Single-slope modification design for experimental study of solar desalination system performance

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ABSTRACT

Large quantities of freshwater from desalination are expected to be commercially produced for global consumption. In this study, experimental testing was conducted to determine the overall characteristics of a desalination device to suit the placement of the test area. A single-slope passive desalination tool model with a slope of 35° has been used for testing because of its low cost and environmentally friendly use of solar energy. performance improvement can be achieved after obtaining the characteristics of the desalination tool. The heat energy absorbed reached 0.31 kWh with a solar intensity of 534.40 W/m^2 simultaneously. The amount of fresh water produced during the test is always related to the solar intensity. We experimentally obtained exergy from a desalination device of 0.53 kW/m^2 with an energy efficiency of 58.4% and the highest hourly freshwater production of 2.6 kg.

Keywords: Desalination; Passive; Single Slope; Solar still.

INTRODUCTION

Researchers have developed several efficient desalination methods to obtain freshwater (Sahota et al., 2016; Rasul et al., 2021). Seawater desalination can be used to solve the current challenges of obtaining freshwater sources (Ambarita et al., 2016). Several researchers have researched and developed many models for solar desalination, including single-tilt and double-tilt models, which have also been classified into passive and active work systems (Singh et al., 2020; Subramaniyan et al., 2021). Among the various desalination methods developed, distillation is the oldest and has undergone many combinations (Sampathkumar et al., 2010). Therefore, one method of utilizing renewable energy is to use solar energy as the primary energy source to increase the water temperature in steam (Sahota et al., 2017; Siregar et al., 2020). Recently, electrical energy has been used to generate large amounts of energy and fresh water. However, using large amounts of electrical energy is expensive due to the fuel cost. Approximately 10.000 tons/yr of fuel are consumed to spin the turbine and generate electricity (Kalogirou et al., 2005). From the point of view of energy absorption, Dwivedi and Tiwari (2010) used an active-system dual-slope model desalination process with a naturally circulating copper collector to test water purification. The amount of energy absorbed by water was 4.7 kW/day. In addition, Dwivedi and Tiwari, (2009) developed a desalination tool for passive and active models, focusing on the large heat transfer coefficients of the two models. Meanwhile, the amount of clean water produced annually in the single-slope model was 499.41 L/m^2, while it was 463.41 L/m^2 in the double-slope model. Modi and Modi (2020) conducted a test on a desalination device and demonstrated that using gunny piles produced 23.71% better results than without axle piles. Murugavel et al. (2010) tested a passive desalination process using a dual-slope model. In this case, the amount of water produced was 0.1 L/m^2. Joshi and Tiwari (2018) developed an active-system single-slope desalination tool with a three-stage copper collector. The results showed that the lowest drinking water production costs were found in the first model (partially covered photovoltaic thermal flat plate collectors). Singh (2017) reported various still designs and related performances and concluded that an appropriate combination of components would help improve the results. Several studies have been conducted using single-slope desalination models. However, basic testing must be conducted in Indonesia because the impact of climate change remains a key element of success. Data analysis should be conducted experimentally, and the results obtained from this research are expected to provide the necessary information for developing a single-slope solar desalination system.

METHODS AND PROBLEM FORMULATION

The desalination system was designed using a single-slope model with a slope of 35° from the bottom of an evaporator with an area of 1 m^2, as shown in Figure 1. Sunlight enters and propagates through the evaporator glass to the surface of the water. For solar thermal energy, there are at least three possibilities for the process of dissipating heat energy: the sun's heat bounces off the glass surface into the surrounding air when it is about to enter the evaporator; the sunlight bounces after touching the surface of the water inside the evaporator; and the sunlight bounces off the bottom surface of the evaporator to the outside environment.

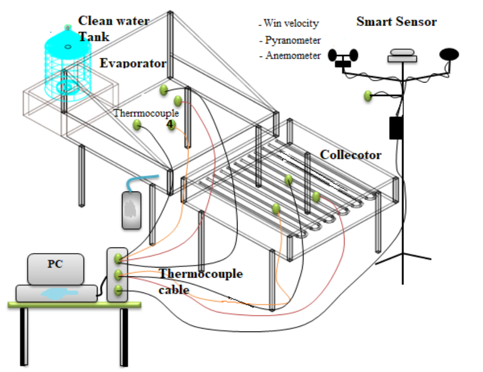

Figure 1. Schematic of single slope desalination.

