The object of this research is a double-slope solar still with the addition of water cooling on the wall (DSSS.WCW). The issue with solar stills is that the temperature of the cover glass is quite high, which consequently reduces the rate of evaporation. Methods to reduce the cover glass temperature involve water cooling, by flowing water and spraying it onto the cover glass. Both of these methods have been shown to reduce the temperature of the cover glass, but they still require additional energy and can decrease the solar radiation energy received by the absorber plate. This research proposes using a water cooling method on the wall that does not require additional energy and can prevent a reduction in the solar radiation energy received by the absorber plate. Experimental and theoretical research was conducted to study the effect of using DSSS.WCW. The results showed a 13.48 % reduction in the cover glass temperature, consequently increasing the temperature difference between the fins and the cover glass by 9.82 °C. The increase in temperature difference resulted in a 13.82 % increase in freshwater productivity theoretically by 2.80 kg/hour and a 13.10 % increase experimentally for the DSSS.WCW by 2.58 kg/hour. In addition, there was a theoretical increase in energy efficiency of 22.29 % and an experimental increase of 22.82 %, along with an increase in exergy efficiency of 15.71 %. The implementation of water cooling on the wall has been shown to enhance the efficiency of the double-slope solar still. In addition, the water cooling method on the wall does not reduce the solar radiation energy that can be received by the absorber plate and does not require additional energy. The results of this research can be applied in remote islands in Indonesia, particularly during the dry season

Keywords: solar still, water cooling, productivity, energy efficiency, exergy efficiency

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IDENTIFYING ENHANCEMENT OF DOUBLE SLOPE SOLAR STILL PERFORMANCE BY ADDING WATER COOLING TO WALLS

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1. Introduction

Indonesia is a country with a population of 279.1 million in 2024. This large population lives on almost all of Indonesia's islands. The dispersion of the population on small islands makes it challenging for the government to distribute various essential goods and services. Freshwater is a fundamental necessity for the population. Therefore, the government's initiatives to address the scarcity of freshwater for residents living on remote islands have encountered challenges, particularly during the dry season [1, 2]. Government efforts to channel water to small island areas using a piping system will undoubtedly incur significant costs and difficulties. The problem of meeting fresh water demands will undoubtedly escalate with the growth in population.

Meanwhile, Indonesia is a country that is crossed by the equator, so the amount of solar radiation energy is very abundant. The utilization of solar energy is very important, because it is renewable energy that is environmentally friendly, available and affordable, and reduces global warming. On the islands there are abundant sources of seawater. The availability of abundant solar radiation energy can be utilized to distill seawater into fresh water. The distillation of seawater into fresh water can use seawater desalination plants, but this equipment requires high technology and large operational costs. The construction of desalination plants in remote areas is difficult due to limited access and high costs. Therefore, seawater desalination plant technology is not suitable to be applied in the archipelago of thousands of islands.

The importance of research conducted in the modern era lies in the continuous efforts to enhance the productivity of distilling clean water from seawater. An alternative technology that could be applied on the islands is solar still technology. This technology utilizes solar energy to evaporate seawater into fresh water [3]. This technology also utilizes materials that are widely available, inexpensive, and easy to construct [4]. However, solar still technology has low productivity and efficiency [5]. Therefore, one of the tasks of researchers is to try to increase the productivity and efficiency of solar stills.

Solar stills are divided into two types, namely active and passive types. The active type uses additional equipment by using electrical energy as a heater in the solar still basin, while the passive type purely uses solar heat to evaporate seawater. Because there is no additional equipment, the efficiency of passive type solar still is lower than that of active type. This research uses the passive type of solar still because it is easier to apply in remote areas.

Fresh water productivity in solar stills is influenced by the evaporation rate, while the evaporation rate is influenced by the temperature difference between the evaporation surface and the condensation surface. Increasing the temperature difference between the evaporation surface and the condensation surface can be done by increasing the absorption of solar radiation heat and by lowering the temperature of the cover glass. Therefore, it is important to increase the productivity of solar stills by reducing the temperature of the cover glass using water cooling on the wall.

Numerous studies have been conducted to enhance the temperature difference between the evaporation surface and the condensation surface. In previous studies, research has been conducted using a cooler on the glass cover [6]. The study results indicate that as the temperature on the glass cover decreases, the cooling process between the solar still basin and the glass cover intensifies. Thus, the amount of clean water produced will also increase. The previous study investigated the cooling effect on the glass cover of a single-slope solar still by implementing water spray and pulsed glass cooling [7]. The study showed that the productivity of clean water increased when using a glass cover with cooling.

Only a few studies have investigated the relationship between the absorber plate and the wall of the double slope solar still. However, considering that the correlation between the cooling media on the glass cover and absorber plate shows a high increase in clean water productivity, it is interesting to investigate the performance of the double slope solar still when using the wall as a cooling media.

Therefore, a study on water cooling on the wall is very interesting research and has a scientific relationship with the need for clean water on a remote island. The optimized and compact double slope solar still design using the wall as a cooling form in this research can be specifically applied to get fresh water in remote islands.

2. Literature review and problem statement

The paper [6] tested the flow rate of film-shaped cooling water on the cover glass. This paper presents the research results on the effect of cooling water flow rate on the cover glass. The research shows that as the cooling water flow rate increases, the productivity of the solar still also increases. The productivity increase was 14 % higher when using a cooling water flow rate of 720 ml/min compared to a cooling water flow rate of 180 ml/min. Water cooling applied to the cover glass can decrease the amount of solar radiation energy transferred to the absorber plate.

The paper [7] presents the research results of a single-slope solar still with hollow square fins mounted on the absorber plate and water cooling on the cover glass by the spraying method. The study showed an increase in productivity of 61.3 % when using hollow square fins and water cooling spray with a duration of 30 seconds every 10 minutes. However, this study has not examined the decrease in temperature due to cooling.

Based on research [8], the problem with passive-type solar stills is how to increase freshwater productivity and efficiency. Freshwater productivity in solar stills is influenced by the evaporation rate, which, in turn, is affected by the temperature difference between the evaporation surface and the condensation surface. Increasing the temperature difference between the evaporation surface and the condensation surface can be done by enhancing the absorption of solar radiation heat and lowering the temperature of the cover glass.

In [9], research has been conducted on enhancing the absorption of solar radiation heat to amplify the temperature difference between the evaporation surface and the condensation surface. This is done to boost the evaporation rate, thereby increasing the productivity of fresh water and the efficiency of the solar still.

