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Performance and Exergy Loss Analysis for a Single Slope Solar Still Using PMMA

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Abstract

A solar still constructed using polymethyl methacrylate (PMMA) represents an improved approach to solar desalination, in which conventional materials such as metal or concrete are substituted or reinforced with PMMA- based composites PMMA sheets are often used as the transparent glazing cover of the solar still instead of glass. It allows maximum solar radiation to pass into the basin, heating the saline/brackish water effectively. A tubular solar still made from polymethyl methacrylate (PMMA) composite is a lightweight desalination system that offers a larger condensation surface compared to conventional designs. The single-slope solar still, a basic yet effective water purification device, utilizes solar radiation to evaporate saline or impure water, and subsequently condenses the vapor to obtain fresh, distilled waterIt consists of a shallow basin filled with saline or contaminated water, covered by a transparent sloping Acrylic Polymethyl Methacrylate (PMMA). The system operates on the principle of evaporation and condensation, mimicking the natural water cycle. The experimental reading was conducted in central India (23.24° N and 77.39° E) in the month of June 2024, from 10 a.m. to 5 p.m. The results indicated that the standard single slope solar still achieved an exergy efficiency of 7.4% and an exergy output of 18 W at peak temperature at 10 am at 39.8 ^{0}C temperature.

Keywords: Single slope, solar still, yield, water, exergy

INTRODUCTION

A solar still is an easy-to-use and efficient device that uses sun energy to desalinate and purify water. Enhanced the productivity of an uninsulated FRP (Fibre Reinforced Plastic) solar still by approximately 29.8% by redirecting solar radiation through three sidewalls using lenses and integrating a vertical mirror". Water consumption is essential not only for humans but also for all living things on Earth. There are other methods to get clean water, however solar desalination via a solar still is the most economical option. It works on the basis of the greenhouse effect, which states that when water in a basin is heated by sunlight, it evaporates. After that, pollutants and impurities are left behind when the vapour condenses on a clear cover and is collected as distilled water. [1]

Types of Solar Stills

- *Single-Slope Solar Still*: Features a slanted condensing cover that directs condensed water into a collection channel.[2]
- *Double-Slope Solar Still*: Has two inclined covers, allowing condensation on both surfaces.
- *Multi-Effect Solar Stills*: Enhance efficiency by utilizing multiple stages of evaporation and condensation.
- *Wick-Type Solar Stills*: Use wicking materials to spread water, increasing the evaporation rate.[3]

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Factors Affecting Performance

- *Water Depth*: Shallower water depths improve heat absorption, increasing evaporation and productivity.[4]
- *Solar Radiation Intensity*: Higher solar energy input enhances water heating and distillation rates.[5]
- *Wind Speed*: Affects condensation efficiency by cooling the condensing surface.[6]
- *Ambient Temperature*: Influences both evaporation and condensation processes.[7]
- *Basin and Cover Material*: Materials with high thermal conductivity and transparency improve performance.[8]
- *Use of Reflectors and Mirrors*: Increases heat concentration, leading to improved water yield.[9]

Solar stills are widely used in remote and arid regions for obtaining fresh water, particularly where conventional water purification systems are unavailable.[10]

Recent advancements focus on improving efficiency through design modifications and the integration of external heat sources.[11]

Role of PMMA in Single Slope Solar Still

Transparent Cover Material

- PMMA sheets are often used as the transparent glazing cover of the solar still instead of glass.
- It allows maximum solar radiation to pass into the basin, heating the saline/brackish water effectively.

Thermal Properties

- PMMA has lower thermal conductivity (~0.19 W/m·K) compared to glass (~0.8–1.0 W/m·K).
- This helps in reducing heat loss to the environment, improving evaporation efficiency.

Light Transmission

- PMMA offers excellent optical transmittance (92–95%), which is higher than conventional glass (~90%).
- This enhances solar energy absorption in the basin water, leading to better distillate yield.

