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Parametric performance test of distiller utilizing solar and waste heat

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ABSTRACT

A seawater distiller utilizing the thermal energy of solar radiation and waste gas from a small electric generator was designed and constructed with a number of configurations to improve its performance. The distiller constructed is a combined model of a basin-type solar still and a vertical multiple-effect diffusion still, consisting of a series of closely spaced parallel plates in contact with saline-soaked wicks. Evaporation and condensation processes were repeated on all the plates by recycling thermal energy to increase distillate productivity in the still. Tests were performed with waste heat of actual exhaust gas from a portable electric generator, changing various experimental conditions such as feeding flow rate of seawater to the wicks, seawater level of the basin, and use of reflecting plate fins. Experimental results show that our two-effect distiller produces 17.1–19.6 kg/(m^2 d) at 3,000 kJ/h and has a Performance Ratio of 14.8–16.9.

Keywords: Desalination; Distiller; Design; Experiment; Solar; Waste heat

1. Introduction

Desalination capacity worldwide has rapidly increased in the last decade because of the rapid growth of world population, the increase in water demand, the decrease in water resources and a significant reduction in the cost of desalination. Presently, the total global desalination capacity is around 66.4 million m^3/d and it is expected to reach about 100 million m^3/d by 2015 [1]. The growth rate of the desalination market is currently about 55% per year [1], a truly stunning figure. It is expected that the total desalination market will reach over US$31 billion by 2015 [2]. About 50% of all desalination investments are for Seawater Reverse Osmosis projects with large plant capacity due mainly to its lower investment and total water cost compared to other conventional source developments, and also to its footprint size and to continuing technological advances. However, major desalination technologies such as distillation and reverse osmosis (RO) have been developed mainly for application to large-capacity water production plants. Scale-up of production capacity of desalination plants is indeed a suitable process to decrease costs of fresh water production. But by the same token, as the production capacity of desalination plants is designed on a smaller and smaller scale, the total cost of water obtained by conventional desalting technology such as RO increases rapidly.

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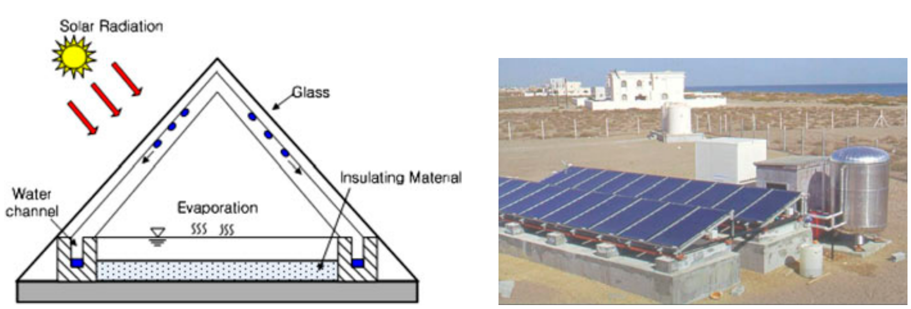
There are still many regions worldwide which do not have water and electricity infrastructure. In such places, like remote areas, islands and developing countries, a large-scale desalination plant is not appropriate due to high initial construction cost, operation and maintenance cost, and/or skills [3]. Undeveloped regions without an electricity grid uses electric generators of small (portable) or medium capacity, and demand a small amount of fresh water, generally less than 200 m^3/d. The desalination technology suitable for these situations may be considered as a distributed-type small facility utilizing renewable energy and/or waste heat from the engine of the generator. The solar distillation method is the oldest and most conventional technology used to turn salt water into fresh water. The solar still and solar distillation facility equipped with a solar thermal collector (STC), heat accumulator and heat exchanger, as shown in Fig. 1, are popular types of solar-powered desalination unit.