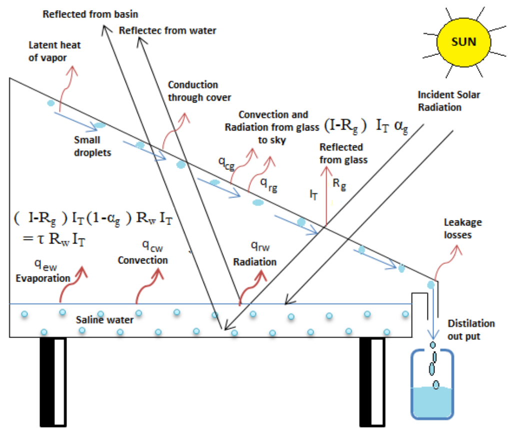

Figure 2. Heat transfer scheme of single slope desalination.

Table 1. Description of the desalination device.

No	Information	Dimensions Specification	No	Information	Specification
1	Sea water tank	19 liters	8	Cooper pipe	3/4 in
2	Evaporator wall	ACP 4 mm	9	Collector glass	Glass / 4 mm
3	Evaporator glass	Clear glass 4 mm	10	Thermocouple	Type K TP3
4	Thermocouple	Type K Dekko TP3	11	Anemometer	Benetech GM8902
5	Fresh water tank	5 liters	12	Pyranometer	Lutron SPM-1116SD
6	Computer	Asus A442U i7	13	R H smart sensor	Lutron COH-9902SD
7	Collector wall	ACP 4 mm	14	Ambient thermocouple	Lutron COH-9902SD

As shown in Figure 2, there are two possible heat losses: from the base and surrounding walls. This is estimated to be very small, considering that the entire insulation process uses good heat insulation. Therefore, the process can be considered adiabatic. However, the heat energy that exits through the base wall and circumference of the evaporator is always observed to ensure that the insulation continues to work properly. In addition, heat loss is necessary when releasing heat from the water vapor attached to the inner glass surface. Therefore, the water vapor falls more quickly into the clean water storage tank. This assumption makes the writer more enthusiastic about the characteristics and performance of desalination tools to carry out development in conducting further research.

MATHEMATICAL FORMULATION

This study compared and developed tests previously conducted in the literature. Therefore, the equations used were adopted from previous studies using the same model. The importance of mapping the heat transfer rate in desalination helps to observe the possibility of heat energy loss during testing.

HEAT TRANSFER COEFFICIENT IN AND OUTSIDE THE EVAPORATOR

The amount of heat energy absorbed by the water during the test was calculated to determine the effectiveness of the desalination device. Before obtaining the amount of energy absorbed by the water, the evaporative heat transfer coefficient absorbed by the water was calculated using the following equation (Singh et al., 2016).

$$h_{e,wg} = 16.273 \times 10^{-3} h_{c,wg} \left[\frac{P_w - P_{gi}}{T_w - T_{gi}} \right], \tag{1}$$

where the evaporative heat transfer coefficient $\boldsymbol{h_{e,wg}}$ [W/m^{2}C], the temperature used to find the internal coefficient, is the data obtained during the test, which is stored in the data logger. The convection heat transfer coefficient $\boldsymbol{h_{c,wg}}$ [W/m^{2}C] can be obtained using the following equation (Singh et al., 2016).

$$h_{c,wg} = 0.884 \left[(T_w - T_{gi}) + \frac{(P_w - P_{gi}) T_W}{268.9 \times 10^3 - P_W} \right]^{\frac{1}{3}}. \tag{2}$$

A high water temperature results in irradiative heat transfer from the water to the inner surface of the glass. This significantly affected the condensation rate of water vapor on the glass surface. The radiative and convection heat transfer coefficients absorbed by the outer glass [W/m^{2}C] can be calculated using the following equation (Boubekri & Chaker, 2011):

$$h_{rga} = \frac{\in_g \times \sigma \times (T_g^4 - T_{sky}^4)}{(T_g - T_a)}, \tag{3}$$

Where the the Stefan–Boltz constant value is used and convection heat transfer coefficient outside the evaporator can use the following equation.

$$h_{cg} = \begin{bmatrix} [5.7 + 3.8 \times V] : \leq 5m/s \\ [6.15 \times V^{0.8}] > 5\text{ m/s} \end{bmatrix}, \tag{4}$$

Where h_{cg} [W/m^{2}C] and the total heat transfer coefficient outside the evaporator are as follows:

$$h_{goTot} = h_{cg} + h_{rg}. \tag{5}$$

ENERGY, EFFICIENCY, AND EXERGY EVAPORATOR

The glass receives the heat energy absorbed by the tool, and almost all surfaces in contact with free air undergo heat propagation from sunlight by convection, conduction, or radiation.