Weight and Handling

- PMMA is lightweight compared to glass, making the solar still easier to install, transport, and maintain.

Durability and Safety

- It is impact resistant and does not shatter like glass, improving operational safety.
- However, PMMA may degrade under prolonged UV exposure unless UV-stabilized grades are used.

Condensation Surface

- The sloped PMMA sheet also serves as the condensation surface where water vapor turns into freshwater droplets, which then trickle down into the collection channel.

Advantages of PMMA over Glass in Solar Still

- Higher solar transmittance → more evaporation.
- Lower weight → portable design.
- Good mechanical strength and shatter resistance.
- Lower thermal conductivity → reduced heat losses.

Limitations

- Susceptible to UV degradation (yellowing, brittleness) if not UV-coated.
- Can scratch more easily than glass, affecting optical clarity.
- Slightly higher cost than regular glass.

Computation Finite Element Method

A computational fluid dynamics (CFD) tool for researching, evaluating, and improving FRP composite material tube solar still designs. A great deal of the literature in this field is structured according to the degree of precision of the models used. There are three separate groups into which the methods fall. Various approaches are outlined, together with their underlying assumptions and governing equation. An attractive and ecologically friendly option for providing arid areas with drinkable water is solar stills.[14]

EXPERIMENTAL SET UP

Methodology

The experiment was carried out at the University of Technology and Applied Sciences' Mechanical Section of the Engineering Department in Bhopal, Madhya Pradesh (24.7242° N, 56.4608° E). Figure 1 depicts the arrangement, including standardized solar still system of basin type. The solar still has a single basin that is 100 cm by 100 cm at the base. It is made of galvanised iron sheets and has a glass cover that is angled. Three internal mirrors and one exterior mirror were added to improve the absorption of solar energy. Furthermore, five thermocouples were placed in key locations to measure a range of temperatures.

Measurments

A solar power meter was used to record the experimental setup and monitor the hourly variations in the observed values. Additionally, calibrated 300 ml flasks are used to quantify and evaluate the distillate production rate hourly. The water depth in the basin used for these studies was always 4 cm. About every 30 minutes, salty water is manually supplied to the stills to maintain a constant water level in the basin, which corresponds to the amount of distillate generated. The measurement uncertainty was calculated using the formula given by Kline and McClintock [12]. Table 1 shows the range, accuracy, and uncertainty values.

RESULT AND DISCUSSION

The performance of each of the aforementioned scenarios was compared using hourly measurements of sun intensity, water temperature, air temperature, temperature at different locations of the solar still, and distillate production. This is due to the factors of the surrounding environment having a greater affinity for freshwater generation.

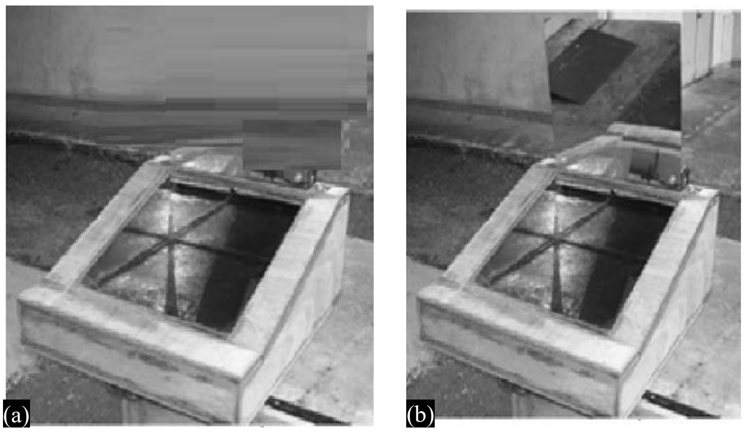

Figure 1. (a) & (b) Experimental set up exiting and modified solar still system of basin type.

Table 1. Type styles accuracy, uncertainty and ranges of applied instruments.[6].

