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EXPERIMENTAL INVESTIGATION OF A SOLAR STILL WITH DIFFERENT HEAT TRANSFER ENHANCEMENT TECHNIQUES

[1]Sharad Moreshwar Sawant, [2]Dr. Nishant Singh Kushwah

[1]M.Tech Student, [2]Assistant Professor, Department of Chemical Engineering
Vikrant University, Gwalior MP

ABSTRACT

Solar stills are simple and environmentally sustainable desalination systems that use solar energy to convert saline or brackish water into freshwater. However, their relatively low freshwater productivity and dependence on intermittent solar radiation limit their practical application. This review examines experimentally investigated heat-transfer enhancement techniques for solar stills, including fins, corrugated absorbers, wick and porous materials, nanofluids, phase change materials (PCMs), nano-enhanced PCMs, cooling methods, and hybrid configurations. The review discusses their heat-transfer mechanisms, performance characteristics, advantages, and limitations, along with important factors such as solar radiation, water depth, material properties, and environmental conditions. Published studies indicate that enhancement techniques can improve freshwater productivity, although the magnitude of improvement varies with solar-still configuration and operating conditions. Hybrid systems show considerable potential through the combined effects of heat-transfer enhancement, evaporation improvement, and thermal storage. However, material durability, additional cost, environmental concerns, and system complexity remain important challenges. The review highlights the need for reliable and comparable experimental evaluation to support the development of efficient and practically sustainable solar-still systems.

Keywords: Solar still; solar desalination; heat-transfer enhancement; fins; wick; nanofluid; phase change material; thermal efficiency; freshwater productivity.

1. INTRODUCTION

Freshwater scarcity is one of the major environmental and socioeconomic challenges affecting many regions of the world. Population growth, industrialization, agricultural demand, climate variability, and depletion of freshwater resources have increased the need for alternative sources of freshwater [1]. Desalination of seawater and brackish water is an important approach for addressing this problem. However, conventional desalination technologies such as reverse osmosis and thermal desalination can require significant energy, infrastructure, and operational resources.

Solar desalination provides an attractive alternative for decentralized applications because solar energy is directly available in many water-stressed regions. Among the various solar desalination technologies, the solar still is one of the simplest configurations [2]. It generally consists of an insulated basin containing saline water and a transparent inclined cover. Solar radiation passes through the cover and heats the absorber and water. The water subsequently evaporates, and the vapour condenses on the relatively cooler inner surface of the transparent cover. The condensate flows into a collection channel and is collected as freshwater.

The fundamental limitation of conventional solar stills is their comparatively low freshwater productivity [3]. The evaporation rate depends strongly on water temperature, solar radiation, water depth, and the temperature difference between the water and condensing surface. In addition, solar radiation varies throughout the day, causing the evaporation rate to decline when solar intensity decreases.

Heat-transfer enhancement techniques have consequently become an important research area. These techniques attempt to increase heat transfer from the absorber to the water, increase the effective evaporation area, improve thermal conductivity, store thermal energy, increase solar absorption, or improve condensation. Recent reviews have examined fins, porous materials, nanoparticles, phase change materials, cooling methods, reflectors, condensers, and hybrid systems as important approaches for improving solar-still performance [4].

The basic heat-transfer mechanism of a basin-type solar still is illustrated in Figure 1. Solar radiation is absorbed by the basin and water, heat is transferred to the water, evaporation occurs at the water surface, and condensation takes place at the transparent cover.