$$T_{go} = \left[\frac{\frac{k_g}{L_g} + T_{gi} + h_{gotTot} T_a}{\frac{k_g}{L_g} + h_{goTot}} \right], \quad (6)$$

where the thickness of the condensation cover L_g is 0.003, the thermal conductivity of the condensation cover k_g is 0.78 W/m^{2}C, and Ta is the ambient temperature. The value T_{W0} is taken from the water temperature when testing. After getting the water temperature in the basin or evaporator, calculate the mass of water every hour during the test as follows (Tiwari *et al*., 2018).

$$m_{eW} = \frac{h_{eW} A_b \left(T_W - T_{gi}\right)}{L} \times 3600 . \quad (7)$$

Following the equation (Tiwari, 2018), the equations for the energy and exergy absorbed by water during testing can be expressed as follows (Tiwari *et al*., 2018).

$$En_{hourly} = h_{ewg} \left(T_w - T_{gi}\right) . \quad (8)$$

The final results of this study will be used as the basis for further research to determine the effectiveness of desalination tools in Asia and Indonesia.

EXPERIMENTAL SETUP

The success of the test will be determined by planning an efficient device in terms of material and energy utilization to obtain clean water from the desalination process. The solar desalination device was designed using an aluminum composite panel (ACP) wall with a thickness of 0.004 m, which was expected to work according to the type of material. Furthermore, the thickness of the cover glass was 0.004 m for the steam condensation process and for the place for sunlight to enter the planned evaporator. The inner surface of the evaporator was painted with a black dye to better absorb sunlight. The outer side of the evaporator was isolated using a Styrofoam material with a thickness of 0.020 m. Seawater was manually entered into the evaporator by opening the drain tap from the seawater storage tank until the water level in the evaporator reached 0.003 m. The size of the evaporator was 1 m^2 with a 35° glass slope towards the south from western Indonesia. The clean water obtained during the test was stored in a plastic bottle connected to the pipe in the evaporator, as shown in Figure 3. Clean water was weighed, and data regarding the number of hours and days was recorded. Comparison data included the amount of clean water that is calculated using the equation 7.

Figure 3. Experimental equipment and data acquisition systems.

Data were acquired to record the temperature changes during testing. Four type K thermocouples were placed on the inside of the evaporator, namely on the bottom side, water, middle chamber, and inside of the condensing glass.

RESULTS AND DISCUSSIONS

The desalination device was directly tested for seven days, and each experiment was conducted for 9 h, from 08.00 a.m. to 05.00 p.m. local time. In the experiment, the heat energy used to increase the temperature of pure water was expected to be the heat from the sunlight without adding a heating collector as an additional electric heater.

OVERALL TEMPERATURE AGAINST SOLAR INTENSITY

The recorded temperature history during testing of the average solar intensity is shown in Figure 4. The temperatures of the water and the outer and inner glass surfaces always follow the solar intensity. The water and air temperatures in the evaporator were always similar because the air in the evaporator was partly water vapor that evaporated from the water surface, which was at its temperature at the time of the test. The highest solar intensity on the fourth day reached 689.1 W/m^2, owing to the significant temperature of the outer glass.

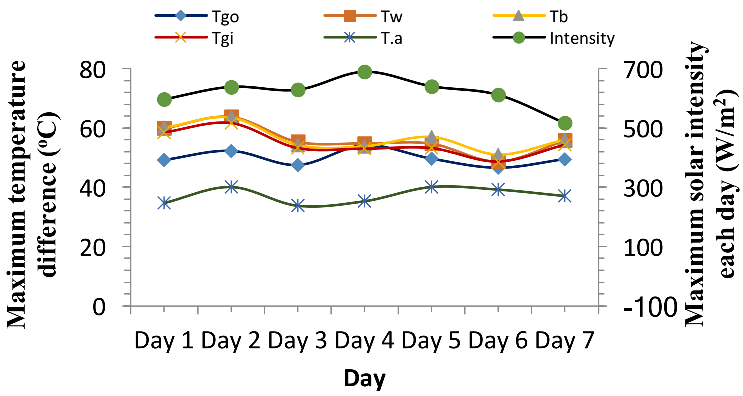

Figure 4. Day variation of maximum temperature difference in terms of solar intensity and overall temperature.

