

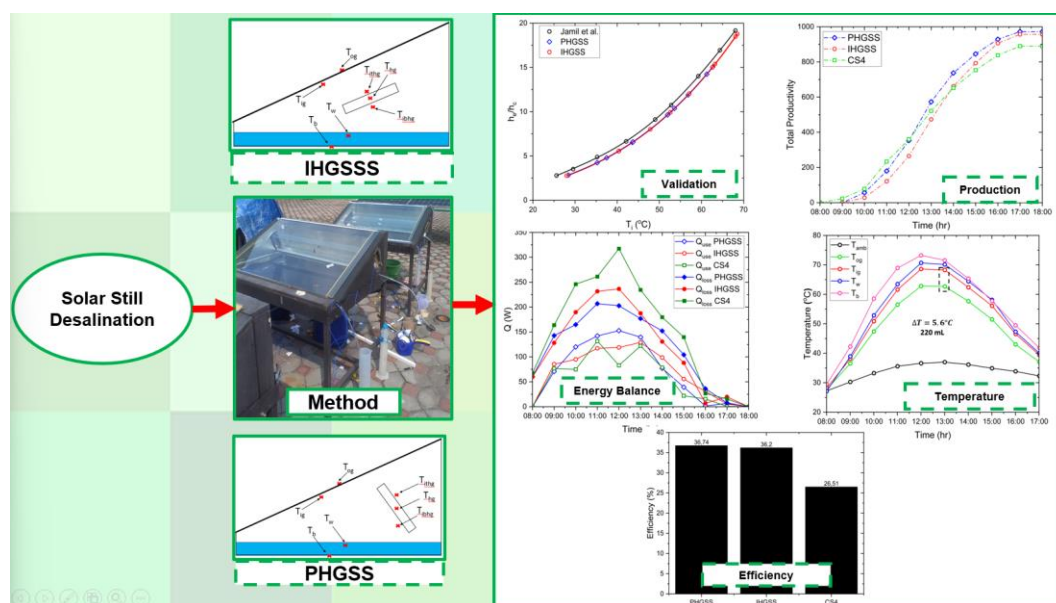
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The new modification of a solar still chamber with hollow glass: An experimental comparison between perpendicular and inline hollow glass configurations

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Highlights:

- This experiment has modified a CS4 chamber with additional hollow glass, which has not been previously explored in desalination research.
- The use of hollow glass is proven to produce condensation of distilled water
- To enhance the validity of the experimental results, this research has been verified with prior studies using the ratio of evaporative to convective heat transfer.

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Abstract

Researchers around the world are conducting comprehensive studies on conventional single-slope solar stills (CS4). Recent trends have focused on minimizing heat loss and improving the productivity of these systems, particularly through modifications to the CS4 chamber. This present study examines the modified chambers of solar stills utilizing Perpendicular Hollow Glass Solar Still (PHGSS) and Inline Hollow Glass Solar Still (IHGSS). It provides a comprehensive analysis of the enhancements, highlighting key aspects such as productivity, energy balance, and efficiency, as well as introducing a potential new condensation site. To ensure accuracy and reliability, the results are validated using the coefficient h_e/h_c from a previous study, which reported a margin of error of 7.76%. The application of hollow glass has proven its ability to produce distillate condensation due to the temperature gradient present between the inner surface of the hollow glass and the cavity it encloses. Moreover, the production and efficiency of both inline and perpendicular hollow glass highly exceeds those of conventional CS4.

Keywords: PHGSS; IHGSS; Hollow glass; CS4 modification; Desalination

1. Introduction

The conventional single-slope solar still (CS4) is a passive solar still device designed for the purification of seawater into drinkable water. This device offers several advantages over commercial desalination techniques, such as reverse osmosis and membrane desalination. These benefits include a simple design, lower construction and maintenance costs, and environmentally friendly characteristics [1], [2], [3]. In the CS4, solar radiation entering the chamber is absorbed by the seawater, causing it to evaporate and turn into saturated vapor. This vapor then condenses intermittently due to the temperature difference between the inner glass surface and the surrounding environment [4], [5]. The basin captures incoming solar energy, leading to the transformation of radiant intensity into heat energy. The literature categorizes the heat energy used in the solar still desalination process into two types: latent heat and sensible heat [6].

In the last few decades, research on CS4 has been massively conducted by scientists to reduce the percentage of heat loss in this device. Notably, over 50% of heat loss occurs through the walls of solar stills [7]. Various efforts have been made by researchers to increase the productivity of solar stills, including through space modification [8], [9], the use of absorbent fins [10], [11], the utilization of nanoparticles [12], and the use of phase change materials [13], [14]. Regarding the research trend of chamber modification, there are various geometrical aspects that influence CS4 performance. The first is the specific height of the solar still wall, which was studied by Jamil *et al.* The height of the solar still wall impacts the convective transfer rate between the absorber basin and the cover glass, leading to the conclusion that the lower the solar still wall, the higher the thermal efficiency is achieved [15]. Additionally, El-Samdhony *et al.* found that the inclination of the cover glass also influences the heat transfer rate within the systems. Their study concluded that increasing the angle of the cover glass slope can modify the radiation shape factor and enhance CS4 performance [16]. Another factor to consider is the thickness of the cover glass, which affects the transmissivity of radiation intensity entering the system [17].

