AN IN-DEPTH REVIEW OF TECHNOLOGICAL ADVANCEMENTS IN SOLAR STILLS FOR ECO-FRIENDLY DESALINATION

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Abstract:
The increasing scarcity of freshwater resources and the growing demand for sustainable desalination methods have driven significant interest in solar still technologies. This paper presents an in-depth review of recent technological advancements in solar stills aimed at enhancing desalination efficiency and environmental sustainability. It explores innovations in solar still design, material enhancements, energy storage integration, and hybrid systems combining solar stills with photovoltaic or thermal collectors. The review highlights key performance metrics such as distillate yield, energy efficiency, and cost-effectiveness. Findings suggest that improvements such as nanomaterial coatings, wick materials, phase change materials (PCMs), and multistage designs have significantly improved water output and thermal performance. The study provides insights into current challenges and identifies potential directions for future research to develop eco-friendly, scalable, and efficient solar desalination systems for water-scarce regions.

1. INTRODUCTION

Access to clean drinking water remains a critical global challenge, particularly in arid and semi-arid regions. Traditional desalination methods such as reverse osmosis and multi-stage flash distillation, though effective, are energy-intensive and environmentally taxing. In contrast, solar stills offer a simple, sustainable, and low-cost solution for desalinating brackish or seawater using solar energy.

A solar still works by mimicking the natural hydrological cycle: solar radiation heats the impure water, causing it to evaporate and then condense into a clean distillate. However, conventional solar stills suffer from low thermal efficiency and limited water output, restricting their practical utility in large-scale applications. Over the past decade, significant research has been conducted to overcome these limitations through technological enhancements in design, materials, and energy integration.

This paper reviews the latest developments in solar still technologies with a focus on improving desalination performance and environmental sustainability. Emphasis is placed on novel designs (e.g., stepped, pyramidal, inclined), improved absorber and glazing materials, the use of nanotechnology, heat storage methods, and hybrid configurations. By consolidating recent research findings, this review aims to offer a clear understanding of how solar stills can evolve into more viable and eco-friendly desalination systems for future deployment.

2. SOLAR STILL BASICS

Solar stills, addressing the imperative challenge of freshwater scarcity, operate on the principles of evaporation and condensation, harnessing solar energy to transform saline or brackish water into freshwater. The evaporation process occurs in a basin covered with transparent materials, allowing sunlight to energize the water molecules and initiate the transition to vapor. Subsequently, the vapor encounters a cooler condensing surface, where it undergoes a phase change back to liquid form, forming freshwater droplets. These droplets are efficiently collected and channeled for consumption or irrigation. Essential components, including the basin, covering material, absorber plate, condensing surface, and collection system, alongside varied configurations like single-slope or double-slope designs, collectively contribute to the efficiency of solar stills. Further innovations, such as integrating phase change materials and nanofluids, amplify their effectiveness in converting saline or brackish water into a sustainable freshwater resource, positioning solar stills as vital components in the quest for sustainable water solutions.

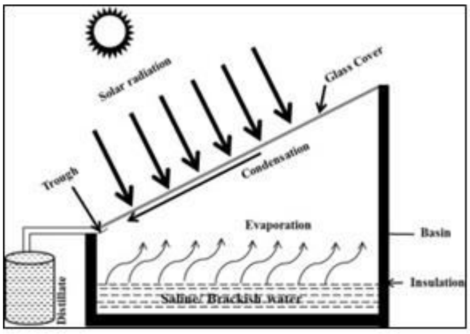

Figure 1.1: Conventional Single Slope Solar Still (AS Abdullah, 2013)

Enhancing Solar Still Performance with Phase Change Materials (PCMs): The incorporation of Phase Change Materials (PCMs) into solar stills has emerged as a promising strategy to enhance their efficiency and freshwater yield. In a notable study by Agrawal et al. (2022), an experimental investigation was conducted, integrating a binary eutectic PCM into a modified solar still. The results demonstrated a significant improvement in freshwater yield (0.31 kg/m^2 h) and energy efficiency (30.42%), as validated by Computational Fluid Dynamics (CFD) modeling. Additionally, Purnachandrakumar et al. (2022) underscored the critical role of CFD in optimizing PCM integration by providing insights into heat transfer, energy distribution, and design parameters. The application of PCMs presents several advantages, including enhanced energy efficiency, extended operation hours, reduced heat loss, and improved freshwater yield. This innovative approach, validated by experimental and simulation results, positions PCM-integrated solar stills as a promising solution for addressing water scarcity, offering sustainability and reliability in clean water production during both daylight and non-daylight hours.

3. NANOFLUIDS IN SOLAR STILLS:

The integration of nanofluids, suspensions of nanoparticles in a base fluid, has emerged as a promising strategy to augment the performance of solar stills. Two pivotal studies, Panchal et al. (2019) and Kabeel et al. (2017), investigated the use of different nanofluids and their impact on distillate output. Panchal et al. (2019) focused on MgO and TiO_2 nanofluids, observing substantial increases in distillate output, particularly with MgO nanofluids, attributed to their lower specific heat capacity and higher thermal conductivity. In a study by Kabeel et al. (2017), the incorporation of Cu_2O and Al_2O_3 nanoparticles significantly improved the daily efficiency of the solar still, showcasing the potential of nanofluids in boosting performance. The advantages of nanofluid integration include enhanced heat transfer, improved energy efficiency, and increased freshwater yield, making it a valuable approach for addressing water scarcity challenges. These studies collectively highlight the potential of nanofluids as a promising avenue for optimizing solar stills, contributing to the sustainable production of freshwater with heightened efficiency and productivity.