The figure shows that the temperature did not always follow the solar intensity. For example, at the end of the test time in the afternoon, the solar intensity drops because it starts in the afternoon. However, the water temperature and the inner glass temperature increase due to the heat accumulation at the bottom of the evaporator in the water. Thus, this will last long enough for the energy stored in the water to run out, owing to the heat transfer process to an environment where the temperature decreases. The environmental temperature here has an impact. However, it did not affect the tropics because the environmental temperature always follows high and low solar intensity and wind speed, in contrast to areas that have winter.

CHARACTERISTICS OF THE SYSTEM

When exploiting the single-slope model of the solar desalination system, the water temperature in the evaporator is expected to be high. The ambient temperature aids the condensation of the water vapor that enters the clean water container. The highest water temperature in the test was on the first day of testing, reaching 59.86 °C, as shown in Figure 5. Moreover, the higher the water temperature in the evaporator, the faster it would produce water vapor. Therefore, the results of clean water obtained during testing are significantly dependent on water temperature, and the efficiency decreases when the heat energy absorbed by the water from sunlight begins to reduce.

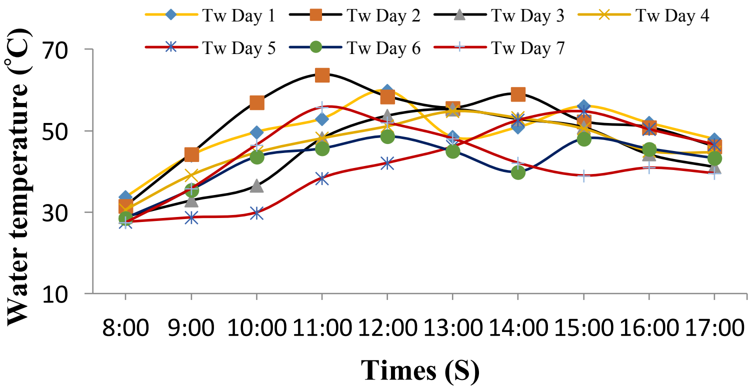

Figure 5. Hourly variation of water temperature (Tw).

The environmental temperature during testing served as the basis and reference for the water temperature because there is no heat build-up in a pure environment that could raise the outside air temperature. The difference in temperature between the water in the evaporator and the ambient temperature represents the amount of energy absorbed by water.

Table 2. Fresh water produced experimentally and numerically.

Experiment	Water Temperature during Experiments [°C]			Fresh water produced [Kg]		Deviation %
	Max	Min	Averaged	Numerical	Experiment	
Day 1	59.86	33.67	46.77	1.76	1.52	15.48
Day 2	63.82	31.45	47.64	1.73	1.46	18.31
Day 3	55.34	28.91	42.13	1.19	0.96	24.07
Day 4	54.81	30.64	42.73	2.56	2.31	10.42
Day 5	54.75	27.51	41.13	0.83	0.73	13.74
Day 6	48.66	28.45	38.56	1.21	0.97	24.78
Day 7	55.75	27.45	41.60	1.59	1.35	17.81

In essence, the water vapor condensation process requires a lower temperature to become water, and the adherent water vapor will return to the water by itself without any additional cooling on the evaporator glass, only expecting a cool airflow rate around the outer glass surface. Deviations on the third and sixth days were phenomena in which the distance between the amount of water from the test results was far below the calculated amount of water, causing a very high range from other days. This fits perfectly with the recorded history of the highest solar intensity data shown in Figure 6, namely on the fourth day of testing. Although on the second day of testing, the maximum water temperature was higher when compared to the fourth day of testing. It happened briefly, and the water temperature did not have time to absorb more energy and convert it into water vapor. The highest clean water production was found on the fourth day of testing, namely 2.5554 kg, with a maximum water temperature of 54.81℃ in the evaporator.

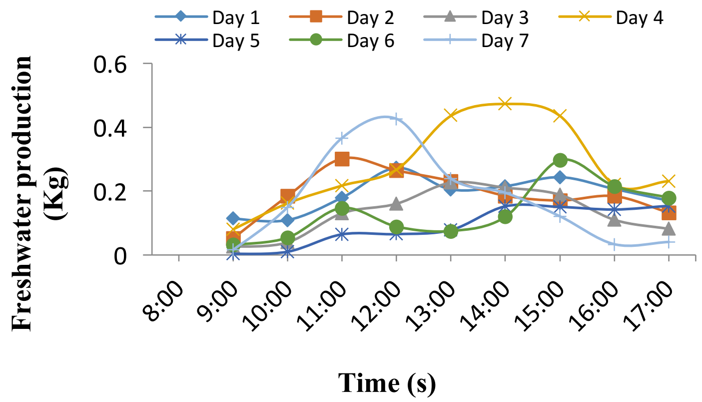

Figure 6. Hourly freshwater production.

