

Improving Solar Still Performance with CuO-Coated Absorber & Ammonia Thermosiphoning

Dinesh Kumar¹, Dr. Raja Ramasamy²
*Department of Mechanical Engineering,
Mewar University Chittorgarh, Rajasthan, India*
¹dinesh23100@gmail.com

Abstract

This research focuses on enhancing the performance of a solar still by integrating copper oxide (CuO) nanoparticle-coated absorbers and ammonia thermosiphoning in repurposed condenser systems. A 20% weight concentration of CuO nanoparticles was mixed into black paint and applied to the absorber plate to improve solar energy absorption. Additionally, ammonia thermosiphoning in the repurposed condensers enhanced the evaporation rate. Experiments were conducted under real climatic conditions during selected days in July 2024. The modified solar still was compared to a conventional still, with efficiency evaluated based on total energy input and distilled water output. The results showed a 47.29% increase in efficiency for the modified system, demonstrating significant improvements in heat transfer and distillate yield. These modifications offer a sustainable and efficient approach to desalination, with potential for increased freshwater production, particularly in arid regions where water scarcity is a major challenge.

Keywords: Solar still, copper oxide nanoparticles, ammonia thermosiphoning, repurposed condenser, freshwater production.

1. Introduction

The distribution of water on Earth is uneven, with only 3% being freshwater, and less than 1% of that is easily accessible in lakes, rivers, and surface water sources, while most is stored in glaciers or underground. In contrast, 97% of Earth's water is saline, found in oceans, and needs desalination for consumption [1]. Distillation is an effective method for converting brackish, saline, or contaminated water into freshwater, and solar distillation provides a cost-effective and efficient solution for small-scale water purification, particularly in arid regions with abundant solar energy. Solar stills use solar energy to evaporate saline or brackish water, which is then condensed into fresh water. Their performance depends on uncontrollable factors like solar intensity and air temperature, as well as design factors such as basin size, glazing angle, materials, insulation, and operational factors like temperature differences and hybrid systems, all of which can be optimized to improve efficiency. Research has shown that optimizing

parameters such as evaporative surface areas, glazing materials, inclination angles, and insulation thickness can improve performance by enhancing heat transfer, solar radiation absorption, and condensation. For example, materials such as wick, sponge, or jute cloth can increase the evaporative surface area, improving performance, with Omara et al. [2] noting a 21% improvement using corrugated absorbers and Abdullah et al. [3] observing a 350% improvement using rotating drums along with heaters and condensers. Reducing basin depth and optimizing water depth can also enhance heat transfer and distillation efficiency, as shown by Tiwari and Tiwari, and Elango and Murugavel [4,5]. The glass cover plays a key role in allowing solar radiation to heat the water while reducing heat loss, with an optimal thickness of 3-4 mm improving evaporation and condensation rates, according to Khalifa and Hamood [6]. The inclination angle, aligned with solar radiation patterns, is essential for thermal performance, as suggested by Akash et al. and Singh and Tiwari [7,8]. Effective insulation materials like thermocol and Styrofoam have been shown to increase distiller productivity by 7% to 180%, with Sahoo et al. [9] reporting an 11% increase with thermocol. Adding heat-absorbing and thermal storage materials such as charcoal, dyes, and Phase Change Materials (PCMs) has further improved performance [10], with studies by Ayoub and Malaeb, and Abdallah et al. [11,12] showing increases, such as a 60% rise with uncoated metallic sponges and a 25% rise using PCMs like paraffin wax combined with graphene oxide. Nanomaterials have been explored for improving thermal conductivity and distillate yield, with research by showing that nonmetallic nanofluids like Al_2O_3 , CuO , ZnO , and TiO_2 enhance productivity, energy efficiency, and distillate yield. For example, Al_2O_3 reduces energy consumption while boosting distillate yield, CuO improves daily efficiency, TiO_2 enhances thermal conductivity, and ZnO increases overall efficiency. Emerging nanomaterials like SiO_2 and SnO_2 have also shown potential, with Kabeel et al. [13] finding that CuO nanoparticles increased productivity by 16% and 25% at 10% and 40% concentrations, respectively. Manoj Kumar et al. [14] studied SiO_2 nanoparticles in black paint coatings, achieving yield increases of 8.78% and 7.83% at different water depths. Similarly, Rajendra Prasad Arani et al. [15] observed a 55.18% increase in productivity with SiO_2 nanoparticle coatings and fins in tubular solar stills, while Kabeel [16] noted a 12% improvement in pyramidal solar stills coated with TiO_2 nanoparticles. Studies by Shahin Shoeibi et al. [17] mixing CuO and Al_2O_3 nanoparticles with paraffin wax led to productivity increases of 55.8% and 49.5%, respectively. Research by Omar Bait et al. [18] focused on nanofluids improving thermal conductivity and distillation efficiency, emphasizing the need for more research into active solar still configurations. The use of MnO_2 nanoparticles in black chrome paint resulted in a 19.5% yield increase at a 20% concentration, according to Hitesh Panchal et al. [19]. Sathyamurthy et al. [20] observed yield increases of 27.2% to 34.2% at different concentrations of fumed silicon oxide nanoparticles. Arunkumar et al. [21] noted that nanoparticles like Al_2O_3 , CuO , and ZnO improve heat transfer and water production rates, while Naveen Kumar et al. [22] emphasized the role of nanomaterials in improving heat transfer and water production in single-slope solar stills. Rasachak et al. [23] found that SnO_2 nanoparticles mixed with black paint improved absorber temperatures, leading to higher distillate production. Studies by Bhupendra Gupta et al. and Ruchir Parikh et al. [24, 25] showed that nanoparticles like CuO , TiO_2 , and SiO_2 can enhance solar still performance, with productivity increases ranging from 20% to 55%. Thakur et al. [26] reported the highest heat transfer and water yield of 0.88 L per hour with RGO-coated solar stills. Kumar et al. [27] found that hybrid nanomaterial-coated stills with reduced graphene oxide and CuO nanoparticles increased energy productivity to 44.18%. Selimefendigil [28] showed that CuO nanoparticles improved productivity by 26.77%, as well as energy and exergy efficiency in single-slope stills.

