Performance Assessment of an Integrated Solar-Driven Direct Spray Evaporator for Artificial Seawater Desalination

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Abstract. An integrated solar-driven desalination system was developed to address increasing clean water demand using renewable energy for artificial seawater treatment. This study aimed to evaluate the performance of a combined evacuated tube heat pipe solar collector (ETHP-SC) and direct spray evaporator in terms of thermal behavior, distilled water productivity, and water quality improvement under outdoor conditions. Artificial seawater from NaCl, $MgCl_2$, and potting soil extract was circulated through an ETHP-SC-plate heat exchanger and sprayed into a vacuum evaporator, with vapor condensed in water-cooled condenser during 8-hour daytime tests in September 2025. The ETHP-SC showed increasing instantaneous thermal efficiency from about 10–20% in the morning to around 60–80% when solar irradiance declined in the afternoon, while average distilled water production reached about 0.91 L/m².h and was strongly governed by solar radiation and system temperature profiles. Distilled water exhibited substantial reductions in conductivity, TDS, and salinity compared with feedwater and brine, although TDS still exceeded drinking water limits and DOC removal remained limited due to volatilization and material leaching. The integrated ETHP-SC-direct spray evaporator effectively harnesses solar energy for desalination but requires further optimization or post-treatment to achieve potable water standard and enhanced organic removal.
Keywords: evacuated tube heat pipe solar collector, direct spray evaporator, distilled water.

1 Introduction

In response to the ongoing expansion of the global population and industrial sectors, the requirement for clean water has become a matter of critical global importance. The United Nations World Water Development Report 2023 projects that by 2050, the global demand

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for clean water will increase by approximately 30–50% [1]. Among the various approaches to mitigating water scarcity, desalination technology has undergone remarkable growth, primarily driven by the reduction in the cost of freshwater production. In particular, seawater desalination has proven to be a reliable and efficient method to overcome this challenge, supported by significant research and development advancements in recent years. Continuous technological progress has notably decreased the unit cost of freshwater production. Moreover, the implementation of discharge regulations concerning concentrated brine generated from seawater desalination has further encouraged the development of high-efficiency and high-salinity desalination processes [2].

Various desalination technologies have been implemented to produce potable freshwater from seawater, including commonly utilized methods such as reverse osmosis, electrodialysis, freezing, and multi-stage flash distillation. Although these approaches are generally efficient and reliable, they depend on auxiliary systems and secondary energy inputs-typically thermal or electrical energy largely sourced from fossil fuels or other non-renewable resources. Conversely, solar energy has gained substantial attention as a promising alternative owing to its renewable nature and environmental sustainability, providing an effective means to meet the increasing global demand for low-carbon energy solutions [3]. In recent decades, a wide range of desalination technologies integrated with solar energy systems have been developed [4]. In this study, an evacuated tube heat pipe solar collector (ETHP-SC) was employed as the solar energy harnessing unit, offering superior efficiency compared to conventional solar collectors. The ETHP-SC represents an advanced solar desalination configuration that enhances the performance of conventional systems through efficient heat transfer via thermal conductivity between the solar collector and the water, resulting in an increased water temperature [5].

The direct-contact spray-assisted evaporation and condensation (DCSEC) approach offers significant potential for overcoming operational challenges commonly encountered in conventional desalination systems. As a tubeless configuration within the vessels, this method employs the direct spraying of externally heated seawater, typically up to 65 °C at the top-brine stage, which provides two major advantages. First, it substantially lowers the initial design and construction costs of the evaporator and condenser units; in terms of production capacity, the capital expenditure (CAPEX) can be reduced to below US $700 per cubic meter of distilled water per day. Second, spraying brine into an empty chamber at each stage minimizes scale formation since dry surfaces are virtually eliminated within the chambers [6].

This study aims to develop an innovative seawater desalination technology that integrates an evacuated tube heat pipe solar collector with a direct spray evaporator. The proposed integration is expected to enhance the production of distilled water in terms of both quantity and quality, while effectively utilizing solar energy as renewable source to increase the feedwater temperature during the seawater desalination distillation process.

2 Methodology

In this study, the integration of the evacuated tube heat pipe solar collector (ETHP-SC) and the direct spray evaporator was conducted using artificial seawater as the feedwater. The artificial seawater was prepared by mixing inorganic salts with a potting soil solution, which serves as a representative source of the organic constituents typically present in natural seawater. The operating conditions in this study were carried out at feed water flow rate of 0.6 L/min, vacuum pressure of -0.8 bar, and average cooling water temperature of 30 ℃. These operating conditions were determined based on laboratory-scale direct spray evaporator testing using heater as the heat source.

