tanaka et al. [17] further theoretically found that on the summer solstice, MEDS-FHP with an 11-effect and 5-mm diffusion gap produces 20.2 kg m^{-2} d^{-1} pure water with 27.4 MJ m^{-2} d^{-1} incident solar radiation at optimal collector tilt angle (10°). At the fixed collector angle (26°) which is the latitude of the MEDS location, MEDS-FHP produces 18.5 kg m^{-2} d^{-1} pure water with 24.8 MJ m^{-2} d^{-1} solar radiation. The measured M_{cov}, M_{sol}, M_{evp} and R_{cov} of MEDS-1L are higher than the calculation of MEDS-FHP [17] by 26%–66%, although the area of solar absorber and evaporating surface used in MEDS-1L is about half of MEDS-FHP.

Although MEDS-FHP was not actually built and tested outdoors [17], the above comparison can prove that the use of the vacuum-tube solar collector in MEDS-1L is the key factor for the increase of performance. MEDS-1L uses less areas of the evaporating surface and a narrower MDU design with 18-effect. The higher temperature gradient produced by the vacuum-tube solar collector makes MEDS-1L perform better.

The feeding rate to MEDS is important in the performance of MEDS [17]. The feeding rate of MEDS-1L was regulated by a valve and set at 120–130 g/min, about twice the maximum production rate of the still, to avoid bubble formation and peer-off of wick material as described in Section 2.1. That is, the flow ratio of inlet water to pure water is in the range 1.3–3.0.

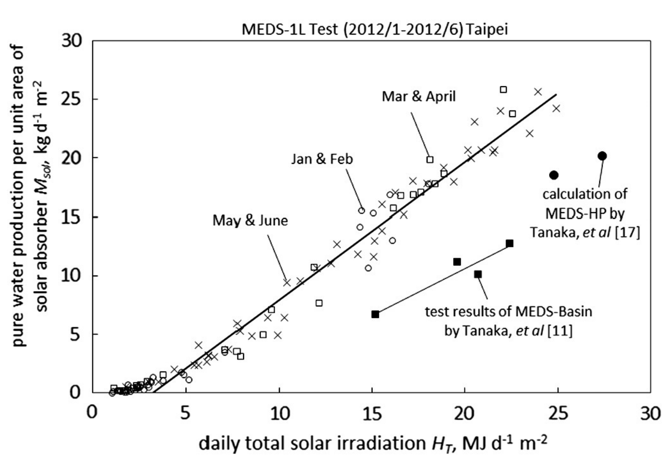

Fig. 18. Comparison of water productivity per unit area of solar absorber.

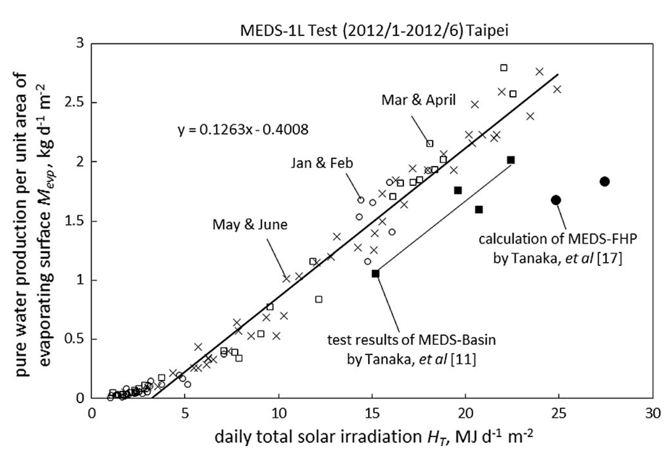

Fig. 19. Comparison of water productivity per unit area of evaporating surface.

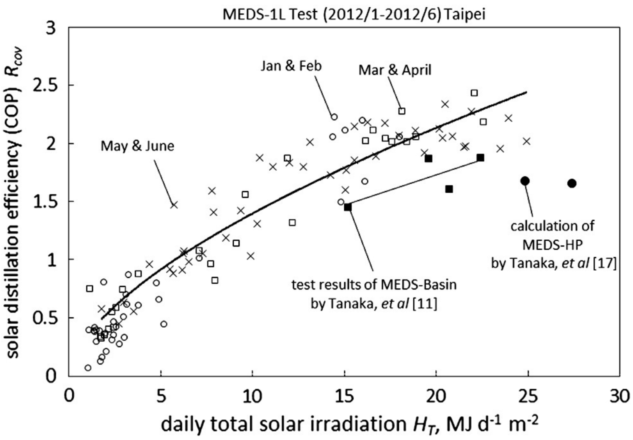

Fig. 20. Solar distillation efficiency comparison of MEDS-1L, MEDS-Basin [11], and MEDS-FHP [17].