In this study, the wall height, cover glass thickness, and cover glass inclination are considered fixed variables. A hollow glass set has been added to the chamber to evaluate its potential to induce condensation outside the primary condensation site (cover glass). Table 1 presents the utilization of various geometrical shapes in solar stills, thereby contextualizing the position of this research.

The condensation rate in solar desalination can be improved by increasing the temperature gradient between the inner glass and the surrounding environment. This gradient contributes to a periodic rise in the convective heat transfer rate, which facilitates the movement of saturated vapor within the chamber. Some literature suggests enhancing the temperature gradient through the use of forced cooling cover glass [18], [19]. For instance, Attia *et al.* implemented a cooling glass treatment using 2 L/h of water, achieving a notable 69.93% increase in solar still productivity [20]. The present study on PHGSS and IHGSS presents a novel approach that incorporates both perpendicular and inline hollow glass. The author aims to investigate innovative modifications in solar still chambers that enable distilled water condensation in locations beyond the cover glass. The research is straightforward and conducted experimentally. The author recognizes several limitations and expresses optimism that this research can be optimized by researchers in diverse locations.

Table 1.
Literature review on various
forms of solar stills

Ref	Shape	Country	Basin geometry	Production	Efficiency
[21]	Double-slope	India	1.00 × 1.00 × 0.40 m	1880 mL	27%
[22]	Single-slope	India	1.00 × 1.00 × 0.50 m	0.902 L	±18%
[23]	Single-slope	Egypt	1.50 × 1.00 × 0.10 m	Summer: 4.00 kg & Winter: 2.10 kg	Summer: 32.50% Winter: 25.60%
[24]	Double-slope	Bangladesh	1.27 × 1.02 m ²	2.46 L	31.84%
[25]	Tubular-SS	Egypt	0.90 × 0.40 × 0.05 m	Water depth 0.50, 0.01, 0.02, 0.03 m resulted in 4.45, 4.20, 3.54, and 3.09 L	Maximum efficiency at water depth of 0.50 is 41.40%
[26]	Tubular-SS	Bangladesh	1.00 × 0.16 × 0.05 m	1.93 L	N
[9]	Hemispherical-SS	Algeria	h=0.03 m, circular area 0.10 m ²	4.80 Kg	37.40%
[27]	Natural Convective Regenerator (NCR- SS)	China	5.00 × 8.40 × 0.002 m	Sunny: 8093 ml/m ² and cloudy 720 ml/m ²	48.40% - 58.90%
[28]	Hemispherical-SS	Algeria	h=0.25 m, circular area 0.10 m ²	450 mL	31.80%

2. Methods

This research utilized chambers from the CS4 modification, specifically the PHGSS and IHGSS models, as depicted in Figure 1a. The dimensions of the basin for seawater containers were 0.90 m × 0.60 m × 0.09 m. The more detailed dimensions were presented in Figure 1b and Figure 1c. The basin is constructed from stainless aluminum, which possesses adequate thermal conductivity to effectively absorb incoming energy, thus accelerating the evaporation process [29]. The chambers have an overall length of 1.06 m, and the internal chamber is covered with a galvanized plate. A gap between the inner and outer walls was insulated with glass wool to minimize heat transfer from the system to the surrounding environment. Experiments were conducted over three consecutive days, namely June 4, 5, and 6, 2024—at the Faculty of Engineering, Universitas Sebelas Maret Surakarta. Prior to the experiments, a one-week trial was conducted to ensure there were no leaks.

The experiment collected data in the forms of temperature, radiation intensity, and productivity, ranging from 08:00 to 17:00. K-type thermocouple is used to measure several temperatures, including water temperature (T_w), outer surface of glass (T_{og}), inner surface of glass (T_{ig}), basin bottom (T_b), upper surface of hollow glass (T_{iuhg}), hollow glass bottom surface (T_{hbg}), and the bottom surface of hollow glass (T_{obhg}) (Figure 2). Radiation intensity was measured using the solar power meter SPM-1116SD, and a measuring cup served as the container for productivity measurements. All data were collected hourly, and the accuracy measurement ranges of the instruments were detailed in Table 2.