The solar still is the oldest type of desalination unit and is still used at present because of its high reliability and maintainability, its simple structure and its low unit cost. However, it has the severe disadvantage of low productivity. The typical productivity of a simple solar still is reported not to surpass 4 L/d per unit area [4]. This low performance is the highest obstacle to its being used widely. Therefore most researches on solar distillers have focused on increasing their productivity. The solar distiller with STC shown in Fig. 1(b) is a promising construction having higher productivity than the simple solar still. It is reported that an MSF powered by a parabolic trough collector can produce fresh water up to 10–60 L/(m^2 d) [5]. However, a solar distiller with STC consists of an STC, heat accumulator, heat exchanger, water generator and vacuum device, and has to be a sealed structure to maintain low pressure inside the evaporation space. These characteristics of the solar distiller with STC result in an increased installation cost and decrease of maintainability compared to the solar still. These two problems are real hurdles when this type of distiller is installed in remote areas where people generally lack the skills of operation and maintenance. Maintainability is the overriding obstacle, making most facilities obsolete in a few years after initial installation regardless of the type of facility. Therefore, installing a general device for such areas should take into consideration simplicity and maintainability as well as installation cost and performance.

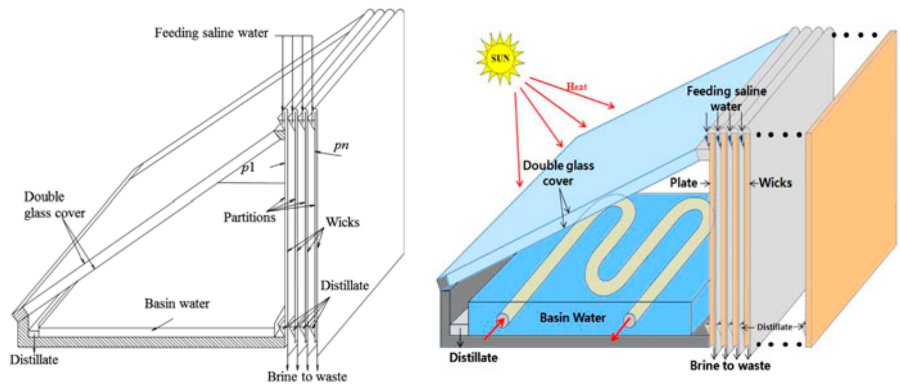
Since Telkes [6] proposed a multiple-effect diffusion (MED) still, using solar radiation effectively in the distillation, many researchers have endeavoured to improve its performance and feasibility, because MED solar stills have great potential for productivity and thermal efficiency. An MED still consists of a series of closely spaced parallel plates and wicks. Evaporated vapour condenses on the front surface of the plates, and latent heat of condensation conducts through them and evaporates seawater flowing down along wicks attached on the rear surface of each plate. The vapour evaporated from the first wick is diffused across a thin layer of air between the plates and condenses on the front side of the second plate. This condensate flows down to be gathered in a water pocket installed at the bottom of each plate. These processes of evaporation, vapour diffusion, condensation and conduction are repeated up to an optimum number of effects.

Fig. 2(a) shows an MED solar still combining the STC and the diffusion still into one. Such MED solar stills with glass covers have been extensively studied theoretically and experimentally. Tanaka et al. [7] showed experimentally that a still with 11 effects produces 14.8–18.7 kg/d distillate per unit effective area of the glass cover at 20.9–22.4 MJ/(m^2 d) solar radiation incident and 19–30 ℃ ambient air temperature. Tanaka et al. [8] showed theoretically that the MED solar still coupled with a heat-pipe solar collector



(a) Simple solar still **(b)** Solar distiller with solar thermal collector

Fig. 1. Examples of solar-powered desalination unit.



(a) Basin-type MED solar still **(b)** Basin-type MED solar still with back-up heat source

Fig. 2. MED still.

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.

