

Solar-Powered Barometric Vacuum Desalination: Modelling, Simulation, and Performance Analysis for Sustainable Water Production

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ABSTRACT

This study introduces an innovative, sustainable, energy-efficient approach to desalination using a Barometric Vacuum Desalination System (BVDS). The system passively creates a vacuum through a barometric column, enabling the production of freshwater from saline water at near-ambient temperatures. By leveraging a passively generated vacuum via a barometric column, the system operates with minimal energy input, making it compatible with solar or other low-grade thermal sources. The configuration includes an evaporation chamber equipped with a solar collector, a condenser heat exchanger, and three vertical water columns for saline intake, brine rejection, and freshwater collection—each connected to its own holding tank. Circulation pumps and control valves interconnect these components, ensuring a cost-effective and low-maintenance setup. A MATLAB-based simulation developed using thermodynamic, fluid dynamic, and heat-mass transfer principles, confirms the system's operational feasibility, energy efficiency, and scalability for high-quality freshwater production. The BVDS also offers a low environmental footprint, making it particularly suitable for deployment in arid or remote regions. Future work will focus on scaling up the system and incorporating thermal storage solutions to enable continuous operation.

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Introduction

Water scarcity is an increasingly critical global issue, currently affecting more than 1.5 billion people. Projections indicate that by 2050, approximately 1.7 billion individuals across 39 countries may experience severe water shortages [1]. This growing crisis is driven by rapid population growth, unsustainable industrial practices, and the degradation of freshwater ecosystems, all of which place mounting pressure on existing freshwater resources. Addressing these challenges necessitates the development of innovative, sustainable, and environmentally responsible water production technologies. Among the potential solutions, desalination particularly when integrated with renewable energy sources emerges as a promising strategy to meet the rising global demand for freshwater. By harnessing solar, wind, or other clean energy sources, desalination can provide a scalable and environmentally sustainable means of augmenting freshwater supplies without further depleting natural reserves. This approach not only addresses immediate water security concerns but also aligns with global efforts to mitigate climate change by reducing reliance on fossil fuels.

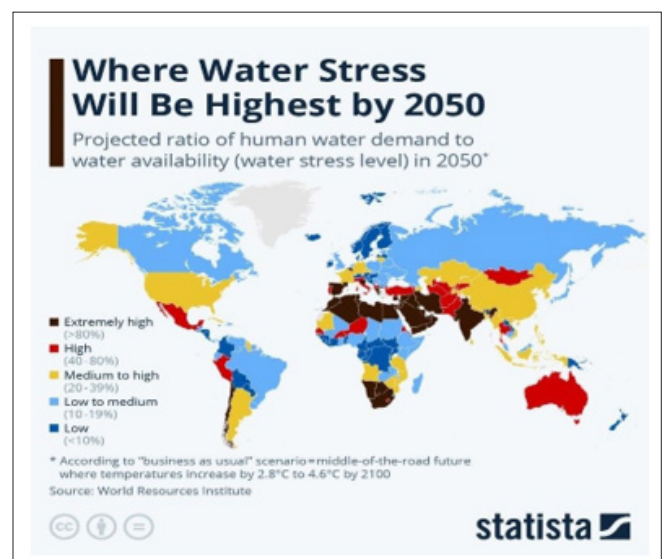


Figure 1: Water Stress Distribution Map Expected by 2024 [1].

Objective

The primary objective of this study is to assess the feasibility of barometric vacuum desalination system (BVDS) as a sustainable and energy-efficient method for producing potable water. This involves the development and validation of a comprehensive

simulation model to analyse various design configurations, enhance system performance, and evaluate scalability potential under varying operational conditions.

System Description and Operating Principle

Barometric Vacuum Desalination System (BVDS) is a thermal desalination technology that works under vacuum created by barometric column. This concept was Initially introduced by Sharma and Goswami in 2003 [2]. The system basically exploits the “Torricelli phenomenon” to establish a low-pressure space at the head of water column. In this space, the pressure approaches near-zero absolute levels, enabling the evaporation of saline water at significantly lower temperatures.

This characteristic makes BVD particularly suitable for integration with renewable and low-grade heat sources, such as solar thermal energy, geothermal energy, wave and wind energy, as well as waste heat from fossil-fuel-based power plants. By utilizing such energy sources, the system offers a sustainable and energy-efficient pathway for desalination.

The basic layout of the system configuration is illustrated in Figure 2. The setup comprises a condenser heat exchanger, an evaporation chamber with a flat plate solar collector installed on its bottom surface serving as the heat source, a water circulation pump, six control valves, and three vertical columns each ten meters in height. Such columns function respectively as the saline water column, the brine withdrawal column, and the freshwater collection column. Each column is connected to a dedicated holding tank positioned at ground level, corresponding to sea level elevation [3].

