Enhancing of Thermal performance of Solar-Powered RO Desalination system using Nanofluids

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Abstract

This study investigates the enhancement of heat transfer and energy efficiency in a solar-powered reverse osmosis (RO) desalination system through the use of SiO_2–water nanofluids as the heat transfer medium. Using concentrations ranging from 0.5% to 3% by volume, SiO_2–water nanofluids were produced with nanoparticle sizes of 12–16 nm. Heat transfer efficiency at 1% concentration showed up to a 22% improvement over conventional water by experimental testing under flow rates of 10–20 L/h and solar irradiation levels from 500 to 1000 W/m². More stable feedwater temperatures within the ideal membrane operating range of 25–30 °C made possible by this improvement helped lower water viscosity by 35%, lower pumping power, and boost permeate output. From 06:00 to 18:30, thermal energy from both water and nanofluids was either sufficient or exceeded according to hourly simulation results. However, lacking solar input, the system failed to satisfy the thermal demand following sunset (19:00–23:00). The collector thermal efficiency increased by up to 22% at 1% nanofluid concentration, with outlet temperature rising by 12–15°C compared to water. Integration of heat accumulators highlights the importance of use of accumulators such kind thermal systems. These findings demonstrate the potential of nanofluid-assisted solar desalination systems for sustainable freshwater production in arid regions.

Keywords: solar desalination system, reverse osmosis, nanofluids, solar thermal collectors, nanofluid

1. Introduction

Freshwater scarcity is emerging as one of the most pressing global challenges of the 21st century (UNESCO, 2024) Although water is the most widespread substance on the Earth's surface, approximately 96.5% of the Earth's total water volume is saline (U.S. Geological Survey, 2023), and less than 1% is readily available freshwater suitable for human use (Kundzewicz et al., 2008; Gleick et al., 2022). As of 2025, global freshwater consumption continues to rise at an average annual rate of 1%, with 2.2 billion people lacking access to safe drinking water and 4 billion experiencing water shortages at least one month per year. Projections suggest that by 2030, two-thirds of the global population may face water stress, especially in arid regions. Desalination has become a strategic solution for freshwater supply, particularly in water-scarce regions. According to (UNU-INWE, 2024), as of 2024, around 16,000 desalination plants operate across 177 countries, collectively producing approximately 95 million m³ of clean water per day. Among various desalination technologies, RO remains the most widely adopted due to its modularity, scalability, and relatively low specific energy consumption. A growing body of research focuses on integrating RO systems with solar photovoltaic (PV) and thermal technologies to enhance sustainability. A substantial body of research highlights the wide applicability of solar-powered RO systems across various scales. (Zeyad et al., 2022; Al-Obaidi et al., 2022) have illustrated the integration of solar photovoltaic technologies with RO units, ranging from small-scale, off-grid systems in rural areas to large-scale industrial desalination plants. Their work presents multiple system configurations utilizing renewable energy sources (RES), either independently or as part of hybrid systems. Collectively, these findings underscore the adaptability and scalability of PV-RO desalination technologies, particularly when tailored to local environmental and infrastructure conditions. Particular attention is given to low-power solar-powered reverse osmosis systems, which are considered among the most promising solutions for ensuring water security in rural areas of Central Asia, particularly in Uzbekistan. According to the Atlantic Council (2025), approximately 80% of Uzbekistan's water resources originate from neighboring countries, primarily Tajikistan and Kyrgyzstan, making the country highly vulnerable to regional water policy changes. Due to the deterioration of infrastructure built during the Soviet period, up to 30% of water supply networks operate intermittently, and in some rural settlements, newly installed pipelines remain nonfunctional (World Bank, 2024). Official estimates suggest that, without substantial improvements,