Apparatus used	Range	Accuracy	Uncertainty
Solar intensity Meter (W/m^2)	0-1999	10	5.6
Thermocouple K –type (◦C)	40-420	±1	0.09
Measuring Flask (ml)	0-500	±1	0.61

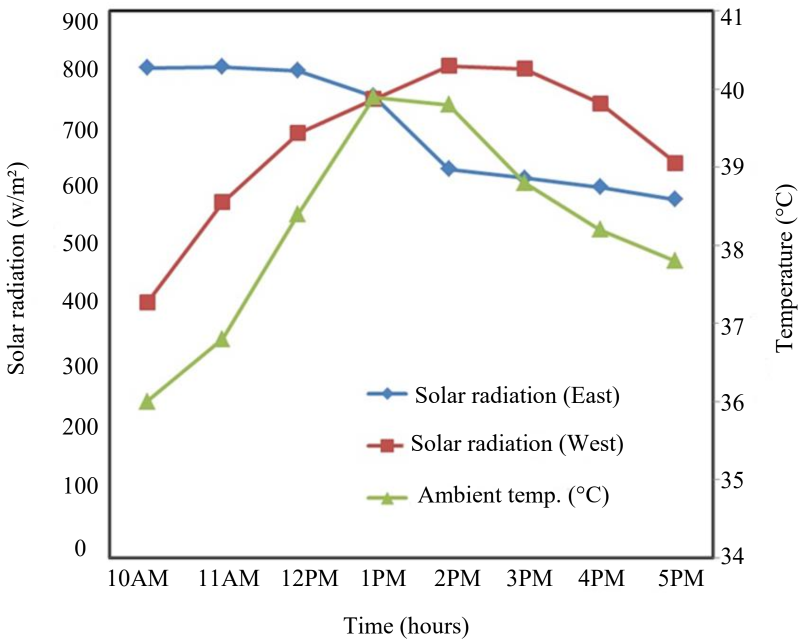

Figure 2. Solar radiation vs ambient temperature with time.

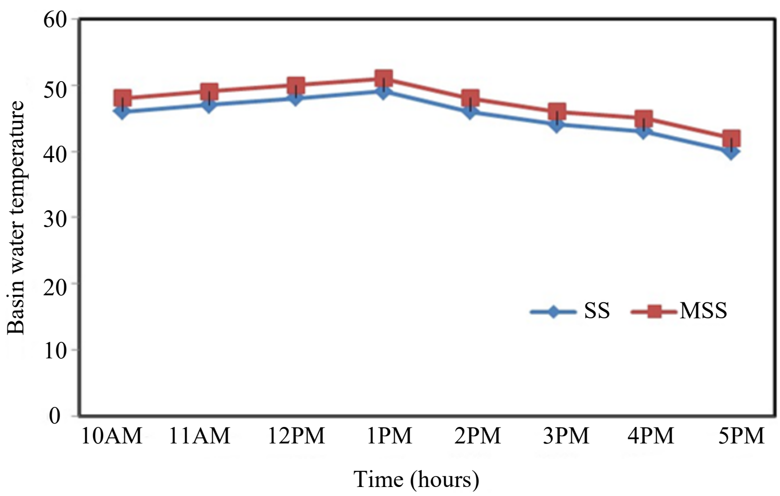

Figure 3. Basin water temperature with time.

This Figure 2 shows a comparison of solar radiation (East and West) and ambient temperature over time during the day (10:00 AM – 5:00 PM).Solar Radiation (East, blue line): Starts high around 850–900 W/m² at 10 AM. Gradually decreases as time progresses, dropping to about 600 W/m² by 5 PM. Indicates strong solar input in the morning hours when facing east. Solar Radiation (West, red line). Starts much lower (~400 W/m² at 10 AM). Increases steadily and peaks around 1–2 PM (~850 W/m²). Gradually declines after 3 PM, reaching ~700 W/m² at 5 PM. Shows maximum solar gain in the afternoon when facing west. Ambient Temperature (green line, right axis): Starts at about 35.5 °C at 10 AM. Increases steadily, peaking at ~40.5 °C around 2 PM. Slowly decreases thereafter to about 38 °C by 5 PM.