Despite these advancements, most existing studies have considered either nanomaterial-based coatings or condenser modifications in isolation. The present work introduces a novel configuration of a conventional solar still by integrating nanomaterial-mixed black paint for enhanced solar absorption with an ammonia-based thermosiphoning mechanism in repurposed condensers to intensify the evaporation–condensation process. This integrated approach provides a cost-effective and energy-efficient solution, offering superior freshwater yield and improved thermal efficiency compared to conventional designs.

2. Materials and Methods

The experimental setup for the solar distillation system consisted of a saline water tank, a conventional solar still (CSS), and a modified solar still (MSS), all fabricated from 1.5 mm-thick galvanized sheets. To improve solar absorption, the interior surface of the CSS was coated with standard black paint, whereas the MSS basin was coated with black paint mixed with copper oxide (CuO) nanoparticles at a weight fraction of 20% (200 g of CuO per 1 kg of black paint).

Both solar stills had basin dimensions of 65 cm in length, 33 cm in width, and a variable height ranging from 24 cm at the rear to 10 cm at the front. The basins were insulated with a 6.5 cm layer of sawdust, further enhanced by additional polystyrene foam to improve heat retention. Each still was covered with a 3.5 mm-thick transparent glass cover, creating a greenhouse effect that allowed sunlight to enter while minimizing heat loss, providing an optimal surface for condensation. Condensed water flowed down the glass cover into a 2.5 cm × 2.5 cm aluminum collection trough, which directed the water into a storage container.

A thermosiphon system utilizing 250 ml of ammonia (NH_3) circulated through copper and rubber tubing to facilitate efficient heat transfer between the evaporator and the condenser. The evaporator and condenser, repurposed from an air conditioner, had dimensions of 60 cm × 63 cm × 2 cm and 32.5 cm × 19 cm × 2 cm, respectively, and were crucial for effective heat exchange. Temperature measurements were recorded using four strategically placed thermocouples, along with a digital K-type thermocouple and a solarimeter to monitor solar radiation. Hourly distillate yield was collected in a calibrated flask via the collection trough. Two valves were installed to regulate saline water flow in both stills, ensuring controlled and consistent operation.