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Uzbekistan's water deficit may reach 15–25% by 2050, while the area of desertified land is projected to expand significantly, posing serious threats to the nation's food and social security. With a population exceeding 38 million (as of 2025), the deployment of autonomous, energy-independent solar desalination systems represents a strategically important pathway for climate adaptation and the strengthening of regional water resilience. The country's annual precipitation is only 206 mm, and 52 km³ of water is withdrawn annually—90% of which is used for agriculture, often with 50% transport losses. Moreover, climate change has intensified glacial retreat in river basins such as the Pskem, Kashkadarya, and Surkhandarya, with ice coverage shrinking by 24–70% over the past 50 years. Projections suggest a 5–15% decrease in the Amudarya and Syrdarya river flows by mid-century (UNECE, 2024). Akhatov et al. (2020) have shown that optimizing feedwater temperature in solar-powered reverse osmosis systems significantly reduces specific energy consumption— from 2.1 kWh/m³ to 1.65 kWh/m³—and increases permeate flow rate, particularly when operating within the optimal membrane temperature range of 25–30°C. This performance improvement is achieved through the integration of solar thermal energy, as illustrated in Figure 1, which shows the schematic configuration of a hybrid photovoltaic–thermal RO desalination system with a closed-loop collector and temperature-controlled membrane unit.

It should be noted that the foundations of effective solar thermal energy utilization for water desalination were established in earlier research by Mahkamov et al. (2008), conducted at Durham University and the Physicotechnical Institute of the Academy of Sciences of Uzbekistan. That study proposed a multistage evaporation–condensation system employing latent heat recovery and partial thermal insulation, which resulted in a twofold increase in distillate productivity compared with conventional greenhouse-type solar stills. These findings provided an important theoretical and experimental basis for the advancement of modern hybrid and nanofluid-assisted solar RO desalination systems investigated in the present work. This work extends previous research by Akhatov et al. (2020) by experimentally validating the thermal enhancement of SiO_2–water nanofluids in a solar-powered RO desalination system. Wole-Osho et al. (2020) have shown that the comparative performance of different nanomaterials used in solar thermal collectors varies significantly depending on their thermophysical properties and concentration. In their comprehensive review, the use of SiO_2–water nanofluids demonstrated thermal efficiency enhancements consistent with our measurements—up to 22% at 1.0 vol%, with concomitant outlet temperature gains of 12–15 °C, while only modestly affecting nanofluid viscosity, thus limiting pumping penalties. In contrast, Al_2O_3–water typically yields 28–33% heat-transfer gains but with 12–20% viscosity increase; CuO–water achieves up to 35% gains with viscosity rises >25% and higher density (6.3 g cm^{-3}). TiO_2–water often provides 20–30% improvements at 0.5–1.5 vol%, though long-term colloidal stability can be limiting. CNT-based nanofluids deliver the highest boosts (40–45%), yet cost and dispersion challenges hinder scale-up. Overall, SiO_2–water offers the best balance of performance, stability and operational safety for solar-thermal desalination and collector applications. The main objective is to quantify the improvement in collector efficiency, outlet temperature, and feedwater thermal stability under simulated solar conditions.

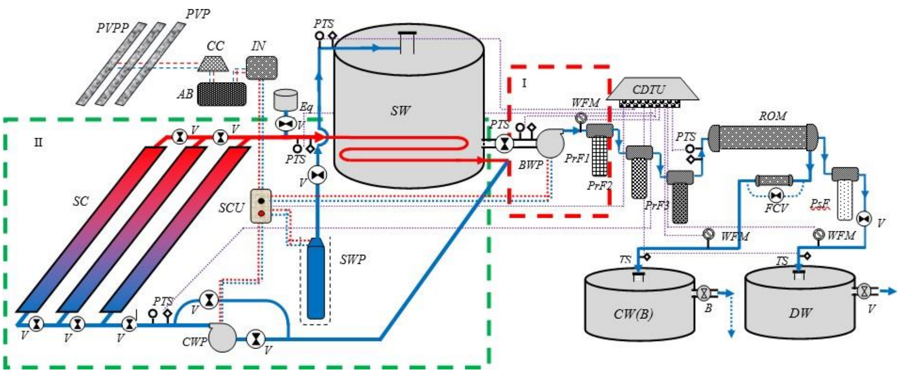

Fig. 1: Schematic diagram of solar water desalination plant based on reverse osmosis with the use of solar photovoltaic and thermal converters : PVPP–photovoltaic power plant; PVP–photovoltaic panel; CC–charge controller; IN–inverter; AB–accumulator battery; SCU–switch-and-counter unit; CWP–circulation water pump; BWP–booster water pump; SWP–submersible water pump; SC–solar collector; V–valve; Eq–equalizer; SW–source (feed) water; DW–desalinated water; PrF–prefilter; PsF–postfilter; ROM–reverse osmosis membrane; PTS–pressure and temperature sensors; WFM–water flowmeter; CDTU–controlling and data transfer unit; FCV—flow control valve; TS—temperature sensor; I - Former study (Akhatov. Et.al, 2020), II - Present study.