This Figure 3 illustrates the variation of basin water temperature (°C) with time (10 AM – 5 PM) for two systems:

- *SS (Single Slope Solar Still):* blue line
- *MSS (Modified Solar Still):* red line

Key Observations:

- At 10 AM, both systems start with nearly the same basin water temperature, around 45 °C.
- As time progresses, the temperature increases steadily in both systems, reaching a peak at 1 PM (~52–54 °C).
- After 1 PM, a gradual decline in basin water temperature is observed in both systems, dropping to about 42–44 °C by 5 PM.
- The MSS (red line) consistently shows slightly higher basin water temperatures (1–2 °C more) than the SS system throughout the day.
- At 10 AM, both systems start with basin temperatures around 40–41 °C.
- Temperatures gradually rise and reach their maximum around 1 PM, with MSS peaking at about 46 °C and SS slightly lower (~44 °C).
- After 1 PM, the basin water temperature decreases gradually in both cases, dropping to about 38–39 °C by 5 PM.
- The MSS consistently maintains higher basin water temperatures (about 1–2 °C more) than SS throughout the operating hours as shown in Figure 4.

Interpretation:

- The modified solar still (MSS) demonstrates better heat absorption and retention, leading to consistently higher basin water temperatures compared to the single slope still.
- The temperature rise corresponds to the increase in solar radiation intensity up to midday, while the subsequent decline is due to reduced solar input in the afternoon.
- The higher water temperature in MSS directly enhances the evaporation rate and distillate yield, confirming the effectiveness of the modifications applied.
- At 10 AM, both SS and MSS start with nearly the same basin temperature (~40–41 °C).
- As solar radiation increases through the day, the basin water temperature rises, reaching its peak around 1 PM:
  - *MSS*: ~46 °C
  - *SS*: ~44 °C
- After 1 PM, basin temperature gradually decreases due to the decline in solar intensity, dropping to about 38–39 °C by 5 PM.
- Throughout the day, MSS consistently maintains slightly higher temperatures (1–2 °C more) than SS as shown in Figure 5.

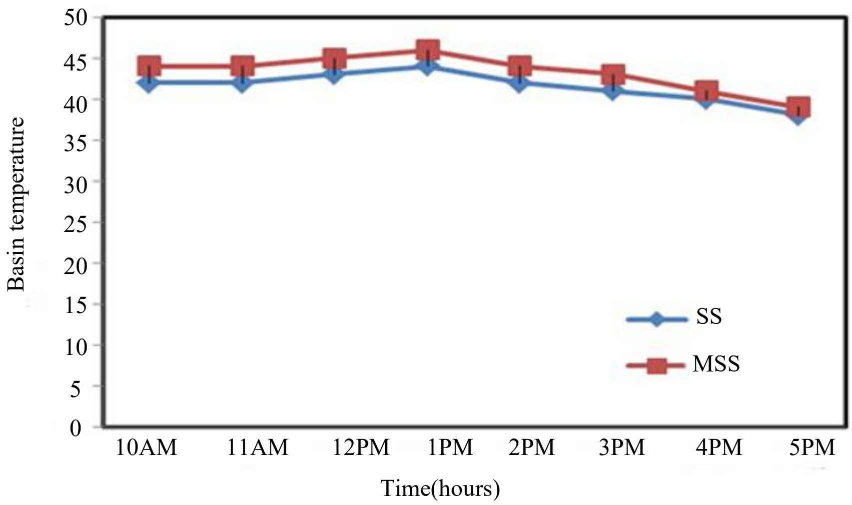

Figure 4. Basin temperature.

