Performance Analysis of a Solar Desalination System with Concentrated Solar Power (CSP)

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Abstract. Malaysia, being located around the tropical belt, enjoys ample solar exposure throughout the year. Harnessing solar energy for different application is making progress nationwide. Besides extending research in the photovoltaic, the solar water heating is slowly progressing through the past decades and nowadays most newly developed residential areas are equipped with solar water heaters. The Malaysia Plan has been steadfast in incorporating green growth and the 11th Malaysia Plan puts “Pursuing Green Growth for Sustainability and Resilience” as one of the strategic thrusts in line with United Nations Sustainable Development Goals (SDG).

Freshwater for living is a pressing concern already and will become a dire emergency in the coming years as according to United Nations (UN), half of the earth’s population could be facing water shortages by 2030 [1]. Rapid depletion of fossil fuel only adds more misery to the situation as most of the water treatment or desalination processes are energy intensive. According to the UN, if the natural environment continues to be degraded and sustainable measures are not taken, 45 percent of the global
gross domestic product, 52 percent of the world’s population and 40 percent of global grain production will be at risk by 2050[2].

Solar desalination is the renewable resource driven desalination technology which will become the next sustainable method of water production. Among different forms of solar energy, the thermal energy is more suitable for desalination [3]. Solar still is among the simplest form of solar desalination processes which consists of a basin containing saline/brackish water with an inclined glass/translucent lid through which the solar heat enters and produces vapour from the contaminated water due to partial pressure and temperature difference between the basin and the glass lid. The generated vapour is condensed on the inner side of the inclined glass/translucent lid and collected as the distillate. The solar irradiation, basin water depth, inclination of the lid are the major factors influencing the production. Solar stills produce high quality but low quantity potable water [4] and are categorized as direct solar desalination method.

In general, solar stills can be classified in two major categories, namely passive solar still and active solar still [5]. In a passive solar still, the solar radiation is the only source of heating with a lower productivity while, in active solar still, an extra energy source (for example, photovoltaic sources) is associated to increase the evaporation rate and in turn to enhance the productivity. Over the past decades solar stills have been modified to achieve the optimized performance in terms of design and advanced materials. Significant amount of work has been reported on using a double/multiple slope solar still to optimize the exposure to solar irradiation [6, 7, 8] and [9]. Using solar power concentration method through parabolic trough or Fresnel lens has been a recent practice [10], [11]. A recent study by a tubular solar still associated with parabolic concentrator shows a significant performance of 3.53L/m² day over 2.953L/m² day from conventional single slope solar still [12].

Although most of the solar power concentrators work using the parabolic arrangement, the parabolic mirrors or the reflectors requires high fabrication cost. According to [13], Fresnel lens could be an alternative to the high cost parabolic solar concentrator. In the recent years, flat concentrators are making their way into solar research [14], [15], [16]. It has been found that flat Fresnel type collectors can achieve a minimum 60% energy saving for both domestic hot water usage and high temperature solar cooling and hot water applications[17]. The low cost Fresnel collectors have a good chance to progress as a promising technology in solar desalination.

In this work, a linear Fresnel concentrator has been associated to the transparent cover of a prototype solar still. The performance between conventional single slope solar still and CSP associated single slope solar still has been compared. The objectives of the research is to identify the effect of flat Fresnel lens on the water yield from solar stills with the aim to increase the water yield of conventional solar still with economic consideration. It has been found from experiments that compared to a plain transparent cover, the Fresnel associated cover has been able to produce 92% more distillate with high quality.

2. Theory
Theoretically, utilizing concentrated solar power (CSP) apparatus, more solar energy could be collected to the solar still. According to [18], solar concentrator concentrates solar energy from a larger surface on a smaller surface, creating a hot spot on the receiver. This reduces heat loss area, thus increasing the overall thermal gain. Hence, better performance of solar still can be achieved. This can be explained from equation (1).

\[ Q_u = [A_r \rho \sigma \tau I(t) - A_r U_i (T_{basin} - T_{ambient})] \]  

Where, \( Q_u \) = Energy collected from solar concentrator (W), \( A_r \) = Area of aperture (m²), \( A_r \) = Concentrated area of receiver, (m²), \( \rho \) = Reflectance of receiver/basin, \( \alpha \) = Absorber transmissivity, \( \tau \) = Absorber absorptivity, \( I(t) \) = Solar radiance, W/m², \( U_i \) = Overall heat loss coefficient.

Area of aperture is the total area of the CSP apparatus, while area of receiver is the area of the concentrated solar ray exposed on the receiver. This indicates that the solar receiver will receive more thermal gain compared to regular flat-plate solar collector. The thermal energy will be transferred to
water. As more thermal energy transferred to the saline water, evaporation of heated saline water is increased as found in equation (2)

\[ Q = m H_v \]

(2)

Where, \( Q \) = heat supplied, (kJ), \( m \) = mass of water vaporized, (kg), \( H_v \) = Latent heat or enthalpy of water vaporization, (kJ/kg)

3. Methodology and Work Plan

Single slope single basin solar still is chosen as the base model of the prototypes for its simple design, ease of fabrication. The study has been conducted in Kuala Lumpur, Malaysia. According to [19], the average global horizontal irradiation around the selected location is ranged from 1680 to 1753 kWh/m². In this study, two similar single slope single basin solar stills will be placed under exposure of the sun for 6 hours in a day for 4 days, with and without the Fresnel collector.