Table 2.
Specification of
measurements device

Device	Range	Accuracy
Measuring Cup / Tank	0-2000 mL	± 1mL
K-type Thermocouple	0-650 °C	±0.5 °C
Solar Power Meter	0-2000 W/m ²	±0.5-1 W/m ²

The error in the research data was determined using Eq. (1), where u represented the bias error derived from the accuracy specifications of each measuring device, and z denoted the actual value obtained from the

$$error = \frac{\sqrt{u}}{z}$$

(1)

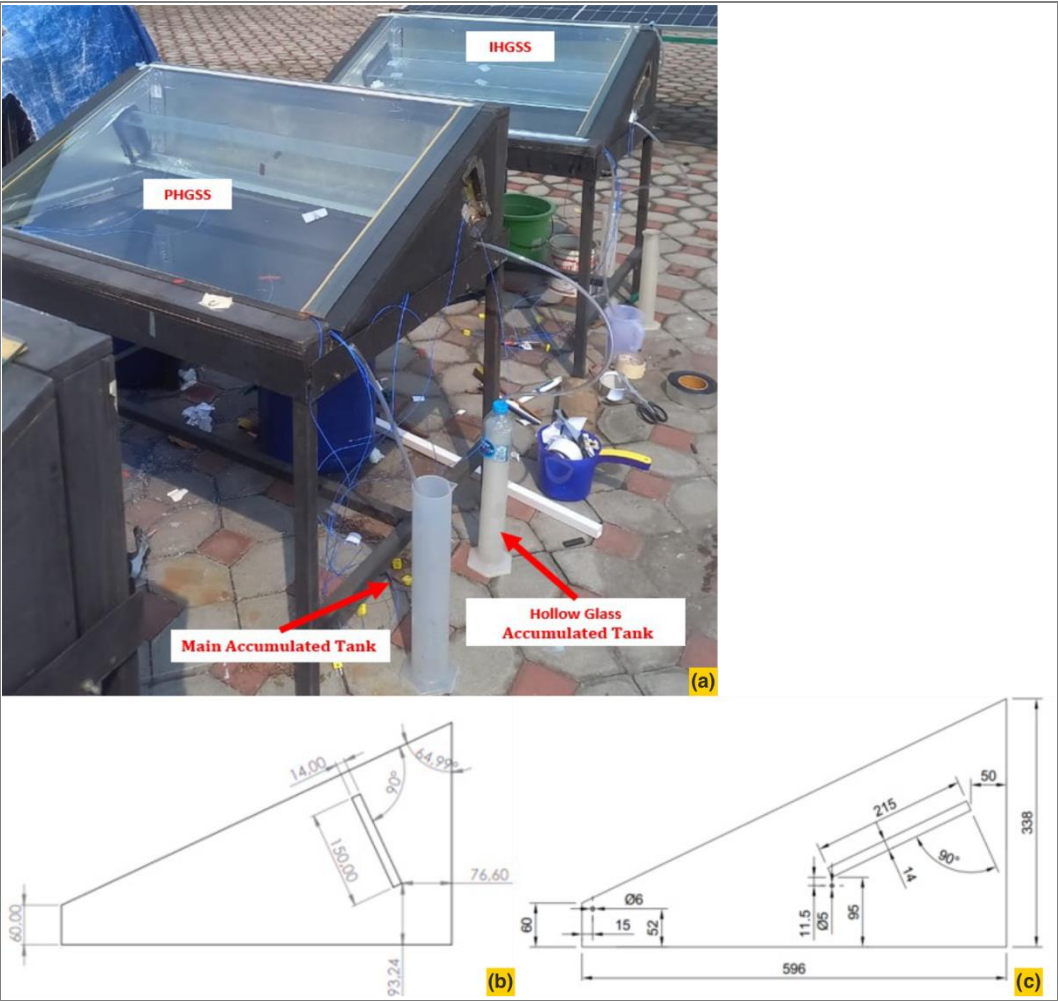
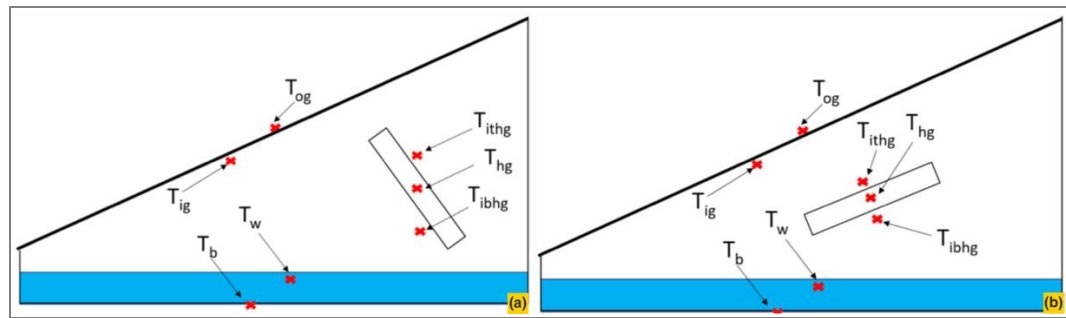


Figure 1.
(a) Chamber PHGSS
& IHGSS;
(b) The dimensions
of PHGSS;
(c) the dimension of
IHGSS

Figure 2.
K-type's
thermocouple
placements



experimental data. The daily average measurement errors for temperature, intensity, and productivity data are 3.69%, 3.63%, and 5.00%, respectively. As a result, this experiment can be considered to have a relatively low data bias error.