Based on research [10], other research has also been conducted on reducing the temperature of the cover glass as a condensation surface. Decreasing the temperature of the cover glass is intended to increase the temperature difference between the evaporation surface and the condensation surface. This, in turn, aims to boost the evaporation rate, leading to higher productivity of fresh water and improved efficiency of the solar still.

Based on research [11], the study showed an improvement in the performance of the double-slope solar still with water cooling on the cover compared to without cooling. The effect of water cooling is to increase the temperature difference between the glass cover and the water temperature, thereby enhancing the performance of the double-slope solar still. Water cooling through the spraying method still requires extra energy and equipment, and it may decrease the amount of radiant energy that the absorber plate can receive.

In [12], the results of a performance study on modified wick and film water cooling are presented, demonstrating a 5.3 % increase in productivity during the day and a 30 % increase for both day and night time. As the flow rate of film cooling increases, productivity also increases. Using a wick along with film cooling can reduce the cover glass temperature by 6–20 °C compared to a conventional solar still. The decrease in the cover glass temperature results in a 45 °C increase in the temperature difference between the basin water and the cover glass. However, the effect of water cooling rate has not been studied, even though the cooling method is still susceptible to reducing the solar radiation energy transmitted to the absorber plate.

The paper [13] presents the results of conventional solar still research, showing that adding graphite flakes, phase change materials, and film coolers can increase productivity by 73.8 %. This increase results from higher water temperature caused by flake graphite and phase change materials, higher water-saturated vapor pressure due to flake graphite, and a greater difference in water-glass temperature facilitated by film cooling. The higher temperature difference in the water-glass caused by film cooling can enhance the evaporation process, leading to increased productivity. However, continuous application necessitates a significant amount of cooling water, which warrants further investigation to optimize the method.

The paper [14] presents the results of research on the effect of cooling water on the double-slope solar still cover glass, which is studied experimentally and theoretically. The research shows that the actual water productivity is 4.36 liters, while the theoretical value is 7.57 liters. While the actual and theoretical efficiency of this system are 52.32 % and 90.88 %, respectively. This study has not compared with no water cooling, so the effect has not been seen.

Another author [15] tried to reduce the temperature of the cover glass by flowing water on the hemispherical cover glass. The study compared using water cooling and without water cooling. The results can reduce the temperature of the cover glass and increase the productivity and efficiency of the solar still. However, it is necessary to evaluate the difference in basin water temperature with the cover glass, where the temperature difference when using water cooling is 19 °C, which is smaller than without water cooling at 21 °C. This condition allows water to cool on the cover glass to reduce the solar radiation energy received by the absorber plate.

The paper [16] presents the research results of adding gravel, wick, and carbon black nanoparticles to improve the scooping process. On the other hand, for condensation enhancement, a passive water-based glass cooling technique was integrated with all cases to lower the glass cover temperature. The study showed an increase in productivity and efficiency of the solar still when using the addition of gravel, wick, and carbon black nanoparticle materials with cover glass cooling. Passive water cooling over the cover glass can reduce the solar radiation energy transmitted to the absorber plate.

According to [17], the study resulted in decreased cover glass temperature, increased freshwater productivity, and solar still efficiency when using water cooling with water droplets and sisal fibers. This shows that the decrease in cover glass temperature has an effect on increasing freshwater productivity and solar still efficiency. However, drip cooling and the presence of sisal fibers still interfere with the entry of solar radiation into the absorber plate.

The paper [18] presents the results of research on cover glass cooling, which shows a decrease in cover glass temperature and can improve the performance of a single-slope solar still. Using water cooling with the water flow method on the cover glass results in reduced solar radiation energy received by the absorber plate.

From the literature review, information was obtained on the importance of reducing the temperature of the cover glass to increase the temperature difference between the evaporating surface and the condensing surface. The temperature difference can increase the evaporation rate [6, 8]. Increasing the evaporation rate can increase the productivity and efficiency of the solar still [9, 10]. The method was used by previous researchers to reduce the temperature of the cover glass by flowing and spraying water over the cover glass. This method can reduce solar radiation energy that can be transmitted by the cover glass to the absorber plate, due to the reflection of water into the environment. This reduction in solar radiation energy can reduce the evaporation rate and decrease the productivity of the solar still. In addition, to drain water and spray water onto the cover glass requires additional energy, additional equipment and a considerable volume of water. From these problems, a method is needed to reduce the temperature of the cover glass by using water cooling on the wall that can reduce the above problems, so that it is expected to have a positive effect on the productivity, efficiency of the solar still and the results are expected to be applied in the archipelago.

3. The aim and objectives of the study

The aim of this study is to identify regularities of the influence of adding water cooling to the wall on improving the performance of a double slope solar still.

To achieve this aim, the following objectives are accomplished:

– to identify the temperature drop of the wall's glass cover when using water cooling as opposed to not using water cooling;

– to identify freshwater productivity and the efficiency of a double-slope solar still with water-cooled walls compared to those without water cooling;

– to identify the comparison of exergy efficiency between walls with water cooling and those without water cooling.

4. Materials and methods

4. 1. Object and hypothesis of the study

The object of this research is a double slope solar still. The main hypothesis of this research is related to water cooling on the wall, which is expected to improve the performance of the double slope solar still compared to without cooling. The methods used are experimental and theoretical. The double slope solar still with and without water cooling on the wall is tested at the same time, so it is assumed that the test takes place under the same conditions. In addition, to simplify the theoretical analysis, it is stated that: the heat capacity of the cover glass, fin absorber and insulating material is ignored; there is no vapor leakage in the solar still; air and water vapor are considered as ideal gases; water flow is simplified in the fin absorber; the physical properties of various materials are constant; and there are no impurities in the cover glass.

The research was conducted at the Laboratory of Solar Power and Alternative Energy, Department of Mechanical Engineering, Widyagama University Malang, East Java, Indonesia. The geographical condition of Malang city has a latitude of 7.266667 and a longitude of 112.716667, corresponding to the coordinates of 7°16′ South latitude and 112°43′ East longitude.

4. 2. Materials

The fin absorber plate uses mortar material and can be seen in Fig. 1. The mortar fin absorber plate uses a composition of 2 parts iron sand and 1 part cement. The fin absorber is painted matte black. The solar still cover is made of 3 mm thick clear glass, while the walls are constructed using 5 mm thick clear glass. To minimize heat loss and water vapor, all glass is sealed with glass adhesive, and the walls are insulated using styrofoam. The walls on the north and south sides are equipped with water cooling (DSSS.WCW). The equipment setup can be seen in Fig. 2.

