

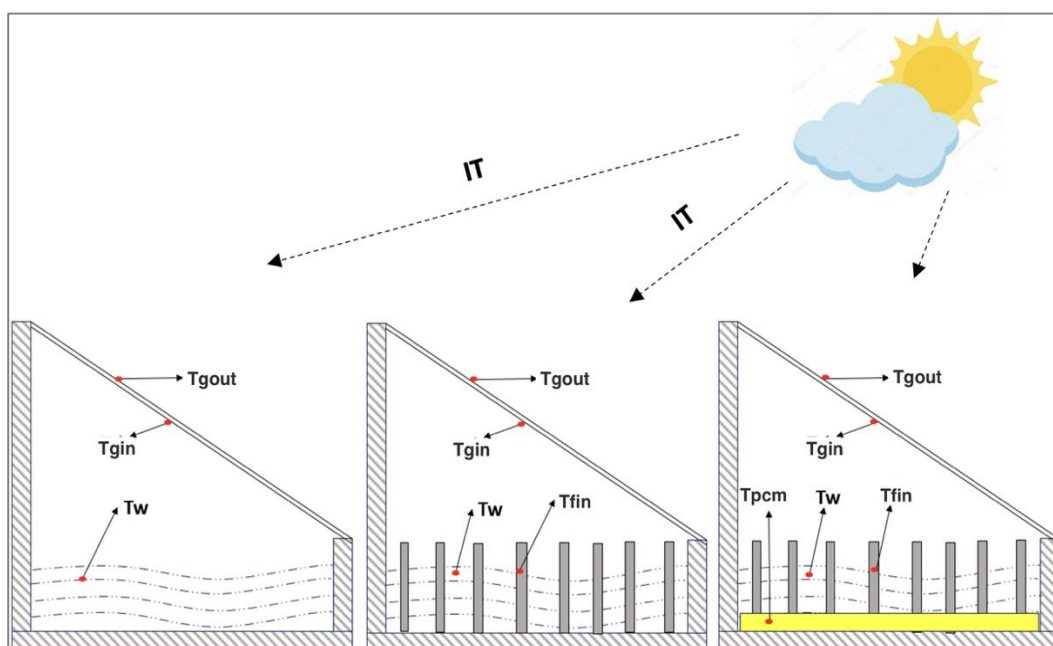
Energy, exergy, and economic (3E) of a single slope solar still by integrating hollow circular fins and soybean wax as a thermal energy storage system

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Highlights:

- Solar still enhanced with hollow fins and soybean wax PCM.
- Distillate yield increased to 1.364 L/m²/day (vs 0.986 L/m²/day).
- Energy and exergy efficiencies improved to 77.6% and 42%.
- Water cost reduced to ~0.05 \$/L/m², ensuring feasibility.

Article info

Submitted:
2025-10-29

Revised:
2026-02-11

Accepted:
2026-02-11



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Publisher

Universitas
 Muhammadiyah
 Magelang

Abstract

Energy, exergy, and economic value are examined for the efficiency and sustainability of a unique design for a single-slope solar still that utilizes hollow cylindrical fins and soybean wax as a phase change material (PCM). The three cases outlined, among others: case 1, a conventional single slope solar still (CS4); case 2, with hollow cylindrical fins (HCFS4), and case 3 with hollow cylindrical fins and soybean wax as PCM (HCFWS4). Performance experimental evaluations of the three cases under the same meteorological conditions ensure a fair comparison of their performances and are carried out for 5 days of testing. The experimental results show that the distillate water yield over five days is 0.986 L/m²/day, 1.243 L/m²/day, and 1.364 L/m²/day for cases 1, 2, and 3, respectively. Also, the maximum energy efficiencies of cases 1, 2, and 3 are 48.9%, 66.1%, and 77.6%, respectively. It is observed that the average exergy efficiency in cases 1, 2, and 3 is 33%, 40%, and 42%, respectively. Furthermore, economic analysis findings revealed that the costs per liter per square meter for cases 1, 2, and 3 are 0.06\$/L/m², 0.05\$/L/m², and 0.05\$/L/m², respectively.

Keywords: Conventional single slope solar still; Hollow circular fins; Soybean wax; Energy; Exergy; Economics

Nomenclature			
PCM	: Phase Change Material	LMC	: Liter Market Cost
TES	: Thermal Energy Storage	T _{gout}	: Temperature outer glass (°C)
S4	: Single Slope Solar Still	T _{gin}	: Temperature inner glass (°C)
CS4	: Conventional Single Slope Solar Still	T _w	: Temperature brackish water (°C)
HCFS4	: Hollow Circular Fins Single Slope Solar Still	T _{fins}	: Temperature Fins (°C)
HCFSWS4	: Hollow Circular Fins and Soybean Wax Single Slope Solar Still	T _{pcm}	: Temperature phase change materials (°C)
SDG	: Sustainable Development Goals	T _{amb}	: Temperature ambient (°C)
TDS	: Total Dissolved Solid	u	: The uncertainty experimental measurement
FAC	: First Annual Cost	$\sum \dot{m}$	: Total accumulated productivity in kg
CRF	: Capital Recovery Factor	h_{fg}	: Average latent heat evaporation of water J/kg
P	: Capital Cost (\$)	A _s	: Absorber surface area in m ²
ASV	: The Annual Salvage Value	$\sum I_{(t)}$	: Total solar radiation intensity in W/m ²
SSF	: The Sinking Fund Factor	η_{ex}	: The exergy efficiency (%)
S	: The Salvage Value	E _{xout}	: Output exergy (evaporation exergy) (%)
AMC	: The Annual Maintenance Cost	E _{xin}	: Exergy input (solar exergy input) (%)
AC	: The Annual Cost	i	: The annual rate (%)
CPL	: The Cost per Liter (\$/L/m ²)	n	: The life time years (years)
Pn	: The Average Annual Distilled Yield Productivity (L/m ² /year)		

1. Introduction

Rapid population growth and increasing water demand have triggered a clean water crisis. This crisis is further exacerbated by population migration, accelerated industrialization, and rising freshwater consumption, which is projected to increase by about 55% by 2050. Limited access to drinking water is currently estimated to affect 768 million people worldwide and is expected to impact around 1.8 billion people by 2027 [1], [2]. Desalination methods have become a promising solution to meet the water needs of the population. Desalination technology functions to convert seawater into freshwater by utilizing the abundant seawater resources, which account for about 98% of the Earth's surface. Solar desalination is categorized as an environmentally friendly technology because it uses solar energy as its primary energy source. The advantages of this technology have the potential to support the achievement of the Sustainable Development Goals (SDGs), particularly in the areas of clean water availability, affordable sanitation, sustainable energy, and climate change mitigation. In general, solar still systems operate on the fundamental principles of evaporation and condensation of brackish or saline water [3], [4]. During their development, significant attention has been directed toward the considerable heat losses associated with the process (Figure 1). Consequently, numerous modifications have been explored, including improvements to the test chamber design, the integration of absorptive materials, and the application of phase change materials (PCM).

Desalination research generally focuses on three key aspects: energy storage materials, chamber geometry modifications, and absorber design improvements. Alaian *et al.* [5] reported that incorporating pin-axis fins enhanced productivity by 23% and efficiency by 55%. Similarly, Raj

Kamal *et al.* [6] compared single-slope and double-slope solar stills, showing that the integration of an external heater in the lower chamber improved thermal efficiency by 15%, with respective productivities of 2.74 kg/m² and 5.78 kg/m².

Other studies have also examined the application of absorber geometry modifications in solar stills. Tirawi [7] investigated an asymmetric Compound Parabolic Concentrating (CPC) solar collector with an inverted absorber, which demonstrated a higher temperature difference between the

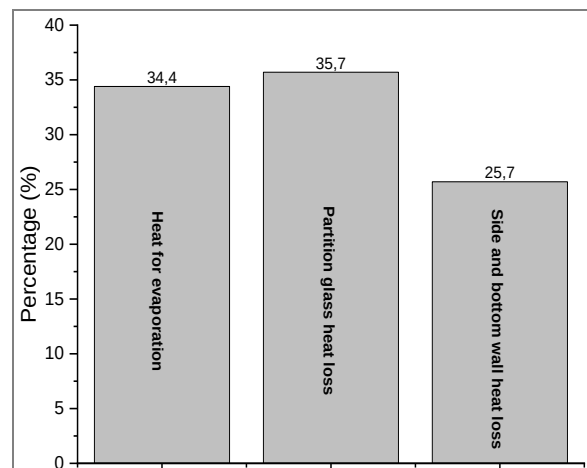


Figure 1.
The percentage of heat loss for the entered solar heat on the solar still

inner and outer glass surfaces and improved thermal efficiency. Kumar *et al.* [8] and Velmurugan *et al.* [9] studied the development of single-slope and double-slope solar stills, considering key factors influencing productivity such as seawater temperature, initial water temperature, and glass cover inclination. Additionally, several studies have investigated variations in basin geometry. Arunkumar *et al.* [10] analyzed a hemispherical model, Tayeb [11] modified the distillation chamber, and Tanaka [12] incorporated reflectors to enhance performance and productivity. Phadatare *et al.* [13] investigated the effect of seawater depth on heat and mass transfer within the basin, reporting a maximum efficiency of 34% at a water depth of 20 mm, with a distillate yield of 1.1 L/m²/day.

Extensive efforts have been made to enhance the performance of solar stills through the application of absorber heat. Dev *et al.* [14] investigated the Inverted Absorber Solar Still (IASS) under different seawater depths, reporting maximum productivities of 6.302, 5.576, and 4.299 kg/m²-day at water depths of 0.01, 0.02, and 0.03 m, respectively. Srivastava *et al.* further tested this system under both winter and summer conditions, achieving continuous operation for 24 hours with a 56% improvement in efficiency [15]. Additionally, the application of square fins with wick materials enhanced productivity by 4.55 kg/m²-day [16]. Alternative methods employing pin-fin absorbers were also implemented, where the integration of pin fins with an external cooling system improved the condensation rate by widening the temperature difference between the internal and external systems [17]. Qiu *et al.* examined plain-fin geometries, focusing on heat transfer characteristics to clarify the physical phenomena and provide theoretical analysis [18]. Similarly, Singh *et al.* proposed a novel absorber-fin design aimed at optimizing natural convection to achieve more effective heat transfer [19].

In an effort to enhance heat harvesting in solar still systems, researchers have combined absorber fins with phase change materials (PCMs). Shrivastava *et al.* [20] investigated circular and triangular fins with seawater depths of 15, 30, and 45 mm, and found that circular fins at a depth of 15 mm achieved the highest productivity of 1.4 L/day. Bady *et al.* [21] examined hollow cylindrical copper fins integrated with paraffin wax as PCM, reporting a daily yield of 7.50 L/m²/day with an efficiency of 73.6%. Saad *et al.* [22] applied longitudinal fins combined with a novel PCM, achieving a daily productivity of 36.25%. Nehar *et al.* [23] studied hollow copper coil fins integrated with paraffin PCM, resulting in a productivity of 1.81 L/m²/day. Furthermore, Abdullatief *et al.* [24] and Bhattacharyya [25] developed external triangular fins integrated with nanoparticles. Dhindsa *et al.* investigated paraffin wax with floating wicks in the basin, where 6000 g of paraffin yielded 3.96 kg/m², representing a 28.14% improvement compared to a conventional solar still. Other integrated fin-PCM applications have also been explored, such as fatty acid-based PCM with pin fins [26] and palmitic acid PCM with aluminum fins [27].