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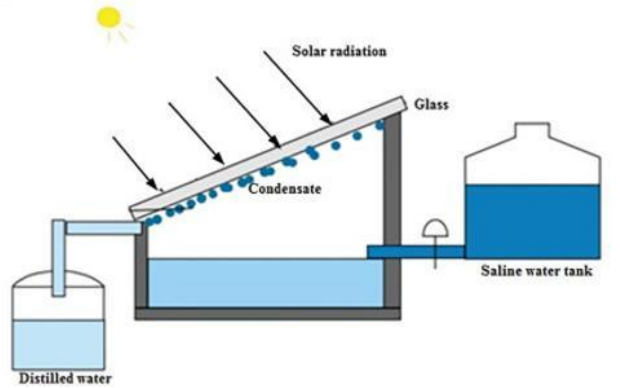

Figure 1: Main heat-transfer pathways in a basin-type solar still [5]

1.1. Objectives of the Review

The review has the following objectives:

- To examine the major heat-transfer enhancement techniques used in solar stills and their mechanisms for improving evaporation, heat transfer, thermal storage, and condensation.
- To compare the performance, advantages, limitations, and influencing factors of different enhancement techniques based on reported experimental investigations.
- To identify the major practical challenges and future requirements for developing efficient, durable, economical, and sustainable solar-still systems.

2. FUNDAMENTALS AND HEAT-TRANSFER MECHANISMS OF SOLAR STILLS

The performance of a solar still depends on a series of heat- and mass-transfer processes. Solar radiation passes through the transparent cover and is absorbed by the basin and saline water. The absorbed solar energy increases the water temperature and provides the energy required for evaporation [6].

The major processes occurring inside a solar still include solar radiation absorption, conduction, convection, evaporation, vapour transport, condensation, and heat loss to the surrounding environment. As the water temperature increases, its vapour pressure also increases, promoting evaporation from the water surface. The generated water vapour moves toward the transparent cover, which is generally maintained at a lower temperature than the water. Condensation consequently occurs on the inner surface of the cover, and the condensed water is collected as freshwater [7].

The useful energy associated with evaporation can be expressed as:

$$Q_e = m_d h_{fg}$$

where Q_e is the useful evaporation energy, m_d is the mass of distilled water, and h_{fg} is the latent heat of vaporization.

Freshwater productivity can be expressed as:

$$P_d = \frac{m_d}{A}$$

where P_d is the distillate productivity and A is the effective basin area.

The thermal efficiency of a solar still can be expressed as [8]:

$$\eta_{th} = \frac{m_d h_{fg}}{A I_t} \times 100$$

where I_t represents the accumulated incident solar energy during the experimental period.

The temperature difference between the saline water and the condensing cover is an important factor governing solar-still performance. An increase in water temperature generally promotes evaporation, while a lower cover temperature favours condensation [9]. Therefore, an effective heat-transfer enhancement technique should increase the evaporation rate while maintaining favourable condensation conditions.

In addition to these thermal processes, solar-still performance is influenced by several operating and environmental parameters, including water depth, basin material, cover inclination, absorber characteristics, salinity, solar radiation, ambient temperature, relative humidity, and wind velocity [10]. These parameters should be carefully considered when comparing conventional and enhanced solar-still configurations.

3. HEAT-TRANSFER ENHANCEMENT TECHNIQUES IN SOLAR STILLS

Heat-transfer enhancement techniques improve the thermal and evaporation performance of solar stills by increasing heat-transfer area, enhancing evaporation, improving thermal transport, storing energy, or promoting condensation. The major techniques include fins, modified absorbers, wick and porous materials, nanofluids, phase change materials (PCMs), cooling systems, and hybrid configurations.

a) Fins and Extended Surfaces

Fins are simple passive devices attached to the absorber or basin to increase the effective heat-transfer area. Aluminium and copper are commonly used because of their high thermal conductivity [11]. Fins can improve heat transfer to saline water and increase evaporation. Their height, thickness, spacing, and arrangement should be optimized because excessive fin density can increase cost and fabrication complexity.

b) Corrugated and Modified Absorber Surfaces

Corrugated absorbers, including V-shaped, wavy, and triangular designs, increase the effective surface area and improve heat distribution. They can enhance absorber-water heat transfer and have also been combined with wicks, nanofluids, and thermal-storage materials.