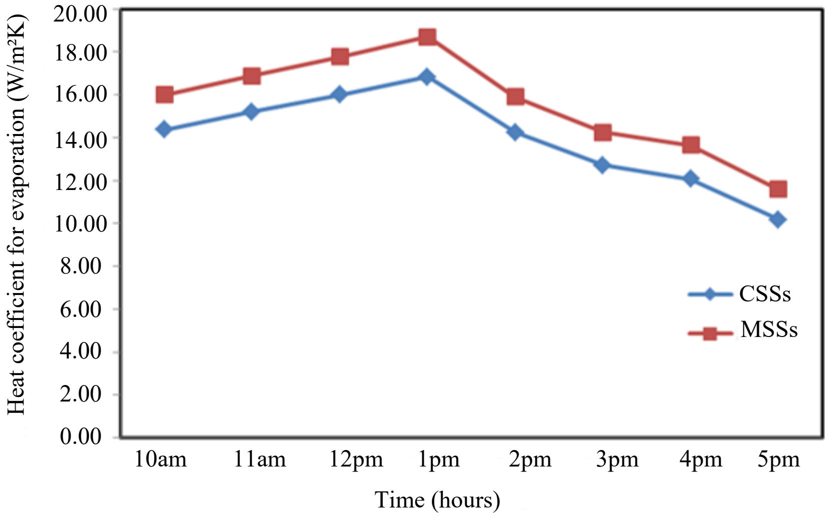

Figure 5. Heat coefficient for evaporation (W/m^{2}K) CTSS and MTSS.

Interpretation:

- The modified solar still (MSS) demonstrates better thermal performance compared to the single slope still.
- The higher basin temperature in MSS indicates improved heat absorption and retention, likely due to design modifications that reduce heat losses or enhance solar energy capture.
- Since the distillate yield of a solar still is directly proportional to basin water temperature, this improvement in MSS suggests higher freshwater productivity.
- The temperature trend (rise till midday, followed by gradual fall) mirrors the solar radiation profile, confirming that basin heating is strongly dependent on solar input.

This Figure 6 illustrates the basin water temperature variation in a Single Slope Solar Still (SS) and a Modified Solar Still (MSS) over the daytime hours (10 AM – 5 PM).

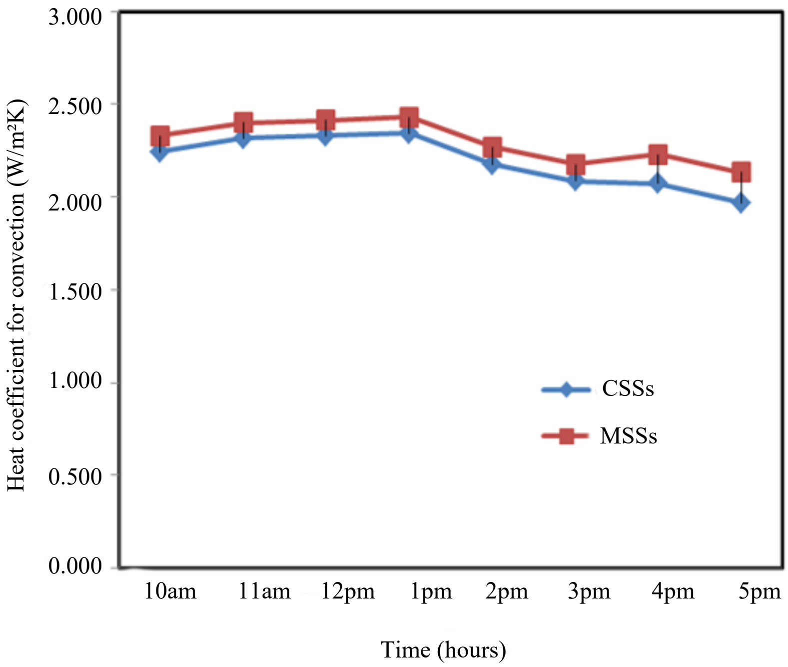

Figure 6. Heat coefficient for convection (W/m^{2}K) CTSS and MTSS.