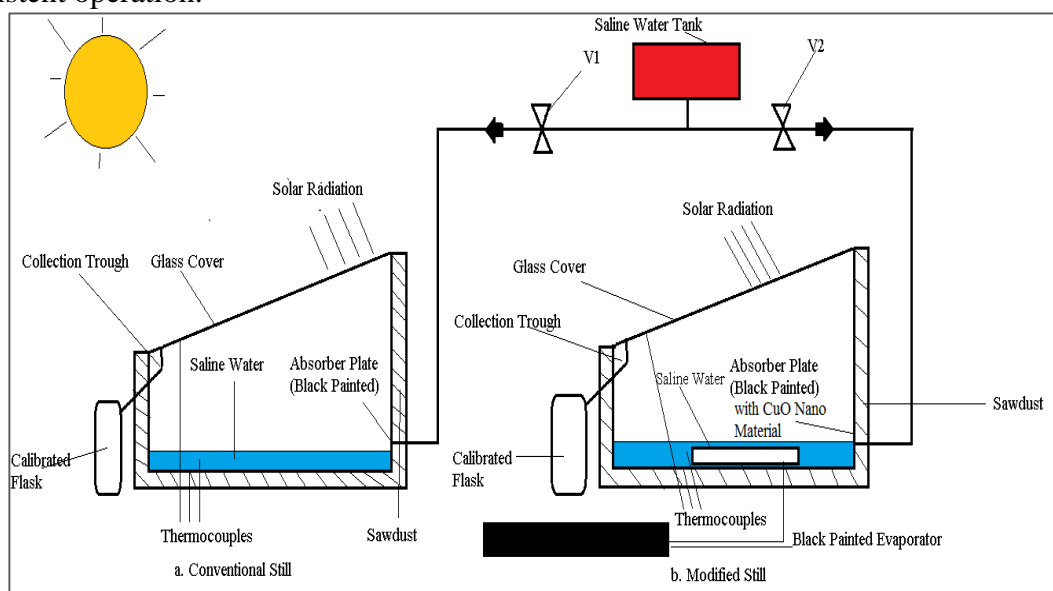


Figure 1 Schematic diagram of experimental Setup



Figure 2 Photograph of experimental setup

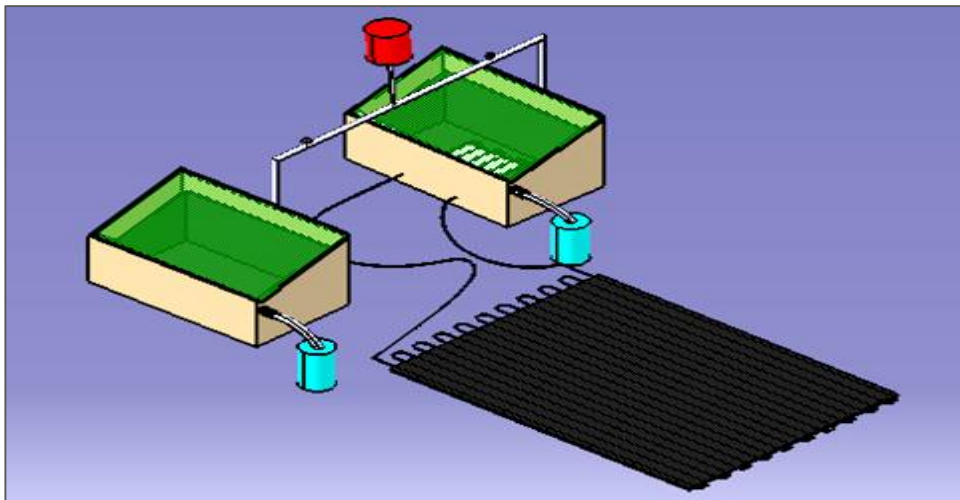


Figure 3 Isometric view of experimental setup

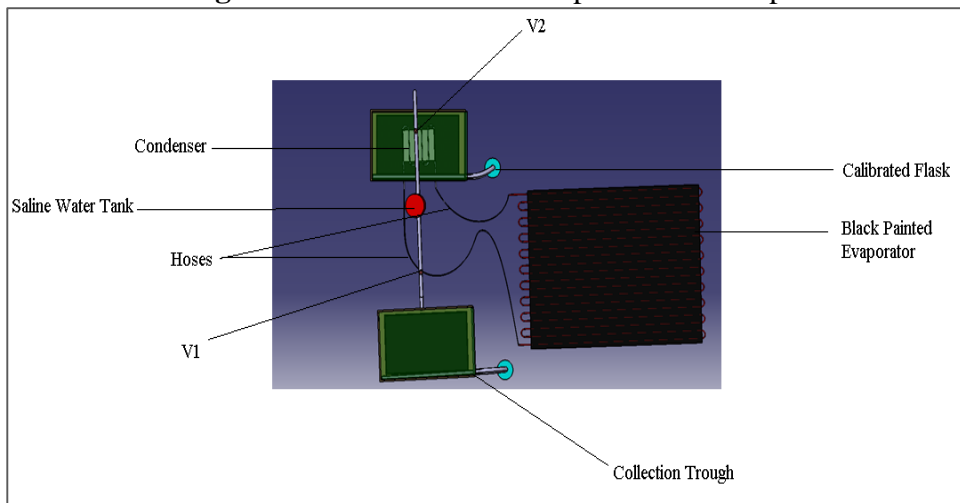


Figure 4 Top view of experimental Setup

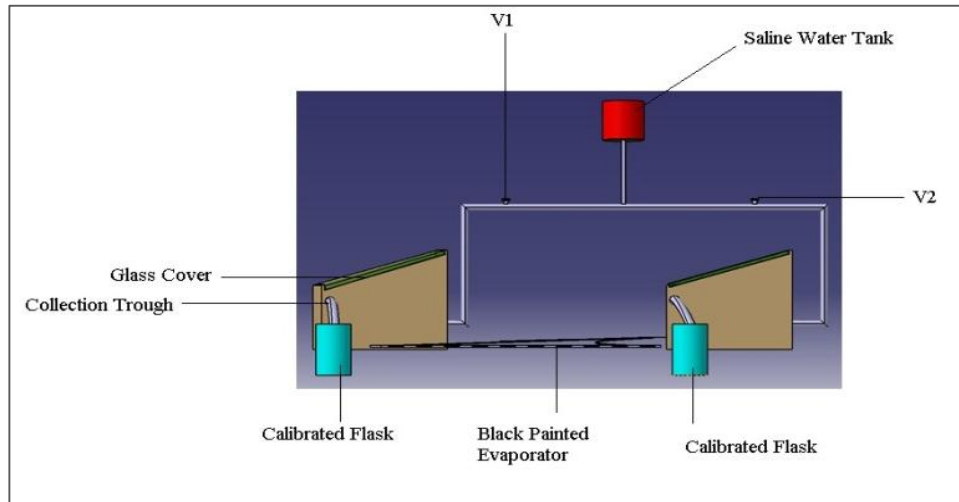


Figure 5 Side view of experimental Setup

The CuO nanoparticle specifications are provided in Table 1. Performance comparisons between the MSS and CSS were conducted, with the MSS utilizing a black paint mixed with CuO nanoparticles at a 20% weight fraction (200 g of CuO to 1 kg of black paint).