2. Methodology

Enhancement of the thermal performance of a solar-driven reverse osmosis desalination system by replacing conventional water with nanofluid in the closed-loop solar thermal circuit is crucial for achieving higher energy efficiency and stable membrane operation. In this study, SiO_2–water nanofluids were employed as the heat transfer medium in flat-plate solar collectors to improve solar energy absorption and thermal conductivity.

2.1. Experimental Setup and Nanofluid Preparation.

The experimental investigation was carried out to validate the thermal behavior of SiO_2–water nanofluids and evaluate their potential for improving heat transfer in solar-assisted desalination systems. The experimental setup consisted of a flat-plate solar collector simulator (area = 10 m²), a stainless-steel pipe-in-pipe heat exchanger (inner pipe Ø = 12 mm, outer pipe Ø = 25 mm, length = 2 m), a calibrated flowmeter (accuracy ±0.5%), and Type-K thermocouples (accuracy ±0.1°C). The nanofluids were prepared using the two-step method, where commercially available SiO_2 nanoparticles (average diameter 12–16 nm) were dispersed into deionized water at volume concentrations ranging from 0.5% to 3%. To enhance dispersion stability, the mixtures were subjected to 30 min of ultrasonic agitation without surfactants. Visual sedimentation observation and zeta potential measurements confirmed satisfactory colloidal stability prior to testing. The experimental setup consisted of a pipe-in-pipe counter-flow heat exchanger connected to a flat-plate solar collector simulator, designed to reproduce solar heating conditions under forced convection. The inner pipe carried the nanofluid, while the outer jacket circulated cooling water to mimic the saline feed loop. Thermocouples with ±0.1 °C accuracy were installed at inlet and outlet positions, and a flow meter monitored the volumetric flow rate, which was varied between 10, 15, and 20 L/h.

To conduct the simulation, meteorological data from a typical measured day in the Uzbekistan region were employed. Based on these observations, solar irradiance ranged from 200 to 1000 W/m², while the ambient temperature peaked at approximately 40 °C, as illustrated in Figure 2.

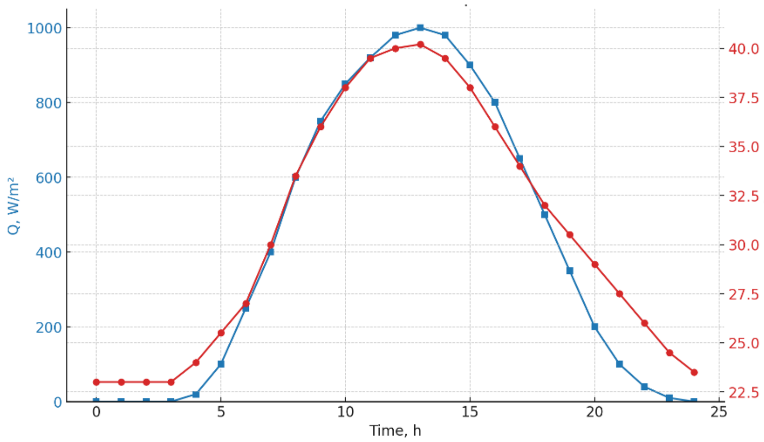

Fig. 2. A change in solar irradiation density and ambient temperature

The collector and heat exchanger efficiencies were determined based on measured temperature differences and flow rates. Experimentally obtained thermophysical properties—namely, density, viscosity, and thermal conductivity—were incorporated into the simulation model described below.

