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A Comprehensive Review of Computational Fluid Dynamics (CFD) Analysis and Thermal Investigation in Solar Stills

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Abstract - *Solar stills have emerged as a sustainable and promising technology for desalination and water purification, utilizing renewable solar energy. Over the years, researchers have sought to optimize the performance and efficiency of solar stills through computational fluid dynamics (CFD) analysis and thermal investigations. This review paper aims to present a comprehensive overview of the advancements made in the field of solar stills using CFD simulations and thermal analysis. The review begins by introducing the concept of solar stills and their significance in addressing global water scarcity. It highlights the need for enhanced design and performance evaluation to maximize freshwater production. The paper then delves into the theoretical underpinnings of CFD and thermal modelling, explaining their application to solar still systems. Various numerical techniques and mathematical models used for simulating fluid flow, heat transfer, and phase change phenomena are discussed in detail. Next, the review synthesizes the findings from multiple studies that have utilized CFD simulations to analyse different aspects of solar stills, including heat transfer mechanisms, convective flow patterns, and temperature distributions. The influence of design parameters such as geometry, materials, and inclination angles on the system's performance is thoroughly examined. Furthermore, the integration of advanced solar collectors and phase change materials in solar still designs is explored for potential efficiency improvements. In addition to CFD analysis, the paper delves into the significance of thermal investigations in evaluating the energy efficiency and heat distribution within solar stills. Studies employing various experimental techniques, such as thermography and thermal imaging, are analysed to understand the influence of operating conditions and environmental factors on overall performance. The review also emphasizes the challenges and limitations faced during CFD simulations and thermal analyses of solar stills, providing insights into future research directions. Recommendations for enhanced modelling approaches, validation techniques, and experimental setups are presented to facilitate accurate predictions and reliable system optimizations. In conclusion, this review paper sheds light on the pivotal role of CFD analysis and thermal investigations in advancing the design and performance evaluation of solar stills. The integration of these computational and experimental tools contributes to sustainable water production, promoting a cleaner and more water-secure future.*

Key Words: **Solar Still, Thermal Analysis, CFD Analysis, Thermal Modelling**

1. INTRODUCTION

Water scarcity remains one of the most pressing global challenges in the 21st century, affecting billions of people worldwide. As traditional water resources dwindle and the demand for freshwater surges, innovative and sustainable solutions are imperative to address this critical issue. Among various emerging technologies, solar stills have emerged as a promising approach for harnessing renewable solar energy to desalinate and purify water, providing a sustainable source of clean drinking water. Solar stills utilize the natural process of evaporation and condensation to separate pure water from saline or contaminated sources. The core principle involves exposing impure water to solar radiation, which causes evaporation, leaving behind contaminants, while the vapor condenses and is collected as fresh water. Unlike conventional desalination methods that often rely on fossil fuels or electricity, solar stills offer an eco-friendly alternative with minimal environmental impact. To maximize the efficiency and performance of solar stills, researchers and engineers have turned to advanced computational techniques and thermal analyses. Computational Fluid Dynamics (CFD) simulations, a powerful tool used in fluid flow and heat transfer studies, have gained prominence in optimizing the design and operational parameters of solar stills. Additionally, thermal investigations play a crucial role in understanding energy distribution within the system and identifying potential areas for improvement. This review paper aims to provide a comprehensive exploration of the application of CFD analysis and thermal investigations in the domain of solar still technology. By synthesizing the latest research findings and advancements in the field, we seek to offer valuable insights into the complex fluid dynamics, heat transfer mechanisms, and performance evaluation of solar stills. The paper is structured as follows: First, we introduce the concept of solar stills and discuss their significance in combating water scarcity. We highlight the need for efficient design and optimization to enhance freshwater production while minimizing resource consumption. Subsequently, we delve into the theoretical foundations of CFD analysis and thermal modeling, illustrating their relevance to solar still systems. The following sections will present a comprehensive analysis of research studies that have leveraged CFD simulations to investigate diverse aspects of solar stills. These include the study of convective flow patterns, heat transfer characteristics, and temperature distributions under varying operating conditions. Furthermore, we explore the impact of design parameters and materials on the overall performance of solar stills. In addition to CFD analysis, this review paper emphasizes the importance of thermal investigations in understanding energy efficiency and heat distribution within solar still systems. We discuss experimental techniques employed to validate CFD results and evaluate the influence of environmental factors on system performance. Furthermore, we address the challenges faced in modeling and analyzing solar stills through CFD simulations and thermal investigations. By recognizing these limitations, we aim to provide researchers with valuable insights for improving modeling accuracy and developing more reliable predictions In conclusion, this review paper endeavors to shed light on the significance of CFD analysis and thermal investigations in the advancement of solar still technology. By harnessing the power of computational and experimental tools, solar stills can be further optimized, making significant strides towards sustainable water production and alleviating the burden of water scarcity on a global scale.