3. General Equation

The solar radiation received by PHGSS and IHGSS serves as the input energy for the desalination process. The input energy (Q_{in}) quantities entering the system can be determined using Eq. (2).

$$Q_{in} = AgI_T \quad (2)$$

Q_{in} denotes the quantity of entering energy absorbed by the absorber within the chamber, while $I_{(t)}$ represent the amount of radiant energy transmitted through the cover glass (W/m^2). Our previous research indicated that the maximum radiation intensity loss before passing through the cover glass was 2.20% [1]. A_g is obtained from the glass cover area of the PHGSS and IHGSS chambers (0.54 m^2). The energy utilized by solar stills is categorized into two types, including sensible heat and latent heat. These types of heat work together in the evaporation of seawater since the beginning of the experiment.

$$Q_s = m \times Cp \times \frac{T_f - T_i}{t} \quad (3)$$

Eq. (3) is used to figure out sensible heat (Q_s). Here, m_s is the mass of the seawater within the chamber, which was 5.4 kg in the initial experiment and temporarily changed to saturated vapor during the evaporation process. Therefore, m_s in the sensible formulation is defined as a function of time, expressed as $m_s = m_{n+1} - m_n$, where n represents the evaluation time starting from 08:00 ($n = 1$). The specific heat value (C_p) of seawater is approximately 4000 kJ/kg, with T_f and T_i representing the final and initial temperatures, respectively, at the transient evaluation point within one hour.

$$Q_u = \frac{(m_u \times h_{fg})}{t} \quad (4)$$

The amount of latent heat can be estimated using Eq. (4), where m_u is the mass of hourly productivity of fresh water and h_{fg} is the latent heat evaporation from seawater (J/kg). As a result, Eq. (5) provides the total heat consumed during the desalination process (Q_{use}), and Eq. (6) can be used to calculate the system's efficiency.

$$Q_{use} = Q_u + Q_s \quad (5)$$

$$\eta = \frac{Q_{use}}{Q_{in}} \times 100\% \quad (6)$$

4. Results and Discussion

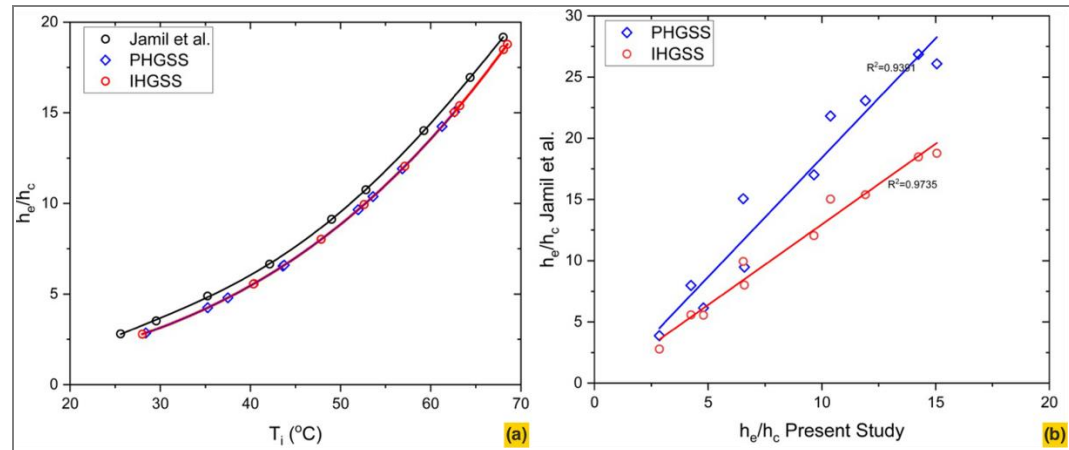
4.1. Validation

To validate the experimental results, the ratio of evaporative to convective heat transfer ($\frac{h_e}{h_c}$) was calculated using Eq. (7). Where T_i is humid water, which can be calculated by $T_i = \frac{T_{ig} + T_w}{2}$. According to Figure 3a, the validation results align closely with the findings of the previous study

conducted by Jamil *et al.* [15]. The validation results comparing experimental data to literature reveal an appropriate correlation, with magnitudes of 0.9391 for PHGSS and 0.9735 for IHGSS (see Figure 3b). These figures illustrate that as the temperature of humid water within the solar still chamber increases, the evaporation heat transfer coefficient becomes more dominant than convective heat transfer, leading to possibly a linear increase in distilled water productivity. Furthermore, the physical results of this validation indicate a 7.78% percentage error compared to the results of Jamil *et al.*, suggesting that this research is generally acceptable.

$$\frac{h_e}{h_c} = 4.23 \times 10^{-5} T_i^3 + 2.5 \times 10^{-4} T_i^2 + 0.058 T_i + 0.035 \quad (7)$$

Figure 3.
Validation through
the previous
literature [15]:
(a) plot h_e/h_c ;
(b) correlation

