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IMPROVING WATER PRODUCTIVITY OF THE HYBIRD DESALINATION SYSTEM

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Abstract:

An integrated desalination system with a combination of electrical heating by power supply and solar heating by Fresnel lens with sun tracking system was investigated in this study. The experiments were carried out under the climatic conditions of Kaohsiung City (22°36'58" N, 120°18'47" E), Taiwan. With only solar heating by Fresnel lens, the temperature of the seawater is strongly dependent on the position of the seawater tray and climatic conditions, and seawater evaporation is not stable. To maintain the uniform evaporation of seawater, an electrical heating plate was also used to provide energy for the desalination process. The results indicate that the production of distilled water is greatly improved with this solar/electrical desalination system. At a power of 60W, the commercial energy efficiency of the system can reach 85 %, and the recovery efficiency can approach 56.52 %. Additionally, a higher annual productivity (6036 L) is obtained, and the cost per liter of distilled water is about 0.152 (US$/L).

Keywords: *Desalination, Solar energy, Sun tracking system, Energy efficiency.*

1. Introduction

The problem of freshwater shortage has been one of the main challenges of mankind. According to a United Nations Organization report [1], throughout the early to mid-2010s, about 1.9 billion people lived in areas where water was potential severely scarce, and by 2050 this could increase to some 2.7 to 3.2 billion. This situation can be tackled only if mankind finds additional methods to produce freshwater.

With over 71 % of the earth's surface area covered by oceans, restoring freshwater from seawater is considered the most reliable method. This method is based on modern desalination technologies with high efficiency, such as reverse osmosis (RO), membrane distillation (MD), multi stage flash distillation (MSF), multi effect distillation (MED) [2]. However, one problem that hinders the wide application of all desalination technologies is the high energy consumption. In addition, using fossil fuel feeding will contribute to the crisis of air pollution, and rising fuel prices will also increase the total operating cost.

For countries that lie in the high solar insolation band, desalination based on solar energy presents a sustainable alternative to using fossil fuel. This technology is especially cheap because it uses cost-free energy and does not have any serious impact on the environment. However, the efficiency of traditional solar thermal desalination technologies is only in the range of 30-40 % [3]. Therefore, in the present study, the electrical heating module and the solar heating module are integrated together to improve energy efficiency, maintain stable water productivity and decrease the cost of production. Additionally, the effects of different system operating conditions, such as electrical input power and evaporation temperature, on the desalinated water production rate, energy efficiency, annual productivity, and cost per liter of distilled water are experimentally investigated to evaluate the feasibility of this solar/electrical desalination system.

2. Experimental setup and theoritical analysis

In this study, experiments are carired out on a hybrid desalination system, which consists of four main components: a vaporization chamber, a solar heating subsystem, an electrical heating subsystem, and a measuring system. The schematic diagram of experimental setup is shown in Figure 1. The structure of the desalination system is depicted in Figure 2. This desalination system is integrated by a solar heating module and an electrical heating module to form the solar/electrical heating desalination system (SEHDS).

In order to understand the energy consumption and distilled water production of system, a single point load cell (Xiamen LoadCell Technology Co., Ltd.), and pyranometer (SONG YIH TECHNOLOGY CO., Ltd.) are used to measure the weight of the distilled water, and the solar irradiation power from the sun, respectively. Additionally, the thermocouples are also used to measure the ambient temperature ($T_{Outdoor}$), temperature of seawater inside vaporization chamber ($T_{Seawater}$), and the temperature of copper plate/heater (T_{Copper}). After that, all measured signals in experimental processes will be transmitted to the data recorder system PR20 (Brainchild Electronic Co., Ltd.) for the real-time monitoring of all measured data.

For a desalination unit, the annual productivity (M_{Yearly}), the annual cost of the system (AC) and the total annual electricity consumption cost of the system (TEC) are the main factors used in the cost analysis. In this study, the cost per liter of the distilled water (CPL) of the system will be determined as follows [4]:

$$CPL = \frac{AC + TEC}{M_{Yearly}} \tag{8}$$

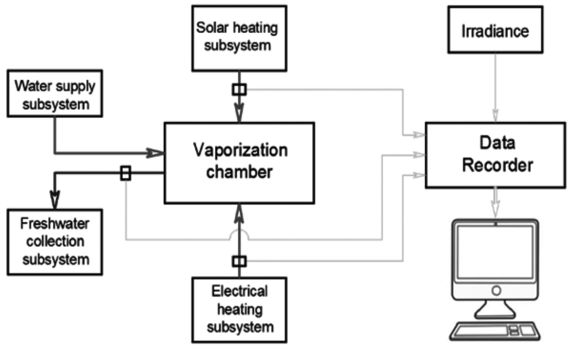

Figure 1. Schematic diagram of the SEHDS

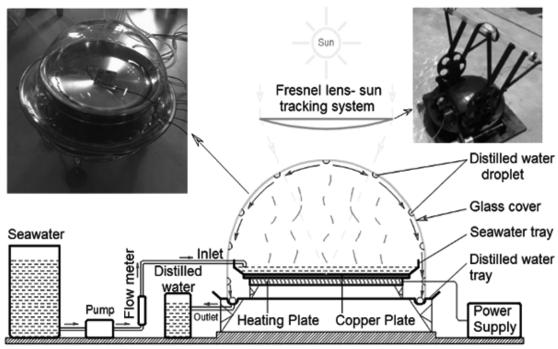

Figure 2. Schematic diagram of the desalination system

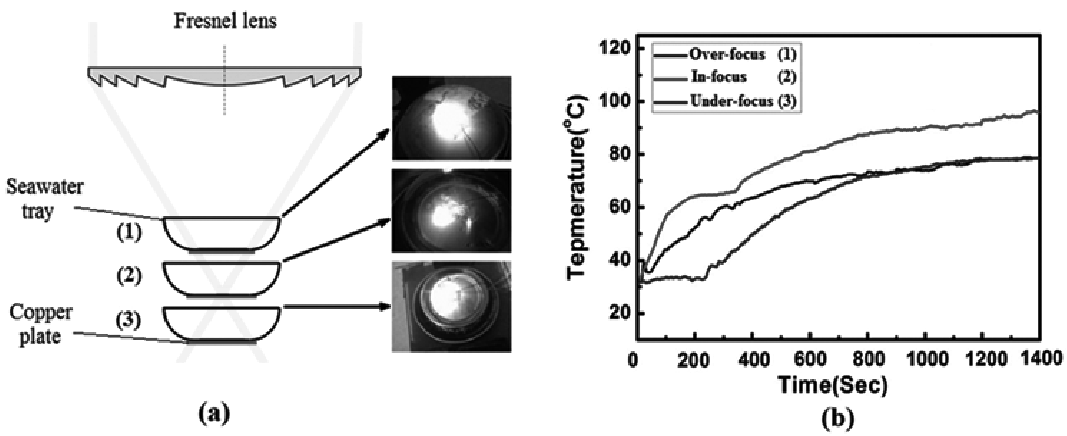

Figure 3. (a) The position of seawater tray at (1) over-focus (2) in focus and (3) under-focus of Fresnel lens and (b) the temperature profiles of seawater by solar heating with Fresnel lens at different positions of seawater tray

3. Results and discussion

3.1. The effect of the position of the seawater tray

In this experiment, a convergent Fresnel lens (the area and focal point of Fresnel lens is 729 cm^2 and 30 cm, respectively) is used to determine the optimum distance from the Fresnel lens to the seawater tray. Figure 3(a) presents the temperature profile of seawater in the seawater tray with different three positions: (1) over-focus, (2) in-focus, and (3) under-focus of Fresnel lens. The results indicate that the temperature of seawater in the seawater tray is highest if the seawater tray is put on the focus of Fresnel lens (in-focus) as shown in Figure 3(b). Hence, in the following experiments, we all put the seawater tray on the focus of Fresnel lens.

3.2. The effect of solar heating, electrical heating, and the combination of both solar heating and electrical heating on the desalination system

In this study, there are three heating modes for the desalination experiment: solar heating by Fresnel lens; electrical heating with a power supply; and a combination of both solar heating and electrical heating subsystems.

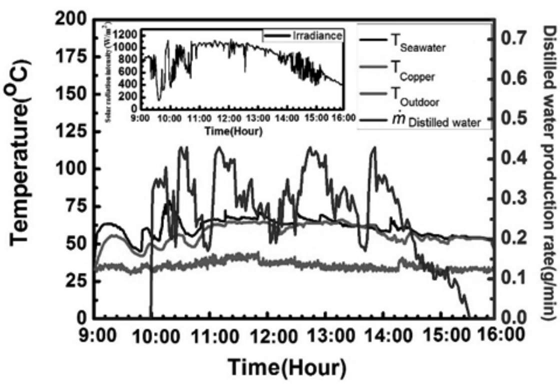

Figure 4. The variation of seawater temperature, temperature of the copper plate, and distilled water production of desalination system with solar heating mode on May 20, 2018