Although the use of PCM to enhance the efficiency of solar stills (SS) has gained increasing attention, its inherently low thermal conductivity limits heat transfer and delays thermal response, particularly during the discharge phase. Previous studies have incorporated PCM beneath the SS basin; however, the potential of employing submerged hollow circular fins to improve the thermal conductivity of PCM has not been adequately investigated. Moreover, the lack of experimental thermo-economic analysis under real climatic conditions leaves a gap in understanding the cost-effectiveness of such hybrid systems.

This study proposes a modified single-slope solar still incorporating stainless steel hollow cylindrical fins and soybean wax as PCM to enhance distilled water yield. Unlike previous works that used solid fins or different PCMs, this design uniquely combines hollow cylindrical fins with soybean wax. The research evaluates the system's energy, exergy, and economic performance across three configurations (CS4, HCFS4, and HCFSWS4). The temperature distribution of fins and PCM is analyzed using Fluent at selected time intervals. The proposed design avoids costly PCMs and complex setups, ensuring simplicity and suitability for remote coastal communities while offering an effective approach for small-scale solar desalination in tropical regions.

2. Method

2.1. Experimental Test-rig

Figure 2 shows the schematic diagram and a photograph of the test facility, while Figure 3a shows the hollow circular fin used in the study, which had 216 hollow circular fins with a 60 mm height, a diameter of 12.5 mm, and a distance between fins is 50 mm, against its properties represented in Table 1. The selection of hollow circular fins, characterized by a high quantity,

increased height, and close spacing, enhances heat absorption and significantly raises the distiller's temperature [28], [29]. Figure 3b shows soybean wax in the chamber with dimensions of 900 mm × 600 mm × 20 mm with a volume of 10 liters. The properties possessed by this material are shown in Table 2.

Specifically, the research was conducted in the courtyard of Building III, Faculty of Engineering, Universitas Sebelas Maret, Surakarta, Central Java, Indonesia (110° 45' 35" East Longitude and 70° 56' South Latitude) for 5 days in August. Our chosen study duration follows the methodology of Kateshia *et al.* [27] and Saad *et al.* [22], who conducted research over three days and one day, respectively. We evaluated the performance of the solar water distiller during August and observed no significant variations in atmospheric conditions, solar radiation intensity, or ambient temperature. Figure 4 shows the placement of the testing chambers ready for the testing process in the courtyard of Building 3.

This study evaluated three different cases: Case 1 is a conventional single-slope solar still (CS4), Case 2 is a hollow circular fins single-slope solar still with 216 fins (HCFS4), and Case 3 is a hollow circular fins (216 fins) with soybean wax as PCM (HCFSWS4).

Table 1.
The properties of the hollow circular fin used during the tests [30]

Properties	Value
Density	7850 kg/m ³
Tensile strength	555×106 N/m ²
Modulus of elasticity	210000 MPa
Impact strength	2800 kJ/m ²
Thermal conductivity	52 W/m K
Specific heat capacity	0.442 kJ/Kg °C
Transmissivity	0

Table 2.
The properties of soybean wax

Properties	Value
Melting Temperature	43.9 °C [31]
Heat latent	100.90 kJ/kg [32]
Thermal conductivity	0.25 W/m K [33]
Density	900 Kg/m ³ [33]
Specific heat capacity	0.496 kJ/Kg K [33]
Thickness	20 mm [34]

The chamber used for research is ensured to be the same size and geometry as the conventional single-slope solar still (CS4). Its model is constructed 900×600 mm in length and width, and the front and back heights are 180 mm and 400 mm, respectively. The upper chamber part is covered by 5 mm partition glass constructed with a 26° inclination. To minimize the propagation of heat to the surroundings, the testing chamber is covered by plywood. It also reduces the internal air exchange in the system with the surroundings.

Figure 2.
The testing variation:
(a) CS4;
(b) HCFS4;
(c) HCFSWS4

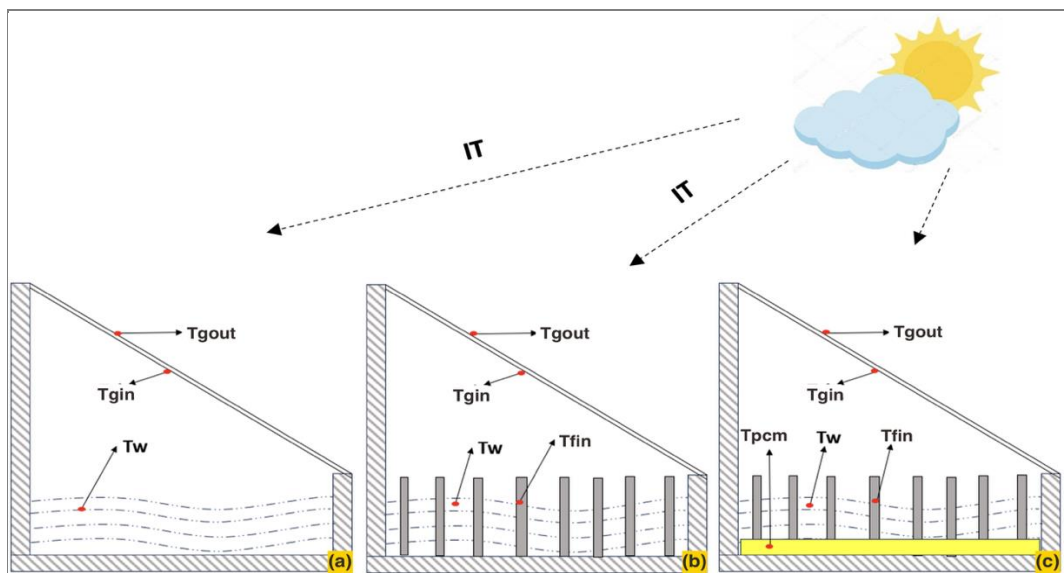


Figure 3.
(a) The hollow circular fin;
(b) Soybean wax PCM



Figure 4.
The placement solar
still testing chamber
and the cylindrical fins



2.2. Procedure and Instrumentations

The three identical testing chambers with each setup variation are investigated under the same seawater conditions. All chambers were ensured with the same seawater volume control, specifically 2 cm height. Its provision was also considered with the earlier research, approximately 10,800 cm³ [35]. When solar radiation reaches the water's surface then it gets heated up and evaporation starts through heat transfer. **Figure 5a** shows a thermal resistance process in a conventional single-slope solar still (CS4) under operation. Likewise, in case 2 (HCFS4), when solar radiation reaches the water and hollow circular fins surface then it happens conduction heat transfer between seawater and fins that caused heated up and evaporation to start through heat transfer, as shown in **Figure 5b**. Next in case 3 (HCFSWS4) when solar radiation reaches the water and hollow circular fins surface then it happens conduction heat transfer between seawater, fins, and PCM that caused thermal losses occur when the sun's intensity enters the basin space which should be able to heat and evaporate the water, but the heat is transferred to the PCM at the bottom, as shown **Figure 5c**.

During the investigation, the chamber temperature was measured in several parts, including the outer glass temperature (T_{gout}), inner glass (T_{gin}), seawater (T_w), fins (T_{fins}), PCM (T_{pcm}), and ambient temperature (T_{amb}) using a Type-K thermocouple. The thermocouple installation details are depicted in **Figure 2**. This appliance is connected to a data logger that records the temperature at 5-second intervals. The solar radiation intensity as the primary source, came into the chamber and was measured with the solar power meter. The production of each chamber was measured with a measuring cup continuously within a 1-hour interval. The measurement began at 07:00 and ended at 21:00. **Table 3** shows the specifications of each measuring instrument used in the study.

Figure 5.

- (a) Thermal resistance network (TRN) for CS4;
- (b) Thermal resistance network (TRN) for HCFS4;
- (c) Thermal resistance network (TRN) for HCFSWS4

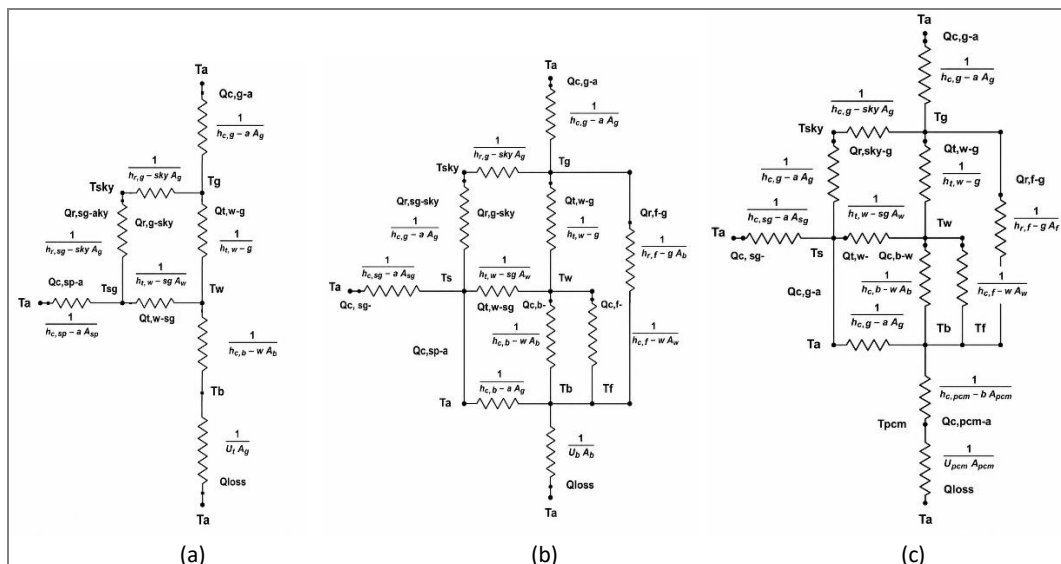


Table 3.

The detailed specification
measurement devices

Device	Parameter	Range	Accuracy
K-type Thermocouple	Temperature	-100 to 1300 °C	± 1 °C
Solar power meter	Solar radiance	0 – 200 W/ m ²	± 1 W/ m ²
Flask	Yield	0 - 2000 ml	2 ml

All measured factors were evaluated to determine the several factors that affected the solar still performance with precision and accuracy. Three devices were used for the testing measurement, and firstly the solar power meter was used to obtain the incoming radiation

intensity. Several thermocouples are placed in **Figure 2** to measure the solar still temperature, and glass measurement is used to calculate solar still production. **Table 3** presents the detailed measurement device with the accuracy and measurement range. The standard uncertainty benchmarked was defined with the root sum square of device accuracy and random errors. The related uncertainty is given in Eq. (1), where α and u represent the device accuracy and random error, respectively.

$$u = \frac{\alpha}{\sqrt{3}} \quad (1)$$

2.3. Internal Heat Transfer

In the context of internal heat transfer, the heat exchange from the shallow water to the glazing within the solar still is primarily governed by radiation, convection, and evaporation, so it's more effective to define these processes separately [36].

