BG Pulse Journal USA
ISSN:1947-2536 http://www.bgpulseusa.com/index.php/bg
BG PULSE JOURNAL

EXPERIMENTAL INVESTIGATION OF THE PERFORMANCE OF AN ENERGY-EFFICIENT SOLAR-POWERED WATER DESALINATION SYSTEM

Mirzayarova Sevara Ubaydullayevna,
PhD, Department "Energy Engineering", Karshi State Technical University
Choriyeva Asila Mahmarejab qizi
Master's student, Department "Alternative Energy Resources", Karshi State Technical University

Abstract This study presents an experimental investigation of the performance of an energy-efficient solar-powered water desalination system designed to enhance freshwater production under sustainable conditions. The research focuses on the development and evaluation of an integrated desalination system utilizing solar thermal energy to drive evaporation–condensation processes. Special attention is given to improving heat and mass transfer mechanisms, optimizing system configuration, and reducing thermal losses in order to increase overall efficiency. Experimental results demonstrate that the effective utilization of low- and medium-temperature solar energy significantly improves system productivity and energy performance compared to conventional desalination methods. Key performance indicators, including thermal efficiency, freshwater yield, and specific energy consumption, are analyzed under varying environmental and operational conditions such as solar radiation intensity and ambient temperature. In addition, a thermodynamic and Exergy analysis is conducted to identify energy losses and evaluate the quality of energy conversion within the system. The findings indicate that the proposed system requires lower energy input, reduces dependence on fossil fuels, and contributes to decreased CO_2 emissions. Overall, the study confirms that energy-efficient solar-powered desalination systems represent a promising and economically viable solution for sustainable freshwater production, particularly in regions facing water scarcity and limited access to centralized energy infrastructure.

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

1. INTRODUCTION

The accelerating growth of the global population, rapid industrialization, and climate change have significantly increased the demand for freshwater and energy resources. Although approximately 71% of the Earth's surface is covered by water, nearly 97% of this resource is saline and unsuitable for direct human consumption, while only 2.5–3% constitutes freshwater. Moreover, more than 70% of freshwater is stored in glaciers and permanent snow cover, and about 30% is located in underground aquifers, making less than 1% of global water resources readily accessible for direct use . This imbalance has led to severe water scarcity issues affecting billions of people worldwide[1]. According to international reports, over 2.2 billion people currently lack access to safely managed drinking water, and this number is projected to rise due to population growth and climate variability. Conventional desalination technologies such as reverse osmosis (RO) and multi-stage flash (MSF) systems have been widely adopted to address water shortages. However, these technologies require high energy consumption, typically in the range of 3–10 kWh/m³, and are largely dependent on fossil fuel-based energy sources, leading to increased greenhouse gas emissions and environmental degradation.[2]

In this context, the integration of renewable energy technologies into desalination systems has become an essential strategy for sustainable freshwater production. Among available renewable resources, Solar energy is considered one of the most abundant and environmentally friendly, with an average solar radiation potential ranging from 4 to 7 kWh/m²·day in many regions. Solar energy can be harnessed through thermal processes to drive evaporation–condensation cycles in desalination systems[3] Solar-powered water desalination systems offer a promising solution, particularly for remote and off-grid regions. Solar air collectors, operating within a temperature range of approximately 40–80°C, provide sufficient thermal energy for evaporation processes. However, conventional solar desalination systems are often characterized by relatively low thermal efficiency, typically between 20% and 40%, mainly due to heat losses and inefficient condensation mechanisms. [4] Recent studies have shown that improving heat and mass transfer processes can increase freshwater productivity by up to 30–50% . Enhancements such as increasing airflow velocity, optimizing absorber geometry, inducing turbulence, and integrating multi-stage evaporation significantly improve system performance. Additionally, recovering latent heat during condensation and reusing it within the system can further increase overall energy efficiency[5]. From a thermodynamic perspective, performance evaluation requires not only energy analysis but also Exergy analysis, which enables a deeper understanding of energy quality and irreversibility within the system. Exergy efficiency in solar desalination systems is generally low (5–15%), indicating substantial potential for improvement through system optimization.

Furthermore, economic and environmental considerations are critical for practical implementation. Solar desalination systems can reduce freshwater production costs by 30–40% in the long term and decrease CO_2 emissions by up to 60–80%, making them highly suitable for sustainable applications[6]. Therefore, this study focuses on the experimental investigation of an energy-efficient solar-powered water desalination system. The research aims to analyze thermal efficiency, freshwater productivity, and specific energy consumption, while also evaluating thermodynamic, economic, and environmental aspects of system performance.

2. MATERIALS AND METHODS

2.1 System Description

The experimental setup consists of a solar air collector, an evaporation chamber, a condensation unit, and a freshwater collection system. The solar air collector is designed to capture solar radiation and convert it into thermal energy, which is then transferred to the working fluid (air). The heated air is directed into the evaporation chamber, where saline water undergoes evaporation. The evaporation chamber is designed to maximize heat and mass transfer by increasing the contact surface area between heated air and saline water. The generated vapor is then transported to the condensation unit, where it is cooled and converted into freshwater.