2.2. Thermal Modeling and Simulation

Building upon the experimental results, a dynamic thermal model was developed to simulate the transient performance of a solar-assisted RO desalination system. The model represents a closed-loop solar thermal circuit, where the heat transfer fluid (HTF) nanofluid—circulates through a flat-plate solar collector and transfers heat to saline feedwater via a heat exchanger. The objective of this model is to evaluate hourly variations in useful thermal energy gain, outlet fluid temperature, and heat delivery to the RO feedwater during typical summer conditions in Central Asia. Hourly solar irradiance and ambient temperature data (from 06:00 to 23:00) were used as input. The governing equations were formulated based on energy balance relations for the collector and heat exchanger components.

1.Useful Thermal Energy Collected

The useful thermal energy absorbed by the solar collector at a given time t is expressed as shown in equation (1):

$$Q_{solar}(t) = A_{sc} \cdot G(t) \cdot \eta_{sc} \quad (1)$$

where A_{sc} = 10 m² - collector surface area, $G(t)$ = 850 W/m²— instantaneous solar irradiance (W/m²) and $\eta_{sc} =$ 0.65 — overall thermal efficiency of the collector.

2.Outlet Temperature of the Heat Transfer Fluid

The outlet temperature of the heat transfer fluid is determined from the collector's energy balance as presented in equation (2):

$$T_{out,HTF}(t) = T_{ambient}(t) + \frac{Q_{solar}(t)}{\dot{m}_{htf} \cdot c_{p,htf}} \quad (2)$$

where $\dot{m}_{htf}$ — mass flow rate of the heat transfer fluid (kg/s) and $c_{p,htf}$ — specific heat capacity of the HTF (J/kg·K).

3.Heat Transferred Through the Heat Exchanger

The heat transferred from the HTF to the saline feedwater through the heat exchanger is calculated using the effectiveness–NTU method, as defined by equation (3):

$$Q_{HX}(t) = \varepsilon \cdot C_{min} \cdot [T_{out,HTF}(t) - T_{in,saline}] \quad (3)$$

The corresponding outlet temperature of the saline water is then obtained from equation (4):

$$T_{out,saline}(t) = T_{in,saline} + \frac{Q_{HX}(t)}{\dot{m}_{saline} \cdot c_{p,saline}} \quad (4)$$

Where ε — heat exchanger effectiveness, and $C_{min} = \min(\dot{m} \cdot c_p)$ — the minimum heat capacity rate between the two working fluids.

4.Required Thermal Energy for RO Operation

The amount of thermal energy required to maintain the saline feedwater at the target temperature for optimal RO operation is given by Equation (5):

$$Q_{required} = \dot{m}_{saline} c_{p,saline} \cdot (T_{target} - T_{in,saline}) \quad (5)$$

This expression provides a benchmark for evaluating whether the heat collected by the solar subsystem is sufficient to sustain the desired feedwater temperature for stable and energy-efficient membrane performance. In particular, comparison of equation (3) and (5) allows assessment of whether the heat delivered by the collector loop is sufficient for RO feedwater heating. The model was solved in Python using hourly time steps and validated with experimental data. The collector efficiency was assumed to vary linearly with irradiance.

3. Results and Discussion

The hourly thermal balance presented in Fig. 3 was evaluated by comparing the heat transferred to the feedwater, calculated from equation (3), with the required thermal energy for RO operation given by equation (5).

Performance improvement of the solar-assisted RO desalination system through the integration of nanofluids in the solar collector loop was investigated experimentally and numerically. The results confirmed that SiO_2–water nanofluid exhibited enhanced thermal conductivity and slightly higher viscosity compared to water. Under simulated solar irradiance levels of 500–1000 W/m² and flow rates of 10–20 L/h, the outlet temperature difference ranged between 10–15 °C, validating the nanofluid's superior heat transfer capability.

Previous studies by Akhatov et al. (2020) indicated that increasing feedwater temperature from 20 °C to 40 °C can reduce viscosity by up to 35% (from 1.0 mPa·s to 0.65 mPa·s), effectively decreasing hydraulic resistance through the RO membrane. In this system, the nanofluid does not contact the saline feed directly but exchanges heat via an intermediate heat exchanger, maintaining optimal membrane operation between 25–30 °C while avoiding fouling risks.