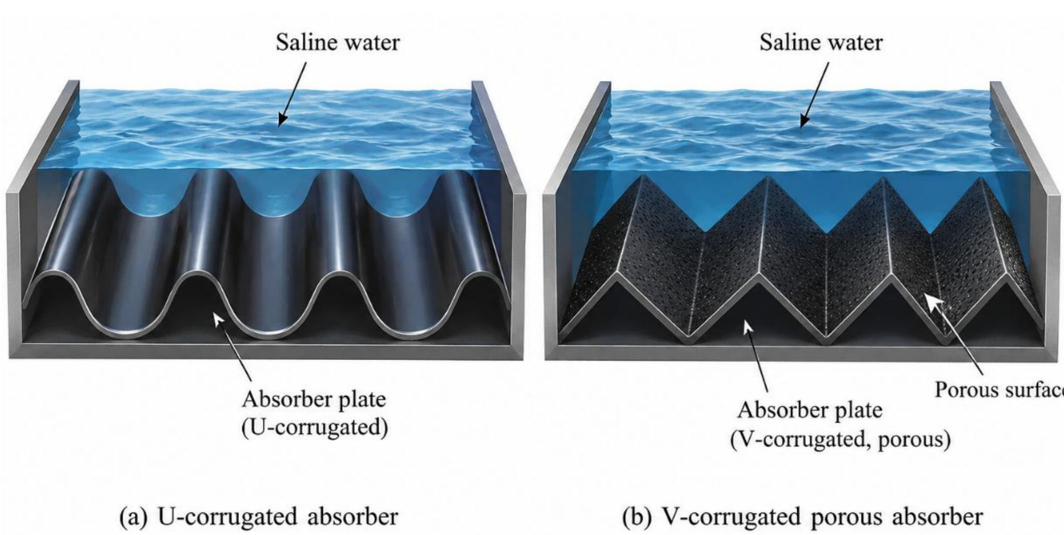

Figure 2: Corrugated and Modified Absorber Surfaces [12]

c) Wick and Porous Materials

Wick materials distribute water over a larger surface through capillary action, producing a thin water layer that can heat and evaporate quickly. Cotton, jute, textile, sponge, metallic mesh, and steel wool have been investigated. However, salt accumulation, pore blockage, and material deterioration can reduce long-term performance.

d) Nanofluids

Nanofluids contain nanoparticles dispersed in a base fluid to improve thermal transport. Their performance depends on particle type, concentration, size, dispersion, and stability. Although they can improve heat transfer, agglomeration, sedimentation, preparation cost, and environmental concerns require consideration [13].

e) Phase Change Materials

PCMs store thermal energy during periods of high solar radiation and release it when radiation decreases. This helps maintain water or absorber temperature and can extend freshwater production beyond peak solar hours. Performance depends on melting temperature, latent heat, thermal conductivity, quantity, and placement.

f) Nano-Enhanced Phase Change Materials

Nano-enhanced PCMs combine thermal storage with improved heat transfer [14]. Nanoparticles can increase PCM thermal conductivity and accelerate charging and discharging. However, excessive nanoparticle concentration can increase cost and stability problems.

g) Cooling and Condensation Enhancement

Cooling techniques reduce the temperature of the transparent cover and increase the temperature difference between the evaporating water and condensing surface. Water or air circulation, fans, cooling channels, and thermoelectric devices can be used [15]. Their additional energy requirements should be considered in overall performance evaluation.

h) Hybrid Enhancement Techniques

Hybrid systems combine two or more techniques, such as fin-PCM, wick-PCM, nanofluid-PCM, and fin-wick-nanofluid-PCM systems. Different techniques can complement each other by improving heat transfer, evaporation, and thermal storage. However, hybrid systems generally involve greater cost and complexity.