2.1 Artificial seawater

Seawater contains a large amount of organic matter and ions, resulting in high salinity. Besides salt, seawater also contains organic substances. In this study, artificial seawater was prepared by mixing 85% NaCl (35,000 mg/L), 15% $MgCl_2$ (35,000 mg/L), and a potting soil solution (19 mg/L) (representing the organic substances content of seawater). The potting soil extract was a mixture of 3.75 kg of Alitura Organics Premium Potting Soil, and further diluted with 14.5 L of warm tap water at 60°C and 0.5 L of 30% sodium hydroxide (NaOH) solution. The entire mixture was left in a sealed/tight container overnight. Two filter bags (1 = 800 μm; 2 = 100 μm) were used sequentially for this purpose [7].

2.2 Experimental setup

Fig. 1 depicts a desalination setup employing evacuated tube heat pipe solar collector and direct spray evaporator. In the initial phase of the study, environmental conditions were measured at a weather station, including solar radiation intensity, ambient air temperature, wind speed, and relative humidity. Solar radiation was captured by the solar collector to increase the temperature of the water in the solar collector tank. This tank was connected to a plate heat exchanger (PHE). The hot water from the solar collector tank then came into contact with the feedwater from the feedwater tank inside the PHE. The feedwater in the feedwater tank was channelled to the PHE and then recirculated to the water tank via a pump. The heated feedwater was then pumped to the direct spray evaporator and sprayed into the evaporator. The evaporator was vacuum-cooled to accelerate the evaporation process. Vapor entered the condenser, where condensation occurred, forming distilled water. Cooling water from the Circulating Thermostatic Bath (CTB) entered the condenser coil to support the condensation process in the condenser. Meanwhile, the brine was recirculated to the feedwater tank. The resulting condensate (distilled water) was then measured for quantity and quality. The feedwater and brine were then measured for quality. Temperature measurements were taken using National Instruments (NI). Testing of the distilled water quantity and temperature was carried out for 8 hours, from 8:00 to 16:00 in September 2025.

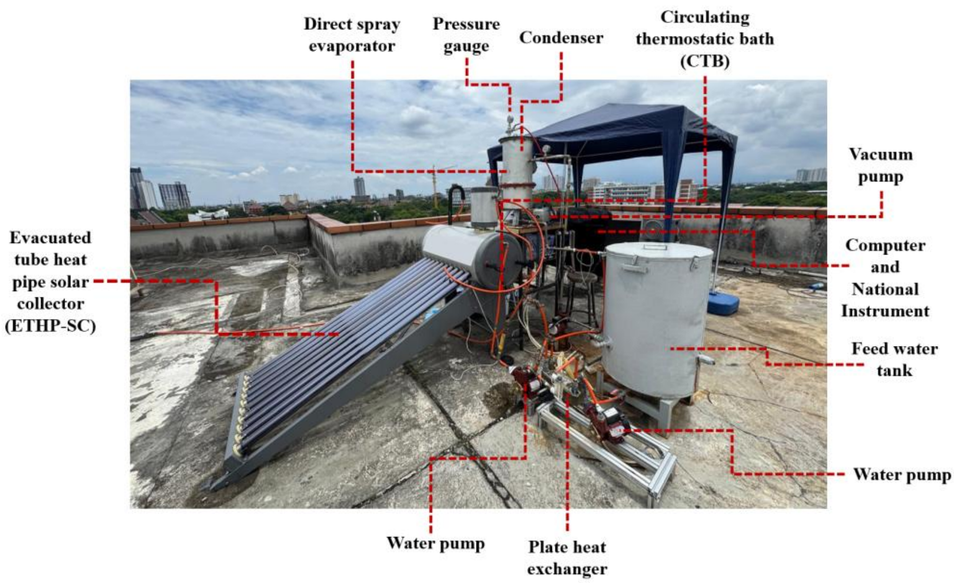


Fig. 1. Desalination equipment configuration: ETHP-SC, PHE, water tank, direct spray evaporator, and condenser.