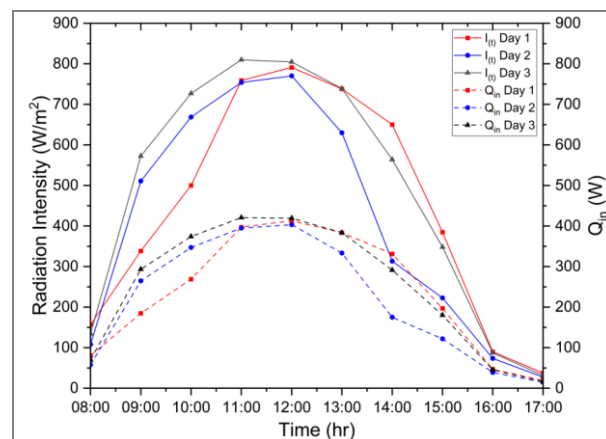


4.2. Discussion

Figure 4 presents the solar intensity levels received by PHGSS and IHGSS during this study. Additionally, the figure also presents the calculated results of the daily input energy received by the solar still. The input energy (Q_{in}) presents a similar trendline to the energy entering the chamber [9], [21]. In this study, PHGSS and IHGSS exhibited the highest radiation intensity on the Day 3. According to Figure 4, the maximum Q_{in} was recorded in the chamber on Day 3, followed by Days 2 and 1. The input energy received by the chamber was 2321.88 W on Day 1, 2151.87 W on Day 2, and 2494.82 W on Day 3.

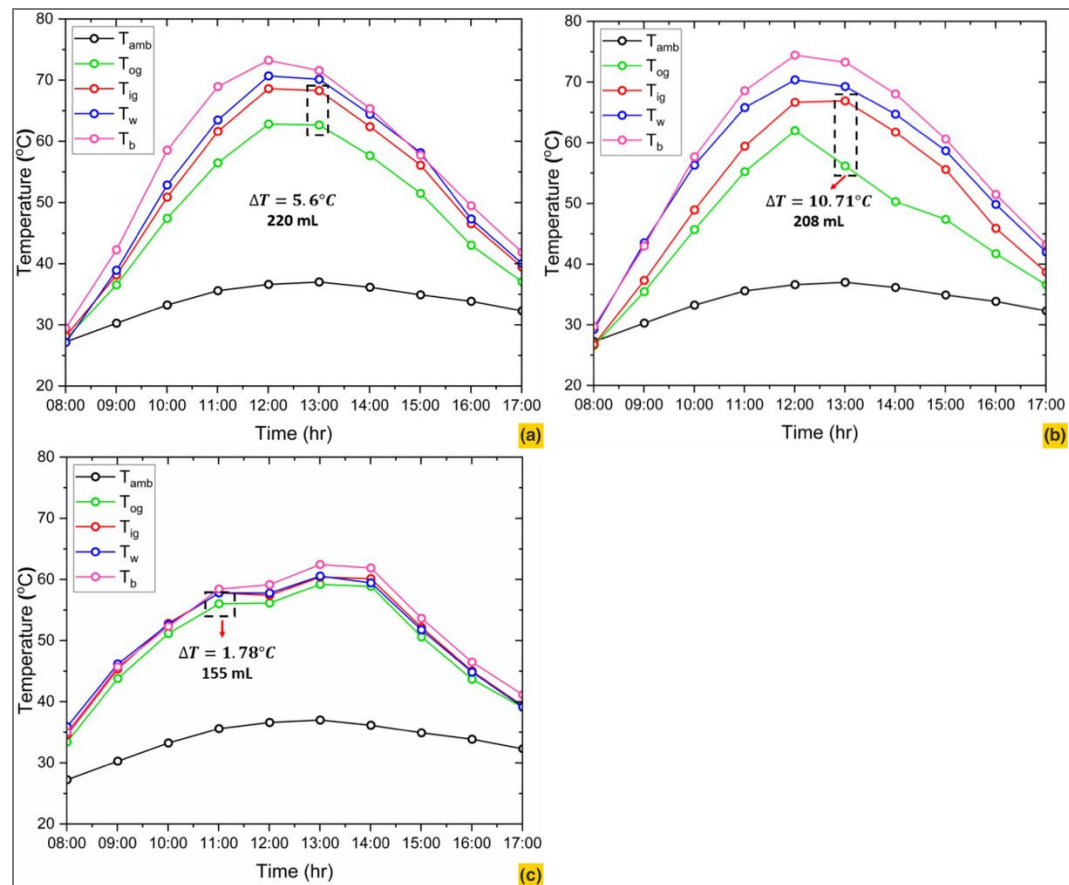
The energy input to the solar still is absorbed by specific areas within the chamber, leading to an increase in temperature. Under consistent average energy input conditions, various sections of the solar still show different temperature variations, as illustrated in Figure 5. A critical factor is the temperature difference between the inner and outer glass ($\Delta T = T_{ig} - T_{og}$), which significantly impacts the productivity of the solar still. At 13:00 in the PHGSS chamber, the maximum recorded ΔT is 5.60 °C, resulting in a productivity of 220 mL. In comparison, the IHGSS also peaks at this time, reaching a ΔT of 10.71 °C and a productivity of 208 mL. Despite having a higher average temperature, the IHGSS produced slightly less distilled water than the PHGSS at that moment. This discrepancy may be attributed to the delayed accumulation process of the condensation drops and the possibility of condensation drops falling back into the basin [30] due to the rapid convective flow on the inner surface of the cover glass. Additionally, seawater temperature (T_w) is another