Fig. 1. Fin absorber plate

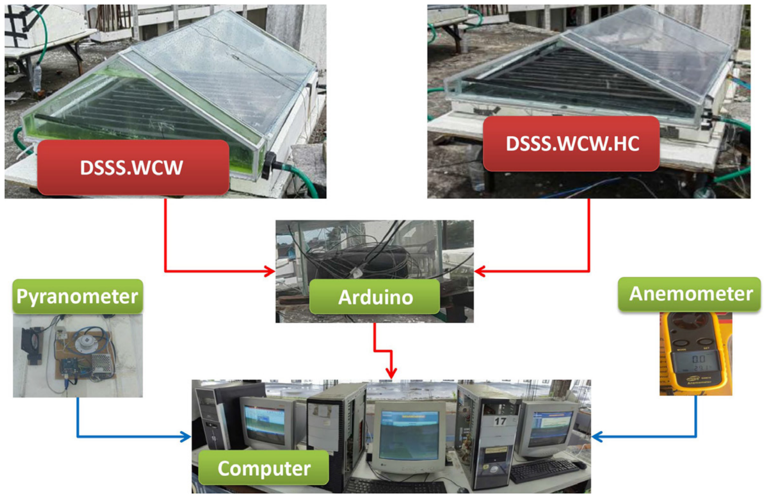

Fig. 2. Solar still research equipment

The solar still measures 1.1 m long, 1.1 m wide, 30 cm high with a glass slope of 15°. The fin absorber plate measures 1 m in length, 1 m in width and 10 cm in height. The water cooler is a glass room filled with seawater with dimensions of 1.1 m long, 10 cm wide and 30 cm high. The condensation is collected using a 1.5 l bottle.

Fig. 1 shows the fin absorber plate being painted. Fig. 2 shows the double slope solar still research equipment with water cooling on the wall (DSSS.WCW) and without cooling (DSSS). In addition, the measuring equipment used and the computer for data acquisition are also shown.

4. 3. Measuring equipment

The various instruments for measuring the parameters used are thermocouples, pyranometers, anemometers, and measuring cups. The associated percentage error, accuracy, and range of the instruments can be seen in Table 1.

Table 1 presents the instruments used with the associated percentage error, accuracy, and instrument range. The thermocouples used are type *k* temperature thermocouples totaling 12 pieces. The thermocouples were installed in the water bath, on the fins, cover glass and the environment. The pyranometer used a Sentec SEM228A Rs232 Solar Radiation Sensor. An anemometer was used to measure wind speed using a GM816 Digital Wind Anemometer. Data from temperature, pyranometer and wind are processed using an Arduino Mega2560. Data obtained on the Arduino is displayed and stored on a personal computer.

Table 1

Measuring equipment

No.	Instrument	Accuracy	Range		% Error
			Min	Max	
1	Thermocouple	±0.1 °C	−100 °C	200 °C	0.25 %
2	Pyranometer	±1.0 W/m^2	0 W/m^2	1200 W/m^2	1 %
3	Anemometer	±0.1 m/s	0 m/s	25 m/s	5 %
4	Measuring cup	±1.0 mL	0 mL	200 mL	1 %

4. 4. Experimental procedure

The slope of the solar still cover glass faces east and west to maximize the intensity of solar radiation. The solar still was filled with seawater to a height of 1 cm. Temperature, solar radiation intensity, wind speed and distillate output were measured every 60 minutes. Measurements of all parameters were taken from 7:00 AM to 5:00 PM.

4. 5. Energy efficiency calculation

The mathematical model of heat balance in the solar still [19] was developed according to the equipment in Fig. 3.

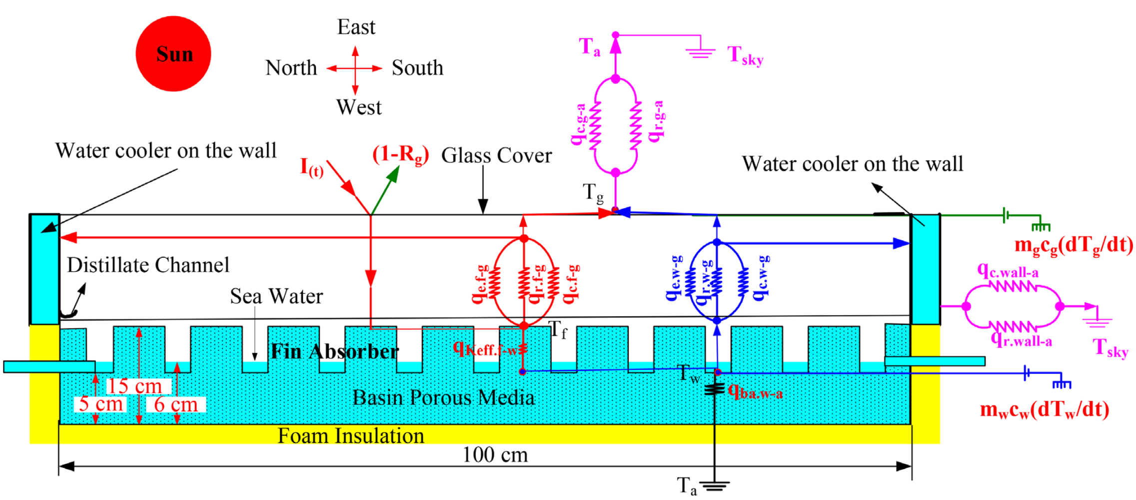

Fig. 3. Heat Transfer Scheme for the addition of water cooling to the wall of a double slope solar still (DSSS.WCW)

Fig. 3 shows the heat balance process in the double slope solar still system using water cooling on the wall. From Fig. 3, the energy balance of each component of the double slope solar still can be analyzed and condensate water productivity and theoretical energy efficiency can be calculated.