The instantaneous thermal efficiency of an evacuated tube heat pipe solar collector is usually defined as [8]:

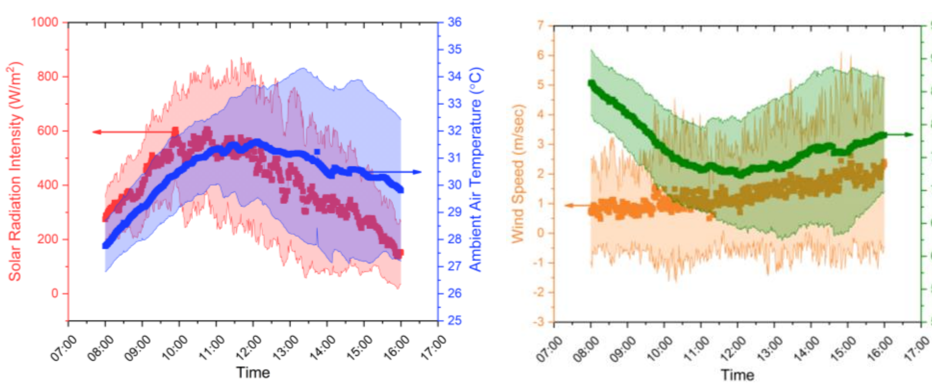
$$\eta_{ETHP-SC} = \frac{\dot{m}C_p(T_{out}-T_{in})}{G.A_c} \times 100\% \qquad (1)$$

where $\dot{m}$ is fluid mass rate (kg/s), C_p is specific heat capacity of fluid $(J/kg.°C)$, T_{out} and T_{in} are inlet and outlet temperature (°C), G is solar radiation intensity (W/m^2), A_c is collector are (m^2).

3 Results and discussion

3.1 Climate conditions

Fig. 2 illustrates the testing of solar radiation intensity, ambient air temperature, wind speed, and average relative humidity conducted for 8 hours, which is from 08.00-16.00. This environmental condition data collection was in September 2025. The intensity of solar radiation, shown in red, increases sharply after 8:00 AM, reaching a peak around midday between 11:00 AM and 12:00 PM with maximum values approaching 700–800 W/m². After reaching its peak, the intensity steadily decreased towards the afternoon, reflecting the movement of the sun and the clear sky conditions that were common during the measurement period. Maximum ambient air temperatures were recorded between 13:00 and 14:00, generally reaching around 33–34°C, and then gradually decreasing towards evening. Wind speeds started at moderate levels in the morning, generally around 1–2 m/s, then after midday, wind speeds tend to increase again with more fluctuations, reaching higher values of 5–6 m/s. Relative humidity started at a high value (around 93%) in the morning and decreases steadily towards the afternoon (around 83%), reaching its lowest point around midday when solar heating was at its strongest. After this low point, relative humidity gradually rised again, as afternoon cooling encouraged moisture retention in the air [9].



(a) (b)

Fig. 2. (a) Average solar radiation intensity and ambient air temperature and (b) wind speed and relative humidity for September 2025.

3.2 ETHP-SC efficiency

From Fig. 3, it can be seen that the intensity of solar radiation increased from morning until near midday and then decreased again, while the collector efficiency increased from morning, was relatively stable around midday, and tend to increase sharply again towards the end of the observation when the radiation had decreased. The irradiance curve peaks around midday (≈500–800 W/m²) and then decreases, while the efficiency of ETHP-SC increased slowly from around 10–20% in the morning to around 40–60% in the afternoon when solar radiation reached its peak, then increased steadily to around 60–80% in the afternoon when radiation began to decrease.

When radiation increased from morning to afternoon, the absorber in the tube absorbed more energy, the fluid in the heat pipe evaporated more, and the rate of heat transfer to the manifold increased, so that $m.C_p.(T_{out} - T_{in})$ increased and the efficiency increased from the range of 10–20% to 40–60% (see Fig. 3). At very high radiation (midday), the surface temperature of the absorber and the heat pipe condenser increased, so that the temperature difference with the ambient air increased and the heat radiation/convection losses on the outside of the tube and from the manifold to the environment increased [10].