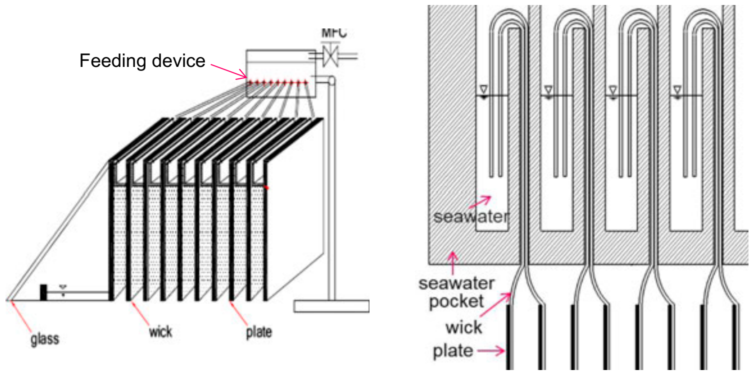
Most previous studies have focused on improvement of the productivity of the still by changing its structure, design and operation parameters. Obviously, these kinds of updated stills improved performance when compared to the 4 kg/(m^2 d) of a simple solar still. However, these studies seldom went to the stage of commercialization of the still because its structure is fairly complicated, and also the feeding device of the saline water into the wick is not easy to construct and involves difficulty in controlling the optimum flow rate. Moreover, they did not consider a backup system such as a subsidiary heating system, which is usually necessary for solar systems and which increases the feasibility of solar stills.

In this research, we have tried to further improve the performance of the solar still by modifying its structure and to increase its feasibility by simplifying the structure and incorporating a backup system. We are expecting that these improvements and simplifications may be a step to commercialization of the still.

2. Experiment

This study started with a design of the MED solar still which can combine a heat recovery device as a backup to the solar-powered system. In remote areas, an electric generator with a small internal combustion engine is commonly used and the waste gas from this engine has been proved to be a possible heat source for distillation [9]. Therefore, we have designed the MED solar still with a basin where waste heat is recovered by heat exchange between the basin seawater and exhaust gas from the engine, as shown in Fig. 2(b). The heat exchanger in the basin seawater was designed based on the exhaust gas temperature and flow rate, and the seawater temperature at steady-state which is almost the same as that of the exhaust gas after heat exchange inside the basin. We employed heat transfer fins on the tubes of the heat exchanger to expedite heat recovery from the exhaust gas of the engine. The upper surfaces of these fins are processed with mirror-polishing so that they reflect the solar light incident on the basin area to the first plate of the MED component. Most vapours evaporated from basin seawater emit their latent heat into the ambient air resulting in condensation on the inclined glass. Therefore, solar energy incident on the basin works as a so-called one-effect, while solar energy incident on the first plate together with latent heat of condensation on the first plate works as a multiple-effect by repeating conduction through the plates, evaporation, vapour diffusion, condensation and conduction through the next plate again. Therefore, refection of solar light hitting the basin onto the first plate may provide further improvement of the overall productivity of our MED solar still. We named these fins *reflecting fins* because they work as both a reflecting plate and a heat transfer fin.

As stated in the Introduction, the seawater feeding device and the method of feeding to the MED component are carefully selected with a view to commercialization through simplification of the whole still. The temperature of each plate in the MED component decreases with heat transfer direction, i.e. from the first plate to the last plate, so that an optimum flow rate of feeding saline water exists for each plate. Tanaka et al. [7] employed a feeding distributor that can feed saline water at different flow rates to each wick using different lengths of capillary tubes, as



(a) Feeding device with capillary tubes **(b)** Simplified feeding device

Fig. 3. Feeding devices of saline water to wick.

shown in Fig. 3(a). However, temperature difference between neighbouring plates is at the most about 2–3 °C at typical operating conditions of the still. Moreover, the seawater pocket at the top part of each plate has to be fabricated in a space of 5 mm which is set as the diffusion length of vapours evaporated from wick in the MED component. This narrow space gives rise to difficulties in fabrication method and selection of materials for the seawater pocket from the point of view of robustness and long term reliability for application in remote locations. Therefore, we have simplified the seawater pocket and feeding distributor as shown in Fig. 3(b). Two wicks of neighbouring plates share one pocket, which allows various options for robust fabrication of the pocket and plate assembly.