2.3.1. Radiative heat loss coefficient ($h_{rad-water}$)

In the present case, the surface of water and glass cover (glazing) has been measured as an inestimable parallel plane, and rate heat transfer is given by;

$$q_{rad-water} = \epsilon_{eff} \sigma \left[(T_{water} + 273)^4 - (T_{gin} + 273)^4 \right] \quad (2)$$

$$q_{rad-water} = h_{rad-water} (T_{water} - T_{gin}) \quad (3)$$

Where $h_{rad-water}$ is the coefficient of radiative heat transfer and is expressed as;

$$h_{rad-water} = \epsilon_{eff} \sigma \left[(T_{water} + 273)^2 + (T_{gin} + 273)^2 \right] (T_{water} + T_{gin} + 546) \quad (4)$$

Where:

$$\frac{1}{\epsilon_{eff}} = \frac{1}{\epsilon_{water}} + \frac{1}{\epsilon_{gin}} - 1 \quad (5)$$

2.3.2. Convective heat loss coefficient ($h_{conv-water}$)

Heat transfer within the solar still takes place through humid air by natural convection, driven by buoyancy effects and density changes caused by temperature differences in the fluid. As a result, the rate of convective heat transfer is determined by the following Eq. (6):

$$q_{con-water} = h_{con-water} (T_{water} - T_{gin}) \quad (6)$$

Now, with the help of the Grashof Number (Gr), Nusselt Number (Nu), and Prandtl Number (Pr), the convective heat transfer coefficient can be expressed as;

$$h_{con-water} = 0.884 \left[T_{water} - T_{gin} + \frac{(P_{water} - P_{gin})(T_{water} + 273)}{(268.9 \times 10^3 - P_{water})} \right]^{1/3} (T_{water} - T_{gin}) \quad (7)$$

2.3.3. Evaporative heat loss coefficient ($h_{evap-water}$)

Now, with the help of the mass transfer coefficient (h_{e-wat}) and the Cooper equation for solar still, the Eq. (7) becomes;

$$q_{evap-water} = 16.27 \times 10^{-3} h_{evap-water} (P_{water} - P_{gin}) \quad (8)$$

Where:

$$h_{evap-water} = 0.01627 \times h_{conv-water} \left[\frac{(P_{water} - P_{gin})}{(T_{water} - T_{gin})} \right] \quad (9)$$

$$h_{l-water} = h_{con-water} + h_{evap-water} + h_{rad-water} \quad (10)$$

2.4. Energy and Exergy

Energy analysis is based on the first law of thermodynamics, used to evaluate any solar-distillation system's energy efficiency and distillate output. Energy analysis deliberates only on the

quantitative aspect of the energy transfer. In contrast, the quality of energy, i.e., availability of energy or exergy, which is defined by the second law of thermodynamics, is usually ignored. The analysis is the most effective thermodynamic tool for achieving the goal of more efficient use of the resources because it enables the locations, the types, and the true magnitudes of energy waste and losses to be determined.

Based on the first law of thermodynamics, the energy balances for this experimental testing must be evaluated. The incoming energy was not all used to evaporate the seawater. A part of them is absorbed by the partition glass, walls, and losses throughout the day of testing. For all these reasons, the second law of thermodynamics has become a consideration for the calculation of energy input and energy used for evaporation and production. Eq. (11) is used to calculate the solar still efficiency [37]. Total accumulated productivity ($\sum \dot{m}$) is the hourly distillate in kg, average latent heat of vaporization (h_{fg}) in J/kg, absorber surface area (A_s) in m^2 , and total solar radiation intensity ($\sum I_{(t)}$) in W/m^2 , which affect the efficiency value.

$$\eta_{th} = \frac{\sum_{i=1}^{i=t} \dot{m} \times h_{fg}}{A_s \times \sum_{i=1}^{i=t} I_{(t)} \times 3600} \quad (11)$$

The average water temperature within the basin (T_w) was a parameter to determine the value of the average latent heat (h_{fg}). It can be calculated with Eq. (12) [38].

$$h_{fg} = 10^3 [2501.9 - 2.40706 \times T_w + 1.192217 \times 10^{-3} \times T_w^2 - 1.5862 \times 10^{-5} \times T_w^3] \quad (12)$$

The amount of latent heat (h_{fg}) used for the evaporation is calculated below [39].

$$h_{fg} = 3.1615 \times (10^6 - 761.6 \times Ti), \quad \text{since } Ti > 70 \quad (13)$$

$$h_{fg} = 2.4935(10^6 - 947.79 \times Ti + 0.13132 \times Ti^2 - 0.0047974 \times Ti^3), \text{ when } Ti < 70 \quad (14)$$

$$Ti = \frac{T_w + T_g}{2} \quad (15)$$

The exergy value was evaluated to analyze the quality and quantity of working energy through the desalination systems. Specifically for the present study, exergy is the ratio between the output evaporation exergy (E_{xout}) and incoming solar exergy (E_{xin}).

The three set-up experiments calculated their daily exergy efficiency throughout the water and PCM mass fraction [40].

$$\eta_{ex} = \frac{E_{xout}}{E_{xin}} \quad (16)$$

Given that input exergy can be calculated by using Eq. (17) and the exergy from evaporation given in Eq. (18) [39].

$$\begin{aligned} E_{xiin} &= E_{xsum} \\ &= I \times A_s \left[1 + \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}} \right)^4 - \frac{1}{3} \left(\frac{T_{amb}}{T_{sun}} \right)^4 \right] \end{aligned} \quad (17)$$

$$\begin{aligned} E_{xout} &= E_{xevap} \\ &= \frac{m \times hfg}{3600} \left[1 - \left(\frac{T_{amb} + 273}{T_{sun} + 273} \right) \right] \end{aligned} \quad (18)$$

The hourly radiation intensity is represented by I with W/m^2K , with the surface area as A_s in m^2 . Several measured temperatures, including ambient (T_{amb}), water (T_w), and outer glass temperature (T_{sun}) in K , where m was the distilled mass per hour.

2.5. Economic Theoretical

Economic analysis for using solar desalination has become an exciting focus to get cheap Production per Liter (CPL) and capital return. As for the considered factors, this research also investigated the economic analysis for CS4, HCFS4, and HCFSWS4. Annual cost analyses were calculated using Eq. (19).

$$FAC = CRF \times P \quad (19)$$

Since the capital cost is represented by P with the capital recovery factor (CRF). Considered the CRF as represented by Eq. (20).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (20)$$

Mentioned that i is the rate per year, and n is the lifetime solar still [41]. To evaluate the asset recovery value of constructing a single slope solar still, the ASV parameter is used. As estimated using the Eq. (21) [41], [42]. Where the S is denoted as the salvage value estimated by Eq. (22) [41].

$$ASV = SSF \times S \quad (21)$$

$$S = 0.2 \times P \quad (22)$$

The sinking fund factor (SSF) became a considerable factor in estimating the available cost to maintain the solar still components. The SSF can be estimated with Eq. (23) [41]. As well as the annual maintenance cost (AMC) per year is approximately 15% of the first annual cost (FAC) estimated by Eq. (24) [41]. Then the whole annual cost (AC) is estimated by Eq. (25) [41].

$$SSF = \frac{i}{(1+i)^n - 1} \quad (23)$$

$$AMC = 0.15 \times FAC \quad (24)$$

$$AC = FAC + AMC - ASV \quad (25)$$

So, the distilled production's cost per liter (CPL) can be written as follows Eq. (26), since the annual average distilled production is denoted as P_n .

$$CPL = \frac{AC}{P_n} \quad (26)$$

Regarding the annual solar still production calculation, the freshwater produced is averaged during sunny days [43], [44], [45], [46]. In Indonesia, the cost for freshwater is approximately 0.357 \$/liter considered from the general market cost. The payback period was also calculated regarding its effect, including fabrication, maintenance, operational, and brackish water input costs [47]. With Eq. (27) the payback period can be calculated.

$$CPL = \frac{AC}{P_n} \quad (27)$$

3. Results and Discussion

Experimental tests on a passive solar desalination device combined with an energy storage system were carried out in five days (1 to 5 August) in the climatic conditions of the city of Surakarta, Central Java, Indonesia, using salt water with a depth of 2.0 cm ($V_w = 10, 8$ liters). Throughout the test day, all temperatures were measured every $\Delta t = 10$ min; however, productivity readings were taken over the course of an hour. Next, the energy stored/recovered in/from the storage medium is estimated by:

$$Q = V_{sm} \times \rho_{sm} \times C_{sm} \times (\Delta t) \quad (28)$$

where, sm (fins and PCM soybean wax), V_{sm} , ρ_{sm} , and C_{sm} is volume, density, and specific heat thermal energy storage.

3.1. Temperature Distribution for CS4, HCFS4, and HCFSWS4

The temperature changes in different components of the solar still, such as the inner glass cover, humid air, saline water, and absorber plate, provide insights into the still's functionality and efficiency. The evaporation of brackish water increases with higher water temperature and a greater temperature difference between humid air and water. Conversely, condensation of evaporated water is influenced by the temperature difference between humid air and glass. Understanding these temperature dynamics can offer valuable insights into the still's operation and productivity, aiding in its optimization and performance evaluation.

Figure 6 illustrates the temperature variations over time for the solar still case 1 (conventional single slope solar still/CS4). It shows that all temperatures generally rise until around 1:00 PM, reaching peak values, before gradually declining until sunset. Additionally, it observes that the glass temperature tends to be slightly higher than the brackish water temperature in the early morning hours, which is attributed to differences in heat capacity and the time taken for the glass to heat up before transferring heat to the water. Subsequently, the water temperature increases faster due to heat dissipation from the glass to the surroundings. During the 5 days of observation, the average temperatures observed for the outer glass cover (T_{gout}), inner glass cover (T_{gin}), and brackish water (T_w) are 57.76 °C, 65.12 °C, and 67.84 °C, respectively. Additionally, the peak values of measured ambient temperature and solar intensity are 34.88 °C and 1009.2 W/m², respectively. It can be observed that the brackish water temperature (T_w) is higher than the outer glass temperature (T_{gout}) because the solar intensity entering through the glass ($k = 1.05$ W/m² K) is transmitted to the water, so the evaporation process increases.

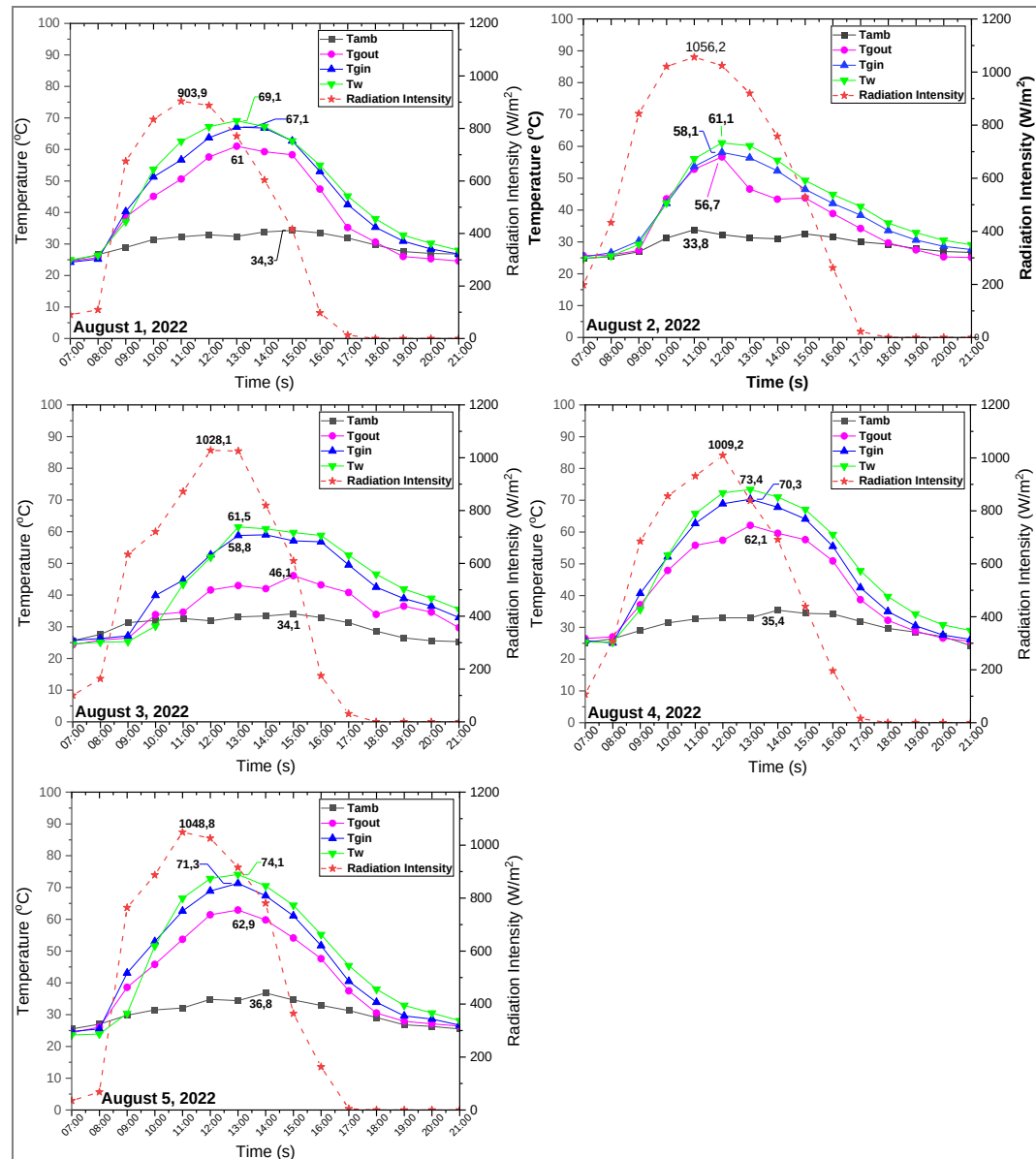


Figure 6.
The graph of
temperature and
radiation intensity for
CS4 (1-5 Days)