Figure 4.
Radiation intensity
and Q_{in} during day-
to-day testing



temperature factor that influences productivity. According to Figure 5a and Figure 5b, the seawater temperature in the PHGSS is higher than that in the IHGSS. This relationship is directly related to the overall productivity of both chambers, as the PHGSS is possibly to produce more distilled water than the IHGSS. Looking at more details in Figure 5c, all the recorded CS4 temperature data is lower than PHGSS and IHGSS. This plot suggested that the CS4 had a lower evaporation rate and production ability.

Figure 5.
Temperature plot in
the chamber:
(a) PHGSS;
(b) IHGSS;
(c) CS4



The correlation between the average $I_{(t)}$ and hourly productivity is illustrated in Figure 6. This linear correlation indicates that both variables increase from the beginning of the study until midday, after which they decrease until the end of the study. A closer examination shows fluctuations in hourly productivity across Days 1, 2, and 3, which are influenced by uncontrollable factors during the experiment. These factors include delays in the accumulation process from the condensation droplets to the productivity storage tank. Additionally, fluctuations in hourly production may be affected by changes in solar energy input and drop in ambient temperature [6]. We observed that some condensation droplets do not flow into the collection tank but instead return to the basin, leading to variations in production. This phenomenon was also noted in a previous study conducted by Al-Sulttani *et al.* [30]. Considering the CS4 chambers (Figure 6c), there is also fluctuation in productivity; however, it is clear that the peak hourly productivity is lower than that of the other chambers. The highest hourly productivity for CS4 is recorded on Day 1 at 165 mL, whereas PHGSS and IHGSS reach a peak of 240 mL on Day 2.

Figure 7 shows that the PHGSS chamber has higher accumulated productivity compared to the IHGSS and CS4. Total production in each chamber was 972.33 mL, 956.67 mL, and 890 mL. Generally, the modifications of CS4 into PHGSS and IHGSS have successfully resulted in increased production, with improvements of 9.25% and 7.48% compared to the conventional CS4. This outcome also aligns with the evaporation rate values, represented by Q_{use} (both latent and sensible), as shown in Figure 9, where PHGSS demonstrates a higher value than the others. Furthermore, the reason is reinforced by the seawater temperature plot, which indicates that the temperature for PHGSS is consistently higher than others, as depicted in Figure 5 (blue line).

The main objective of this study was to identify new condensation sites within the CS4-type solar still chamber by implementing both perpendicular and inline hollow glass parts. In the PHGSS chamber, the installation of hollow glass resulted in very low productivity, approximately ± 2.30 mL (within the hollow glass accumulated tank, Figure 1a). This productivity could potentially be higher; however, due to the limited volume of condensation, some of the water that is condensed in the hollow glass may evaporate back into the system due to the high temperatures. The condensation process is influenced by the temperature differences between the inner top (T_{ithg}), inner bottom (T_{ibhg}), and center (T_{hg}) of the hollow glass (see Figure 8). Notably, in the IHGSS chamber, any condensation in the hollow glass does not make it to the accumulation tank; instead, it evaporates before it can be collected. This issue represents a significant area for future research, as both the

