INTERNATIONAL MULTI DISCIPLINARY JOURNAL FOR RESEARCH & DEVELOPMENT
eISSN 2394-6334 Impact factor: 8.854 Volume 13, issue 02 (2026)

PERFORMANCE INVESTIGATION OF AN ENERGY-EFFICIENT SOLAR AIR COLLECTOR-BASED WATER DESALINATION SYSTEM.

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Abstract: This study is devoted to the development of constructive and technological solutions aimed at improving the thermal and energy efficiency of an energy-efficient water desalination system operating on the basis of solar air collectors. The results demonstrate the feasibility of effectively utilizing low- and medium-temperature thermal energy generated in solar air collectors for water evaporation–condensation processes. The research focuses on evaluating and optimizing the main energetic performance indicators of the system, including thermal efficiency, specific energy consumption, and water production productivity. The integrated operation of the proposed system requires lower energy input compared to conventional methods, reduces carbon emissions, and ensures environmental sustainability. Therefore, the findings confirm the prospects and economic viability of implementing this technology in regions experiencing shortages of drinking water.

Keywords: Solar air collector; desalination; energy-efficient system; heat and mass transfer; hydrodynamic characteristics; environmental sustainability; thermal efficiency; specific energy consumption; carbon emission reduction.

Approximately three-quarters of the Earth's surface is covered with water, making it one of the largest natural resources on our planet. About 97% of the total water available on Earth is located in the oceans and consists of saline water. The remaining 3% represents freshwater, which is found in polar ice caps, underground reserves, lakes, and rivers [1; pp. 1–2]. More than 70% of the world's 3% freshwater resources are stored in glaciers, permanent snow cover, and permafrost regions. Approximately 30% of global freshwater reserves are located underground, most of which are situated in deep aquifers, making their extraction technically challenging and economically demanding. Surface water resources, including rivers, lakes, and accessible groundwater, constitute the primary sources for meeting domestic, agricultural, and industrial water demands. Globally, about 70% of freshwater is used for agricultural purposes, 20% for industrial activities, and the remaining 10% for domestic consumption [2; pp. 1–2; 3; pp. 1–23].

A comprehensive study conducted by Khaled S. Al-Karaghouli et al. [4] analyzed the performance of solar energy-based water desalination technologies. Their research demonstrated that the productivity of solar distillation systems can be significantly improved by reducing thermal losses and enhancing the condensation process. According to the findings, optimized solar distillation systems reduce energy consumption by approximately 40–50%. In conventional systems, a considerable portion of latent heat is dissipated into the surrounding air during vapor condensation. In optimized configurations, however, this latent heat is recovered and redirected to preheat the incoming saline water in subsequent stages. Moreover, operating under reduced pressure allows water to evaporate at lower temperatures, thereby decreasing the thermal energy demand from the solar collector. The authors proposed several technical solutions to maximize solar radiation capture throughout the day. Furthermore, by integrating additional solar collectors (parabolic or flat-plate types) into the system, productivity can be increased by up to three times. In addition to performance evaluation, Al-Karaghouli also conducted an economic assessment. Studies published in the Elsevier ScienceDirect database indicate that although system optimization slightly increases initial capital costs, it reduces the long-term cost of produced water by 30–40%. The study conducted by A.A. El-Sebaii [5] in 2002 represents a significant advancement in improving the efficiency of solar air collectors. He proposed a novel single-pass double-flow design in which air flows simultaneously above and below the absorber plate, unlike conventional collectors. This configuration effectively doubles the heat transfer surface area. The results showed that directing airflow on both sides of the absorber significantly enhances the collector's thermal efficiency, reaching values of 60–75% compared to conventional systems. The research mathematically demonstrated the critical role of airflow velocity and turbulence in enhancing heat transfer to the working fluid. The heated air from the collector serves as the primary energy source for water evaporation. El-Sebaii's model also contributes to stabilizing the outlet air temperature from the collector. G.N. Tiwari [6] conducted extensive research on modeling and experimental analysis of solar thermal desalination systems. His studies revealed that accelerating the evaporation process using solar air collectors increases distilled water production by 30–40%. The optimized system demonstrated substantially higher energy efficiency compared to conventional configurations. Increasing airflow velocity, optimizing absorber surface characteristics, and enhancing turbulence in the evaporation chamber were identified as key strategies for maximizing system performance. The research confirms the feasibility of producing potable water through an energy-efficient and environmentally sustainable approach using solar energy. A.S. Nafey [7] focused on advancing indirect solar desalination technologies through the integration of solar collectors with industrial-scale distillation units. Unlike simple greenhouse-type solar stills, his work proposed effective methods for coupling solar collectors with multi-stage flash (MSF) desalination systems. Nafey introduced a dual thermal storage tank configuration, in which one tank feeds the MSF unit while the other stores heated water from the solar collector. The tanks alternate operation every 24 hours, ensuring continuous day-and-night system performance. His research demonstrated that reducing vacuum pressure by 20% increases the distillation coefficient by 53%, enabling higher freshwater production even at relatively low solar collector temperatures. Nafey also optimized the preheating of saline water using specialized heat exchangers integrated with solar collectors. As a result, freshwater production increased from 4.2 kg to 7 kg per day per square meter of collector area during summer conditions. Furthermore, Nafey developed advanced simulation techniques based on a coordinate storage scheme to accurately predict system performance prior to construction. His studies primarily targeted compact solar-assisted MSF systems designed for remote communities. The estimated production cost of freshwater in Nafey's solar collector-assisted MSF systems was approximately $0.015 per liter.

Conclusion

The results of the present study demonstrate that solar air collector-based water desalination systems represent a promising technological solution for the efficient utilization of low- and medium-temperature thermal energy. A comprehensive analysis of the system's thermal and energetic performance indicators—namely thermal efficiency, specific energy consumption, and freshwater productivity—was conducted, and their interrelationships were systematically evaluated. The findings confirm that optimizing airflow dynamics, improving absorber surface characteristics, minimizing thermal losses, and recovering latent heat released during the condensation process significantly enhance the overall energy performance of the system.

Furthermore, the implementation of low-pressure evaporation conditions reduces the thermal energy demand from the solar collector and increases distilled water output. The integrated structural approach enables a reduction in energy consumption compared to conventional desalination technologies, contributes to lower carbon emissions, and supports environmental sustainability. Energy and economic assessments indicate that long-term operation of the proposed system leads to a reduction in the unit cost of produced water. Therefore, the proposed solar air collector-assisted desalination system can be considered a technologically feasible, energetically efficient, and economically viable solution for regions experiencing shortages of potable water, particularly in areas with limited access to centralized energy infrastructure.

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