The pure water contamination was not found in the present test since the feeding rate was carefully controlled such that no bubble formation and dry-out occur in the wick. We performed a simple test using dyed (colored) water in feed flow and observed no contamination in pure water.

No leakage of brine into pure water was observed since the flow path of MDU is carefully designed and manufactured as described in Section 2.1. We also did not observe any flow to the pure water collector at night.

The effect of wick scaling on performance needs a long-term observation. For the test period of MEDS-1L in 6 months, we observed no significant performance degradation. Nevertheless, a regular replacement of wick material in MDU is always necessary if using seawater or sewage. The modular-type design of the present MDU makes it easy for the replacement of wick material.

Loss of feeding water to MEDS due to water supply failure needs to be carefully treated in order to avoid burn-out of wick and damage of heat pipe due to very high temperature supply from the vacuum-tube solar collector in sunny weather by accident.

It has been shown that a MEDS-1L coupled with one set of solar collectors (1.08 m^2) can produce a maximum of 27.9 kg per day pure water in sunny weather, which is enough to supply drinking water for about 8 people in a day. The purchase price of the vacuum-tube solar collector used in MEDS-1L is around USD400 per set (absorber area 1.08 m^2) which is about two times of a flat-plate collector. The material cost of MDU and heat pipe is around USD150. It is expected that the mass production cost of the whole MEDS-1L will be around USD800. The cost can be reduced if the design of MEDS-1L is improved by modifying the design of MDU for better efficiency.

5. Conclusions

Conventional MEDS design uses a flat heating plate laminated with wick material. The heating plate deformation and peel off of wick material from the plate cause low water productivity and reliability. The flat-plate solar collector is used to supply heat which cannot reach higher temperatures. The productivity is thus lower due to a limited temperature gradient in MDU.

The present study develops a MEDS with a bended-plate 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 heat to the MDU. The test results of MEDS-1L show that in sunny weather, the solar collector supply temperature T_h reaches 100 °C at solar radiation higher than 800 W m^{-2}. T_h reaches 80 °C at solar radiation of 400 W m^{-2}. The highest daily pure water production area (D_W) obtained is 27.9 kg d^{-1}.

Four kinds of performance indexes of MEDS are proposed in the present study for the performance evaluation of MEDS, including the daily pure water production per unit area of glass cover, solar absorber, and evaporating surface (M_{cov}, M_{sol}, M_{evp}, respectively), and the solar distillation efficiency (COP) R_{cov}.

The highest M_{cov} of MEDS-1L is 23.9 kg m^{-2} d^{-1} which is about 29% higher than MEDS-Basin [11]. The highest M_{sol} of MEDS-1L is 25.9 kg m^{-2} d^{-1}, about 102% higher than MEDS-Basin [11]. The highest M_{evp} of MEDS-1L is 2.79 kg m^{-2} d^{-1}, about 38% higher than MEDS-Basin [11]. The highest R_{cov} of MEDS-1L is 2.44, about 30% higher than MEDS-Basin [11]. The measured R_{cov} of MEDS-1L is 1.5–2.44, while MEDS-Basin [11] is 1.45–1.88, at high solar radiation.

It is also found that the measured M_{cov}, M_{sol}, M_{evp} and R_{cov} of MEDS-1L are higher than the calculation of a heat-pipe coupled MEDS-FHP [17] by 26%–66%.

The comparison of test results with published results [11,17] using four performance indexes verifies that the present MDU coupled with the vacuum-tube solar collector is able to raise the temperature gradient of MDU and increase the pure water productivity. The reduced heat loss using symmetric design of MDU is another factor to reach high productivity. The bended-plate design of MDU causes no peel-off of wick and pure water contamination. No performance deterioration was observed in the continuous operation for 6 months. Further study is required in improving the design of MDU to increase the productivity of MEDS.