Table1: Specification of CuO nano particle

Property	Specification
Chemical Symbol	CuO
Density	6310 kg/m ³
Thermal Conductivity	32.9 W/m·K
Specific Heat	540 J/kgK
Average Particle Size	10–30 nm
Melting point	1201 °C
Boiling point	2000 °C

3. Results and Discussions

Experiments were conducted from 08:00 to 20:00 hours on July 21 and 22, 2024, at the Mewar University campus, Chittorgarh, Rajasthan, India. Thermocouples were strategically installed at various points in both the conventional solar still (CSS) and the modified solar still (MSS) to measure glass surface, basin, water, and evaporator temperatures (for the MSS), as well as ambient temperature. Hourly distillate yields were also recorded for both systems.

Figure 6 presents the hourly variation in solar radiation (W/m²) during the experimental days. The solar radiation exhibited a characteristic diurnal pattern, peaking around noon to early afternoon and declining during late afternoon and evening. Maximum radiation was observed between 12:00 and 14:00, with values ranging from 687 W/m² to 923 W/m², while the lowest values were recorded in the early morning and evening. These fluctuations were influenced by the sun's position and atmospheric conditions.

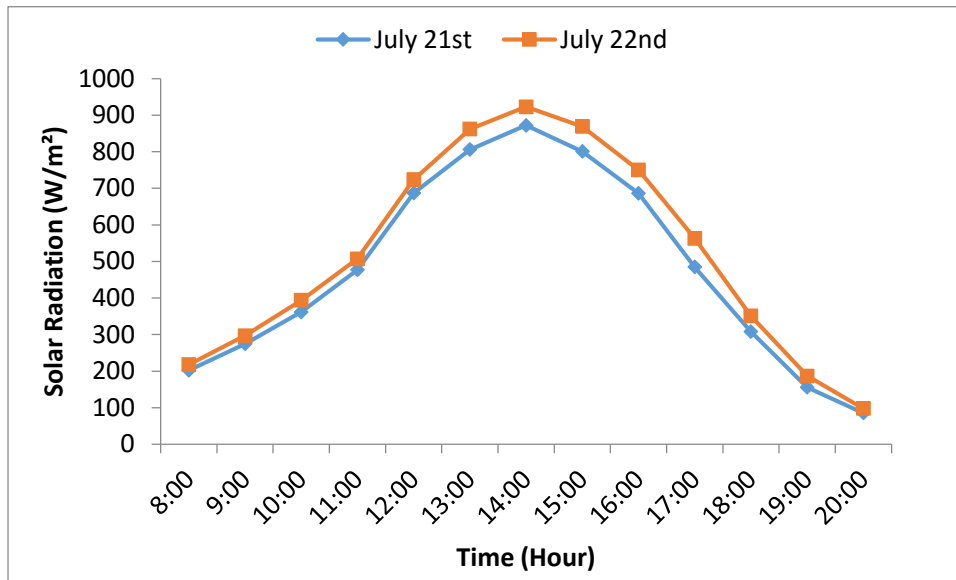


Figure 6 Hourly solar radiation

Figure 7 shows the hourly variation of ambient, glass, water, and basin temperatures for the CSS. All temperature parameters increased progressively from morning (08:00) to early afternoon (13:00–14:00), coinciding with the peak solar irradiance, followed by a gradual decline in the late afternoon. Peak basin temperatures reached 60°C and 62°C on July 21 and 22, respectively.