4. 5. 1. Energy balance in the cover glass

The heat balance of the cover glass is influenced by several factors: heat absorption of the cover glass from the intensity of solar radiation, heat released by the fin absorber (convection, radiation, and evaporation), heat released by the basin water (convection, radiation, and evaporation), and heat released by the cover glass to the atmosphere (convection and radiation). The heat balance on the cover glass [20], then developed, becomes:

$$\alpha_g\left(1-R_g\right)I_{(t)}+q_{t.w-g}+q_{t.f-g}=q_{t.g-a}, \quad (1)$$

where α_g is the intensity of solar radiation absorbed by the cover glass, R_g is the intensity of solar radiation reflected by the cover glass, $I_{(t)}$ is the intensity of solar radiation at a certain time, $q_{t.w-g}$ is the total heat from the water basin to the glass, $q_{t.f-g}$ is the total heat from the water basin to the glass, and $q_{t.ga}$ is the total heat from the glass to the atmosphere. To calculate $q_{t.w-g}$, $q_{t.f-g}$ and $q_{t.ga}$ use the following equations:

$$q_{t.w-g}=\left(q_{c.w-gc}+q_{c.w-wall}\right)+\left(q_{e.w-gc}+q_{e.w-wall}\right)+ +\left(q_{r.w-gc}+q_{r.w-wall}\right), \quad (2)$$

$$q_{t.f-g}=\left(q_{c.f-gc}+q_{c.f-wall}\right)+\left(q_{e.f-gc}+q_{e.f-wall}\right)+ +\left(q_{r.f-gc}+q_{r.f-wall}\right), \quad (3)$$

$$q_{t.g-a}=q_{c.gc-a}+q_{r.gc-a}+q_{c.wall-a}+q_{r.wall-a}, \quad (4)$$

where in equation (2), $q_{c.w-gc}$ is the heat of convection from the water basin to the glass, $q_{c.w-gw}$ is the heat of convection from the water basin to the glass wall, $q_{e.w-gc}$ is the heat of evaporation from the water basin to the glass, $q_{e.w-gw}$ is the heat of evaporation from the water basin to the glass wall, $q_{r.w-gc}$ is the heat of radiation from the water basin to the glass and $q_{r.w-gw}$ is the heat of radiation from the water basin to the glass wall. In equation (3), $q_{c.f-gc}$ is the heat of convection from the fins to the glass, $q_{c.f-gw}$ is the heat of convection from the fins to the glass wall, $q_{e.f-gc}$ is the heat of evaporation from the fins to the glass, $q_{e.f-gw}$ is the heat of evaporation from the fins to the glass wall, $q_{r.f-gc}$ is the heat of radiation from the fins to the glass and $q_{r.f-gw}$ is the heat of radiation from the fins to the glass wall. In equation (4), $q_{c.gc-a}$ is the heat of convection from the glass cover to the atmosphere, $q_{r.gc-a}$ is the heat of radiation from the glass cover to the atmosphere, $q_{c.gw-a}$ is the heat of convection from the glass wall to the atmosphere and $q_{r.gw-a}$ is the heat of radiation from the glass wall to the atmosphere.

4. 5. 2. Heat balance in the fin absorber

The heat balance of the fin absorber is influenced by the fin heat absorption from the solar radiation intensity transmitted by the cover glass, the heat released by the fin absorber to the cover glass (convection, radiation and evaporation), the effective conduction heat transferred to the basin water and the sideways heat loss. Equation [20] was developed into:

$$\left(1-\propto_g\right)\left(1-R_g\right)\left(1-R_f\right)\propto_f I\left(t\right)=q_{tf-g}+q_{c.eff}+q_{sa}, \quad (5)$$

where R_f is the intensity of solar radiation reflected by the fins, α_f is the intensity of solar radiation absorbed by the fins, $q_{c.eff}$ is the effective conduction heat and q_{sa} is the heat loss to the side.

4. 5. 3. Effective conduction heat transfer

The heat transfer from the fin absorbing surface to the basin water [21], becomes:

$$q_{c.eff}=k_{eff}A_f\frac{dT}{dx}. \quad (6)$$

To calculate the effective conductivity coefficient [21, 22]:

$$k_{eff}=\left(\left(1-\varepsilon\right)*k_f\right)+\left(\varepsilon-k_w\right), \quad (7)$$

where k_{eff} is the effective heat conductivity, A_f is the area of fins, dT/dx is the temperature gradient, ε is the porosity of the material, k_f is the heat conductivity of fins and k_w is the heat conductivity of water.

4. 5. 4. Heat balance in the basin water

The heat balance in the basin water is influenced by effective conduction heat, total heat released by the basin water to the cover glass (convection, radiation and evaporation) and heat storage in the basin water. The equation becomes:

$$q_{c.eff}=q_{t.w-g}+q_{b-a}+m_w c_w\left(dT_w/dt\right), \quad (8)$$

where q_{ba} is the heat loss to the bottom of the system, m_a is the mass of the water basin, c_w is the specific heat water, dT_w is the water temperature difference and dt is the time difference.

4. 5. 5. Distillation output productivity and efficiency

Productivity and efficiency of distillation output resulting from the basin water and fin evaporation processes. To calculate freshwater productivity, use the following equations:

1. Productivity of distilled water from the basin water. From the theory written in [23], the equation becomes:

$$M_w=\left(q_{e.w-gc}\times3{,}600\right)/\left(L_{ev}\right)+\left(q_{e.w-wall}\times3{,}600\right)/\left(L_{ev}\right). \quad (9)$$

Evaporation latent heat using equation [24]:

$$L_{ev}=\left(2{,}501.67-2.389T_w\right)\times10^3,\ (\text{J/kg}). \quad (10)$$

2. Condensate water productivity from the fins:

$$M_f=\left(q_{e.f-g}\times3{,}600\right)/\left(L_{ev}\right)+\left(q_{e.f-wall}\times3{,}600\right)/\left(L_{ev}\right). \quad (11)$$

Total productivity becomes:

$$M_{fw}\left(t\right)=M_f+M_w. \quad (12)$$

Total productivity is the result of freshwater productivity obtained from the solar still system as a whole. Freshwater productivity is identified from evaporation from the fins to the glass and from the water to the glass.

4. 5. 6. Energy efficiency of solar stills

Enhancing the energy efficiency of solar stills is crucial for increasing their viability as a sustainable method for producing fresh water, as it directly influences the amount of solar energy converted into usable heat for the distillation process. By integrating water cooling, the energy efficiency of solar stills can be significantly boosted, making them more effective and practical for large-scale implementation in water-scarce regions.

Efficiency value [25]:

$$\eta_{(t)}=\frac{M_{fw}(t)\times L_{ev}}{A_b\cdot I(t)\cdot \Delta t}. \qquad (13)$$

Energy efficiency is the output energy divided by the input energy. Energy output consists of freshwater productivity multiplied by the latent heat of vaporization, while energy input is the solar radiation energy that can be received by the absorber plate at a certain area and time.