A narrower space between plates increases greatly the productivity of distillate [10]. However, there are a few obstacles to making the gap narrower. One of these is the problem of maintaining a constant gap distance throughout the entire area of $1 \times 1\,m^2$ plates. The plate is apt to deform because of various factors such as plate weight, thermal deformation and locally applied force during handling for fabrication. Therefore, we have employed nine spacers between the plates to narrow the gap to a distance equal to the theoretical droplet radius of water on the vertical wall, which is the theoretical limit of the gap required to avoid contamination between the saline water and condensate.

The basin-type MED solar still in Fig. 2(b) consists of a 10-effect still that has 11 plates and 10 wicks. The glass cover has a $1 \times 1\,m^2$ effective area and a 45° inclination from the horizontal floor. Therefore, the projected area of our distiller is $0.772\,m^2$ including the area of the MED component of $0.055\,m^2$. Temperatures of the still are measured with 106 T-type thermocouples attached to the condensation surface of each plate, feeding saline water, surroundings, glass cover, basin seawater, humid air and exhaust gas from the engine. The flow rate of the exhaust gas is measured with a mass flow meter (SF-586b at Softflow.de) having an accuracy of ±1%. Insolation is recorded with a pyranometer of PSP model from the Eppley Company. All the measured data are collected with DAQ of NI-PXI and SCXI.

Experimental parameters in this study are feeding flow rate of saline water to wick, m_f, seawater level in the basin, L_w, heat input to the basin, Q_{in} and the presence of *reflecting fins*. Seawater level, L_w ranged 30–10 mm in consideration of the height, 25 mm, of the heat exchange tube in the basin, which is too deep to operate the typical solar still. Other parameters related to operation and design of the still will be handled in future experiments. One of the purposes of the present study is to find optimal operation and design conditions for our MED solar distiller under given weather conditions or at a given heat input. However, parametric testing with solar energy requires many repetitions of the experiment over a long term because insolation energy varies day by day and even from moment to moment. It is nearly impossible to create the same conditions of solar energy input for a parametric test. Therefore, we have performed the test with waste heat from the engine as a heat source simulating solar radiation. A movable sun-blocking enclosure was used to eliminate sun and wind effects on the experimental results.

3. Experimental results

Distillate amount from the MED component depends mainly on heat input onto the first plate, while distillate from the second to the eleventh plate has a consistent tendency to show a certain rate of decrease. Therefore, a parametric experiment was performed with a two-effect still assembly.

Fig. 4 shows variation in the first plate temperature T_{p1} with feeding flow rate of saline water m_f, at a given heat input Q_{in}. The T_{p1} ranges from 80 to 73˚C at $m_f = 9.5$ ccm (cubic centimetre per minute) and decreases with increasing m_f under all Q_{in} conditions. Therefore, it is easy to predict the optimum feeding flow rate m_f that does not cause dry-out on the wick and gives the maximum plate temperature as well as maximum distillate at each plate.

Figs. 5 and 6 show the effects of the reflecting fins on the recovered heat Q_{in}, on temperatures of basin seawater T_{sw} and on outlet exhaust gas $T_{\text{gas,out}}$. Installation of the reflecting fins does not seem to increase the Q_{in} apparently when the gas inlet temperature $T_{\text{gas,in}}$ is fixed at 283˚C. This is considered to be attributable to increase of the gas outlet temperature $T_{\text{gas,out}}$ by the installation of the fin as shown in Fig. 6. The reflecting fins also increase the basin seawater temperature T_{sw} by almost 10˚C. The fins are not considered to increase the Q_{in} and therefore the amount of distillate when the heat source of the distiller is waste heat from exhaust gas, because the area for heat transfer through stainless tubes is already designed to be sufficient to recover the waste heat. However, the fins do seem to increase heat flux to the basin seawater, resulting in a large rise in T_{sw}. The effect of the reflecting fins on the Q_{in} and m_d in the case of solar radiation as heat source may be higher than in that of waste heat because the