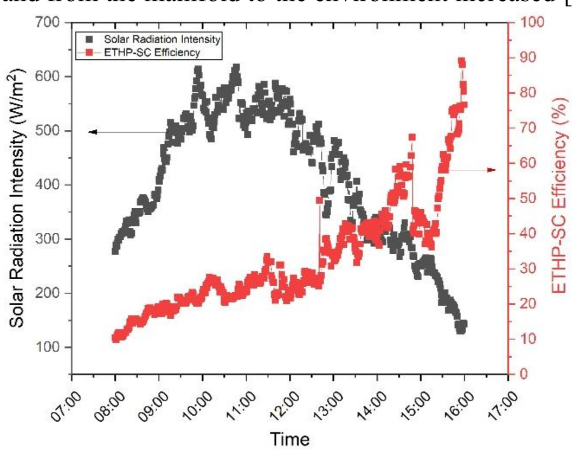


Fig. 3. (a) Average solar radiation testing of solar radiation intensity and efficiency of ETHP-SC average for 8 hours with direct spray evaporator : September 2025.

3.3 Temperature profile

Fig. 4 shows temperature profiles at various points in the desalination system, measured from 8:00 AM to 4:00 PM. Each curve represents a different stream: feedwater (T_1), water vapor (T_2), brine (T_3), cooling water inlet (T_4), and cooling water outlet (T_5). These data reveal how heat is transferred during the process, which is a critical aspect of desalination system performance. Feedwater and brine temperatures increased gradually in the morning, peaking around noon, and then stabilized with some fluctuations. Water vapor temperatures remained consistently higher than feedwater and brine, indicating an efficient heat supply for evaporation [11]. Cooling water inlet and outlet temperatures were lower than the other streams but showed a steady increase, reflecting heat absorption during condensation. Heat transfer in desalination depends on maintaining a temperature difference between streams (e.g., water vapor and brine, brine and cooling water).

3.4 Distilled water production

During the test period (Fig.5), the measured distilled water production ranged from 0.34 to 1.63 L/m²·h. The average distilled water volume was approximately 0.92 L/m²·h. The highest productivity, 1.63 L/m²·h, was observed on September 22, 2025 (day 13), likely reflecting optimal solar conditions or operational parameters, while the lowest value, 0.34 L/m²·h, occurred on September 8, 2025 (day 4), likely during less favorable weather or reduced sunlight.

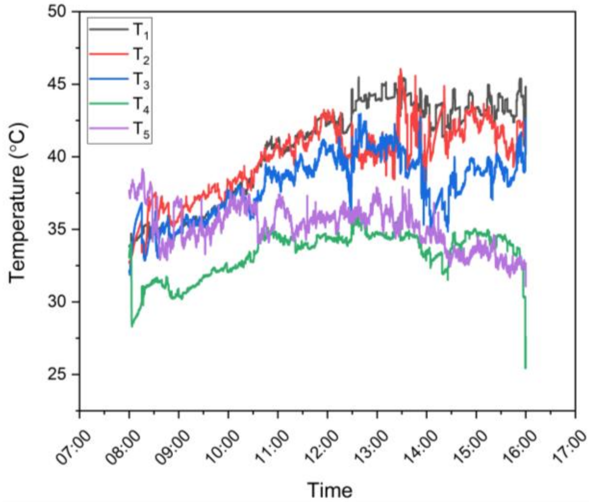


Fig. 4. Temperature profile at five temperature measurement points on September 2-29, 2025.

Daily fluctuations in distilled water volume indicate that system performance is significantly influenced by the intensity of sunlight captured by the ETHP-SC each day. Solar radiation directly determines the temperature inside the desalination system, which in turn determines the evaporation and condensation rates essential for producing distilled water. As with other solar-thermal desalination technologies reported in the literature, this dependence on weather and sunlight can lead to significant variability in water production. Siregar *et al.* [12] showed that solar still performance is not only highly sensitive to solar intensity, but that the highest distilled water yields coincide with peak radiation hours. They also noted that the efficiency of the desalination system is fundamentally related to the solar energy available at any given time. Another relevant study by [13] simulated the impact of solar intensity on freshwater productivity, and reported that production rates consistently followed changes in solar radiation. These data highlight the importance of optimizing collector design, system orientation, and operational time to maximize distilled water volume, especially in locations with varying climate patterns.