4. 6. Exergy efficiency calculation

The exergy efficiency calculation of a solar still involves analyzing the quality of energy inputs and outputs to assess how effectively the system converts available solar energy into useful work during the distillation process.

The exergy efficiency calculation is formulated by [26]:

$$\eta_{ex}=\frac{Exergy\ output}{Exergy\ input}. \qquad (14)$$

The exergy associated with the solar distillation yield is transferred from the fins and seawater to the glass through evaporation, i.e. $E_{xe.f\text{-}g}$ and $E_{xe.w\text{-}g}$. Therefore, the exergy efficiency equation from [27] is expanded to:

$$\eta_{ex}=\frac{Ex_{e.w-g}+Ex_{e.f-g}}{Ex_{sun}}. \qquad (15)$$

The exergy efficiency is the accumulated evaporation exergy from the fins and seawater to the glass divided by the sun exergy.

5. Results of adding water cooling on the wall to improve the performance of double slope solar stills

5. 1. Temperature drop of water-cooled glass cover on the wall compared with no water cooling

The study aims to reduce the temperature by comparing the addition of water cooling on the walls of a double slope solar still (DSSS.WCW) with no cooling (DSSS). The test data on solar radiation intensity and wind speed are presented in Fig. 4. The intensity of solar radiation received by the fin absorber plate is used for evaporation, convection, radiation to the cover glass, and partially transferred to seawater/basin. The mortar fin absorber plate has pores that can function as capillary water flow media and heat flow media, so evaporation occurs on the fin body [28].

The results of the tests carried out are displayed in Fig. 5, 6.

The temperature test results are presented in Fig. 5, 6. The average temperature using DSSS.WCW is lower than that of DSSS. The average temperature of the DSSS.WCW cover glass is lower by 13.48 % compared to the DSSS cover glass temperature. This condition indicates the success of this study, which has the aim of reducing the cover glass temperature and the results of this study are in line with previous research [29].

Fig. 5, 6 shows the temperature difference between DSSS.WCW and DSSS. The temperature difference is presented in Fig. 7.

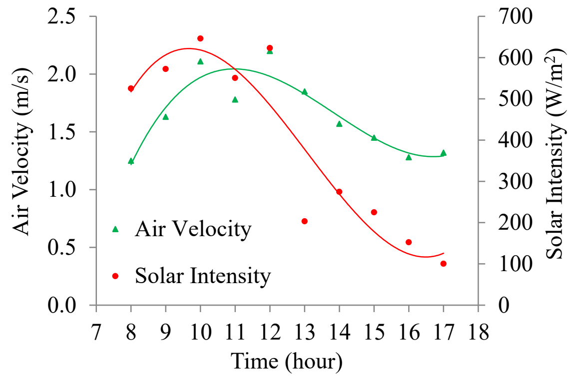

Fig. 4. Wind speed and solar intensity

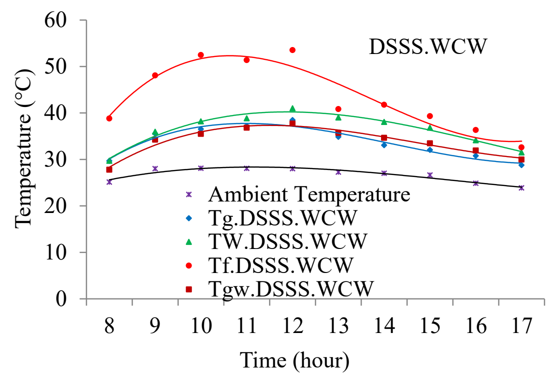

Fig. 5. Temperature in double slope solar still equipment with water cooling on the wall (DSSS.WCW)

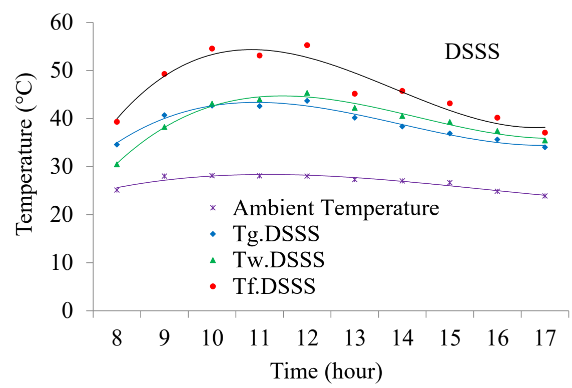

Fig. 6. Temperature in double slope solar still (DSSS) equipment

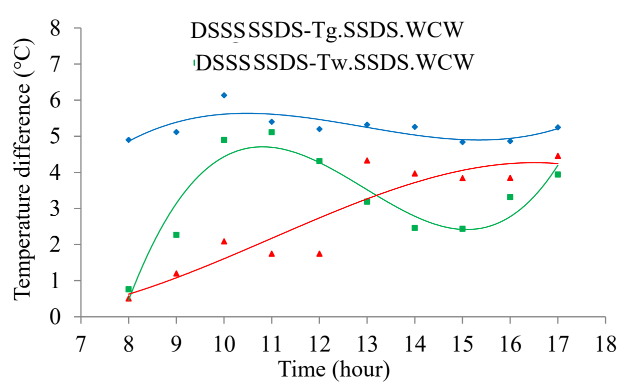

Fig. 7. Temperature difference

Fig. 7 shows the temperature difference between DSSS and DSSS.WCW. The temperature difference provides information about the higher temperature of DSSS compared to DSSS.WCW. The average cover glass temperature difference is 5.23 °C, the average basin water temperature difference is 3.43 °C and the average fins temperature difference is 2.92 °C. The temperature difference also provides information about the temperature drop when using water cooling on the wall. The temperature drop occurs on the cover glass, water basin and fins.

A decrease in the temperature of the glass cover, water basin and fins can have an effect on the temperature difference of the fins to the glass cover and the temperature of the water basin to the glass cover [15]. Fig. 8 shows that DSSS.WCW has a higher temperature difference of the fins to DSSS he glass cover and the water basin to the glass cover compared to DSSS. In DSSS.WCW, the average temperature difference from the fins to the glass cover is 9.82 °C and the water basin to the glass cover 2.63 °C. While in DSSS, the average temperature difference from the fins to the glass cover is 6.08 °C and the water basin to the glass cover 1.31 °C. The increase in temperature difference from the fins to the glass cover and the water basin to the glass cover in DSSS.WCW indicates an increase in the evaporation and condensation process [30].