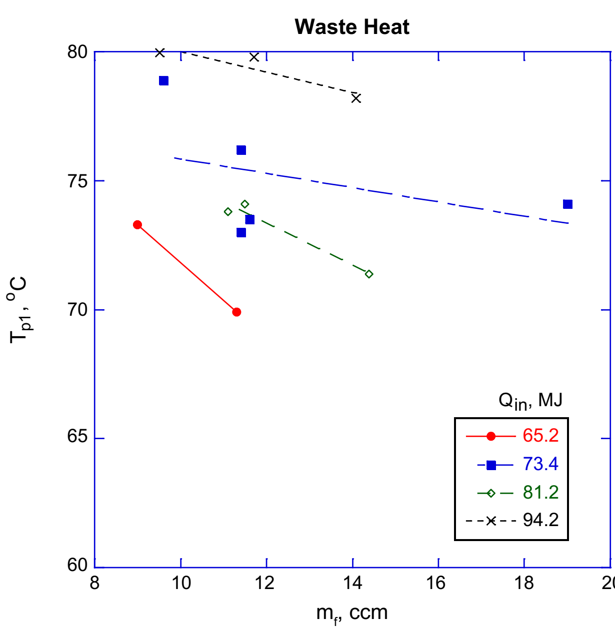


Fig. 4. Variation of the first plate the temperature T_{p1} with flow rate of feeding saline water, m_f.

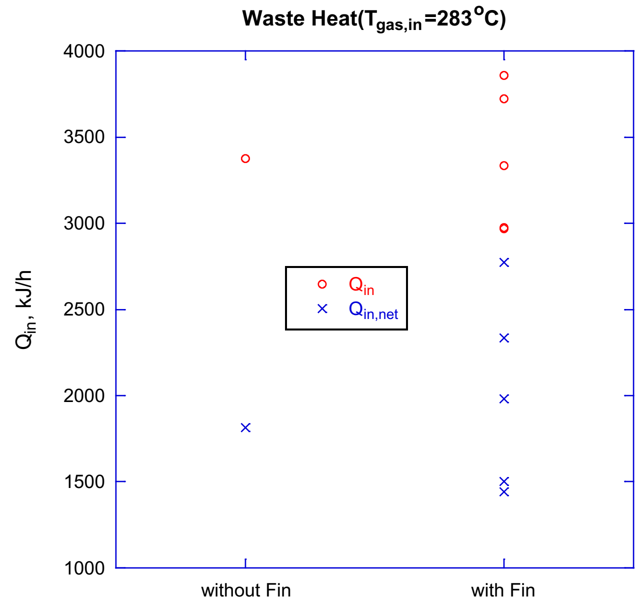


Fig. 5. Effect of reflecting fins on Q_{in}.

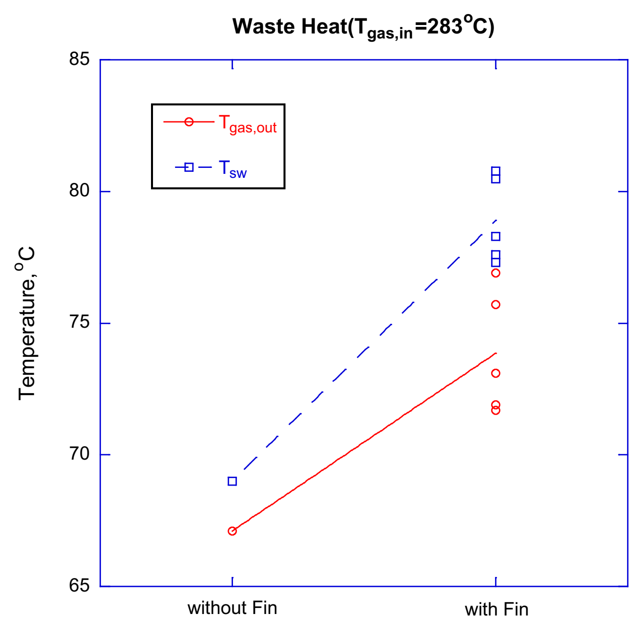


Fig. 6. Effect of reflecting fins on $T_{\text{gas,out}}$ and T_{sw}.