With solar heating by Fresnel lens alone, the productivity of water is influenced by climatic conditions such as solar radiation, ambient temperature, and cloud isolation [5]. Indeed, Figure 4 shows that in the early stages of solar heating, from 9:00 to 10:30, the intensity of solar irradiation was unstable due to the influence of clouds, and the seawater temperature $T_{Seawater}$ oscillated noticeably in the range of 45 °C to 75 °C. After 10:30, the seawater temperature increased slightly as the intensity of solar irradiation increased. In this solar heating mode, the seawater temperature is more stable than the solar irradiation profile because of the high heat capacity of the copper plate under the seawater tray, but strongly depends on the solar irradiation. At the beginning of the experiment, from 9:00 to 10:00, there was no production of distilled water. The input of solar energy was used to raise the temperature of both the initial and replenished seawater in the vaporization chamber. At 10:00, distilled water began to be produced as the seawater began to evaporate from the surface. As shown in Figure 4, in the period from 10:00 to 14:00, the distilled water production was higher, but the distilled water production rate was very unstable because a little cloud blocking or gusts of wind made the solar irradiation unstable. Besides, the temperature of seawater in seawater tray was also reduced as seawater was added. These factors lead to a great variation in the seawater temperature, which causes instability in the distilled water production. After 15:30, the distilled water production decreased because of cloud blocking and the decrease of solar irradiation. Moreover, with the addition of seawater, the solar heating power was not enough to maintain the desalination process. Therefore, although solar power was being collected by the Fresnel lens, the distilled water production after 15:30 was zero.

For electrical heating mode with a power supply alone, as shown in Figure 5, the results indicate that the seawater temperature in the seawater tray was almost entirely dependent on the heat supplied by the heating plate, and the variation profiles of seawater temperature and copper plate temperature had marked similarity. In the experiment, the heating power can be change by the power supply, at an electrical heating power of 60 W, the seawater temperature reached the boiling point (102 °C). The vaporization of seawater was intense due to the boiling of the seawater that occurred at this heating power, which was high enough to supply enough energy for both the replenished and original seawater to reach the boiling point quickly. The temperature profile of the seawater in the seawater tray was also more stable than that of solar heating mode. As a result, the distilled water production increased significantly to reach about 0.75 (g/min), and the system recovery efficiency and the energy efficiency achieved were 34.3 % and 51.62 %, respectively. The results also indicate that distilled water production is strongly dependent on electrical power, especially at 60 W, because this power can maintain the seawater temperature at the boiling point.

At a heating power of 60 W with the addition of solar energy source, the boiling of seawater occurred, and the temperature profile of seawater is also more stable than that of solar heating mode as shown in Figure 6. In this state (saturation condition), the temperature of the water no longer increases and seawater absorbs the heating energy to vaporize. The solar heating energy from the Fresnel lens was thus absorbed by the seawater, accelerating its rate of vaporization. As a result, the distilled water production rate of the SEHDS increased dramatically to reach 1.2 (g/min), and it increased about 1.6 times compared to the electrical heating system alone. Table 1 shows the recovery efficiency of the system that is defined as the ratio of the total mass of distilled water output over the total mass of seawater input, and the energy efficiency of the system (η_E) that is determined by the ratio between the total energy required for the vaporization process to the total energy supplied for the system during operation process. With only solar heating (heating power is zero), the recovery efficiency and energy efficiency were 9.65 % and 18.5 %, respectively. However, by adding solar heating, the recovery efficiency of the SEHDS reaches 56.52 %. Moreover, as also shown Table 1, because the SEHDS uses a solar energy source without any cost, the commercial energy efficiency (η_{CE}) is greater than the energy efficiency. The commercial energy efficiency of the SEHDS reached 85.13 % with a power of 60 W. This is significantly higher than the energy efficiency (51.62 %) of the system using only electrical heating.

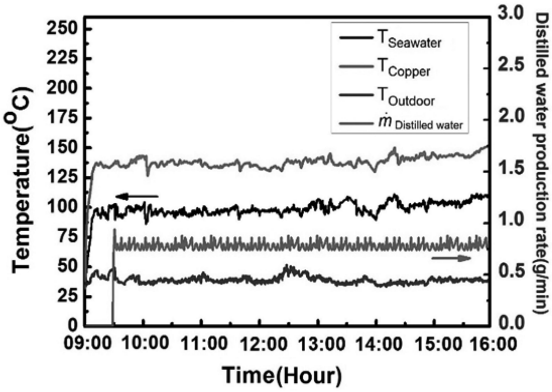

Figure 5. The variation of seawater temperature, temperature of the copper plate, and distilled water production of desalination system with electrical heating mode at the power of 60 W