In addition, the effect of water cooling on the wall occurs in the total heat transfer from the fins and water basin to the glass cover, as can be seen in Fig. 9.

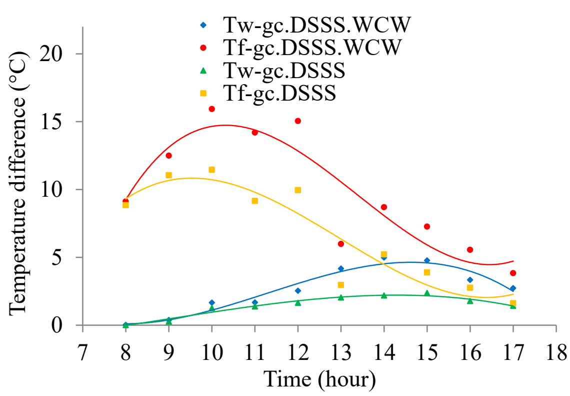

Fig. 8. Water basin to glass cover temperature difference and fins to glass cover difference

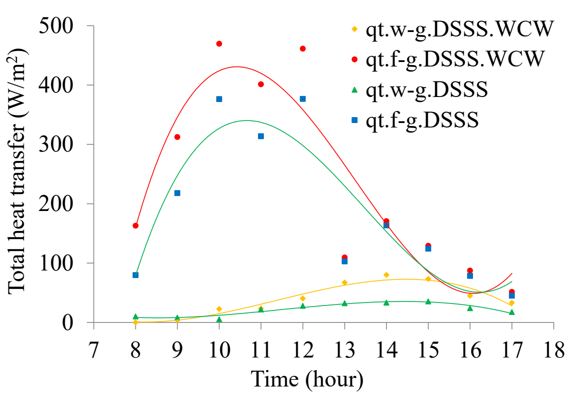

Fig. 9. Total heat transfer of water to glass and fins to glass in DSSS.WCW and DSSS

The total heat transfer is high from morning to noon and decreases from noon to evening. This condition is in accordance with the energy received, besides that the heat from the fins is also transferred to the water basin. The heat received by the water basin is transferred to the glass cover and some heat is stored. The heat stored by the water basin and the fin absorber plate will be used effectively when the ambient temperature is lower [31].

During the day, the total heat transfer from the fins to the glass cover in DSSS.WCW with DSSS experienced a significant difference, but in the afternoon it was relatively the same. This indicates that cooling is more effective when the intensity of solar radiation is high. At low solar radiation intensity, the water basin can help the total heat transfer from the water basin to the glass cover.

5. 2. Performance of the double slope solar still with water cooling on the wall compared to without water cooling

The performance of the solar still in terms of productivity and efficiency of the double slope solar still using water cooling on the wall compared to without water cooling. In addition, the experimental results are compared with theoretical calculations.

In Fig. 10, it can be seen that the accumulated water productivity experimentally and theoretically using DSSS.WCW is higher than in DSSS. Using the addition of water cooling on the wall can reduce the cover temperature and can expand the condensation surface, so as to increase the temperature difference between the evaporation surface and the condensation surface [32]. Increasing the temperature difference between the evaporation surface and the condensation surface can increase the evaporation energy value ($q_{e.f\text{-}gc}+q_{e.f\text{-}gw}$) [33]. Increasing the value of evaporation energy can increase freshwater productivity [34].

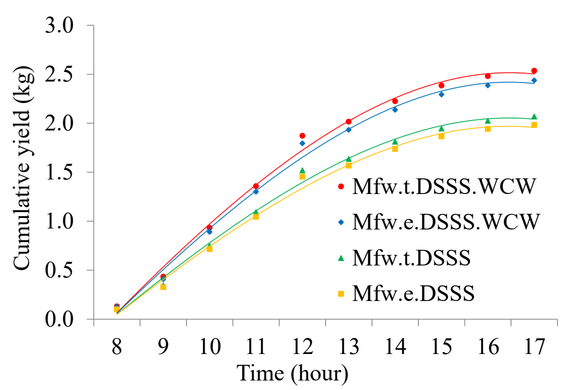

Fig. 10. Cumulative yield of DSSS.WCW and DSSS experimentally ($M_{fw.e}$) and theoretically ($M_{fw.t}$)

From the results of the experiment for 5 days, the productivity of fresh water is accumulated every day. In addition, theoretical calculations were made based on the experimental temperatures. A comparison of daily experimental and theoretical freshwater productivity is presented in Fig. 11.

In Fig. 11, it can be seen that the highest freshwater productivity on the third day of testing using DSSS.WCW theoretically amounted to 2.80 kg/10 hours and experimentally amounted to 2.59 kg/10 hours, while the highest productivity using DSSS theoretically amounted to 2.46 kg/10 hours and experimentally amounted to 2.29 kg/10 hours at an average solar radiation intensity of 312.75 W/m^2. The third day of testing showed an increase in freshwater productivity theoretically by 13.82 % and experimentally by 13.10 %.

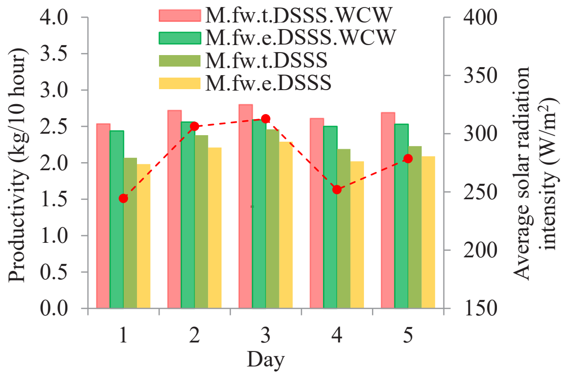

Fig. 11. Daily productivity of DSSS.WCW and DSSS experimentally and theoretically

In Fig. 12, the theoretical and experimental energy efficiency is presented. The difference in energy efficiency values experimentally and theoretically is not significant in both DSSS.WCW and DSSS. The highest energy efficiency was obtained using DSSS.WCW compared to DSSS. This condition is caused by the difference in temperature of the fin absorber plate to the glass cover and the temperature of the water basin to the glass cover. The difference in temperature of the fin absorber plate to the glass cover and the temperature of the water basin to the glass cover can increase the evaporation rate. A high evaporation rate can increase the productivity of condensate water. High condensate water productivity can increase energy efficiency [35].