Figure 7 illustrates the average temperature parameters for Case 2, which utilizes a solar still equipped with hollow circular fins (HCFs4). Over a 5-day observation period, the system recorded maximum average temperatures of 57.92 °C for the outer glass cover (T_{gout}), 61.46 °C for the inner glass cover (T_{gin}), 65.84 °C for the brackish water (T_w), and 66.16 °C for the fins (T_{fins}). The solar still also measured an average maximum solar radiation of 1009.24 W/m² and an ambient temperature (T_{amb}) of 34.88 °C.

The average temperature difference between the maximum brackish water temperature (T_w) and the outer glass temperature (T_{gout}) in Case 2 was 7.92 °C, which is lower than the 10.08 °C

difference in Case 1. This reduction results from energy distribution at sunrise for heating the water and heating the fins, which lowers daytime distillation productivity. However, stored thermal energy in the fins extends heat release by approximately three hours after sunset, thereby enhancing nighttime productivity. Previous studies demonstrated that solar stills with pin-fin heat sinks achieve higher afternoon maximum temperatures for humid air and water than conventional stills, with respective increases of 4% and 3% [40].

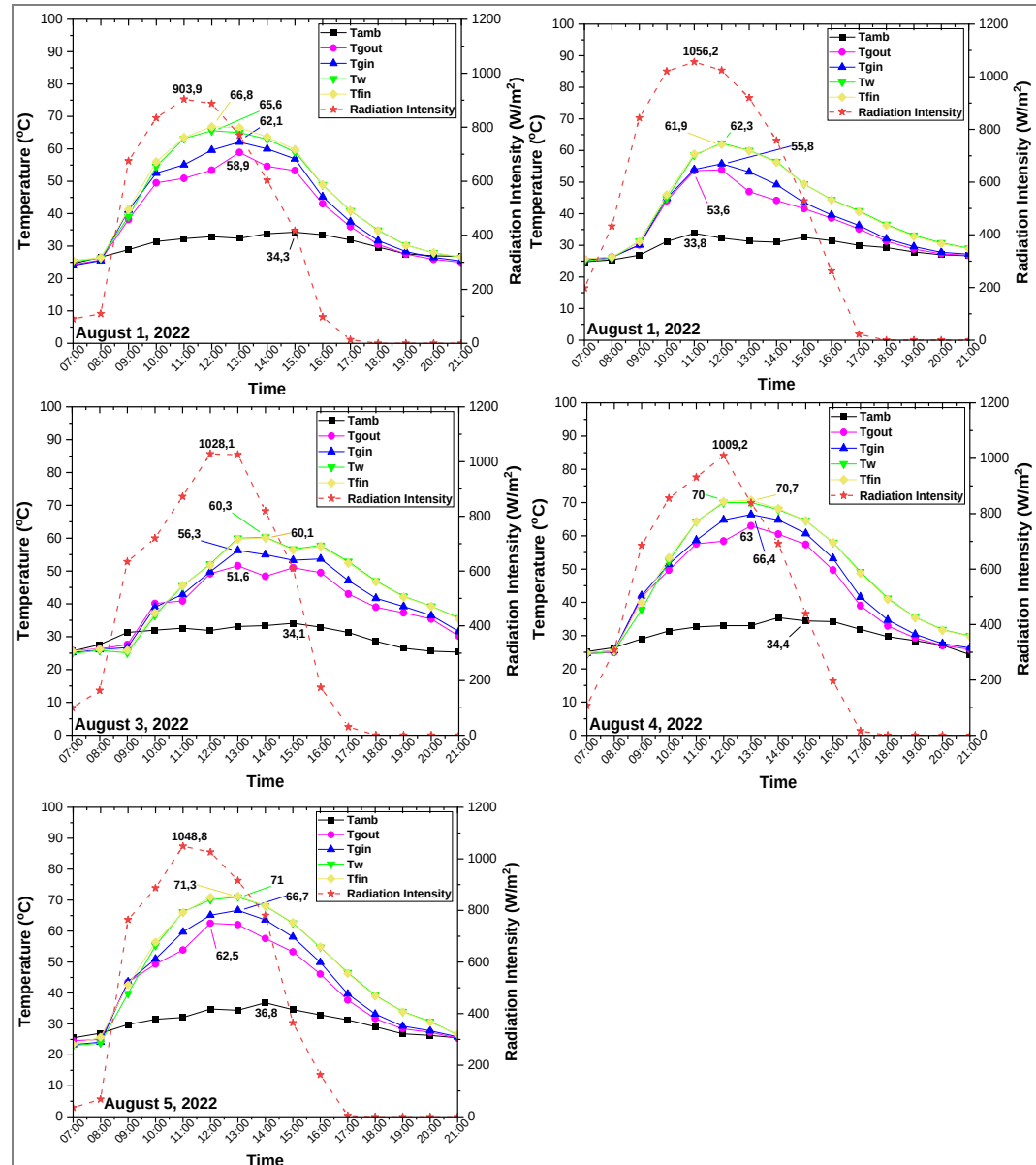


Figure 7.
The graph of
temperature and
radiation intensity for
HCFS4 (1-5 Days)

Figure 8 is presented to illustrate the distribution of average maximum temperatures for the outer glass (T_{gout}), inner glass (T_{gin}), brackish water (T_w), fins (T_{fin}), PCM (T_{pcm}), ambient temperature (T_{amb}), and solar radiation (I_T) in Case 3 of the solar still with a PCM reservoir and pin fins (HCFSWS4). The component temperatures were observed to increase until noon and decrease in the afternoon. Average maximum temperatures of 57.7 °C (T_{gout}), 60.9 °C (T_{gin}), 61.48 °C (T_w), 66.12 °C (T_{fin}), and 54.96 °C (T_{pcm}) were recorded, along with a peak solar radiation of 1009.24 W/m^2 and an ambient temperature of 34.88 °C.

The temperature difference between T_w and T_{gout} in Case 3 was measured at 3.78 °C, which is lower than the 10.08 °C and 7.92 °C differences recorded in Cases 1 and 2. This reduction was attributed to the distribution of energy at sunrise among heating the water, fins, and PCM, which reduced daytime productivity. However, thermal energy stored in the fins and PCM was found to extend heat release by approximately five hours after sunset, thereby enhancing night time productivity.

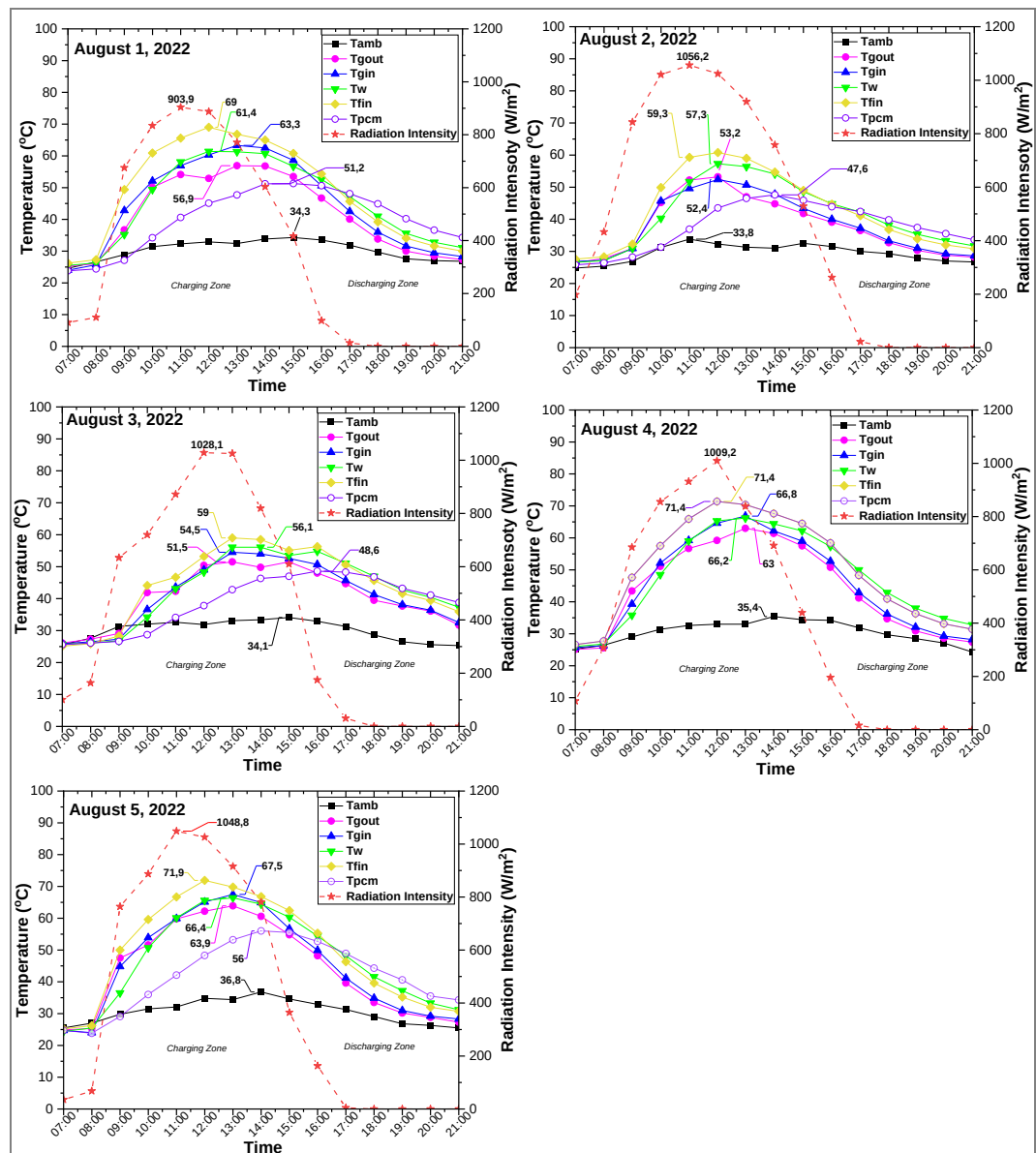


Figure 8.
The graph of
temperature and
radiation intensity for
HCFSWS4 (1-5 Days)

Figure 6 to Figure 8 illustrate the temperature variations of the outer glass cover and brackish water for Cases 1–3. Throughout the day, the brackish water temperature remained higher than that of the outer glass cover, indicating continuous evaporation. From morning until 2:00 PM, the outer glass and brackish water temperatures in Case 3 were lower than those in Cases 1 and 2, with Case 2 exhibiting higher values than Case 1. After 2:00 PM, Case 3 recorded the highest inner glass and brackish water temperatures among all cases.