3.1. Model Fabrication

The design of the model and the prototype is shown in Figure 1(a) and (b) respectively. The models consist of 2 part and is detachable to make cleaning and refilling easier. Table 1 summarizes the dimensions.

Two sample rigs were fabricated based on the specifications. The flat-plate solar collector is made out of food-graded transparent plastic lining while the basin is made from polystyrene for its thermal insulation. The frame of the solar collector is covered with plastic sheets with insulating properties to trap the solar energy inside the solar still. In short, the design aims to reduce the heat loss from the basin. A PVC pipe is placed beneath the end of the slope to collect the condensate. Concentrated solar collector installed on the model is a Fresnel lens. The Fresnel lens has an area of 400x300 mm², with a focal length of 510 mm and light intensity of 92%. The prototypes above has been placed under sun for two
days in order to find the potential error such as leakage and deformation. Water yield testing was conducted after the prototypes showed no problem during the pre-test.

3.2. Water Yield Experiment Setup
Saline water is used as feed water inside the basin. The simulated saline water was prepared from mixing tap water and sodium chloride salt in a ratio of 1000 to 35 in grams to achieve the standard salinity of 35 parts per trillion (PPT), which is the average salinity of seawater. 5 litres of this simulated saline water is poured into each solar still models. The solar still models are placed in a garden that is wide open and is free from obstacles. The solar receiver used in the solar stills are aluminium wool to increase the heat transfer.

3.3. Water Conductivity Test
According to the World Health Organization, the drinking water TDS standard must be below 500 parts per million (PPM). Theoretically, the water yield from solar still is in the distilled form, but conductivity test must be made to prove that the condensate is safe to drink. Each sample from the saline water and condensate is tested with the table top conductivity metre.

4. Results and Discussion
The models were placed at the same spot under the exposure of sun for 6 hours, starting from 12.00 p.m. to 6.00 p.m. The models were tested for 4 days intermittently because of the rainy days. The result of the water yield from the prototypes is compared to identify the performance of both solar still models.

![Figure 2. Temperature distribution of the Saline Water](image)

The temperature of the water inside the basin has been recorded during the first day of the test. It is found that the solar still model with Fresnel lens harnesses more solar energy as the temperature of the model has average of 28.3% higher than the model without flat-plate solar collector. It can be anticipated that with more solar energy concentrated on a spot, more thermal energy can be transferred to the water, hence, higher evaporation rate. Figure 2 shows the temperature distribution throughout the day.

Another finding of this test is that the water temperature of the solar still model with Fresnel lens has relatively unstable temperature flow compared to the model with flat-plate solar collector. This is due to the movement of the sun throughout the day. In other words, CSP solar collector is very sensitive to optical factor and hence the weather condition, sun movement and location must be considered during design of solar still. It was found that the temperature of the saline water in the CSP associated solar still is higher than conventional flat plate solar still. As mentioned, the higher temperature resulted in higher evaporation rate and thus more distillate was obtained.

4.1. Water Yield Result
From the result, it has been found that the CSP associated solar still has a higher water yield compared to that from the still without Fresnel lens. An average of 92% increment in distillate has been observed.
This can be explained as the Fresnel lens concentrate the solar energy on the solar receiver, increasing the heat transfer of the hot spot to the water, thus increases the heat gain of the water. Eventually, when the heat gain is higher than the heat loss of the saline water to the ambient, more thermal energy is contributed to the evaporation of saline water. Figure 3 shows the distillate collected from the stills for 4 days. It may be concluded that, the larger the difference between heat gains and heat loss of the water, the higher is the evaporation rate. Following equation (1), with a larger CSP lens more thermal energy could be harnessed. The heat gain and heat loss should have a significant difference to maintain a higher distillate production with the size of the solar receiver remaining unchanged.

4.2. Water Conductivity Result
The water conductivity was measured by table top conductivity metre. The table top conductivity metre was rinsed with distilled water to ensure no error before making a new measurement. Other than that, temperature is another factor that influenced the conductivity test. The result of water conductivity test is listed in table 2.

| Solution    | Temperature, (°C) | Conductivity, (µS) | Total Dissolved Solid, (PPM) |
|-------------|-------------------|--------------------|------------------------------|
| Saline Water| 26.1              | 2982               | 1911.5                       |
| Condensate  | 25.4              | 39                 | 25                           |

From the result, it is seen that the condensate’s TDS value is 25 PPM, which meets the standard of drinking water very well. This proves that the fresh water yield from the solar still is drinkable with some preferable post-treatment.