Table 1: Classification of Heat-Transfer Enhancement Techniques [16]

Enhancement technique	Primary mechanism	Major advantage	Major limitation
Fins	Increased heat-transfer area	Simple passive enhancement	Geometry and corrosion
Corrugated absorber	Increased surface area and improved heat distribution	Better absorber-water heat transfer	More complex fabrication
Wick materials	Thin-film evaporation and capillary action	Increased evaporation area	Salt accumulation and deterioration
Porous materials	Increased effective evaporation surface	Enhanced evaporation	Pore blockage
Nanofluids	Improved thermal transport	Better heat-transfer characteristics	Stability and environmental concerns
PCM	Latent heat storage	Extended operation after peak solar radiation	Relatively low thermal conductivity
Nano-PCM	Improved PCM thermal transport	Faster thermal charging and discharging	Higher material complexity
Cover cooling	Enhanced condensation	Greater water-cover temperature difference	Additional energy requirement
Hybrid systems	Combination of enhancement mechanisms	Potentially high productivity	Higher cost and complexity

As summarized in Table 1, each technique improves a different aspect of solar-still operation. Therefore, the selection of an enhancement method should depend on the specific thermal limitation of the solar-still configuration and the intended operating conditions.

4. EXPERIMENTAL INVESTIGATIONS REPORTED IN THE LITERATURE

Experimental studies are essential for evaluating the actual effectiveness of heat-transfer enhancement techniques because solar-still performance depends on still geometry, water depth, materials, environmental conditions, and operating parameters.

Several studies have investigated individual techniques such as fins, wicks, corrugated absorbers, nanofluids, and phase change materials (PCMs), while others have combined multiple approaches. Reviews by Alwan et al. (2024), Bhargva and Yadav (2021), and Jathar et al. (2022) indicate that these modifications can improve solar-still productivity, although their effectiveness varies with the system configuration and operating conditions.

Finned absorbers increase the effective heat-transfer area, while wick materials improve evaporation by maintaining a thin water layer over a larger surface. Nanofluids have also been investigated for improving thermal transport, with their performance depending on factors such as particle concentration and stability (Rashid et al., 2024).

PCMs provide thermal storage by absorbing heat during periods of high solar radiation and releasing it as solar intensity decreases. Advanced configurations have also used thermal localization and multistage evaporation to improve solar-to-vapour conversion. Xu et al. (2020) demonstrated this approach using a thermally localized multistage solar still.

Hybrid systems have also produced substantial improvements. A tubular solar still using a V-corrugated aluminium basin, wick, carbon-black nanofluid, and nano-enhanced PCM reported an approximately 88.84% increase in daily freshwater productivity compared with a conventional system. Similarly, a tray solar still incorporating fins, jute wick, reflecting mirrors, and nano-enhanced PCM demonstrated the potential of combined enhancement techniques.

Recent studies have continued to investigate combinations of fins, PCM, and nanofluids. A 2026 square-pyramid solar still using hollow PCM fins and an organic nanofluid reported a maximum yield of 4056 mL/m^2·day under the tested experimental conditions.

Table 2: Selected Experimental and Literature Investigations of Solar-Still Enhancement

Enhancement approach	Solar-still configuration	Major reported observation	Reference
Fins and modified absorber	Different configurations	Increased heat-transfer area and productivity potential	Alwan et al. (2024) [17]
Nanofluids	Various configurations	Improved thermal transport and evaporation; concentration and stability are important	Rashid et al. (2024) [18]
Fins + jute wick + reflector + nano-PCM	Tray solar still	Combined enhancement improved freshwater productivity	Abdullah et al. (2022) [19]
V-corrugated basin + wick + nanofluid + nano-PCM	Tubular solar still	Approximately 88.84% increase in daily productivity	Abdelaziz et al. (2021) [20]
Thermal localization + multistage evaporation	Multistage solar still	Improved solar-to-vapour conversion	Xu et al. (2020) [21]
Thermal concentration	Floating solar steam-generation system	Enhanced steam generation under one-sun irradiation	Ni et al. (2016) [22]