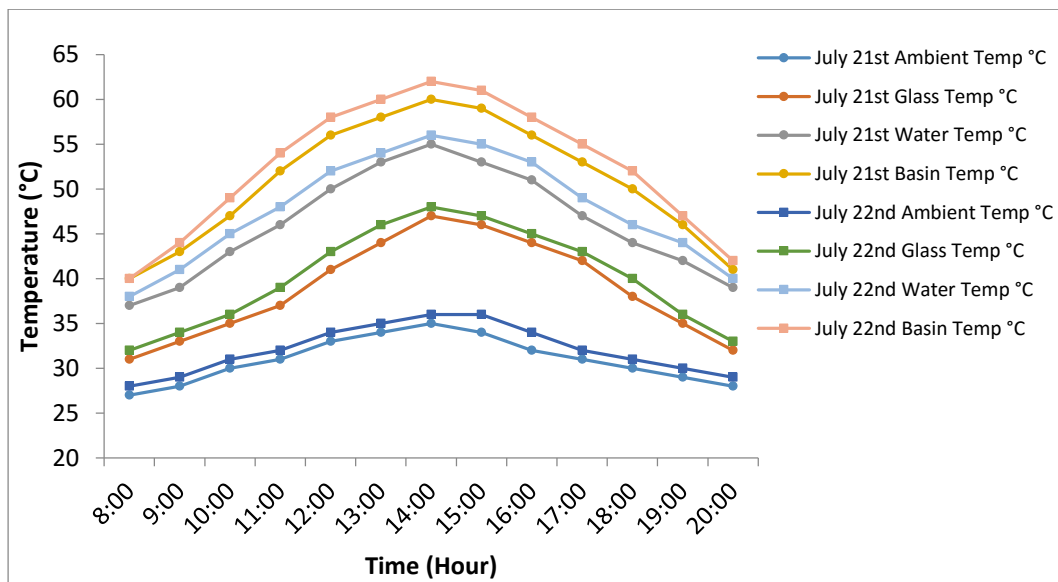


Figure 7 Hourly temperature variations in conventional solar still

Figure 8 illustrates the temperature distribution within the MSS, including the evaporator surface. The evaporator temperature consistently exceeded the water temperature, facilitating the thermosiphoning effect. Similar to the CSS, all temperature parameters increased from morning to midday and decreased in the afternoon. The MSS exhibited superior thermal performance, with basin temperatures reaching 69°C and 71°C at approximately 14:00, indicating enhanced heat absorption and retention.

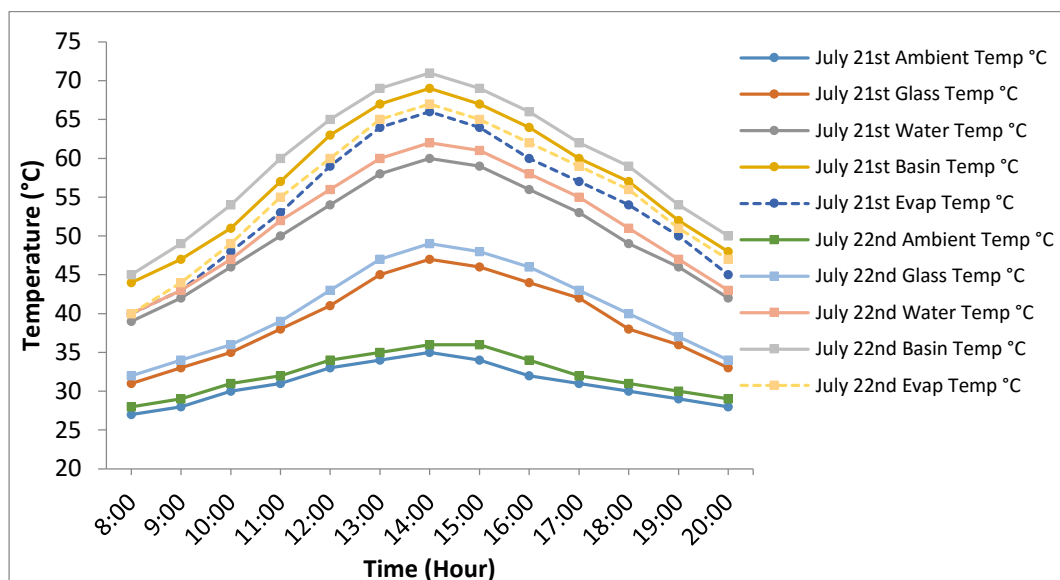


Figure 8 Hourly temperature variations in modified solar still

The hourly variation in distillate yield for the CSS is presented in Figure 9. The production rate followed a diurnal pattern, progressively increasing in the forenoon, peaking around midday, and declining toward evening. Maximum distillate yields of 479 mL/h and 505 mL/h were observed on July 21 and 22, respectively. Minor variations between the days were attributed to changes in solar radiation, thermal losses, and system efficiency.