5. Conclusion
The distillate yield test and conductivity test have been conducted successfully. Performances of two single slope single basin solar stills with and without Fresnel lens have been tested and compared. From the results it is found that Fresnel lens based CSP increases the average water yield of solar still. An average increment of 92% in water yield has been recorded in 4 days.

The behaviour of the temperature distribution using different solar collectors has been identified as well. It is found that the temperature gain of the CSP utilized solar still is relatively unstable compared to flat-plate solar collector. However, the CSP associated solar collector contributed in rising the average temperature of saline water by 28.3% higher compared to the plain solar still. Thus, even though it is optically sensitive, CSP is capable to concentrate more heat on a spot, making heat transfer between the solar receiver and saline water more effective.

During the investigation, it is found that the highly sensitive CSP solar receiver may results in unstable heat gain. Longer duration of solar exposure with proper insulation and associated thermal
storage such as phase changing material (PCM) could be the solution for the stable thermal gain. Solar still associated with flat-type CSP collector and PCM could be studied in the future research.

References
[1] B. ki Moon, “Water Summit 2013,” in Opening Speech, 2013.
[2] U. Nations, “Sustainable Development Goal 6 Synthesis Report on Water and Sanitation,” 2018.
[3] “Solar-thermal powered desalination: Its significant challenges and potential,” Renew. Sustain. Energy Rev., vol. 48, p. 152–165.
[4] H. Sharon and K. S. Reddy, “A review of solar energy driven desalination technologies,” Renewable and Sustainable Energy Reviews, vol. 41, pp. 1080–1118, 2015.
[5] R. Dev and G. N. Tiwari, “Characteristic equation of the inverted absorber solar still,” Desalination, vol. 269, no. 1–3, pp. 67–77, 2011.
[6] H. Aburideh, A. Deliou, B. Abbad, F. Alaoui, D. Tassalit, and Z. Tigrine, “An experimental study of a solar still: Application on the sea water desalination of Fouka,” in Procedia Engineering, 2012, vol. 33, pp. 475–484.
[7] K. Kalidasas Murugavel, K. K. S. K. Chockalingam, and K. Srithar, “An experimental study on single basin double slope simulation solar still with thin layer of water in the basin,” Desalination, vol. 220, no. 1–3, pp. 687–693, 2008.
[8] H. Yan, B. Hu, and T. Xu, “Study on the supporting and repairing technologies for difficult roadways with large deformation in coal mines,” Energy Procedia, vol. 14, pp. 1653–1658, 2012.
[9] T. Abderachid and K. Abdenacer, “Effect of orientation on the performance of a symmetric solar still with a double effect solar still (comparison study),” Desalination, vol. 329, pp. 68–77, 2013.
[10] T. Arunkumar, D. Denkenberger, A. Ahsan, and R. Jayaprakash, “The augmentation of distillate yield by using concentrator coupled solar still with phase change material,” Desalination, vol. 314, pp. 189–192, 2013.
[11] S. Gorjian, B. Ghebadian, T. Tavakkoli Hashjin, and A. Banakar, “Experimental performance evaluation of a stand-alone point-focus parabolic solar still,” Desalination, vol. 352, pp. 1–17, 2014.
[12] M. Elashmawy, “An experimental investigation of a parabolic concentrator solar tracking system integrated with a tubular solar still,” Desalination, vol. 411, pp. 1–8, 2017.
[13] V. Kumar, R. L. Shrivastava, and S. P. Untawale, “Fresnel lens: A promising alternative of reflectors in concentrated solar power,” Renew. Sustain. Energy Rev., vol. 44, pp. 376–390, 2015.
[14] D. Chemisana and M. Ibáñez, “Linear Fresnel concentrators for building integrated applications,” Energy Convers. Manag., vol. 51, no. 7, pp. 1476–1480, 2010.
[15] T. Sultana, G. Morrison, and R. Taylor, “Performance of a Linear Fresnel Rooftop Mounted Concentrating Solar Collector,” Aust. Sol. Energy Soc. Annu. Conf., no. December, pp. 6–7, 2012.
[16] P. Dell'compagni and J. Franco, “Potential uses of a prototype linear Fresnel concentration system,” Renew. Energy, 2018 (In Press).
[17] T. Sultana, G. L. Morrison, R. Taylor, and G. Rosengarten, “TRNSYS Modeling of a Linear Fresnel Concentrating Collector for Solar Cooling and Hot Water Applications,” J. Sol. Energy Eng., vol. 137, no. 2, p. 021014, 2015.
[18] G. N. Tiwari, A. Tiwari, and Shyam, Handbook of Solar Energy: Theory, Analysis and Applications. Singapore: Springer, 2016.
[19] Solar resource data: Solargis, “Solar resource maps of Malaysia,” The World Bank, 2017. [Online]. Available: https://solargis.com/maps-and-gis-data/download/malaysia/.