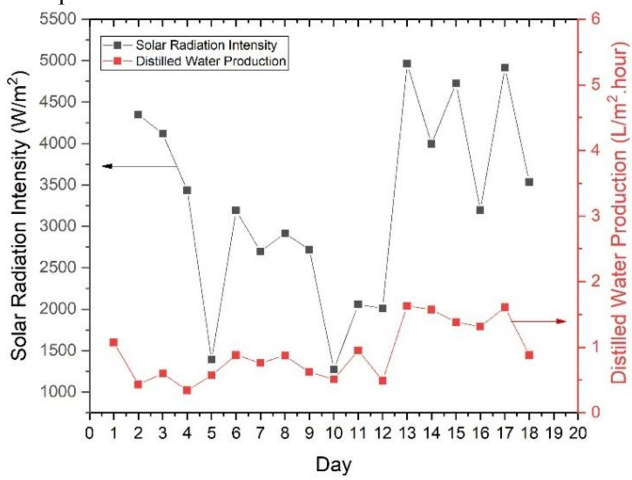


Fig. 5. Solar radiation intensity testing and distilled water production on ETHP-SC and direct spray evaporator September 2025.

3.5 Feed water, distilled water, and brine quality

Table 1 presents a comparative analysis of water quality parameters from a desalination system combining ETHP-SC and a direct spray evaporator. From the results of desalination processing, average distilled water quantity of 0.91 L/m^2.hour was obtained for 7333 minutes. The pH parameter in the distilled water was within the standard range of clean and drinking water quality. The conductivity, TDS, and salinity parameters of the distilled water experienced a significant decrease compared to feedwater and brine, but the TDS parameter of the distilled water produced did not meet the quality standards of clean and drinking water.

In this desalination system, the DOC concentration of distilled water decreased only slightly compared to the feedwater and brine is likely attributed to several concurrent mechanisms. First, volatile and low-molecular-weight organic substances can be transferred with the water vapor phase and thus pass into the distilled water, even when salt rejection remains high, as reported in studies on thermal-based desalination processes. Second, leaching of organic matter from construction materials in contact with the distilled water, such as polymers, sealants, or coatings, may increase DOC levels because low-ionic-strength distilled water readily dissolves organic residues from surfaces [14].

Table 1. Feed water, distilled water, and brine quality.

Parameter	Unit	Clean water quality standard*	Drinking water quality standard**	Feed water	Distilled water	Brine
Average quantity	L/m^2.h	-	-	-	±0.91	-
Total test time	minutes	-	-	-	7333	-
pH	-	6.5−8.5	6.5-8.5	7.05−7.71	6.91−7.34	7.21−7.71
Conductivity	μS/cm	-	-	39,100−42,100	2400−7300	39,600−41,700
Total dissolved solid (TDS)	mg/L	1000	<300 g/L	19,500−21,100	1280−2480	19,700−20,800
Salinity	mg/L	-	-	22,700−25,700	1200−3690	24,100−25,300
Dissolved organic carbon (DOC)	mg/L	10 ($KMnO_4$ organic)	-	4.95−6.32	4.82−5.00	5.01−5.95

* Minister of Health Regulation Number 32 of 2017 concerning Environmental Health Quality Standards for Water for Hygiene and Sanitation Purposes
**Minister of Health Regulation Number 2 of 2023 concerning Drinking Water Quality Requirements

4 Conclusion

The integrated desalination system combining evacuated tube heat pipe solar collector (ETHP-SC) and a direct spray evaporator demonstrated promising performance for artificial seawater treatment under outdoor conditions, achieving an average distilled water productivity of about 0.91–0.92 L/m^2.h during 8-hour operation (08:00–16:00) with a cumulative operating time of 7333 minutes over multiple days (18 days) in September 2025. Daily distilled water production varied between 0.34 and 1.63 L/m^2.h, indicating a strong sensitivity of freshwater yield to day-to-day fluctuations in solar radiation and the resulting temperature profiles within the collector, evaporator, and condenser. The ETHP-SC exhibited increasing instantaneous thermal efficiency from about 10–20% in the morning to around 40–60% near midday, and up to approximately 60–80% in the afternoon as irradiance decreased, demonstrating effective heat utilization under varying climatic conditions and confirming the central role of solar input in governing evaporation–condensation rates. Water quality analysis showed substantial reductions in conductivity, total dissolved solids, and salinity in the distilled water relative to feedwater and brine, with pH remaining within the range of clean and drinking water standards ; however, TDS still exceeded potable limits and dissolved organic carbon removal was limited due to volatile organic carryover and possible leaching from construction materials. Overall, the system effectively harnesses solar energy for desalination but requires further optimization and post-treatment to fully meet drinking water quality requirements.

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