5. PERFORMANCE EVALUATION AND COMPARATIVE ANALYSIS

Freshwater productivity is the most commonly used parameter for evaluating solar-still performance. However, productivity alone does not provide sufficient information about the effectiveness of a heat-transfer enhancement technique [23]. A proper comparison should also consider thermal behaviour, energy utilization, operating conditions, economic performance, and long-term stability. The percentage improvement in productivity relative to a conventional solar still can be calculated as:

$$\text{Productivity Improvement (\%)}=\frac{P_e-P_c}{P_c}\times 100$$

where P_e is the productivity of the enhanced solar still and P_c is the productivity of the conventional solar still. Thermal efficiency is another important performance parameter and can be expressed as:

$$\eta_{th}=\frac{m_d h_{fg}}{A I_t}\times 100$$

where m_d is the total mass of distilled water, h_{fg} is the latent heat of vaporization, A is the effective basin area, and I_t is the total incident solar energy over the experimental period.

The temperature profiles of the water, absorber, and transparent cover should also be examined. An enhancement technique that increases the water and absorber temperatures while maintaining a relatively lower cover temperature can provide favourable conditions for evaporation and condensation [24]. Hourly temperature and productivity measurements are particularly useful for identifying the periods of maximum evaporation and the contribution of thermal-storage materials after solar radiation decreases.

Exergy efficiency provides additional information because it considers the quality and availability of energy rather than only the amount of energy transferred [25]. Economic analysis is also important, particularly for systems incorporating nanomaterials, active cooling, pumps, fins, or complex thermal-storage arrangements. Parameters such as energy consumption, material cost, maintenance requirements, and cost per litre of freshwater can help determine practical feasibility.

Table 3: Parameters Recommended for Comparative Performance Evaluation [26]

Parameter	Purpose	Importance
Daily freshwater productivity	Measures total water production	Primary productivity indicator
Hourly productivity	Shows transient performance	Identifies peak and post-solar production
Water temperature	Indicates evaporation conditions	Important for heat-transfer assessment
Absorber temperature	Indicates solar-energy absorption	Helps evaluate absorber modification
Cover temperature	Indicates condensation conditions	Important for vapour condensation
Thermal efficiency	Measures solar-energy utilization	Allows comparison of thermal performance
Exergy efficiency	Measures useful energy quality	Useful for thermodynamic assessment
Energy consumption	Measures additional power requirement	Important for active systems
Cost per litre	Measures economic performance	Indicates practical feasibility
Durability	Measures long-term stability	Important for practical application

Published studies demonstrate considerable variation in reported productivity improvements. This variation is expected because experiments are conducted using different basin areas, water depths, solar intensities, climatic conditions, enhancement materials, and experimental durations. Therefore, comparisons should consider both the reported improvement and the experimental conditions under which it is obtained.

6. FACTORS AFFECTING HEAT TRANSFER AND FRESHWATER PRODUCTIVITY

Solar radiation is the principal energy source for a solar still and directly influences water and absorber temperatures. Higher solar radiation generally increases evaporation, although the resulting freshwater productivity also depends on ambient temperature, humidity, wind conditions, and condensation characteristics [27].

Water depth is another important parameter. A deeper water layer has greater thermal mass and requires more energy to reach a higher temperature. In contrast, a shallow water layer responds more rapidly to solar radiation and can provide higher instantaneous productivity. Therefore, water depth should be kept constant when comparing different enhancement techniques.

The material and geometry of the enhancement device also affect heat transfer. For fins, thermal conductivity, thickness, height, spacing, and orientation determine the rate of heat transfer. For wick materials, porosity, thickness, wettability, capillary action, and effective surface area influence water distribution and evaporation.

