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Thermodynamics of Freshwater Production via CuS-Infused Porous Membrane Solar Absorber in Seawater Desalination

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Abstract. In our advanced modern world, ensuring the availability and access to freshwater resources remains a significant global challenge. Seawater desalination is viewed as one of the most promising solutions to address the increasing human demand for freshwater. This study theoretically examines the thermodynamics of a novel desalination system that integrates a copper sulfide (CuS) nanomaterial-porous membrane solar absorber for freshwater production. The governing partial differential equations for energy and mass balance in the model were derived from conservation laws and solved numerically using the method of lines. The impact of various parameters on steam temperature and freshwater production rate was analyzed in two scenarios: (i) under constant solar radiation flux in a controlled laboratory setting, and (ii) as a time-dependent function under typical daily solar radiation conditions. The pertinent results were presented graphically and discussed. It was found that the Nusselt number at the surface of the porous membrane solar absorber increases with the infusion of CuS nanomaterial. The desalination system reached a steady state with steam temperature, and the rate of freshwater production improved as the volume fraction of CuS nanomaterial in the porous membrane solar absorber increased. Additionally, an increase in steam generation and condensation Biot numbers further boosted the freshwater production rate.

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1 Introduction

The demand for freshwater has surged due to enhanced quality of life and living standards. Key factors contributing to water shortages include environmental changes, increasing pollution, rising human demand, and overexploitation of water resources [27]. Despite water covering roughly 75% of the Earth's surface, only 3% is freshwater suitable for direct use, with the remaining 97% being saltwater [17]. Experts predict that freshwater demand will quadruple in the next 30 years [11]. The World Health Organization estimates that around 50% of the global population will experience freshwater shortages [26]. To address this challenge, various strategies have been developed, such as improved freshwater management, wastewater reclamation, and seawater desalination [9, 25].

Desalination, which involves removing salt and minerals from seawater, is considered a primary solution to freshwater shortages. Desalination methods include thermal processes and membrane-based techniques [8]. Thermal desalination primarily uses thermal energy generated from fossil fuels, but it tends to have high operational and maintenance costs and relatively low efficiency [3]. Membrane desalination involves using semipermeable membranes to separate salt from water. Polymer membranes are widely used in seawater desalination due to their mechanical strength, flexibility, chemical stability, superior film-forming ability, and cost-effectiveness [4]. Common polymer membrane materials include polyamide (PA), polyvinylidene fluoride (PVDF), polytetrafluoroethylene (PTFE), polyvinyl alcohol (PVA), polyacrylonitrile (PAN), polyethersulfone (PES), and chitosan [30]. Membrane desalination technologies can be pressure-driven, temperature-driven, or chemically driven.

The ample daily availability of solar radiation, particularly in arid and coastal regions where freshwater scarcity is most pronounced, presents a sustainable, cost-effective, and environmentally friendly energy source for seawater desalination [1]. This renewable energy resource fosters energy independence and aligns effectively with patterns of freshwater demand, thereby promoting overall sustainable development. In this innovative technology, seawater is directly vaporized through a solar membrane-based desalination system utilizing incoming solar radiation, with the evaporated vapours subsequently condensed into freshwater. Shafieian and Khiadani [24] proposed a solar direct contact membrane-based desalination system incorporating energy recovery concepts, while Anwar *et al.* [5] examined the impacts of operation parameters on design and optimal performance of solar driven membrane-based desalination systems. Additional theoretical and experimental research has explored solar-driven stand-alone desalination systems for remote regions, assessed the performance of diverse membranes in solar setups [2]. Solar