The process begins by pumping cold saline water from the saline water tank using the circulation pump. As the water passes through the condenser heat exchanger, it absorbs thermal energy from the incoming vapor originating from the evaporation chamber. This heat exchange preheats the saline water while simultaneously condensing the vapor into freshwater, thereby reducing the energy required for subsequent evaporation. The preheated saline water is then directed into the evaporation chamber, which operates under vacuum pressure to enable evaporation at a significantly lower temperature—just slightly above the normal ambient temperature. A flat-plate solar collector provides the necessary thermal energy to drive the evaporation process.

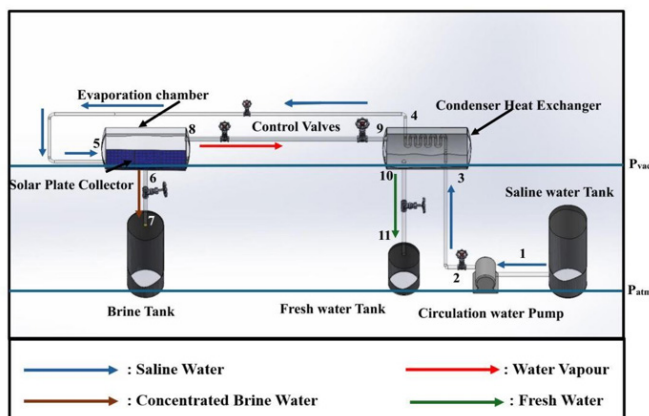


Figure 2: Illustration Diagram of the Proposed Configuration.

The vapor thus produced flows into the condensation chamber, while the concentrated brine (concentrated saline solution) is discharged into the brine tank. Inside the condenser, the vapor

cools and condenses into freshwater, which then descends into the freshwater tank for collection. By leveraging vacuum conditions to reduce the boiling point, this configuration achieves highly efficient and effective freshwater production from saline sources.

Methodology

A comprehensive mathematical model of the BVDS is developed to optimize freshwater yield while minimizing energy consumption. Each system component is individually analyzed using principles of thermodynamics, fluid dynamics, and heat and mass transfer, before being integrated into a unified simulation framework.

The model employs iterative numerical techniques to solve key variables including temperature, pressure, mass flow rate, and heat flux and is implemented in MATLAB for high computational flexibility and precision in simulating complex processes.

Analysis

The model employs a one-dimensional, steady-state approach based on fundamental equations for mass, momentum, and energy. Key physical phenomena, such as heat transfer, friction, boiling, and condensation are incorporated using empirically validated correlations to enhance accuracy. The analysis follows a systematic methodology, structured as follows:

- **Model Development:** The model is built and coded in MATLAB software, which provides flexibility and precision in simulating complex
- **Model Validation:** The numerical predictions are rigorously benchmarked against experimental data and established analytical solutions to verify the model's reliability and accuracy.
- **Optimization and Scaling:** The validated model is applied to identify optimal operating conditions and assess potential for system scale-up.

Results and Discussion

The mathematical model results indicate that solar irradiance (the primary energy input) has the greatest influence on system performance. As solar irradiance increases, the system exhibits substantial improvements in operational efficiency. Specifically, elevated heat source temperatures lead to a rise in saline water temperature, which in turn enhances the rates of vaporization and condensation, thereby improving freshwater productivity [4].

However, an increase in solar collector wall and glass temperatures was found to reduce the vaporization rate, likely due to enhanced thermal losses or reduced effective heat transfer to the saline water. Furthermore, the model reveals the critical role of cooling-side parameters—particularly the inlet cooling water temperature and flow rate. These variables directly govern condensation efficiency by influencing the temperature gradient across the condensation surface. Higher flow rates and lower inlet temperatures enhance the heat extraction process, thereby supporting more efficient condensation and contributing positively to the system's overall thermal performance [5].

These findings align with prior studies on solar-driven desalination systems, reinforcing the importance of balancing thermal input and cooling efficiency to optimize performance. Striking this balance is essential for maximizing system efficiency and freshwater output [6].