From morning to noon, cases 1 and 2 show higher temperatures for both the outer glass cover and the saltwater compared to case 3. This increase results from a larger pool water exposure area, the use of hollow circular fins, and improved heat transfer between the pool and water, which enhances evaporation rates and increases freshwater productivity in cases 1 and 2. In contrast, case 3 transfers heat from seawater to the fins and the PCM, which functions as the charging zone.

At 3:00 PM, the glass cover and brackish water temperatures in case 3 exceed those in cases 1 and 2, as solar intensity decreases and the PCM releases stored heat in the discharge zone, as shown in Figure 8.

3.2. Fresh Water Production in Each Testing Chamber

Figure 9 illustrates the cumulative variation in freshwater productivity for the three cases, providing a comparison of hourly productivity throughout the day. Figure 10 presents freshwater productivity as a function of hourly intervals and includes a corresponding graph of solar intensity.

Figure 10 shows that before 4:00 PM, hourly freshwater productivity in the solar still with soybean wax as PCM (case 3) is lower than in cases 1 and 2 because heat from the brackish water

is absorbed by the PCM, reducing water temperature. From 4:00 PM to 9:00 PM, productivity in case 3 increases as the PCM releases stored heat, maintaining a higher brackish water temperature.

This increase is driven by a significant temperature difference ($T_w - T_{gin}$) between the seawater and inner glass cover, indicating continued evaporation and condensation, while productivity in cases 1 and 2 declines. The average $T_w - T_{gin}$ values from 4:00 PM to 9:00 PM are 2.85 °C, 4.02 °C, and 4.75 °C for cases 1, 2, and 3, respectively. These results align with Jahapanah *et al.* [48], who reported that larger $T_w - T_{gin}$ differences enhance condensation rates.

The five-day average cumulative productivity for CS4, HCFS4, and HCFSWS4 was 0.986 L/m²/day, 1.243 L/m²/day, and 1.364 L/m²/day, respectively. As shown in Figure 10, CS4 and HCFS4 exhibited higher productivity than HCFSWS4 from the morning until midday during the experiment.

This study highlights the influence of incorporating hollow circular fins and a PCM reservoir beneath the basin. The integration of highly conductive stainless-steel hollow circular fins and a PCM reservoir was found to enhance solar still productivity as a result of improved thermal transmission within the PCM. Conversely, the solar still with only a hollow circular fin reservoir (Case II) exhibited lower heat transfer performance.

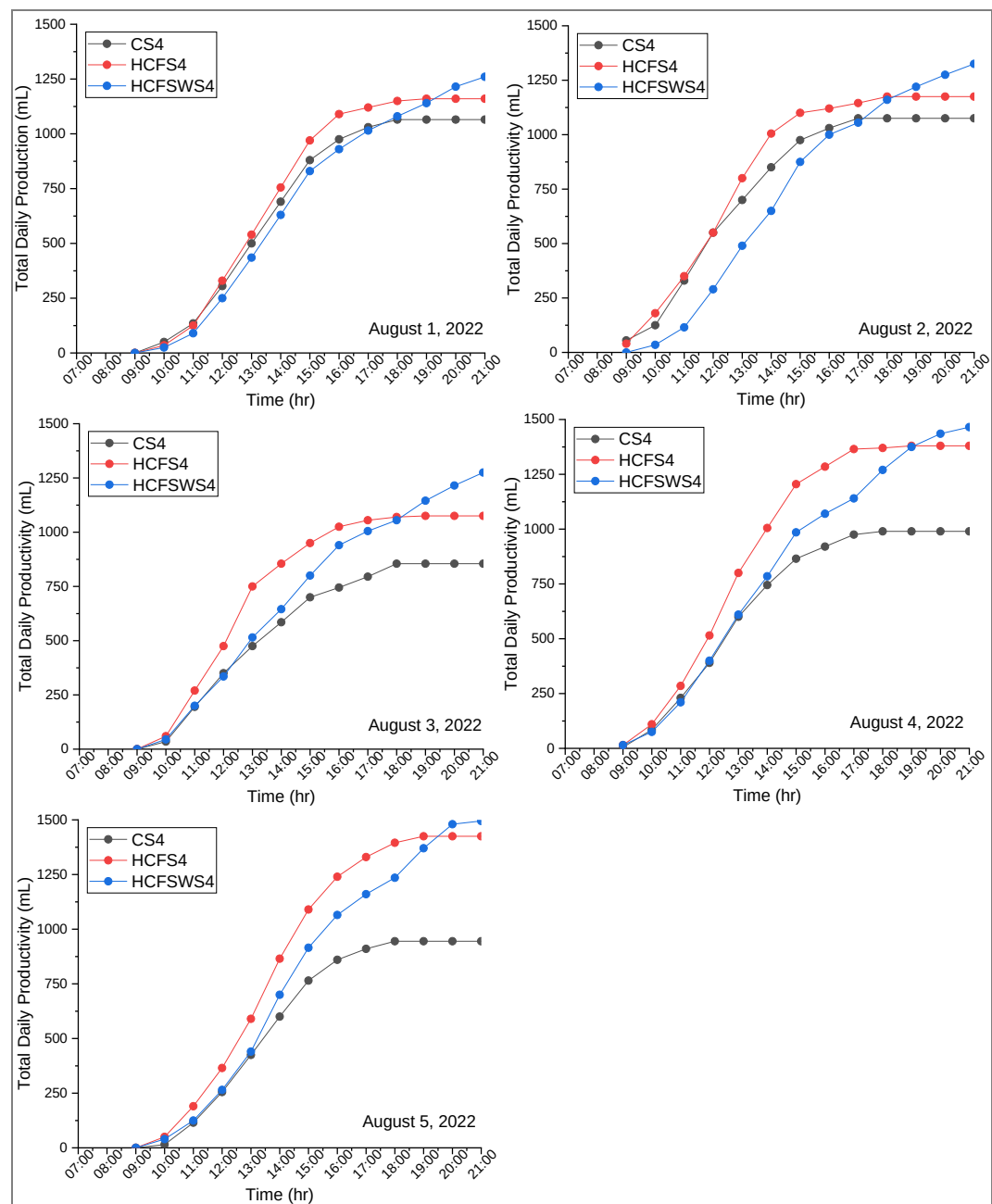


Figure 9.
The total day
production for each
testing chamber

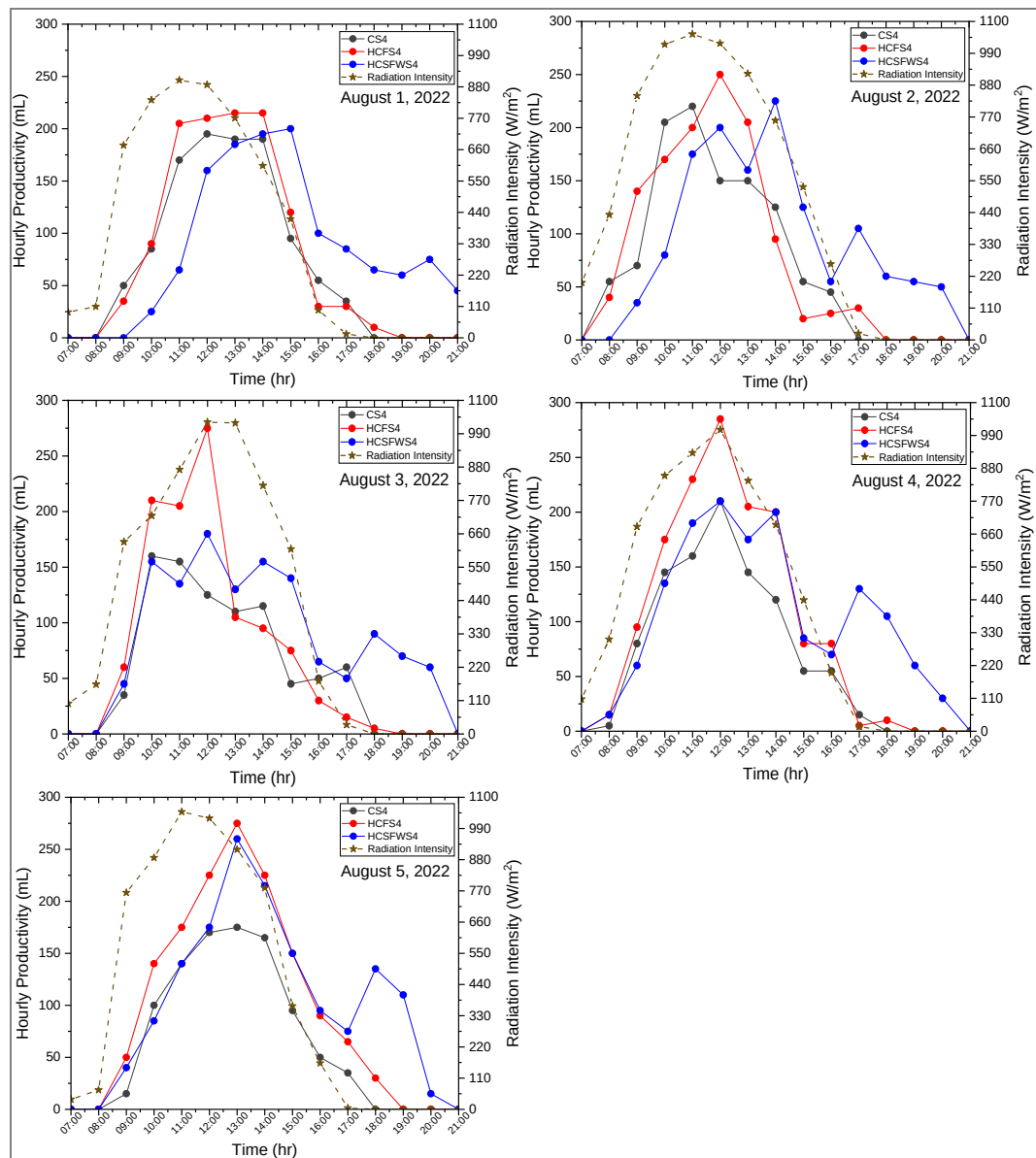


Figure 10.
The hourly production
of freshwater from
each testing chamber

3.3. Heat Storage with Hollow Circular Fins

During daytime operation, the brackish water is directly exposed to solar radiation, with part of the absorbed heat transferred through the glass cover and stored in the fins, which act as sensible heat storage. The maximum daily brackish water temperatures for Case 1 (CS4), Case 2 (HCFS4), and Case 3 (HCFSWS4) were recorded over five days. In Case 1, the recorded maximum temperatures were 69.1 °C, 61.1 °C, 61.5 °C, 73.4 °C, and 74.1 °C (Figure 6); in Case 2, they were 65.6 °C, 62.3 °C, 60.3 °C, 70 °C, and 71 °C (Figure 7); and in Case 3, they were 61.4 °C, 57.3 °C, 56.1 °C, 66.2 °C, and 66.4 °C (Figure 8).

These variations are explained by differences in heat absorption and distribution across the three designs. In Case 1, the brackish water absorbs most of the incoming solar radiation directly, leading to relatively higher water temperatures. In contrast, in Cases 2 and 3, the absorbed solar energy is distributed between the brackish water, the hollow circular fins, and the phase change material (PCM) beneath the basin. This configuration enables more effective thermal energy storage, which moderates water temperature and results in lower daytime brackish water temperatures compared to Case 1.