Observations:

- At 10 AM, both systems show almost the same basin water temperature (~40–41 °C).
- As time progresses, temperatures rise steadily, reaching a maximum around 1 PM:
  - *MSS*: ~46 °C
  - *SS:* ~44 °C
- After 1 PM, a gradual decline is observed in both systems as solar radiation decreases, ending at ~38–39 °C by 5 PM.
- The MSS consistently maintains 1–2 °C higher basin temperature compared to the SS throughout the day.

Interpretation:

- The higher basin temperature in MSS indicates better thermal efficiency, likely due to modifications that enhance solar energy capture and heat retention.
- Since evaporation rate is directly influenced by basin water temperature, the MSS is expected to produce more freshwater yield compared to the SS.
- The trend (rise till early afternoon, then decline) directly follows the solar radiation intensity pattern, showing that basin heating is strongly solar-dependent.

Exergy Efficiency

The following formula may be used to analyse the solar still's daily efficiency and calculate the performance improvement brought about by implementing different changes [13].

$$\eta_{\text{daily,ex.}} = \frac{\sum Ex_{\text{out}}}{\sum Ex_{\text{in}}} \times 100\ (\%)$$

$$Ex_{\text{out}} = h_{e,w-g} \times A_s \times (T_w - T_g) \times \left(1 - \frac{T_a}{T_w}\right)$$

$$E_{x_{in}} = A_s \times I(t)\left[1 - \frac{4}{3}\left(\frac{T_a + 273.15}{6000}\right) + \frac{1}{3}\left(\frac{T_a + 273.15}{6000}\right)^4\right] \quad (2)$$

Implementation of a single slope solar still without a reflector and a modified single slope solar still with a reflector. The most crucial factors in choosing the new geometry for the present project were accessibility, cost, sunlight resistance, transparency, and outdoor environment suitability. This work used glass material for MSSs as SSs and MSSs coverings. Two distinct SSs setups were used for the studies, both with similar results, but one alternative geometry—such as reflector glass—was used to raise the water temperature within the basin. The following conclusions may be drawn from the study. At a water depth of 4 cm, the daily exergy efficiency of SSs and MSSs increased by 7.4% and 5.2%, respectively as shown in Figure 7.

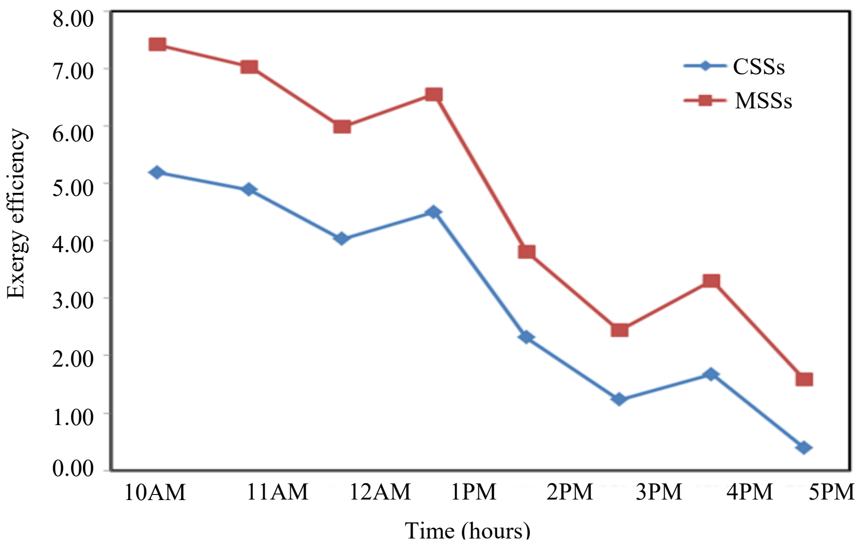

Figure 7. Exergy efficiency with time.