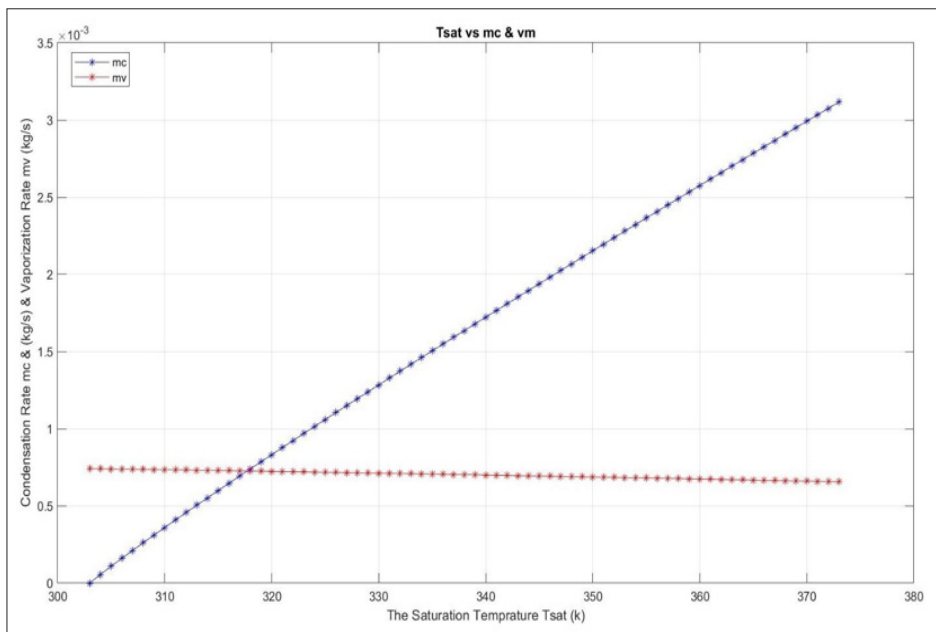


Figure 3: Saturation Temperature Vs Condensation & Vaporization Rates.

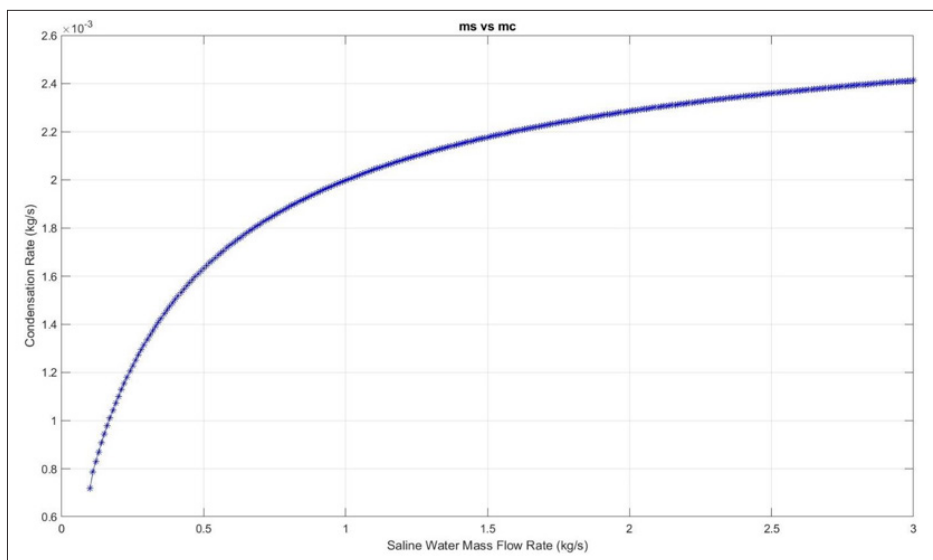


Figure 4: Saline Water Mass Flow Rates Temperature Vs Condensation Rates

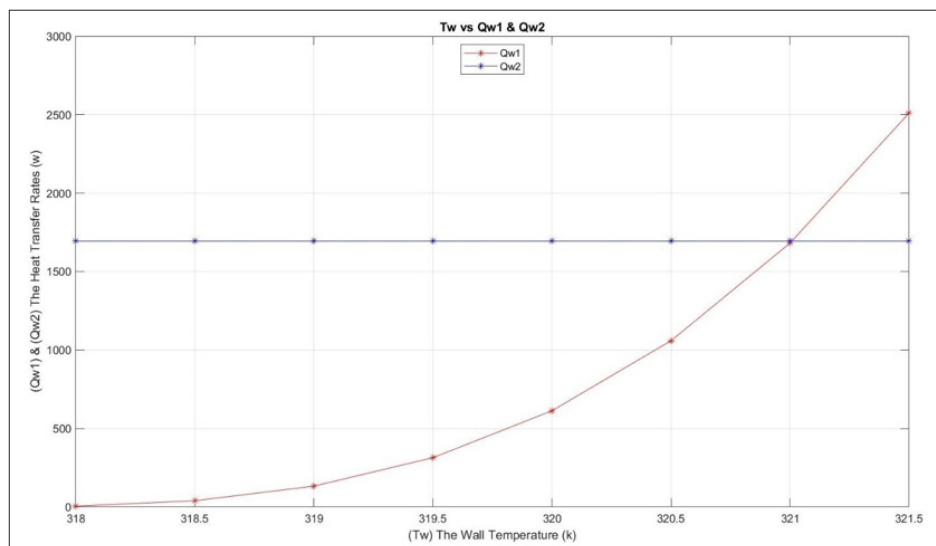


Figure 5: Wall Temperature vs Heat Flux Rates

Conclusion

The NVBD concept introduces an innovative approach to address water shortage issues, particularly in rural and remote regions. The proposed configuration demonstrates that utilizing a vacuum barometric distillation method employing solar irradiance as the primary heat input, as a practical, sustainable and efficient alternative solution. This configuration is highly efficient, low maintenance, low cost, economic, requires less manpower an environmentally friendly and provides high quality of output water.

To further enhance system performance, future research could explore the implementation of multi-stage distillation processes. Additionally, integrating thermal energy storage systems and advanced cooling mechanisms may allow for continuous operation, including during periods of low solar irradiance, such as nighttime hours.

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