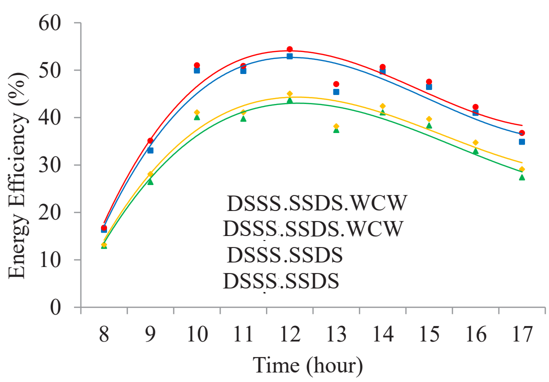

Fig. 12. Energy efficiency of DSSS.WCW and DSSS experimentally and theoretically

In the afternoon to evening, the energy efficiency is high, this condition is caused by the nature of the fin and water absorbing plate material, which still stores energy. The highest energy efficiency using DSSS.WCW is theoretically 54.42 % and experimentally 52.92 %, while the highest energy efficiency using DSSS is theoretically 45.05 % and experimentally 38.94 % at a solar radiation intensity of 623.15 W/m^2.

The research was conducted for 5 days, then the energy efficiency was calculated. The calculation uses equation (13) experimentally and theoretically and the results can be seen in Fig. 13. In Fig. 13, it can be seen that the daily average energy efficiency using DSSS.WCW theoretically amounted to 44.93 % and experimentally amounted to 43.38 %, while the daily average energy efficiency using DSSS theoretically amounted to 36.74 % and experimentally amounted to 35.32 % at an average solar radiation intensity of 312.75 W/m^2. The third day of testing showed an increase in energy efficiency theoretically by 22.29 % and experimentally by 22.82 %.

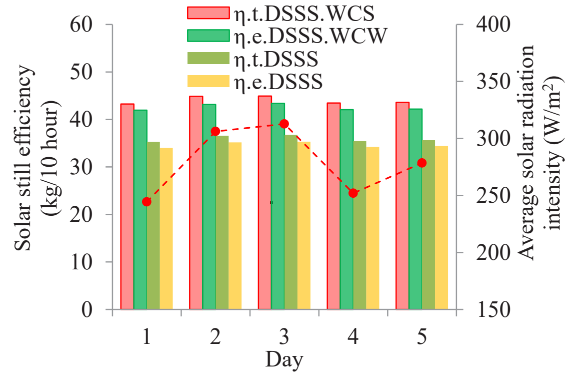

Fig. 13. Daily energy efficiency of DSSS.WCW and DSSS experimentally and theoretically

5. 3. Comparison of exergy efficiency with water cooling on the wall and without water cooling

From the experimental data, the exergy efficiency calculation is then carried out. The results of the calculation can be seen in Fig. 14, 15.

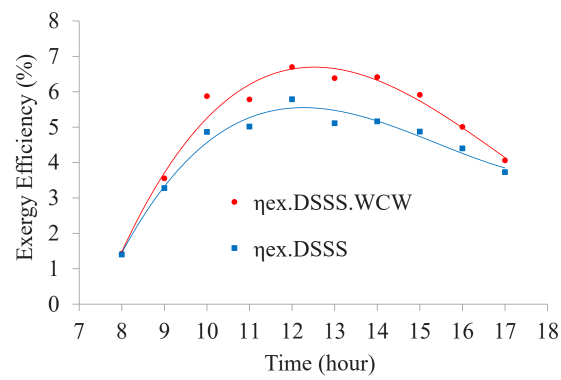

Fig. 14. Exergy efficiency of DSSS.WCW and DSSS

Fig. 14 shows the exergy efficiency pattern for each hour. This pattern shows that the difference using DSSS.WCW and DSSS in the morning is relatively the same, but in the afternoon there is a significant difference. This condition provides information that during the day using water cooling on the wall is more effective than without cooling. The average exergy efficiency at each hour is the highest using DSSS.WCW at 6.70 % compared to DSSS at 5.79 %.

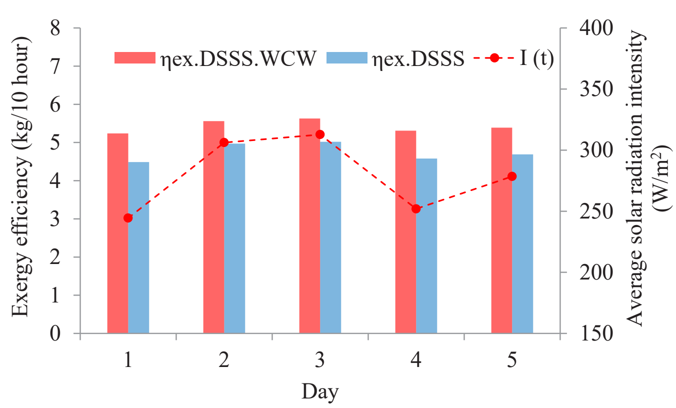

Fig. 15. Daily exergy efficiency of DSSS.WCW and DSSS

The research was conducted for 5 days, then the exergy efficiency was calculated. The calculation uses equation (15) and the results can be seen in Fig. 15.

Fig. 15 shows the results of the exergy efficiency calculation. From the calculation results, it can be seen that the highest daily average exergy efficiency using DSSS.WCW is 5.63 % and using DSSS is 5.02 %. From the highest exergy efficiency, there is an increase in exergy efficiency of 15.71 %.

6. Discussion of the research results on the effect of water cooling on the wall applied to the double slope solar still

The research was conducted experimentally. In Fig. 4, it can be seen that the intensity of solar radiation with wind speed has a pattern that is not the same, this is due to natural factors that can't be determined by conditions. In Fig. 5, 6, it can be identified that DSSS.WCW experienced a decrease in cover glass temperature by 13.48 % compared to DSSS. In Fig. 7, it can be identified that the average temperature difference between DSSS.WCW and DSSS is 5.23 °C for the cover glass temperature, 3.43 °C for the basin water temperature and 2.92 °C for the fins temperature. From the decrease and temperature difference, information is obtained about the positive effect of water cooling on the wall applied to the double slope solar still.