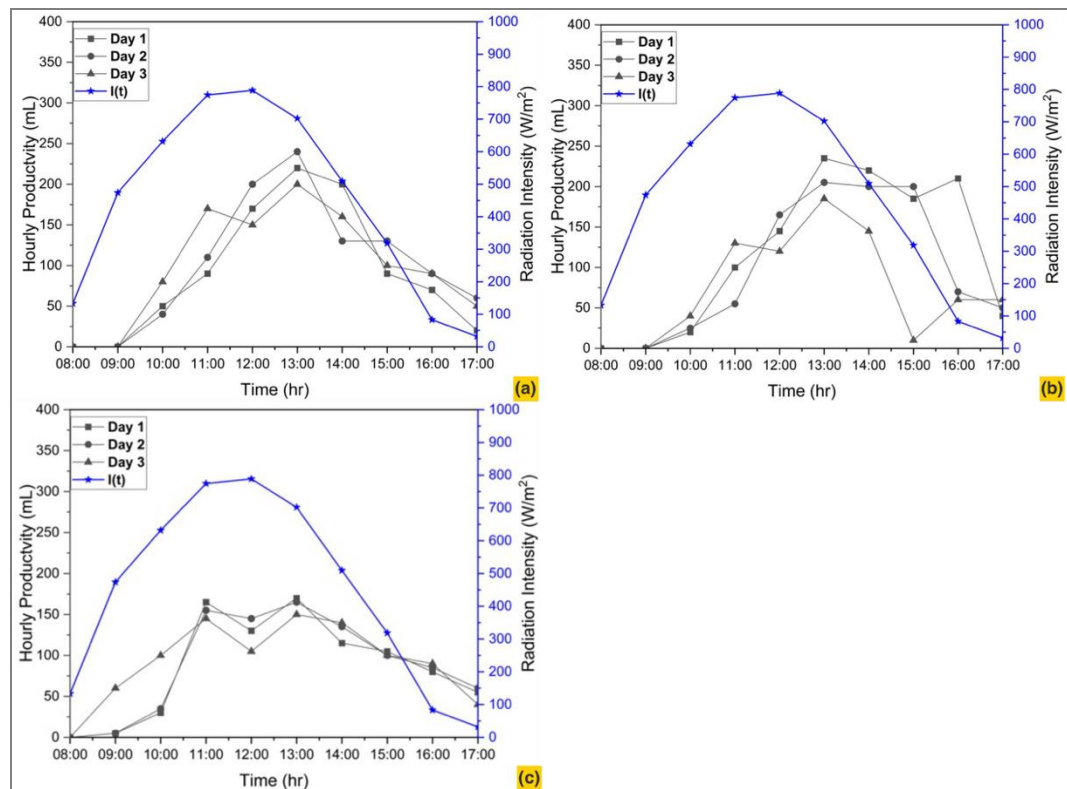


Figure 6.
The relationship
between $I(t)$ and hourly
productivity in:
(a) PHGSS;
(b) IHGSS;
(c) CS4

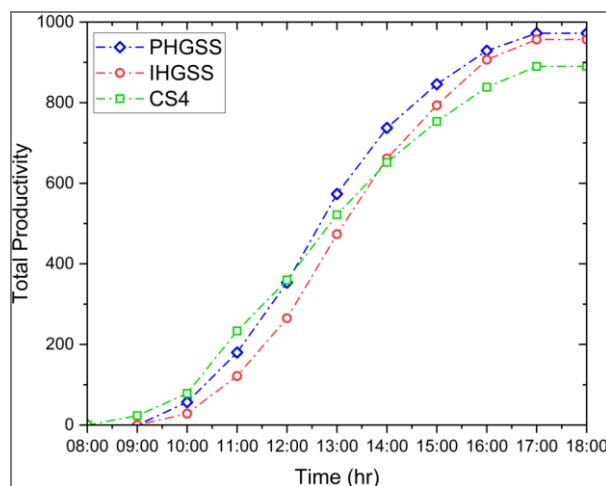


Figure 7.
Total accumulated
productivity of
PHGSS and IHGSS

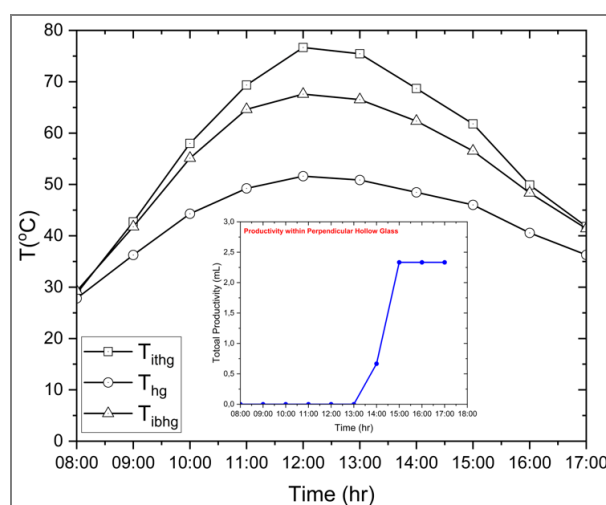


Figure 8.
Plot of T_{ithg} , T_{ibhg} , T_{hg} , and
the productivity results
of hollow glass PHGSS

IHGSS and PHGSS designs are recent modifications of the CS4 chamber. Although these innovations create opportunities for new condensation, the current setup remains suboptimal. The system's configuration delays the transfer of condensation droplets to the accumulation tank, allowing some of the condensation on the hollow glass to evaporate before it can be captured. In this context, we offer for scientists and engineers to optimize these findings regarding using inline and perpendicular hollow glass. Furthermore, this new modification could establish a trend for advancing solar still desalination technology.

The energy balance in a passive solar still system is essential for its assessment. Current research trends show ongoing efforts to improve the efficiency and productivity of solar stills, particularly in addressing significant heat losses that can exceed 50% [2]. This study categorizes the energy consumed in the system into two types: sensible heat and latent heat. Sensible heat refers to the energy required to raise the seawater temperature within the chamber, and it is calculated using Eq. (3). Additionally, the total energy

comprising latent heat (Q_u) and sensible heat (Q_s) is represented as Q_{use} ($Q_s + Q_u$) in Figure 9. The PHGSS chamber shows a higher cumulative Q_{use} compared to the IHGSS chamber, with averages of 749.99 W and 736.38 W, respectively. In contrast, the conventional CS4 has a lower energy

consumption than both, with 605.26 W. The energy loss (Q_{loss}) in the IHGSS and CS4 chamber are greater than that in the PHGSS chamber. The system's efficiency is determined using Eq. (7), with the results displayed in Figure 9b. The efficiencies for the PHGSS, IHGSS, CS4 chambers are 36.74%, 36.20%, and 26.51% respectively. Previous studies indicate that most of the energy entering the system is lost through the sides and bottom of the chamber. Heat is transferred through the walls of the solar still via conduction and is subsequently released into the environment through convection [31]. Furthermore, significant heat loss is also exacerbated by the reflection of some of the radiation intensity off the cover glass, water surface, and the basin bottom, as highlighted in prior research [32].