The evaporation rate of the water vapor in the evaporator is derived from the heat of the sun. Although the test starts at 08.00 a.m., clean water was taken from 09.00 a.m. The time span of one hour corresponded to the process of water evaporation. The amount of energy absorbed by the water was observed during the test, as shown in Figure 7, with a comparison of the heat energy source and the temperature of evaporation in the evaporator.

EXERGY AND ACHIEVEMENT

The effectiveness of the desalination tool was measured by calculating the exergy energy. The curve in Figure 8 shows the amount of energy useful for increasing the temperature of the water to form water vapor that flows into the clean water tube. The amount of exergy energy does not appear to be similar to the value of energy efficiency because the amount of energy used is not forced, which means that heat energy works naturally in the heating water. There was no forced heating of the water. There was an increase in the water temperature owing to the large heat energy during absorption, and the water heating process occurred naturally.

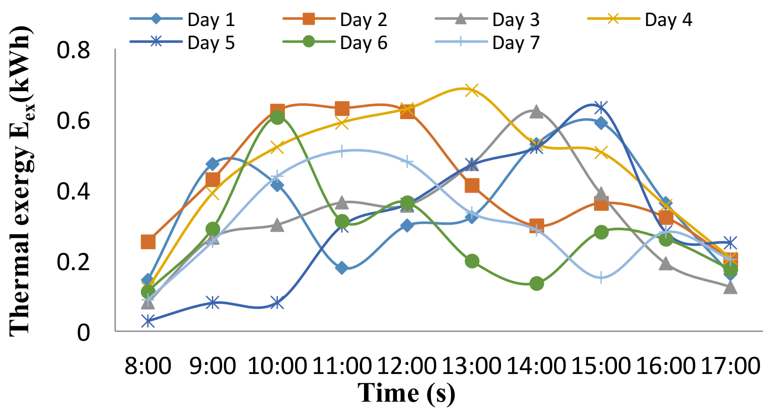

Figure 8. Hourly variation of thermal exergy.

The results of using thermal exergy energy from the desalination device are shown in Figure 9.

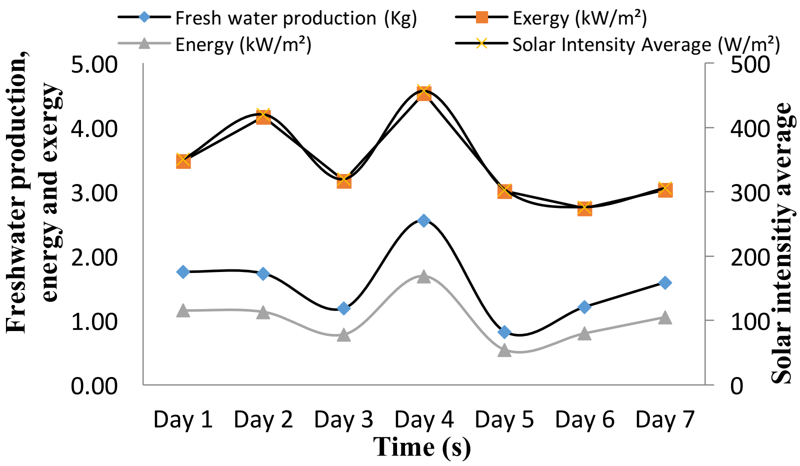

Figure 9. Average solar intensity against energy, exergy, and water production.

The curve in Figure 9 illustrates that the work of the solar desalination tool still depends on the solar intensity absorbed by the water at the time of testing. Freshwater production during testing always follows the rhythm of the energy absorbed by the water. This strongly correlates with freshwater production, energy, exergy, and solar intensity. The observation from the test was that the water content increases if the water temperature is higher than the naturally accepted heat. However, it is feared that the wind speed outside the collector cover glass will be unable to reduce the condensation vapor's temperature adequately. Therefore, it is necessary to consider adding heat energy to the condensation steam cooler. The water temperature during the highest test on the second day reaches 63.54 $^{\circ}$C with a water evaporation coefficient value of 24.62 W/m^2 at a wind speed of 3.35 m/s. The amount of water produced was 0.304 kg, which was a natural fit. If the water temperature is increased without cooling the condensing glass, the process will be inefficient as the condensation process requires a low temperature to convert water vapor into water.