The cooling effect of water on the wall can reduce the temperature of the cover glass, fins and water basin. The decrease in temperature has a positive effect on the temperature difference between DSSS.WCW and DSSS. The effect of the decrease in temperature can also have an effect on the temperature difference between the fins to the glass cover and the water basin to the glass cover, this difference can be used as an indicator of increased evaporation energy. From Fig. 8, it can be identified that the average temperature difference from the fins to the glass cover is 9.82 °C and the water basin to the glass cover is 2.63 °C. While in DSSS, the average temperature difference from the fins to the glass cover is 6.08 °C and the water basin to the glass cover 1.31 °C. The high temperature difference in DSSS.WCW is the effect of water cooling on the wall, so as to increase the energy for evaporation, this is in accordance with the papers [29, 30].

In addition, the effect of water cooling on the wall on the total heat transfer from the fins and water basin to the glass cover can be seen in Fig. 9. Total heat transfer consists of evaporative heat transfer, convection heat transfer and radiation heat transfer. The high total heat transfer in DSSS.WCW can provide information about the high rate of evaporative heat transfer, making it possible to increase the productivity of the solar still.

Using water cooling on the wall results in a smaller decrease in the temperature of the glass cover compared to the results in [12]. In addition, using the water cooling method on the wall has an effect on the temperature difference between the evaporation surface and the condensation surface, which is smaller than that of [15]. This condition is caused by the water cooling on the wall being fixed and not flowing. However, the water cooling method on the wall does not reduce the solar radiation energy transmitted by the cover glass, does not require a large volume of cooling water, does not use additional energy, and uses relatively cheap materials. From the results of the study, the decrease in the temperature of the cover glass is relatively small, so development is needed to further reduce the temperature of the cover glass.

Water-cooled walls can be used as condensing surfaces. Utilizing the water-cooled wall as a condensation surface can expand the condensation surface, so it can help reduce the temperature of the glass cover. The decrease of glass cover temperature in DSSS.WCW can increase the temperature difference from the fins to the glass cover and from the water basin to the glass cover. The effect of increasing the temperature difference can increase the evaporative heat transfer from the fins to the glass cover and from the water basin to the glass cover. Such increased heat transfer can increase water vapor production and further increase freshwater productivity. From the research results in Fig. 10, 11, it can be seen that using DSSS.WCW resulted in higher freshwater productivity experimentally and theoretically compared to DSSS. The results showed an increase in freshwater productivity theoretically by 13.82 % and experimentally by 13.10 % at an average solar radiation of 312.75 W/m^2. This increase in productivity has a value comparable to the research paper [12] between 5.3–30 %, but smaller than in the research paper [13] of 73.8 % and the paper [7] of 61.3 %. Previous studies have not studied the relationship between the percentage of freshwater productivity increase with solar radiation intensity. In addition, development is still needed to further reduce the cover glass temperature, so as to increase the temperature difference from the fins to the cover glass and from the water basin to the cover glass. This increase in temperature difference can increase the productivity of the solar still.

Increased freshwater productivity can improve the energy efficiency of the solar still. The increase in energy efficiency in DSSS.WCW is higher experimentally and theoretically compared to DSSS. Fig. 12 shows the highest energy efficiency using DSSS.WCW theoretically 54.42 % and experimentally 52.92 % at a solar radiation intensity of 623.15 W/m^2. While in Fig. 13, it can be seen that the average daily energy efficiency using DSSS.WCW theoretically amounted to 44.93 % and experimentally amounted to 43.38 % at an average solar radiation intensity of 312.75 W/m^2. In [14], the actual efficiency of 52.32 % is comparable to the experimental efficiency of this study, but the theoretical efficiency in [14] is 90.88 %, which is greater than in this study, which is 54.42 %. By looking at the efficiency results that differ greatly in previous studies compared to this study, it is necessary to examine the equations used.

The performance of the solar still can be evaluated in terms of productivity and efficiency, both experimentally and theoretically. From the results of theoretical studies of freshwater productivity and energy efficiency, there are insignificant differences with experimental results. Although the difference in productivity and efficiency of solar stills experimentally and theoretically is not significant, it is necessary to conduct a study to further minimize the difference.

The research shows that using DSSS.WCW produces an exergy efficiency of 6.70 %, which is higher than in DSSS at 5.79 %. While the average daily exergy efficiency using DSSS.WCW is 5.63 % and using DSSS is 5.02 %. From the highest exergy efficiency, it can be seen that the average daily exergy efficiency increased by 15.71 %. This condition is caused by a decrease in the cover glass temperature due to water cooling on the wall. Low cover glass temperature can increase the value of the temperature difference between the absorber plate fins and the cover glass, and between the water basin and the cover glass, thereby increasing the value of the evaporation exergy $Ex_{e.f\text{-}gc}+Ex_{e.f\text{-}gw}$. Increasing the evaporation exergy can increase the exergy efficiency and decrease the exergy damage [36]. The decrease in cover glass temperature is still small, so further research needs to be done to further reduce the cover glass temperature. In addition, this study also still has limitations on the condition of solar radiation intensity, which cannot be conditioned during the experiment.

Water cooling research on double slope solar still walls resulted in an experimental productivity of 2.58 kg/10 h and theoretical 2.80 kg/10 h at an average solar radiation intensity of 312.75 W/m^2. If each person consumes 2 liters/day and a family consists of 4 people, then the total fresh water requirement is 8 liters/day. From the total fresh water demand, about ±3 m^2 of water-cooled double slope solar still is needed for each family. Indonesia has an area of 1,905 million km^2 with 17 thousand islands, so it has a variety of solar radiation intensity, so it is necessary to determine the need for solar stills in the first study. From the research conducted, the results have prospects for application in the community, because solar stills have a design that is easy to construct, using materials available in the market, cheap, easy to operate and maintain, solar radiation energy is available almost all day and free.

7. Conclusions

1. Using the DSSS.WCW has an effect on the temperature difference between the evaporation surface and the condensation surface compared to DSSS. Research using DSSS.WCW can reduce the cover glass temperature by 5.23 °C, basin water temperature by 3.43 °C and fins temperature by 2.92 °C compared to DSSS.

2. Solar still performance can be identified from the productivity and efficiency of the solar still. Using DSSS.WCW resulted in higher freshwater productivity and efficiency experimentally and theoretically compared to DSSS. DSSS.WCW produces the highest freshwater productivity experimentally at 2.58 kg/hour and theoretically at 2.80 kg/hour. DSSS.WCW produces an average daily energy efficiency experimentally of 43.38 % and theoretically 44.93 %.

3. Using DSSS with water-cooled walls (WCW) lowers the glass cover temperature, consequently enhancing the evaporation exergy compared to DSSS. The daily average exergy efficiency using DSSS.WCW is 5.63 % and using DSSS is 5.02 %.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the current work.

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