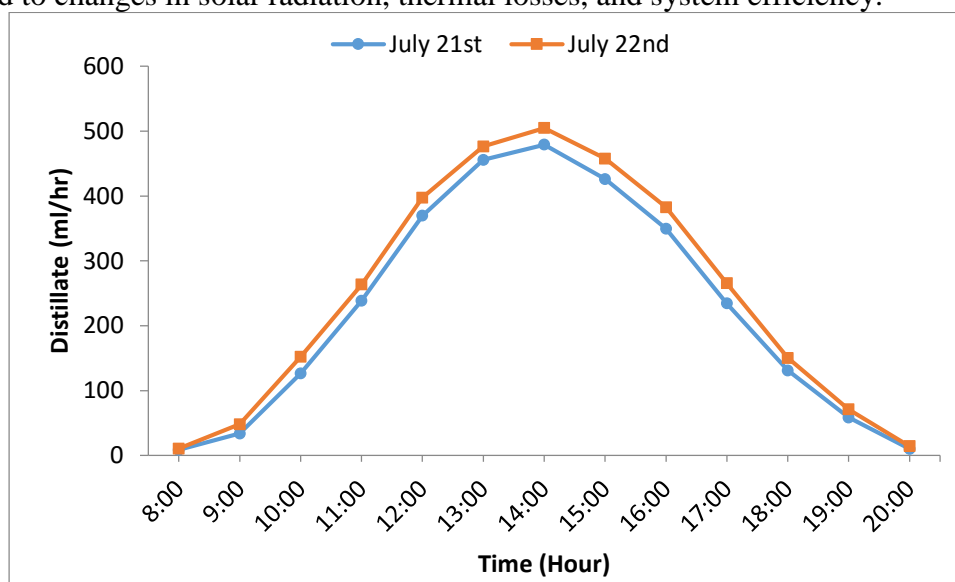


Figure 9 Hourly distillate for conventional solar still

Figure 10 shows the corresponding distillate production for the MSS. Although the diurnal trend remained similar to the CSS, the MSS achieved substantially higher productivity, with peak outputs of 678 mL/h and 712 mL/h on July 21 and 22, respectively. This enhancement was primarily attributed to the synergistic effect of the CuO nanoparticle coating, which increased solar absorptivity, and the ammonia-based thermosiphoning mechanism, which improved internal heat transfer. Consequently, the MSS demonstrated a markedly higher thermal efficiency than the CSS.

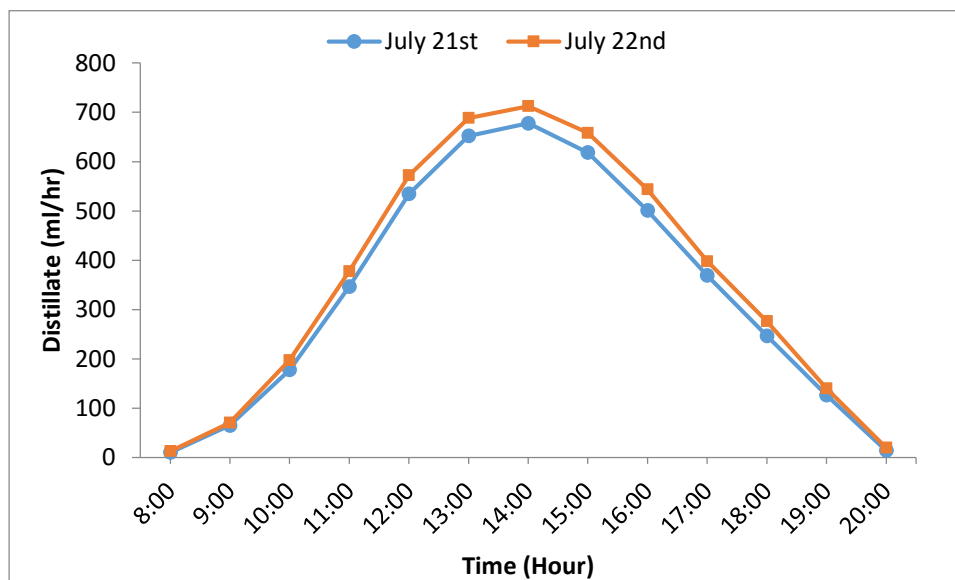


Figure 10 Hourly distillate for modified solar still

Figures 11 and 12 present the cumulative distillate yields for the CSS and MSS, respectively. For the CSS, total accumulated distillate reached 2,921.3 mL and 3,195 mL by 20:00 on July 21 and 22, respectively, while the MSS achieved higher total yields of 4,340.1 mL and 4,668.5 mL. The MSS consistently outperformed the CSS throughout the day, highlighting its enhanced thermal performance and efficiency.