Analysis of storage media temperatures highlights distinct thermal behaviors between Case 2 (HCFS4) and Case 3 (HCFSWS4). The maximum daily fin temperatures in Case 2 were 66.8 °C, 61.9 °C, 60.1 °C, 70.7 °C, and 71.3 °C (Figure 7), while Case 3 recorded 69 °C, 59.3 °C, 59 °C, 66.2 °C, and 71.9 °C (Figure 8). The higher daytime fin temperatures in Case 2 result from limited heat transfer, whereas in Case 3, effective heat distribution to the PCM lowers fin temperatures and enhances thermal energy storage efficiency.

Analysis of the fin-based heat storage and recovery process over five sunny days shows an average stored and recovered energy of 1.4×10^7 J. These results indicate high system efficiency, attributed to clear skies and elevated solar radiation.

3.4. Heat Storage with Soybean Wax (PCM)

Soybean wax phase change material (PCM) was selected as thermal energy storage (TES) due to its abundance in Indonesia, low cost, melting point of 43.92°C , freezing point of 38.49°C , and high latent heat of 100.90 kJ/kg. It stores and releases latent heat through solid–liquid phase transitions, absorbing heat during melting and releasing it during solidification.

This section presents experimental results on soybean wax as a thermal storage medium in a passive solar desalination system. Tests conducted over five days recorded maximum solar intensities of 903.9 , 1056.2 , 1028.1 , 1009.2 , and 1048.8 W/m^2 (Figure 6). As expected, temperatures T_g , T_w , T_b , T_{fins} , and T_{pcm} (Figure 6 to Figure 8) followed solar intensity trends due to the PCM charging phase. Figure 11 shows PCM temperature evolution and liquid fraction (f_{liq}) during charging and discharging, with f_{liq} defined by Boroojerian [49]:

$$f_{liq} (Y) = \begin{cases} 0 & \text{for } T < T_{sol} \\ \frac{T - T_{sol}}{T_m - T_{sol}} & \text{for } T_{sol} \leq T \leq T_m \\ 1 & \text{for } T > T_m \end{cases} \quad (29)$$

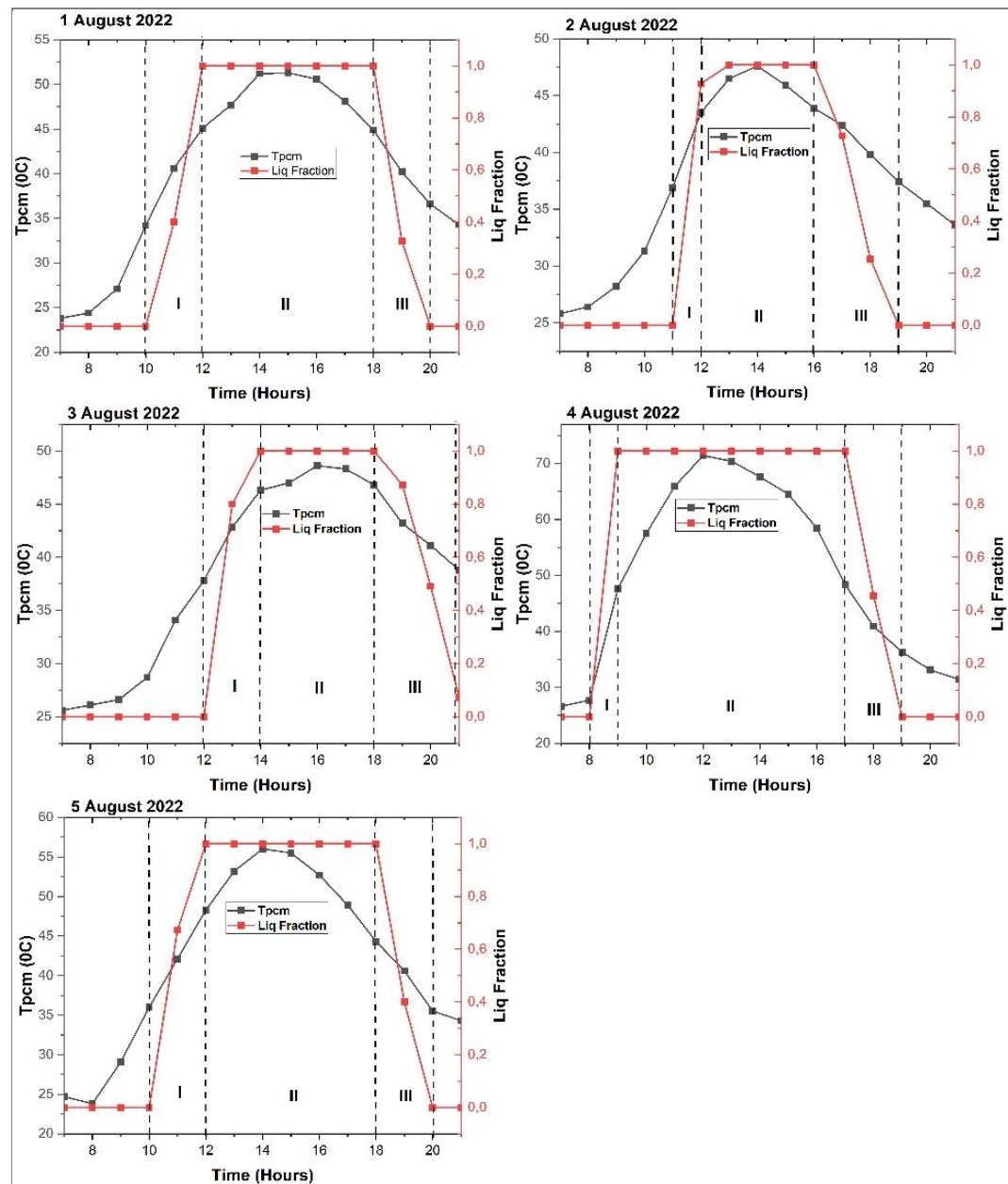


Figure 11. Temperature distribution of soybean wax and liquid fraction during the charging and discharging periods

Figure 11 analyzes temperature profiles and liquid fraction during PCM charging. Sensible heat storage peaked around 10:00 on August 1, 2, and 5, and around 12:00 and 09:00 on August 3 and 4, 2022, initiating latent heat storage. The sensible phase lasted ~ 2 hours. A mushy zone ($43.0\text{--}52.0\text{ }^{\circ}\text{C}$, $\Delta T = 9.0\text{ }^{\circ}\text{C}$) was observed, with its brief duration significantly influencing heat storage and retrieval performance.

The five-day results show that latent heat storage dominates, while sensible heat storage occurs briefly. This confirms the system's reliance on latent heat storage, which offers higher energy capacity but greater losses [50]. The estimated heat stored and recovered from soybean wax is $2.1 \times 10^5\text{ J}$.

3.5. Prediction Temperatures PCM

Polynomial regression was applied to model PCM temperature variation over five days, providing a more accurate fit than linear regression. The polynomial degree controls model complexity: higher degrees capture intricate trends but risk overfitting, while lower degrees may underrepresent curvature. Model performance was evaluated using metrics such as R^2 to balance accuracy and complexity. The PCM temperature (y) as a function of time (x) was fitted using a quadratic polynomial expressed as following Eq. (30) and Eq. (31).

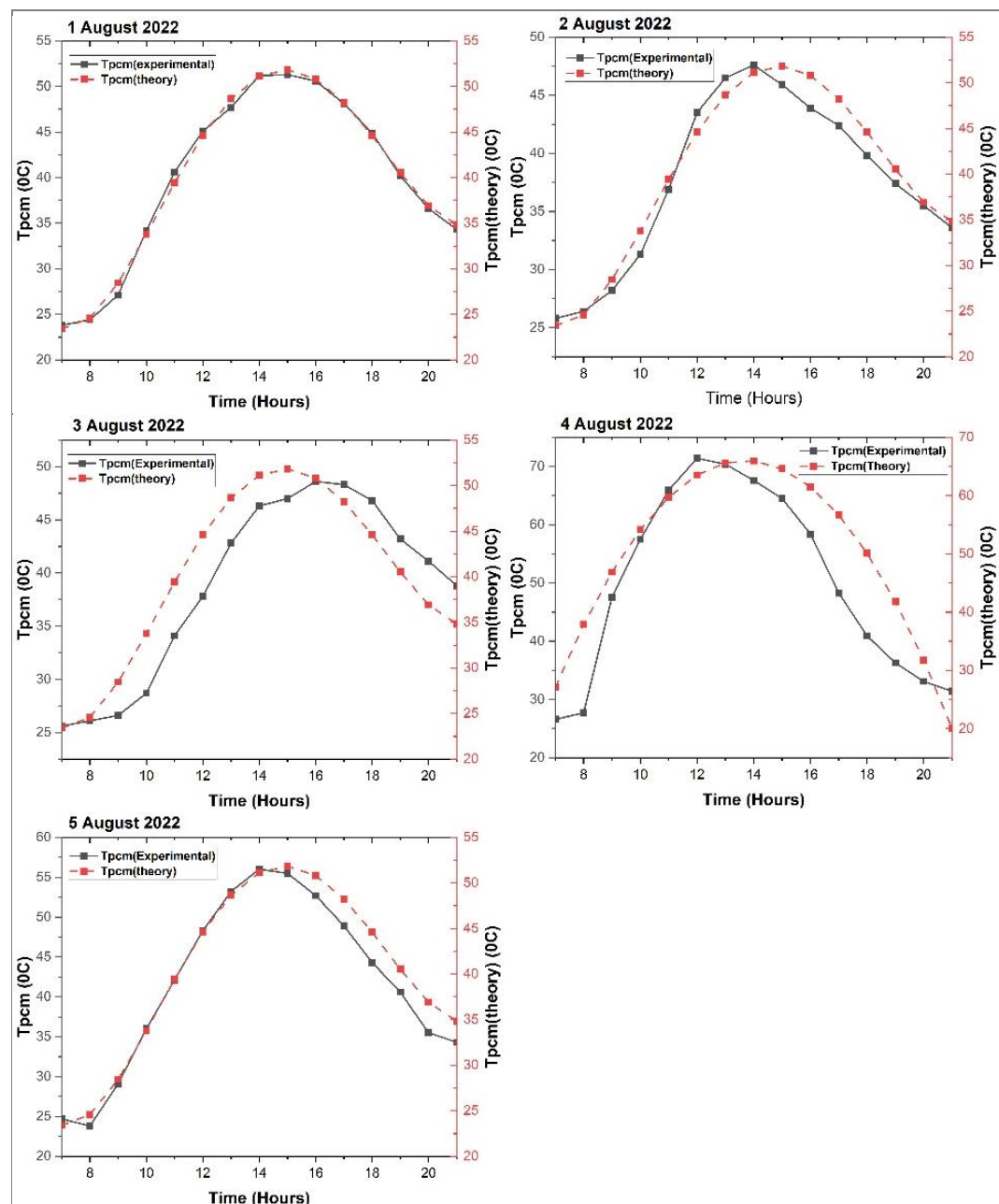


Figure 12.
Prediction of the PCM
temperatures of the
soybean wax
experimental and
theoretical

$$y = 0.009x^4 - 0.3043x^3 + 2.9571x^2 - 5.7051x + 26.443 \quad (30)$$

$$R^2 = 0.996 \quad (31)$$

A comparison between the results obtained experimentally and those obtained by this model is depicted in Figure 12. Comparing the experimental results with those calculated from Eq. (30) showed excellent agreement between the two results. This proves the validity of the derived model.