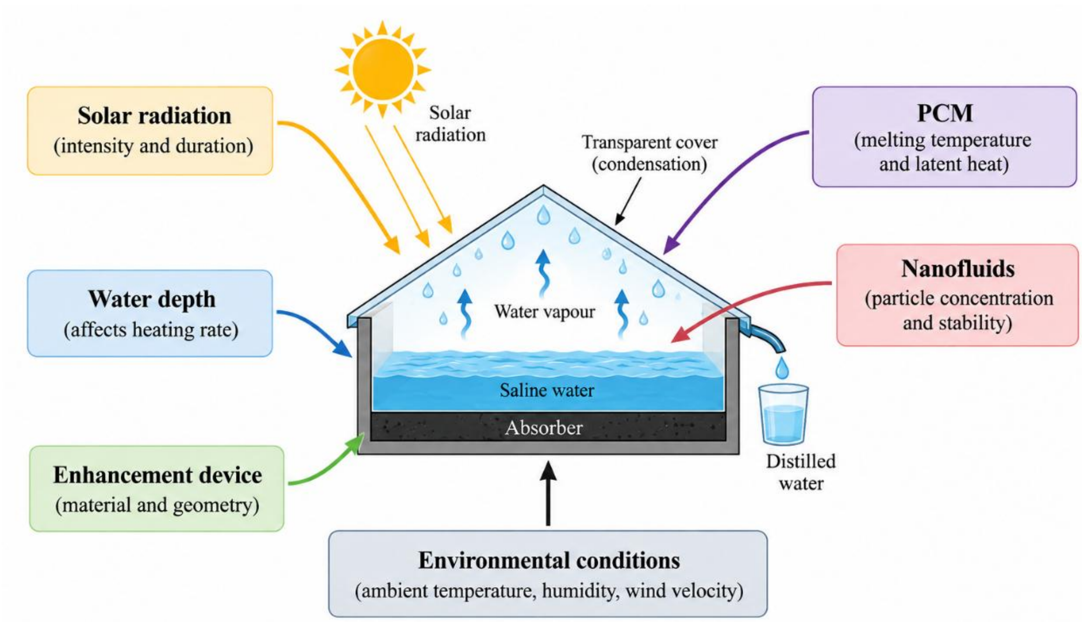

Figure 3: Factors Affecting Heat Transfer and Freshwater Productivity [28]

For PCM-based systems, melting temperature and latent heat determine thermal-storage performance. Nanofluid performance depends mainly on particle concentration, size, dispersion, and stability. Environmental conditions should also be recorded because they directly affect evaporation and condensation. For reliable comparison, experiments should maintain similar basin geometry, water depth, cover inclination, measurement procedures, and operating conditions.

7. CHALLENGES

Despite considerable progress in solar-still heat-transfer enhancement, several practical challenges remain. Variations in still geometry, water depth, climatic conditions, measurement procedures, and operating conditions can significantly influence the reported performance of enhancement techniques [29].

Long-term operation is another challenge. Continuous exposure to saline water, solar radiation, and changing environmental conditions can affect the thermal performance and durability of enhancement components.

Material durability is also important. Metallic fins may experience corrosion, while wick and porous materials can accumulate salts and lose their evaporation and capillary performance. Nanofluids may experience sedimentation or agglomeration, whereas PCMs may have limited thermal conductivity.

Economic feasibility presents an additional challenge because advanced enhancement techniques may require specialized materials, fabrication, equipment, and maintenance. Similarly, nanoparticle-based systems require attention to stability, possible release, water quality, and disposal.

Hybrid systems can further increase system complexity and cost [30]. Therefore, improving freshwater productivity while maintaining simplicity, durability, affordability, and safe operation remain a key challenge in solar-still development.

8. CONCLUSION

Heat-transfer enhancement techniques provide effective approaches for improving the performance of solar stills by increasing heat-transfer area, enhancing evaporation, improving thermal transport, storing thermal energy, and promoting condensation. Fins, corrugated absorbers, wick and porous materials, nanofluids, PCMs, cooling methods, and hybrid systems can improve freshwater productivity, although their effectiveness depends on solar-still geometry, water depth, materials, solar radiation, and environmental conditions. Hybrid configurations offer the potential for greater performance through combined enhancement mechanisms, but they also introduce higher cost and complexity. Practical application therefore requires careful consideration of thermal performance, energy consumption, economic feasibility, material durability, and environmental safety. Overall, standardized experimental conditions and integrated thermal, exergy, economic, and environmental evaluation are important for developing reliable and sustainable solar-still desalination systems.

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