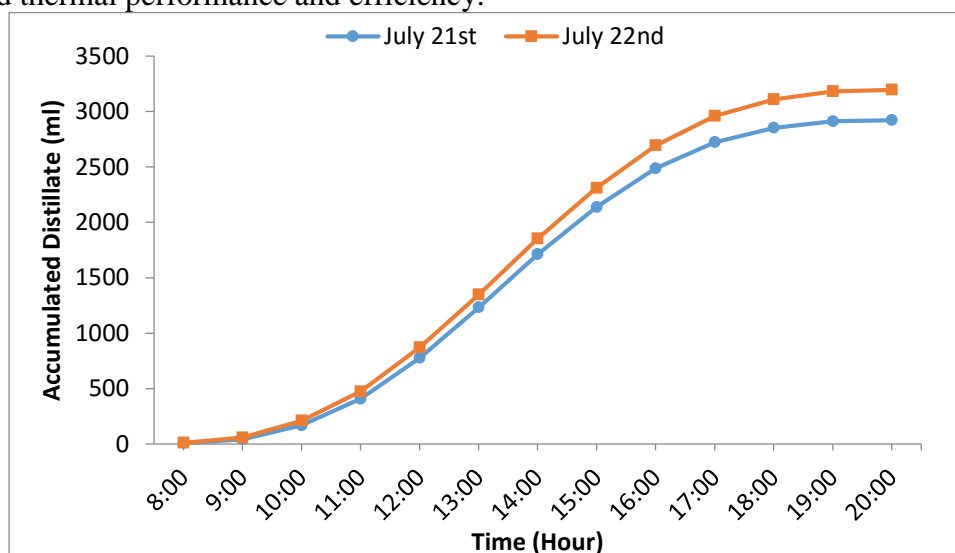


Figure 11 Total distillate for conventional solar still

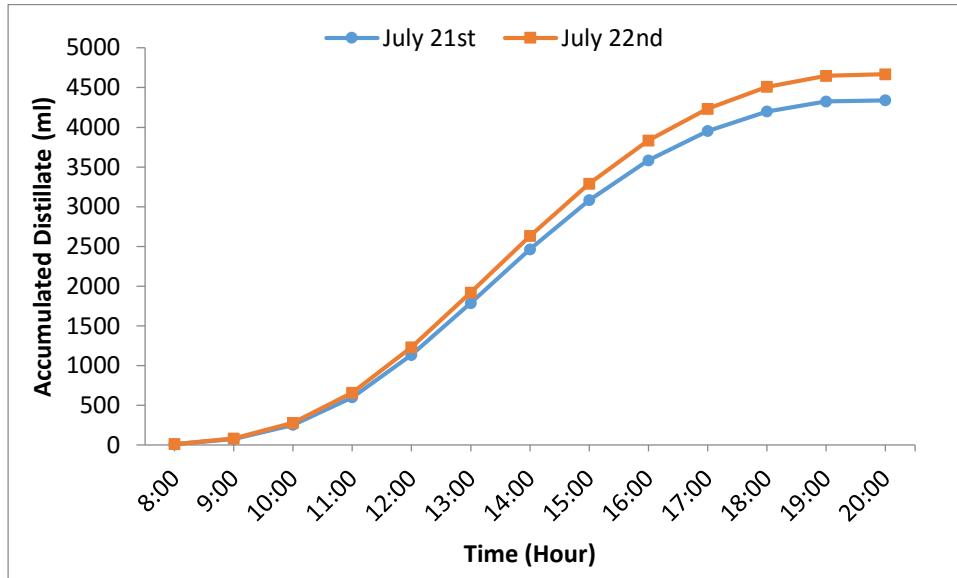


Figure 12 Total distillate for modified solar still

Figures 13 and 14 provide a comparative analysis of hourly and cumulative distillate yields between the MSS and CSS. The MSS consistently demonstrated superior performance, particularly during peak solar radiation hours, owing to improved heat absorption and optimized thermal distribution. As a result, the MSS achieved higher distillate outputs both hourly and cumulatively, significantly surpassing the CSS.