3.6. Heat Transfer Coefficient and Energy, Exergy Efficiencies

The total internal heat transfer coefficient of the single-slope solar still is the sum of convective, evaporative, and radiative components. Figure 13 shows hourly variations in total heat transfer for Cases 1–3, with Case 3 exhibiting the highest transfer between water and glass during PCM charging and discharging. Analysis confirms that evaporative heat transfer (Figure 15) dominates over convective and radiative modes in determining system performance.

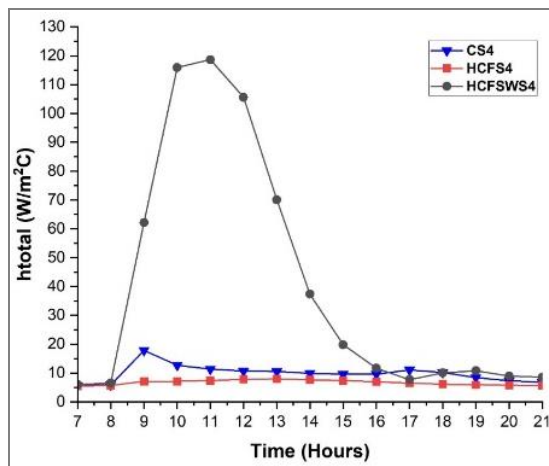


Figure 13.
Hourly changes in total
heat transfer for 3
cases

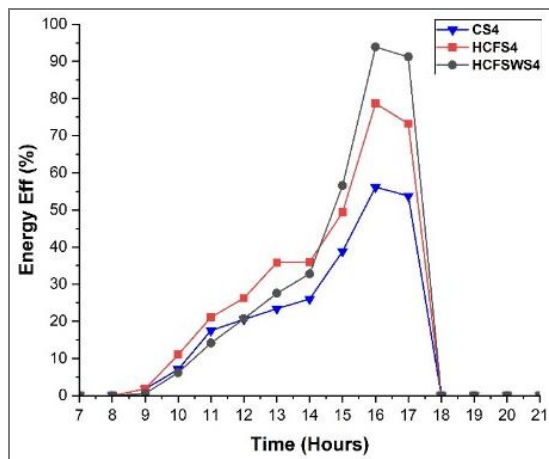


Figure 14.
Hourly energy efficiencies
for 3 cases

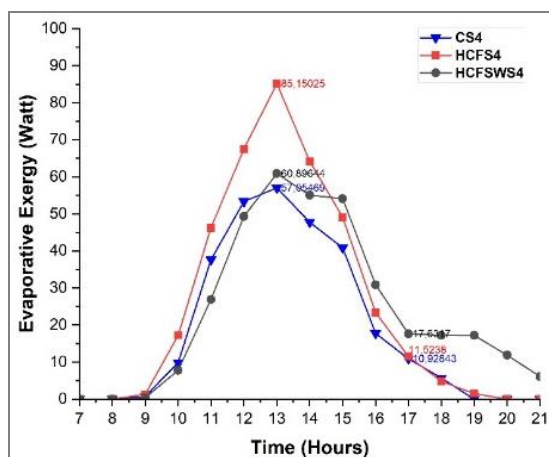


Figure 15.
Hourly variations of
evaporative exergy for
3 cases

Figure 14 shows hourly variations in instantaneous energy efficiency for the three cases, following the trend of solar radiation and productivity. Efficiencies rise through midday before declining, with maximal of 48.9% (Case 1), 66.1% (Case 2), and 77.6% (Case 3). Incorporating hollow circular fins and soybean wax PCM increased average daily efficiency by 18% and 29% over the conventional still, driven by higher freshwater productivity (Figure 9 and Figure 10).

Figure 15 shows evaporative exergy rates rising until 1 PM and declining toward sunset, reflecting their strong dependence on water temperature. Maximum evaporative exergy values were 57.85 W (Case 1), 85.15 W (Case 2), and 60.89 W (Case 3). Case 2 achieved the highest morning exergy due to its increased evaporation area and enhanced solar absorption from hollow circular fins.

But towards 4 PM, the evaporative exergy value in cases 1 (CS4) and 2 (HCFS4) decreases. This is due to the process of releasing heat from seawater and the hollow circular fins which also decreases as the intensity of the sun decreases. This is different in case 3 (HCFSWS4), where the brackish water temperature is still kept hot due to the soybean wax discharging process as thermal energy storage. The evaporative exergy values in the afternoon from cases 1, 2, and 3 are 10.92 W, 11.52 W, and 17.63 W, respectively.

Hourly variations of exergy efficiency for the three considered (case 1/CS4), (case 2/HCFS4), (case 3/HCFSWS4) cases are plotted in Figure 16. That picture presents hourly exergy efficiency variations for Cases 1–3, showing a gradual rise until late afternoon (~5:00 PM) followed by a steady decline. Maximum efficiencies reached 33% (Case 1), 40% (Case 2), and 42% (Case 3).

Cases 2 and 3 outperformed the conventional still (Case 1) due to higher evaporative exergy rates. Among all cases, the solar still with hollow circular fins and soybean wax PCM (Case 3) achieved the highest average exergy efficiency, attributed to sustained water temperature and elevated evaporative exergy into the evening. Comparing exergy and energy efficiency reveals that exergy analysis provides a deeper evaluation by accounting for both energy quantity and quality, whereas

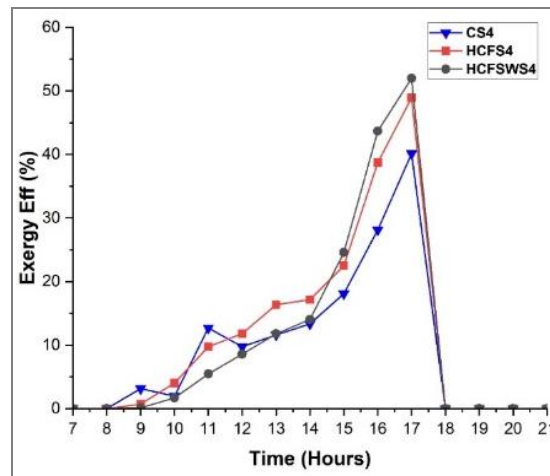


Figure 16.
Hourly exergy
efficiencies for 3 cases

energy efficiency (Figure 14) reflects only overall energy balance. Energy efficiency values appear higher as they omit losses from energy degradation and system irreversibilities, whereas exergy efficiency (Figure 16) accounts for temperature gradients, entropy generation, and energy quality. Exergy and energy balances for all chambers (Table 4) show reduced exergy efficiency, reflecting solar radiation quality degradation during conversion. Consequently, exergy efficiency is lower than energy efficiency, this is according to the statement by Yousef [40].

Table 4.
Energy and exergy in
each testing chamber

Solar still	Average Productivity (mL)	Energy efficiency (%)	Exergy efficiency (%)
CS4	986	48.9	33
HCFS4	1243	66.1	40
HCFSWS4	1364	77.6	42

3.7. Comparison of Yield Productivity, Energy, and Exergy With Previous Research

Table 5 compares production, energy, and exergy performance from this study with previous work, where exergy was calculated using Eqs. 14–16. While earlier studies employed PCMs such as paraffin and salt hydrates, this study used soybean wax and hollow circular fins. CS4 demonstrated moderate efficiency (48.9%), whereas HCFS4 and HCFSWS4 achieved high efficiencies of 66.1% and 77.6%, exceeding values reported in prior research.

3.8. Economic Analysis

Table 6 presents the data for the economic analysis of each testing case, considering the calculation used in the equation stated in the theoretical analysis. The economic analysis overviews the solar still chambers implemented based on their cost. As mentioned in this table, the fin-PCM solar distiller was the most efficient and economical due to its higher production than others. The cost per liter (CPL) values for CS4, HCFS4, and HCFSWS4 are 0.06, 0.05, and 0.05 \$/L/m², respectively. The payback period values for CS4, HCFS4, and HCFSWS4 are 366, 322, and 303 days, respectively. Thus, the productivity costs of freshwater solar distillation (CS4) with PCM and pin fins (HCFSWS4) and solar distillation with hollow circular fins (HCFS4) are lower than conventional solar distillation (CS4).

Table 7 presents a comparison of the economic values for different types of solar stills (CS4, HCFS4, and HCFSWS4) of current desalination system capital costs (P), CRF, FAC, S, SFF, ASV, AMC, AC, and CPL with previous studies. The CPL value of each type of conventional solar still, with the addition of fins, corrugated v, and PCM, is between 0.01 and 0.067 \$/L/m² with a basin area between 0.5 and 1m².

3.9. Distribute Temperature Fins and PCM with Fluent

Figure 17 shows the mesh of hollow circular fins and soybean wax PCM, with element sizes of 1.0×10^{-3} mm and 3.0×10^{-2} mm, respectively. Figure 18 illustrate the simulated temperature distribution obtained via ANSYS Fluent. Under solar radiation, the fins absorb thermal energy, raising the outer wall temperature to 319 K at 10 AM—notably higher than the middle and lower fins (315 K). These vertical fins facilitate the transfer of solar thermal energy into both the brackish water and the Phase Change Material (PCM). As the PCM begins charging from the top, it reaches 304 K, while the bottom remains near the initial 299 K. Within the PCM layer, a distinct, uniform

horizontal temperature stratification is observed, indicating stable conductive or convective heat transfer. This linear color gradient, aligned parallel to the channel walls, further demonstrates a highly uniform heat distribution.

Table 5.
The production, energy,
and exergy comparison
between the present
study and the earlier
study

Authors	Study	PCM	FINS	Productivity (L/m ² /day)	Energy Efficiency (%)	Exergy Efficiency (%)
[present study]	Conventional single slope solar still (CS4)	-	-	0.986	48.9	33
Saad et al. [22]	Conventional single slope (CSS)	-	-	1.6	24.97	19
Hasan et al. [51]	Conventional single slope (CSS)	-	-	9.75	-	13.1
Hasan et al. [52]	Conventional single slope (CSS)	-	-	1.8	60	13.35
Yousef et al. [53]	Traditional solar still (TRD Still)	-	-	3.26	31.8	22
Sankar et al. [54]	Conventional Single slope solar still	-	-	1.955	38.6	24.1%
[present study]	Hollow Circular Fin Single Slope Solar Still (HCFS4)	-	216 hollow circular fins	1.243	66.1	40
Yousef et al. [40]	Solar still integrated fins	-	225 fin circular fins	3.78	45.5	44
Sankar et al. [54]	Single slope solar still with cylindrical fins	-	56 cylindrical fins	2.322	47	31.8
Hameed et al. [55]	Solar still integrated cross-section hollow fin	-	24 square hollow fin	3.12	40	-
Hansen et al. [56]	Solar still with fin-shaped absorber	-	80 rectangular-shaped straight fins	5.210	38.3	-
Mirmanto et al. [57]	Effect of Various Fin Designs	-	15 rectangular-shaped fins	1.404	18.5	-
[present study]	Hollow Circular fin soy bean wax single slope solar still (HCFSWS4)	Soybean wax	216 fin	1.364	77.6	42
Saad et al. [22]	Longitudinal fins with paraffin	Paraffin	Longitudinal fins	2.5	36.25	99.2
Ahmed et al. [58]	V corrugated solar still with PCM	Fatty acid, paraffin, hydrated salt	Plate V corrugated	4.5	-	-
Abdullah et al. [59]	V corrugated solar still with PCM	Paraffin and CuO nanoparticles	Plate V corrugated	4.3	87	-
Suraparahu et al. [60]	Solar still integrated PCM and cross-section hollow fin	Paraffin wax	Circular hollow 220 fins	0.7	52.4	-
Kateshia et al. [27]	Solar still with PCM storage and pin fins	Palmitic acid	Circular 81 fin	5.4	57	55.4
Yousef et al. [61]	Solar still with PCM and fins	Paraffin	Circular 225 fins	3.81	46	-
Shalaby et al. [62]	Solar still with PCM and V corrugated	Paraffin wax	Plate V corrugated	3,76	37.1	-
Shoeibi et al. [63]	Solar still with PCM	Nano-enhanced PCM	-	1.3	55.8	17.41
Rajasekhar et al. [64]	Solar still with PCM nanomaterials dispersed in paraffin	Nano material (Al ₂ O ₃)	-	4.3	66	-
Hamadani et al. [65]	Solar still with PCM	Mysristic acid and Lauric acid	-	1.090	34.4	29
				1.480	39.6	74

Table 6.