CONCLUSION

Water temperature increased with the brightness level of the day during the test (solar intensity). In the afternoon, the water temperature lasted several hours higher than the environmental temperature because of heat accumulation in the evaporator. Thus, the water production process continued until the evening, even without sunlight. With high solar intensity, the heat energy absorbed by water lasts until the afternoon, which is consistent with the conclusion of the previous statement. Sufficient wind speed was required in the desalination process to speed up the condensation process on the glass surface. Therefore, the evaporator needs a new function as a cooler. The freshwater production rate was 2.31 kg/day. However, large amounts of freshwater cannot be obtained at all high temperatures; it will be difficult for water vapor to condense into water because of the high temperature of the evaporator chamber, and a large amount of energy will be wasted. Water vapor adhering to the inner glass surface must be cooled to flow more easily into the freshwater tank. This is a topic for future research.

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REFERENCES

Ambarita, H. (2016). Study on the performance of natural vacuum desalination system using low grade heat source. *Case Studies in Thermal Engineering **8*** (July), 346–358.

Boubekri, M., & Chaker, A. (2011). Yield of an improved solar still : numerical approach. *Energy Procedia **6*****,** 610–617.

Dwivedi, V. K., & Tiwari, G. N. (2009). Comparison of internal heat transfer coefficients in passive solar stills by different thermal models: An experimental validation. *Desalination **246***(1–3), 304–318.

Dwivedi, V. K., & Tiwari, G. N. (2010). Experimental validation of thermal model of a double slope active solar still under natural circulation mode. *Desalination **250***(1), 49–55.

Joshi, P., & Tiwari, G. N. (2018). Energy matrices, exergo-economic and enviro-economic analysis of an active single slope solar still integrated with a heat exchanger: A comparative study. *Desalination **443*** (May), 85–98.

Kalogirou, S. (2005). Seawater desalination using renewable energy sources. *Progress in Energy and Combustion Science **31*** (3), 242–281.

Modi, K. V., & Modi, J. G. (2020). Influence of wick pile of jute cloth on distillate yield of double-basin single-slope solar still: Theoretical and experimental study. *Solar Energy **205*** (February), 512–530.

Murugavel, K., Sivakumar, S., & Ahamed, J. R., (2010). Single basin double slope solar still with minimum basin depth and energy storing materials. *Applied Energy **87*** (2), 514–523.

Rasul, A, M., Hamakhan, I, A., & Ibrahim, A, M. (2021). Absorber Type Optimization for Night-Shift Operation of Solar Air Heater. *Journal of Engineering Research (Kuwait) **9***: 1–16.

Sahota, & Tiwari, G. N. (2016). Effect of nano fluids on the performance of passive double slope solar still: A comparative study using characteristic curve. *Desalination **388***, 9–21.

Subramaniyan, C., Prakash, K, B., Kalidasan, B., and Kumar, S., M. (2021). Experimental and Numerical Evaluation on Performance of Potable Water Productivity with Rectangular Fins Basin Triangular Solar Still. *Journal of Engineering Research (Kuwait)* 9: 1–18.

Sahota, Lovedeep, Shyam, & Tiwari, G. N. (2017). Analytical characteristic equation of nanofluid loaded active double slope solar still coupled with helically coiled heat exchanger. *Energy Conversion and Management **135***, 308–326.

Sampathkumar, K., Arjunan, T. V., Pitchandi, P., & Senthilkumar, P. (2010). Active solar distillation-A detailed review. *Renewable and Sustainable Energy Reviews **14***(6), 1503–1526.

Singh, D. B. (2017). Improving the performance of single slope solar still by including N identical PVT collectors. *Applied Thermal Engineering*, *November*.

Singh, D. B., Tiwari, G. N., Al-Helal, I. M., Dwivedi, V. K., & Yadav, J. K. (2016). Effect of energy matrices on life cycle cost analysis of passive solar stills. *Solar Energy **134***, 9–22.

Siregar, M. A., & Damanik, W, S., (2020). Energy analysis desalination of single slope solar still. Proceedings of the 3rd ICEAT 2020 International Conference on Engineering and Applied Technology, Sorong, West Papua, Indonesia.

Tiwari, G. N., & Sahota, L. (2018). Exergy and Technoeconomic Analysis of Solar Thermal Desalination. In *Renewable Energy Powered Desalination Handbook: Application and Thermodynamics*.