reflecting fins may increase the input heat to the first plate by reflecting the insolation into the basin to the first plate, and therefore the performance of the MED component will be enhanced, resulting in enhancement of the overall performance of whole distiller.

Fig. 7 shows the temperatures of basin seawater T_{sw}, humid air in the basin component T_{ha} and the

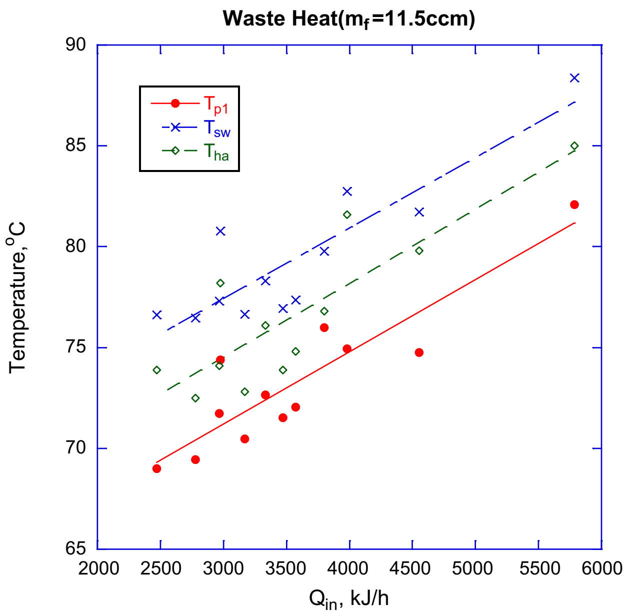


Fig. 7. Basin part temperatures with Q_{in}.

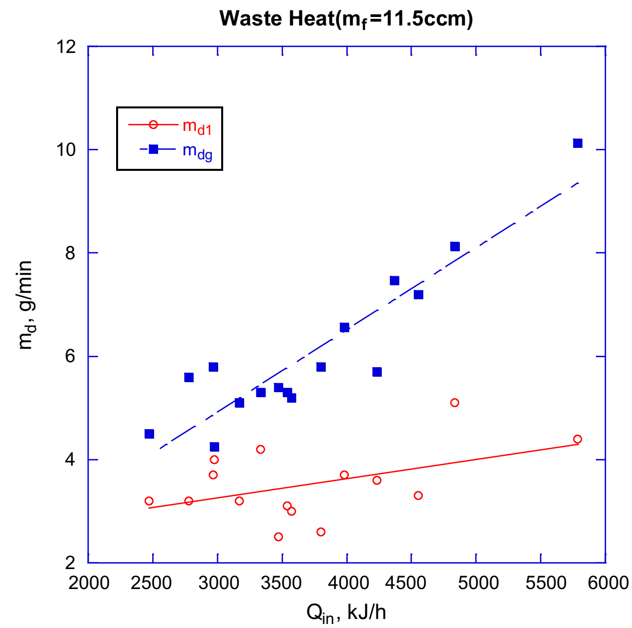


Fig. 8. Basin part distillates with Q_{in}.

first plate T_{p1} with input heat Q_{in} at m_f = 11.5 ccm. All the temperatures have similar increasing slopes and increase almost linearly with Q_{in}, ranging T_{sw} = 76–88℃ and T_{p1} = 69–82℃. It is interesting that the relative order of the temperatures is $T_{\text{sw}} > T_{\text{ha}} > T_{p1}$, reflecting the transfer route of heat recovered by basin seawater from waste gas. This relative order may differ in the case of a solar heat source because solar radiation hits the first plate directly.