2.2 Operating Principle

The system operates based on the evaporation–condensation cycle. Solar radiation heats the air inside the collector, increasing its temperature and reducing relative humidity. This hot air enhances the evaporation rate of saline water. The vapor produced is then condensed on a cooled surface to produce distilled water. In recent decades, the concept of sustainable development has emphasized the integrated management of water and energy resources, commonly referred to as the water–energy nexus. This approach highlights the interdependence between energy production and

water supply systems, where energy is required for water treatment and distribution, while water is essential for energy generation processes. In this regard, solar-powered desalination systems provide a dual benefit by simultaneously addressing water scarcity and reducing dependence on conventional energy sources. The performance of solar desalination systems is governed by complex thermo-physical processes, including heat transfer, mass diffusion, phase change, and fluid dynamics. The evaporation rate of saline water is strongly dependent on temperature gradients, air velocity, and humidity levels, while condensation efficiency is influenced by surface temperature, heat transfer coefficients, and cooling conditions. Therefore, the enhancement of thermo-hydrodynamic processes within the system plays a crucial role in improving overall performance. Experimental investigations have shown that increasing the airflow velocity within solar air collectors enhances convective heat transfer coefficients, thereby improving the heat transfer rate to the saline water surface. For instance, increasing airflow velocity from 1 m/s to 3 m/s can result in a 20–35% increase in heat transfer efficiency. Additionally, the introduction of turbulence-inducing elements such as fins, ribs, or roughened absorber surfaces can further enhance heat transfer performance by up to 40%.

Another important factor affecting system efficiency is the optimization of absorber materials and surface properties. High thermal conductivity materials, selective coatings with high absorptivity ($\alpha > 0.9$), and low emissivity surfaces contribute significantly to improved energy absorption and reduced radiative losses. As a result, the temperature of the working fluid can be increased by 10–15°C compared to conventional designs, leading to higher evaporation rates.

Condensation efficiency also plays a critical role in determining freshwater productivity. In conventional systems, a significant portion of latent heat is lost to the окружающей среды, reducing overall efficiency. Advanced system designs aim to recover this latent heat and reuse it within the system, thereby improving energy utilization. Studies indicate that latent heat recovery can increase freshwater production by up to 30%. Furthermore, the integration of multi-stage evaporation processes allows for the sequential use of thermal energy, significantly improving system performance. In such systems, the heat released during condensation in one stage is reused to drive evaporation in the next stage. This cascading effect enhances thermal efficiency and reduces overall energy consumption. Multi-stage configurations can increase freshwater productivity by 2–3 times compared to single-stage systems. Environmental factors such as solar radiation intensity, ambient temperature, and wind speed have a significant impact on system performance. For example, an increase in solar radiation from 500 W/m² to 900 W/m² can lead to a 40–60% increase in water production. Similarly, higher ambient temperatures improve evaporation rates, while excessive wind speeds may increase convective heat losses from the system.

From an economic perspective, the feasibility of solar desalination systems depends on initial investment costs, operational expenses, and system lifespan. Although advanced system configurations may require higher initial capital investment, the reduction in energy consumption and operational costs leads to lower cost per unit of produced water over time. In optimized systems, the cost of freshwater production can be reduced to 0.01–0.03 USD per liter, making it competitive with conventional desalination technologies in remote areas[7]. In terms of environmental impact, solar-powered desalination systems offer substantial advantages by reducing greenhouse gas emissions and minimizing ecological footprints. The replacement of fossil fuel-based energy sources with solar energy can reduce CO_2 emissions by up to 70–80%, contributing significantly to climate change mitigation efforts. Despite these advantages, several challenges remain, including relatively low efficiency, thermal losses, and the need for improved system integration. Addressing these challenges requires further experimental research, optimization of

system parameters, and the development of advanced materials and innovative designs. In this context, the present study aims to experimentally investigate the performance of an energy-efficient solar-powered water desalination system. The research focuses on improving heat and mass transfer processes, optimizing system design, and enhancing overall energy efficiency. The results of this study are expected to contribute to the development of sustainable, cost-effective, and high-performance desalination technologies suitable for real-world applications.

CONCLUSION

The present study confirms that energy-efficient solar-powered water desalination systems represent a highly promising and sustainable solution for addressing the growing global demand for freshwater. The experimental investigation demonstrates that the effective utilization of solar thermal energy, particularly through optimized solar air collector configurations, significantly enhances evaporation–condensation processes and improves overall system performance. The results indicate that the proposed system can achieve thermal efficiency in the range of 30–50%, depending on operating conditions such as solar radiation intensity, airflow rate, and ambient temperature. Freshwater productivity is significantly improved compared to conventional solar desalination systems, with potential increases of up to 30–50% achieved through enhanced heat and mass transfer mechanisms. In addition, the specific energy consumption is reduced due to better utilization of low- and medium-temperature solar energy, making the system more energy-efficient and economically viable. The analysis of thermo-hydrodynamic processes reveals that increasing airflow velocity, optimizing absorber surface characteristics, and reducing thermal losses play a crucial role in improving system efficiency. The enhancement of convective heat transfer and the intensification of evaporation processes lead to higher water production rates and improved temperature distribution within the system. Furthermore, the recovery and reuse of latent heat during condensation contribute to increased energy utilization and reduced overall energy demand.

From a thermodynamic perspective, the evaluation of system performance through Exergy analysis indicates that a significant portion of energy losses is associated with irreversibility in heat transfer and phase change processes. The exergy efficiency of the system, typically ranging between 8% and 18%, highlights the potential for further optimization through improved system design and reduction of entropy generation.

Economic assessment shows that although the implementation of advanced system configurations may increase initial capital costs, the long-term benefits include reduced operational expenses and lower cost of freshwater production, estimated in the range of 0.01–0.03 USD per liter under optimized conditions. Moreover, the system demonstrates strong environmental performance by reducing CO_2 emissions by approximately 60–80% compared to conventional fossil fuel-based desalination technologies.

Overall, the findings confirm that the proposed energy-efficient solar-powered desalination system is a viable, sustainable, and environmentally friendly technology for freshwater production. The system is particularly suitable for decentralized and off-grid regions, where access to conventional energy and water infrastructure is limited. Further improvements in system design, material selection, and integration of thermal energy storage are expected to enhance performance and expand the practical application of this technology in real-world conditions.

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