Nomenclatures

A_{cov}	total area of glass cover in MEDS, m^{-2}
A_{evp}	total evaporating surface area for vaporization in MDU, m^{-2}
A_{sol}	total solar absorber area for collecting solar energy, m^{-2}
h_{fg}	latent heat of water, kJ kg^{-1}
H_T	daily-total solar irradiation on glass cover, MJ m^{-2} d^{-1}
I_T	instantaneous solar irradiation on glass cover, W m^{-2}
M_{cov}	daily-total pure water production per unit area of glass cover, kg d^{-1} m^{-2}
M_{evp}	daily-total pure water production per unit area of evaporating surface, kg d^{-1} m^{-2}
M_{sol}	daily-total pure water production per unit area of solar absorber, kg d^{-1} m^{-2}
D_W	daily-total pure water production, kg d^{-1}
R_{sol}	daily-total solar distillation efficiency (COP) of MEDS
T_a	ambient temperature, °C
T_h	solar collector supply temperature to MDU, °C
T_{p1}	MDU first-plate temperature, °C

Acknowledgment

This publication is based on work supported by Award No. KUK-C1-014-12, made by King Abdullah University of Science and Technology (KAUST), Saudi Arabia, and by Grant No. NSC101-2221-E-002-067-MY2, Ministry of Science and Technology, Taiwan.

References

[1] M.A.S. Malik, G.N. Tiwari, A. Kumar, M.S. Sodha, Solar Distillation, Pergamon Press, Oxford, 1982. 59–71.
[2] K. Tanaka, Doctoral Thesis, Keio University, Yokohama, Japan, 1985. 1–26.
[3] H. Tanaka, Doctoral thesis, University of the Ryukyus, Okinawa, Japan, 2001, 4–24, 33–46.
[4] R.V. Dunkle, Solar water distillation: the roof type still and a multiple effect diffusion still, International Heat Transfer Conference, Part 5, University of Colorado, 1961, pp. 895–902.
[5] P.I. Cooper, J.A. Appleyard, The construction and performance of a three effect wick type tilted solar still, Sun Work 12 (1) (1967) 4–8.

[6] M.M. Elsayed, K. Fathalah, J. Shams, J. Sabbagh, Performance of multiple effect diffusion stills, Desalination 51 (2) (1984) 183–199.
[7] S. Toyama, T. Aragaki, K. Murase, K. Tsumura, Simulation of a multiple-effect solar distillator, Desalination 45 (1983) 101–108.
[8] S. Toyama, T. Aragaki, H.M. Salah, K. Murase, Dynamic characteristics of a multistage thermal diffusion type solar distillator, Desalination 67 (1987) 21–32.
[9] H.M. Yeh, S.W. Tsai, N.T. Ma, Proc. 22nd Intersociety Energy Conversion Engineering Conference, August 10–14, Philadelphia, Pennsylvania, 4, American Institute of Aeronautics and Astronautics, New York, 1987, pp. 1723–1727.
[10] B. Bouchekima, B. Gros, R. Ouahes, M. Diboun, Performance study of the capillary film solar distiller, Desalination 116 (1998) 185–192.
[11] H. Tanaka, T. Nosoko, T. Nagata, Experimental study of basin-type, multiple-effect, diffusion-coupled solar still, Desalination 150 (2) (November 1 2002) 131–144.
[12] T. Nosoko, T. Kinjo, C.D. Park, Theoretical analysis of a multiple-effect diffusion still producing highly concentrated seawater, Desalination 180 (2005) 33–45.
[13] Development of Desalination Technology Using Multiple-Effect Diffusion Solar Distillation Method, Annual Report, Water-Reuse Center Foundation, 1985.
[14] Hiroshi Tanaka, Experimental study of vertical multiple-effect diffusion solar still coupled with a flat plate reflector, Desalination 249 (2009) 34–40.
[15] Hiroshi Tanaka, Yasuhito Nakatake, A vertical multiple-effect diffusion-type solar still coupled with a heat-pipe solar collector, Desalination 160 (2004) 195–205.
[16] Hiroshi Tanaka, Yasuhito Nakatake, Masahito Tanaka, Indoor experiments of the vertical multiple-effect diffusion-type solar still coupled with a heat-pipe solar collector, Desalination 177 (2005) 291–302.
[17] Hiroshi Tanaka, Yasuhito Nakatake, Katsuhiro Watanabe, Parametric study on a vertical multiple-effect diffusion-type solar still coupled with a heat-pipe solar collector, Desalination 171 (2004) 243–255.