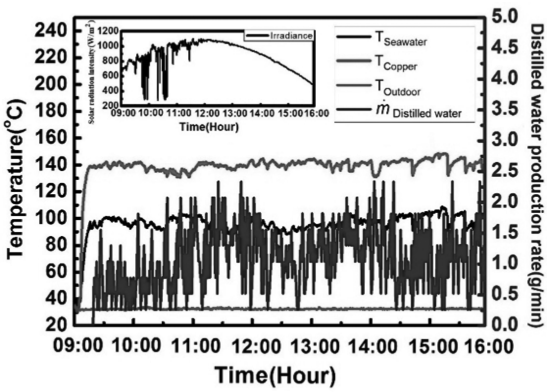

Figure 6. The variation of seawater temperature, temperature of the copper plate, and distilled water production of SEHDS system at an electrical power of 60W on May 22, 2018

Table 1. The recovery efficiency, energy efficiency and commercial energy efficiency of desalination systems

Item / Heating Power	Recovery efficiency		Energy efficiency		
	Only electrical heating energy	SEHDS	Only electrical heating energy	SEHDS	
				η_E	η_{CE}
0W	-	9.65%	-	18.50%	-
60W	34.3%	56.52%	51.62%	51.4%	85.13%

3.3. The feasibility of the system

Table 2 shows the CPL and M_{Yearly} comparison between the SEHDS and other solar desalination systems [5, 6-7]. The results indicate that the desalination system which integrates solar heating with the electrical heating module has higher annual productivity than others.

Table 2. The cost comparison with other different desalination systems

S. No	Type of solar desalination system	M_{Yearly} (L)	CPL (US$/L)
1	SEHDS system (present article)	6036	0.152
2	Thermoelectric solar still [6]	180	0.18
3	Passive solar still-single slope [5]	1043	0.024
4	Passive solar still (sun tracking)-single slope [7]	958	0.071

In terms of the production cost of distilled water, the CPL of the SEHDS system is about 0.152 (USD/L). The results indicate that the CPL of distilled water in this study is higher than with solar heating alone. However, as also illustrated in Table 2, when this system is compared with solar desalination systems with thermoelectric condensation devices, the CPLs are very similar but the SEHDS has better annual productivity. The annual productivity of SEHDS is six times higher than the average annual productivity of traditional solar desalination systems because it can continue to operate in unfavorable climatic conditions.

4. Conclusion

In this study, the integration of solar heating and electrical heating for seawater desalination (SEHDS) was investigated. At a power of 60 W, and the addition of solar energy source, the distilled water production rate of the SEHDS system is improved significantly. It increases by about 1.6 times compared to that of the system that uses only electrical heating. The annual productivity of the SEHDS is six times higher than the average annual productivity of traditional solar desalination systems. With the energy efficiency and recovery efficiency of the SEHDS is about 51.4 %, and 56.52 %, respectively. Moreover, the commercial energy efficiency of SEHDS reaches 85 %, much higher than the energy efficiency of 51.62 % of the system that uses only electrical heating at the same power. Therefore, in this study, the solar/electrical heating desalination system (SEHDS) can increase distilled water productivity and reduce production expense based on the efficient exploitation of solar energy and electrical heating energy.

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NÂNG CAO NĂNG SUẤT NƯỚC CỦA HỆ THỐNG KHỬ MUỐI LAI

Tóm tắt:

Nghiên cứu này được thực hiện để đã khảo sát một hệ thống khử mặn tích hợp là sự kết hợp giữa một mô đun gia nhiệt bằng năng lượng điện với một mô đun gia nhiệt bằng năng lượng mặt trời sử dụng thấu kính Fresnel với hệ thống theo dấu mặt trời. Các thí nghiệm được thực hiện trong điều kiện khí hậu tại thành phố Cao Hùng (22°36'58" N, 120°18'47" E), Đài Loan. Khi chỉ sử dụng mô đun gia nhiệt bằng năng lượng mặt trời, nhiệt độ của nước biển phụ thuộc nhiều vào vị trí của khay nước và điều kiện khí hậu nên sự bốc hơi nước biển không ổn định. Để duy trì sự bay hơi đồng đều của nước biển, một tấm gia nhiệt điện đã được sử dụng để cung cấp năng lượng cho quá trình khử muối. Kết quả cho thấy, việc sản xuất nước tinh khiết được cải thiện rõ rệt với hệ thống khử muối lai này. Ở công suất nguồn 60 W, hiệu suất năng lượng thương mại của hệ thống có thể đạt 85 % và hiệu suất phục hồi có thể đạt 56,52 %. Bên cạnh đó, mục đích nâng cao năng suất hàng năm của hệ thống cũng đã đạt được (6036 L) với chi phí cho mỗi lít nước tinh khiết giảm còn khoảng 0,152 (US $ / L).

Từ khóa: *Khử muối, năng lượng mặt trời, hệ thống theo dấu mặt trời, hiệu quả năng lượng.*