The results from PHGSS and IHGSS were also compared with findings from previous studies (see Table 3). We summarized related literature with experimental data for the conventional CS4 chamber for comparison. The efficiencies of the PHGSS and IHGSS chambers were recorded at 36.74% and 36.20%, respectively. These results indicate that PHGSS and IHGSS are competitive with the conventional CS4 chamber, as noted in previous studies. They outperform literature [33], [34], and [35] but yield lower results than literature [36]. It is important to note that literature [36] reflects ambient temperature conditions and experiences higher temperatures in summer, which significantly enhances its productivity and efficiency.

Figure 9.
(a) Plot of Q_{use} and Q_{loss} ;
(b) Average system
efficiency over 3 days
of testing

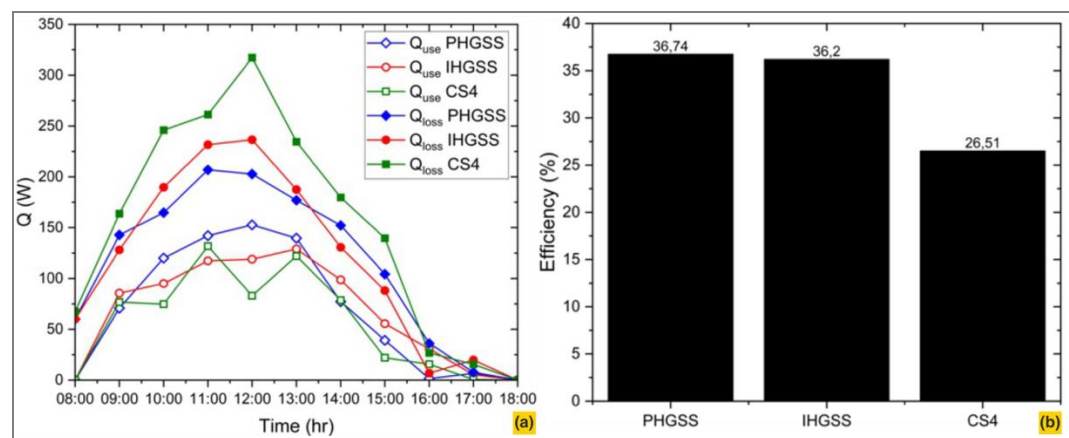


Table 3.
Comparison with
previous study

Ref.	Conventional Chamber Shape	Country	Absorber geometry	Productivity	Efficiency
Present Study	Modified CS4 (PHGSS)	Indonesia	0.54 m ²	975 mL/day	36.72%
Present Study	Modified CS4 (IHGSS)	Indonesia	0.54 m ²	958 mL/day	36.20%
[37]	CS4	India	0.25 m ²	2.61 L/m ²	N/A
[36]	CS4	India	0.60 m ²	±2390 mL/m ²	62.67%
[33]	CS4	Algeria	0.25 m ²	3.60 Kg/m ² /day	25.81%
[38]	CS4	Iraq	1.00 m ²	0.605 – 1.605 L/day	20-49%
[34]	CS4	Oman	0.675 m ²	1.89 -2.68 L/day	21-31%
[39]	CS4	India	0.36 m ²	2.90-3.85 kg/m ²	28.86-38.47%
[35]	CS4	Tunisia	0.64 m ²	0.73-0.83 kg/m ²	±15%

5. Conclusion

Research has been conducted using a newly modified solar still chamber. This study demonstrates that the use of hollow glass, whether oriented in cross-section (perpendicular) or parallel (inline), can lead to the condensation of distilled water, although the output remains relatively small. Several limitations have been discussed in detail in the discussion section. The PHGSS chamber has been found to outperform the IHGSS in terms of productivity and efficiency. When compared with the conventional CS4, both inline and perpendicular configurations show higher efficiency and productivity. This research offers new insights into using hollow glass for new condensation parts within the solar still. Although the current results have not reached optimal performance levels, they hold promising potential for further development. The experimental data reported have been validated against prior research, showing a margin of error of 7.78%. The highest average productivity recorded was achieved by the PHGSS, reaching 972.33 mL/day, with an efficiency of 37.74%. The gains in productivity and efficiency from PHGSS were 9.25% and 38.80%, respectively, while the IHGSS achieved gains of 7.48% and 36.57%.

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Authors' Declaration

Authors' contributions and responsibilities - The authors made substantial contributions to the conception and design of the study. The authors took responsibility for data analysis, interpretation and discussion of results. The authors read and approved the final manuscript.

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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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