RESULTS & DISCUSSION

The thermal performance of solar stills is strongly influenced by the heat transfer processes occurring at the water surface, namely convection, evaporation, and radiation. In the present study, the heat transfer coefficient for convection in the single slope solar still (SS) and modified solar still (MSS) was found to be approximately 2.3 and 2.4 W/m^2K, respectively. This slight improvement in the MSS highlights the effectiveness of the modifications in enhancing heat exchange between the basin water and the cover surface. A higher convection coefficient implies that the thermal energy absorbed by the water is more efficiently transferred to the inner surface of the glass cover, where condensation of the evaporated vapor occurs. Consequently, this results in a marginal but consistent enhancement in freshwater productivity for the MSS compared to the SS.

On the other hand, the heat transfer coefficient for evaporation was observed to be around 18 W/m^2K for the SS and 16.2 W/m^2K for the MSS. This indicates that, although the modified design improves convection, the effective rate of evaporative heat transfer is slightly lower compared to the conventional still. This reduction could be attributed to design adjustments that limit excessive evaporation losses while maintaining higher basin water temperatures. Evaporation remains the dominant mode of heat transfer in solar stills, as it is directly responsible for the conversion of liquid water into vapor. Hence, even small variations in this coefficient can have a noticeable impact on overall yield.

These findings must be interpreted within the broader context of seasonal variations and water demand. Seasonal conditions have a significant effect on both solar intensity and ambient temperature, which directly influence the performance of solar stills. During the summer months, higher solar radiation leads to increased basin water temperatures, higher convection coefficients, and enhanced evaporation rates. This results in greater freshwater output from solar stills. Conversely, during the winter season, reduced solar insolation and lower ambient temperatures cause a decline in thermal performance, leading to reduced water productivity.

Seasonal water requirements also play a decisive role in shaping desalination strategies. In many regions, water demand rises sharply in the summer due to agricultural irrigation needs, increased drinking water consumption, and greater requirements for cooling purposes. For instance, rural and semi-arid communities rely heavily on freshwater for crop irrigation during prolonged hot and dry periods. Similarly, urban populations demand more water for domestic and industrial cooling applications. To meet this surge, desalination facilities—whether based on solar stills, reverse osmosis, or multi-stage flash distillation—typically increase their output during summer months. In contrast, the demand in cooler seasons is comparatively lower, which can lead to scaled-down operations or reduced freshwater production.

Understanding the interplay between seasonal elements and desalination plant operations is therefore crucial. Solar stills, with their direct dependence on solar energy, naturally exhibit higher productivity during peak summer, aligning well with the increased demand. Larger commercial desalination facilities often employ operational modifications such as adjusting throughput, increasing plant load, or integrating with thermal energy storage systems to ensure a consistent supply of freshwater year-round. By correlating seasonal solar radiation patterns, ambient temperature variations, and user demand, operators can optimize plant efficiency and resource allocation.

In conclusion, the measured heat transfer coefficients for convection and evaporation in SS and MSS systems provide valuable insight into the mechanisms governing freshwater output. While the MSS shows slightly higher convective heat transfer, the SS demonstrates a marginally higher evaporative coefficient. When viewed against the backdrop of seasonal water demand and desalination strategies, these results emphasize the importance of tailoring operational practices to both environmental conditions and societal needs. Seasonal optimization not only enhances freshwater productivity but also ensures sustainable management of limited natural water resources.

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CONCLUSIONS

The heat coefficient for convection (W/m^2K) SSs and MSSs were found to be around 2.3 and 2.4 (W/m^2K), respectively. heat coefficient for evaporation (W/m^2K) for SSs and MSSs are around 18 and 16.2 (W/m^2K) , respectively, according to the results. seasonal conditions result in increased water use for cooling, irrigation, and drinking. Additionally, desalination facilities boost output in the summer to fulfil the increased demand in areas with limited natural freshwater supplies. It would be easier to understand the relationship between seasonal elements and desalination plant operating modifications if this background were explained.

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