The performance comparison between the present study to the previous study

Type	CS4	HCFS4	HCFSWS4
n (years) [51]	10	10	10
i (interest rate %) [27]	0.1	0.1	0.1
CRF	0.16	0.16	0.16
P (Capital cost \$)	129	143	148
S	25.8	28.6	29.6
FAC	20.99	23.27	24.09
SFF	0.063	0.063	0.063
ASV	1.62	1.79	1.85
AMC	3.15	3.49	3.61
AC	22.52	24.97	25.84
Pn (L/m ² /year)	359.89	453.69	497.86
CPL (\$/L/m ²)	0.06	0.05	0.05
Payback period (days)	366.47	322.25	303.93

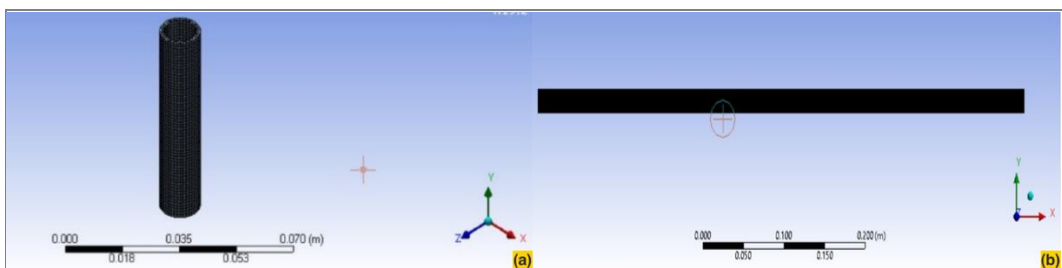
Table 7.

The cost comparison of different solar still with the previous research

Authors	Type of SS	Area, m ²	P	CRF	FAC	S	SFF	ASV	AMC	AC	CPL
Fath <i>et al.</i> [66]	CSS	1.527	275	0.177	49	55	0.057	3.5	7.5	53	0.035
Samee <i>et al.</i> [67]	CSS	0.54	190	0.177	34	38	0.057	2	5	37	0.063
Kumar <i>et al.</i> [68]	CSS	1	250	0.177	44.2	50	0.057	3	6.6	47.8	0.14
Vigneswaran <i>et al.</i> [69]	CSS	0.5	61.8	0.15	9.21	12.36	0.069	0.85	4.6	8.81	0.067
Kateshia <i>et al.</i> [27]	CSS	0.49	1.29	0.1	15.1	25.7	0.017	0.4	2.3	16.9	0.02
Sampathkumar <i>et al.</i> [70]	CSS	0.6	108	0.298	32.2	40	0.148	3.24	4.8	36.56	0.058
Hammad <i>et al.</i> [71]	TFBSD	1.8	105	-	18.58	-	-	1.19	5.57	22.69	0.037
[present study]	CS4	0.54	129	0.16	20.99	25.8	0.063	1.62	3.15	22.52	0.06
Deenadayal <i>et al.</i> [72]	SS with Fins	1	200	0.17	36	40	0.057	2.5	5.5	39	0.054
Velmurugan <i>et al.</i> [73]	SS with wick fins	1	250	0.17	44.3	50	0.057	3	6.6	47.9	0.065
Suraparaju <i>et al.</i> [60]	SS-Pond Fibres	0.6	108	0.2	21.6	88.8	-	-	3.24	23.77	0.01
Hammad <i>et al.</i> [71]	VBSD	1.8	115	-	20.35	-	-	1.31	6.10	25.14	0.028
[present study]	HCFS4	0.54	143	0.16	23.7	28.6	0.063	1.62	3.15	22.52	0.05
Nair <i>et al.</i> [74]	CCSC	0.6	60	-	10.62	-	-	1.26	1.58	12.98	0.05
Sampathkumar <i>et al.</i> [70]	PCMAAF-SS	0.6	144	0.298	42.94	53.3	0.148	4.32	6.43	48.75	0.054
Vigneswaran <i>et al.</i> [30]	GIBSS-PCM	0.5	109.8	0.15	16.36	21.96	0.069	1.51	8.18	15.67	0.01
Kateshia <i>et al.</i> [27]	PCM and Fins	0.5	148	0.1	17.4	29.6	0.017	0.5	2.6	19.5	0.01
Hammad <i>et al.</i> [71]	FBSD-PCM&Fins	1.8	132	-	23.36	-	-	1.50	7.00	28.86	0.031
[present study]	HCFSWS4	0.54	148	0.16	24.09	29.6	0.063	1.85	3.61	25.84	0.05

Figure 17.

Fine meshing of:
(a) Hollow circular fins;
(b) Soybean wax as PCM



Temperature distribution analysis provides insight into single-slope solar still performance, revealing temperature gradients critical for design optimization. Results show that increased solar radiation heats the hollow circular fins, which transfer heat to the basin water and underlying soybean wax PCM. The simulated temperature profiles closely match experimental data, confirming the model's accuracy.

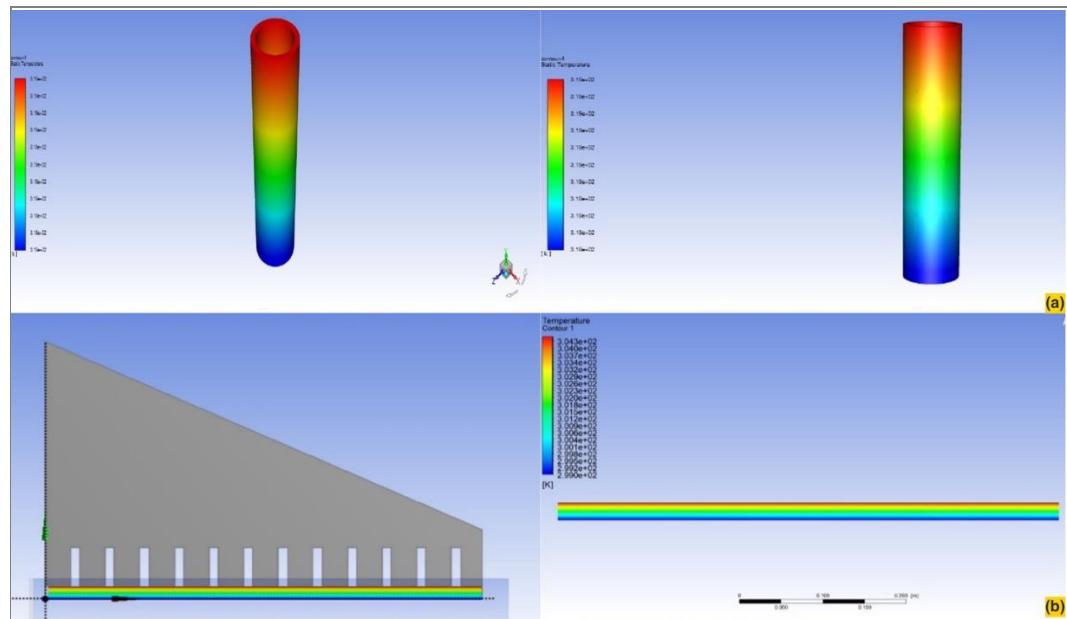


Figure 18.
Temperature
distribution:
(a) Hollow circular fins;
(b) Soybean PCM at 10
AM

3.10. Challenges and Future Perspectives

Solar-driven interfacial evaporation represents a sustainable method for purifying saline or contaminated water. Solar distillation systems are particularly advantageous for freshwater-scarce coastal regions, as they are cost-effective to manufacture, operate independently of the electrical grid, and require minimal technical expertise.

Recent innovations in solar absorber configurations and structural designs—specifically the integration of thermal energy storage (TES) elements like fins and Phase Change Materials (PCMs)—have markedly improved freshwater yields. Despite these gains, the technology faces significant hurdles, primarily PCM leakage and the challenge of managing thermal kinetics. To optimize performance, there is a growing need for composite PCMs that combine high specific heat capacity with tailored thermal conductivity to ensure stable heat retention.

Lately, the use of nanoporous silica as a stabilizing framework for PCMs—including soybean wax, paraffin, and stearic acid—has gained significant traction among researchers and environmentalists. This approach is favored for its enhanced stability, sustainability, and low cost. Furthermore, the integration of xylem-based filters warrants closer examination as a pretreatment strategy to reduce salinity and pollutant load before the water enters the evaporation chamber.

4. Conclusion

This study evaluates the energy, exergy efficiency, and economic feasibility of an experimental single-slope solar still using hollow circular fins and soybean wax as thermal energy storage. Three cases are considered, namely, case 1: conventional solar still (CS4), case 2: solar still with hollow circular fins (HCFS4), and case 3: solar still with hollow circular fins and soybean wax as PCM (HCFWS4). The performance of the three cases using three identical solar stills is experimentally evaluated and compared to each other under the same meteorological conditions. The main conclusions were summarized:

- The yield productivity of CS4, HCFS4 and HCFWS4 was 0.986 L/m²/day, 1.243 L/m²/day, and 1.364 L/m²/day respectively.
- The energy thermal efficiency of CS4, HCFS4 and HCFWS4 was 48.9%, 66.1% and 77.6% respectively.
- The exergy efficiency of CS4, HCFS4 and HCFWS4 was 33%, 40% and 42% respectively.
- The CPL of CS4, HCFS4 and HCFWS4 was 0.06 \$/L/m², 0.05 \$/L/m² and 0.05 \$/L/m².
- The hollow circular fins system stored and recovered relatively large amounts of heat, with an average of 1.4×10^7 J, and the PCM soybean wax amount of heat stored/recovered is estimated to be 2.1×10^5 J.
- PCM soybean wax charging from 10.00 AM to 4.00 PM, and begins to discharge heat energy the afternoon after.

5. Future Scope

We will expand the planned investigation to assess the efficiency of solar water distillers throughout the year, specifically during the rainy and dry seasons in Surakarta, Indonesia. Furthermore, researchers can improve distiller designs by implementing PCMs enhanced with nanoporous silica, as this composite offers a promising way to boost performance. Our environmental analysis includes CO₂ emissions, CO₂ mitigation (ΦCO_2), carbon credits earned (Z_{CO_2}), and the energy matrix. Ultimately, a thorough investigation of this highly conductive composite PCM will advance solar water distiller technology.

Acknowledgments

This research was funded by Universitas Sebelas Maret, Surakarta, Central Java Indonesia, through the International Collaboration Research Scheme.

Authors' Declaration

Authors' contributions and responsibilities - IS: Conceptualization, Methodology, and writing. MDS & SA: Writing, data, and simulating processing. EPB: Review and editing. SH: Project head, Supervision.

Funding – Universitas Sebelas Maret, Surakarta, Central Java Indonesia, through the International Collaboration Research Scheme.

Availability of data and materials - All data is available from the authors.

Competing interests - The authors declare no competing interests.

Additional information – No additional information from the authors.

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