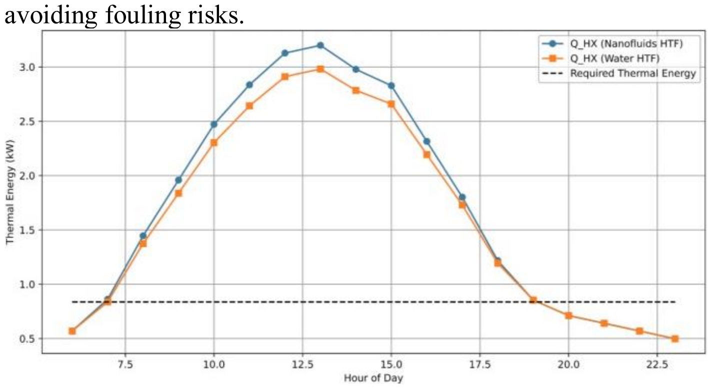

Fig.3. Comparison of required energy (Nanofluid vs Water) for holding target temperature of saline water during a one day.

Figure 3 presents a comparative analysis of the hourly thermal energy supplied by the collector when using nanofluid versus water. From 06:00 to 18:30, both fluids provided sufficient—sometimes excess—heat to sustain the target thermal power of approximately 0.85 kW. After sunset (19:00), solar irradiance declined sharply, causing insufficient heating power. To mitigate this, a thermal storage unit is proposed for integrating into the system. Such a unit would store excess heat during peak sunshine hours and release it during evening operation, ensuring continuous desalination and stable membrane performance.

A ±10% change in solar irradiance caused only ±3% variation in outlet temperature, indicating high stability of the nanofluid-based collector performance.

By integrating SiO_2-based nanofluids within a sealed circulation circuit, the system achieves enhanced heat delivery, reduced thermal losses, and improved overall energy efficiency. The developed model quantitatively demonstrates that nanofluids offer a practical pathway toward optimizing solar-assisted RO desalination in arid climates like Central Asia, supporting sustainable freshwater production.

Future work will focus on optimizing the accumulator design, assessing long-term nanofluid stability, and conducting full-scale outdoor validation under Central Asian climate conditions.

4. Conclusion

This study evaluated the enhancement of thermal performance in a solar-powered reverse osmosis (RO) water desalination system using SiO_2–water nanofluids as the heat transfer medium. Experimental and simulation results confirmed that the addition of SiO_2 nanoparticles (12–16 nm) at concentrations ranging from 0.5 to 3 vol.% significantly improves collector efficiency, outlet temperature, and thermal stability. At the optimal concentration of 1 vol.%, the thermal efficiency of the collector increased from 0.68 to 0.83, corresponding to an approximate improvement of 22%. An outlet temperature rise of 12–15 °C enabled the feedwater to remain within the optimal membrane operating range of 25–30 °C, while viscosity decreased by up to 35% compared to water. Hourly thermal modeling for summer conditions in Central Asia (from 06:00 to 23:00) showed that the useful thermal energy produced by the nanofluid-based collector exceeded the heating requirement for RO feedwater between 06:00 and 18:30, achieving an average energy surplus of 2.3 MJ/day. After sunset (19:00 to 23:00), solar energy input dropped to nearly zero, leading to an energy deficit of 28–35%. Therefore, to ensure uninterrupted operation, integration of a thermal storage unit is recommended. A ±10% change in solar irradiance resulted in only a ±3% variation in outlet temperature, confirming the high thermal stability of nanofluid-based heat transfer.

Compared to previous studies using Al_2O_3- and CuO-based nanofluids (Wole-Osho et al., 2020; Zeyad et al., 2022), the SiO_2–water mixture demonstrated a superior balance of efficiency, viscosity, and long-term stability. The developed model and experimental validation provide a reliable basis for optimizing hybrid solar–RO systems in arid climates. These findings confirm that nanofluid-enhanced collectors can improve energy efficiency, reduce pumping losses, and support sustainable freshwater production under climate change conditions.

Acknowledgments

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