4. Modified Absorber Plates and Materials in Solar Stills:

The efficiency of solar stills crucially depends on the design and materials employed for the absorber plate, prompting researchers to explore modifications for performance enhancement. In the study by Sathyamurthy et al. (2020), the incorporation of fumed silica nanoparticles into black paint on the absorber plate of a stepped solar still yielded noteworthy improvements in water and absorber plate temperatures, resulting in a substantial increase in freshwater yield. Gnanadason et al. (2015) experimented with copper sheets and various enhancements, such as black paint coating, pebbles, fins, and lowpressure conditions, demonstrating heightened rates of evaporation and improved efficiency. Additionally, AS Abdullah (2013) investigated an inclined copper-stepped solar still integrated with a solar air-heater collector and aluminum filling, showcasing increased productivity during periods of low solar radiation. These studies collectively underscore that modifications to absorber plates and the use of specific materials significantly enhance solar still performance, leading to elevated temperatures, improved evaporation rates, and overall efficiency. Such advancements contribute to positioning solar stills as more effective and reliable solutions for sustainable clean water production.

5. Innovative Basin Designs in Solar Stills:

The basin design is a pivotal factor influencing the efficiency of solar stills, prompting researchers to explore inventive modifications for performance enhancement. Muftah et al. (2018) focused on a stepped solar still, introducing internal and external reflectors, absorber fins, and external condensers, resulting in a substantial 29% increase in daily productivity. Kalidasa et al. (2010) explored a single basin double slope solar still with an effective basin material, showcasing its potential in converting waste or brackish water into potable water using solar energy. Although not directly referenced, variations in basin depth and the incorporation of sensible heat storage materials further contribute to the overall efficiency of solar stills. These studies collectively emphasize the significance of innovative basin designs, incorporating reflectors, unique materials, and distinct configurations, in addressing water scarcity challenges and advancing solar stills as reliable and effective solutions for sustainable clean water production.

6. Computational Modeling and Fluid Dynamics in Solar Stills:

The role of computational modeling and fluid dynamics in advancing solar still technology is paramount, as demonstrated in key studies. Chauhan et al. (2021) emphasized the crucial role of numerical simulations, particularly computational fluid dynamics (CFD), in design innovation and optimization. Their review highlighted how CFD simulations enable a detailed understanding of fluid and thermal behavior within solar stills, aiding in the enhancement of productivity, efficiency, and cost-effectiveness. Edalatpour et al. (2016) further supported the significance of numerical studies in estimating productivity and refining solar still configurations, pointing out ongoing opportunities for innovation in CFD simulation. The theoretical and experimental validation approach is also underscored, emphasizing the need to correlate theoretical predictions with real-world data to ensure the applicability of simulation insights to practical solar stills. Collectively, these studies highlight the indispensable role of computational tools in shaping the evolution of solar stills, making them more reliable and effective solutions for addressing water scarcity challenges.

7. Factors Influencing Solar Still Productivity:

Solar still productivity is intricately influenced by numerous factors, as comprehensively reviewed by Selvaraj et al. (2018). The study identified key parameters, including solar radiation intensity, temperature difference, collector area, basin water depth, insulation, angle of inclination, glass cover plate thickness, and wind velocity, emphasizing the multidimensional nature of solar still performance. Climatic conditions, collector area, and wind velocity were highlighted as particularly critical factors. Regions with high solar radiation, temperature differences, and low humidity were deemed optimal for solar still operation. Larger collector areas were found to enhance distillate production, while wind velocity had a dual effect, with gentle winds improving heat transfer and strong winds potentially leading to heat loss. The study also offered recommendations for future research, emphasizing the need for innovative designs, advanced materials, improved modeling, energy storage solutions, and climate-adapted designs to further optimize solar still efficiency. Understanding and addressing these factors will be instrumental in advancing solar still technology and ensuring its effectiveness in addressing water scarcity challenges worldwide.

8. CONCLUSION

Solar stills have emerged as a promising solution for clean water production in regions lacking centralized water infrastructure. This review has highlighted how advancements in materials, design configurations, and thermal management strategies have significantly boosted the performance and sustainability of solar still systems.

Technologies such as nano-enhanced absorbers, PCMs for thermal storage, wick-assisted evaporation, and solar-PV hybrids have enabled higher distillate yields and operational efficiency. However, despite these advancements, challenges remain in terms of scalability, continuous operation under varying climatic conditions, and cost-effectiveness.

To unlock the full potential of solar stills as a mainstream desalination technology, future research should focus on system integration, automation, lifecycle cost analysis, and the use of environmentally friendly construction materials. In conclusion, with continued innovation and investment, solar stills can play a vital role in building resilient and eco-friendly freshwater solutions for the world's most vulnerable communities.

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