Fig. 8 shows distillate productivity of the basin component with Q_{in} at m_f = 11.5 ccm. The distillate of the inclined glass cover, m_{dg} and the distillate of the first plate, m_{d1} both increase with Q_{in}, but the rate of increase of m_{d1} is much lower than that of m_{dg}. Amount of distillate of m_{dg} is much larger than m_{d1} and the difference becomes larger with increasing Q_{in}. This may be attributed to the diffusion direction of evaporated vapour. The first plate is installed in a vertical direction that is parallel to the diffusion direction of most vapours evaporated.

Fig. 9 shows the total distillate m_d by a 2-effect still with Q_{in} at m_f =11.5 ccm, which is a summation of m_{dg}, m_{d1}, and the 2nd plate distillate m_{d2}. Productivity m_d increases linearly with Q_{in} to about 21 kg/d at Q_{in} = 5,800 kJ/h. Our distiller can expect to produce 12.2–14.1 kg/d (17.1–19.6 kg/(m^2 d)) at Q_{in} = 3,000 kJ/h, although it is only a two-effect distiller and heat insulation is not perfect. The distiller shows a Performance Ratio (PR) of 14.8–16.9, the definition of which is shown in Eq. (1).

$$\text{PR} = \frac{m_d (hfg + C_p\, dT)}{Q_{\text{in}}} \tag{1}$$

where h_{fg} is latent heat of condensation and $C_p\, dT$ is sensible heat of water.

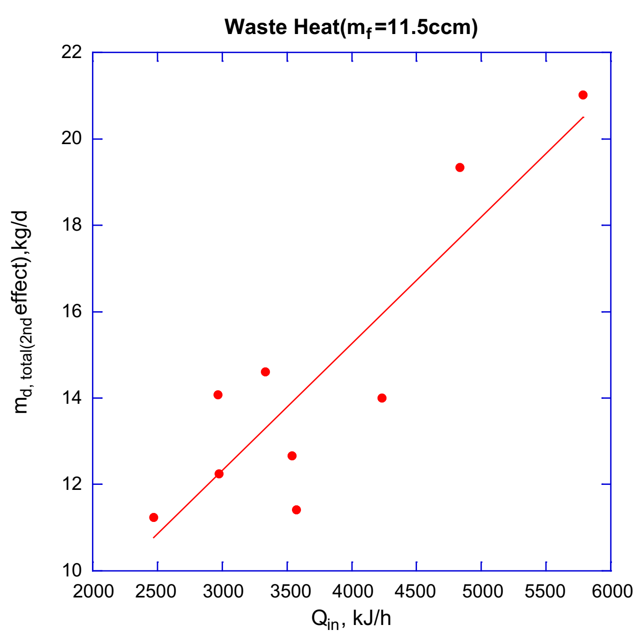


Fig. 9 Total distillate of two-effect still with Q_{in}.

4. Conclusions and discussion

We have designed and constructed a basin-type MED solar distiller with a back-up heat source recovered from the exhaust gas of a portable electric generator. We have tried to improve the performance and feasibility of the solar distiller in order to move forward to commercialization. Our distiller shows experimentally productivity of 17.1–19.6 kg/(m^2d) at Q_{in} = 3,000 kJ/h and PR of 14.8–16.9, although it is only a two-effect distiller. This amount will be much larger in the case of 10-effect distillation. We believe that these performance figures, the simplified feeding device for saline water, and the back-up heat source will give better chances for commercialization. However, there are still many future issues to address, such as the optimum feeding flow rate with various heat inputs from the viewpoint of distillate amount, and the effect of basin seawater level on heat recovery rate. It is also necessary to perform the experiment with a solar thermal source, which will show the primary effect of the reflecting fins.

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