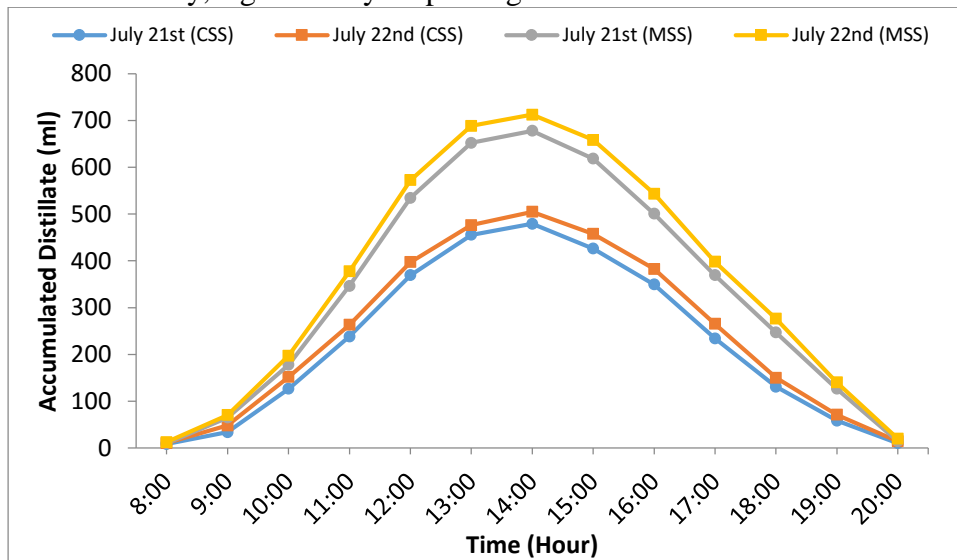


Figure 13 Comparison of hourly distillate for MSS and CSS

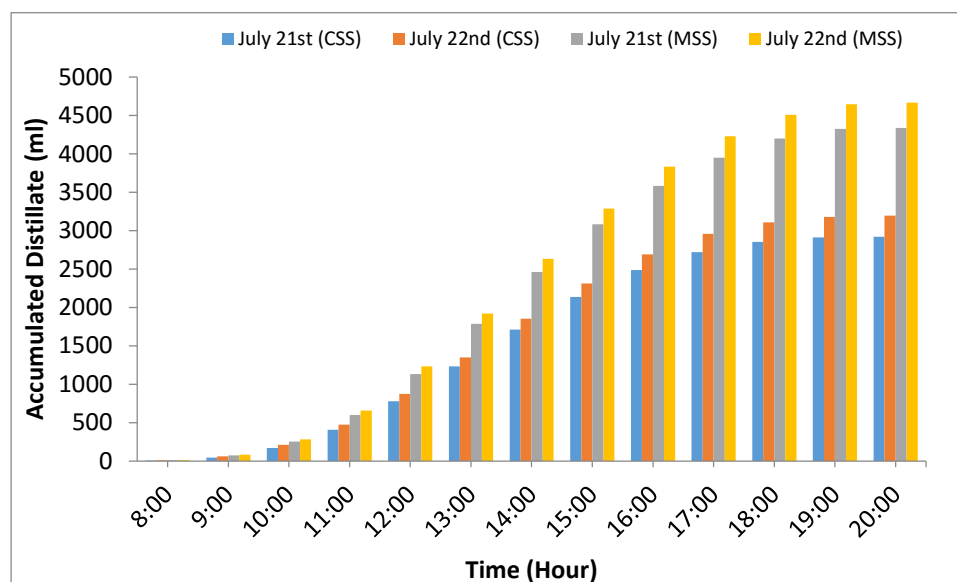


Figure 14 Comparison of total distillate for MSS and CSS

The performance of the modified solar still incorporating CuO nanomaterials and an ammonia thermosiphoning system was evaluated against a conventional still. The conventional system achieved an efficiency of 13.42%, whereas the modified still reached 19.07%, corresponding to a 42.11% improvement. The enhancement is attributed to the increased thermal conductivity and solar energy absorption provided by CuO nanomaterials, along with the improved heat distribution and circulation enabled by ammonia thermosiphoning. This synergistic effect facilitated more efficient energy transfer, resulting in higher freshwater yield.

These findings align with previous studies that reported efficiency gains through nanomaterials or active heat transfer mechanisms individually. For example, Kabeel et al. [13] observed 16–25% productivity improvements with CuO nanoparticles, Manoj Kumar et al. [14] reported 8–9% gains with SiO₂ nanoparticle coatings, and Abdullah et al. [3] achieved up to 350% enhancement using rotating drums with condensers. The present study, however, demonstrates that combining nanomaterial coatings with ammonia thermosiphoning produces superior performance, exceeding improvements reported for single enhancement strategies.

Table 2. Comparison of Present Study with Previous Research

Study	Enhancement Method	Efficiency / Productivity Improvement	Key Observation
Present study	CuO nanomaterials + Ammonia thermosiphoning	42.11% increase (13.42% → 19.07%)	Synergistic effect of nanomaterials and thermosiphoning enhances heat transfer and distillate yield.
Kabeel et al. [13]	CuO nanoparticles in basin water	16–25% increase	Nanoparticles improved thermal conductivity and absorption.
Manoj Kumar et al. [14]	SiO ₂ nanoparticles in black paint	8.78–7.83% increase	Improved solar absorption via nanomaterial coating.

Abdullah et al. [3]	Rotating drum with heaters and condensers	350% increase	Active heat transfer enhanced productivity.
Rajendra Prasad Arani et al. [15]	SiO ₂ nanoparticle coatings + fins	55.18% increase	Nanoparticles combined with structural modifications improved efficiency.
Shahin Shoeibi et al. [17]	CuO + Al ₂ O ₃ nanoparticles with paraffin wax	49.5–55.8% increase	Hybrid nanofluids enhanced heat storage and efficiency.

This comparative analysis confirms the novelty and effectiveness of the proposed hybrid system, showing that integrating nanomaterials with ammonia thermosiphoning achieves higher thermal efficiency and distillate production than previously reported individual enhancement methods.

4. Conclusion

The results shows the improved performance of the modified solar still in comparison to the conventional system. By incorporating copper oxide nanoparticle-coated absorbers and ammonia thermosiphoning, the modified system consistently outperforms the conventional solar still in both peak distillate production and total accumulated distillate. The improved heat absorption and transfer of the modified still lead to significantly higher distillate yields, particularly during peak solar radiation hours, with a notable increase in system efficiency. Key findings from the results include:

- **Increased Distillate Production:** The modified solar still achieves peak production of 712.4 ml/hr, compared to 504.8 ml/hr on July 22nd for the conventional still.
- **Higher Accumulated Distillate:** By 8:00 PM, the modified still accumulates significantly more distillate, with totals reaching 4668.5 ml on July 22nd, compared to 3195 ml for the conventional system.
- **Improved Efficiency:** The modifications result in a 47.29% increase in efficiency, significantly enhancing the overall performance of the solar still compared to the conventional design.

Conflict of Interest: All authors declare that they have no conflict of interest

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