2. LITERATURE SURVEY

Thapar V et. al., [1], This paper emphasizes the importance of accurate modeling for optimizing wind turbine systems. It highlights the significant factors influencing wind turbine performance, such as wind speed distribution, hub height, and power output curves. The study conducts a comparative analysis of various modeling methods using an algorithm and references three commercially available wind turbines. The findings reveal that modeling approaches based on fundamental equations struggle to replicate real wind turbine behavior effectively. Simple models assuming a presumed power curve shape lack accuracy but perform satisfactorily at higher average wind speeds. However, modeling methods utilizing the actual power curve, developed through curve fitting techniques like the method of least squares and cubic spline interpolation, yield accurate results for turbines with smooth power curves. For turbines with less smooth power curves, the method of least squares emerges as the most suitable modeling approach. **Hong J-S et. al., [2],** This study examines how tidal currents affect wave energy in the western sea off Jeju Island. It finds that wave energy is strongly influenced by the relative direction of waves and currents, with energy transfer taking place between shorter and longer wave periods. Ocean-wave coupling increases model accuracy when compared to uncoupled models, which makes it beneficial for determining site selection and wave energy potential. **Shoeibi S, et. al., [3], This** research focuses on solar stills for converting salty water to fresh water. It emphasizes the need for economic and environmental analysis. The study compares various system designs and discovers that water production costs range from \$0.0014 to \$0.29 per liter. Solar stills combined with photovoltaic, thermal, and solar collectors produce the best CO_2 reduction results, with an estimated reduction of 1129.53 tons over their lifetime. This data assists researchers in developing low-cost, environmentally friendly solar stills. **Shoeibi S et. al. [4]** Recent research has focused on enhancing solar stills due to their cost-effectiveness and eco-friendliness. These improvements involve modifying design aspects and utilizing various methods like nanoparticles, thermoelectric heating, and solar collectors to increase water temperature. Simultaneously, techniques such as glass cooling and external condensers reduce condensation area temperatures. The best results were achieved with water glass cooling and PV/T, which improved water productivity sixfold over conventional solar stills. The lowest cost per liter was found in solar stills with external condensers, PCM, and wick material, at about \$0.011 per liter. Future research directions for hybrid techniques are also discussed. **Khosravi R et. al., [5]** This study analyzes microchannel heat sinks with wavy fins using a graphene-platinum/water nanofluid. It examines factors like wave amplitude, nanoparticle concentration, and Reynolds number, keeping heat flux constant. Results show reduced thermal entropy generation with increased input variables and highlight the importance of thermal entropy. An artificial neural network model is developed to predict entropy generation based on these factors. **Olia H et. al., [6**], The paper reviews the latest developments in the use of nanofluids as working fluids in parabolic trough collectors (PTCs). **Alanezi AA et. al., [7],** The study provides a numerical analysis of a DCMD system that accounts for different membrane unit inclinations and a 500–2000 Reynolds number range. In the work, a two-dimensional model based on the Navier-Stokes, energy, and species transport equations is solved using the finite volume method (FVM). The results show that the heat transfer coefficient increases as the Reynolds numbers increase, except for a 60° inclination angle. Additionally, a membrane slanted at a 90° angle (vertical membrane) and with a Reynolds number of 2000 may result in the lowest temperature differential. **Abd Elaziz et. al. [8],** The study uses Ensemble Random Vector Functional Link Networks (EnsRVFL) to predict the yield of active solar stills with nanoparticles, with the addition of Cu_2O and Al_2O_3 nanoparticles and the use of a suction fan resulting in higher yield. In terms of accuracy, the proposed EnsRVFL method outperforms standalone RVFL, with coefficient of determination (R^2) values ranging from 0.982 to 0.991 for EnsRVFL versus 0.942 to 0.978 for RVFL. **Sharshir et. al., [9],** The improved thermal, financial, and environmental results of a solar still using eco-friendly materials including floating coal, cotton fabric, and carbon black nanoparticles are presented in the research. In comparison to a conventional solar still, the modified solar still with cotton fabric over the coal and carbon black nanoparticles sprinkled on top demonstrated the largest gains in yield, energy efficiency, exergy efficiency, cost savings, and carbon emission reduction. **Safaei MR et. al., [10],** The goal of the project is to increase the productivity of a solar still for desalination applications by using phase-change materials (PCMs) made of graphene oxide (GO) distributed in paraffin. In comparison to utilising simply PCM, adding graphene oxide to paraffin lowers the melting temperature and increases solar still productivity by 25%. **Shoeibi S et. al. [11],** This paper focuses on mathematical modeling to find the ideal fin thickness for a heat sink in a thermoelectric solar still. It uses eight different cooling nanofluids with water as the base fluid, including nanoparticles like aluminum, alumina, titanium, copper, and more. The study assumes laminar flow across fins made of high thermal conductivity copper. Various nanofluid compositions and nanoparticle sizes are analyzed. The research also includes economic and environmental analyses of the thermoelectric solar still. The optimal volume fraction for nanofluids falls between 3.65% and 3.95%. The study reports a carbon dioxide mitigation of approximately 23.78 tons and 1.04 tons based on environmental and exergue environmental parameters, respectively, in the solar still. **Y.A.F. El-Samadony et. al., [12],** This research examines the theoretical performance of a stepped solar still with water film cooling over the glass cover as well as the impact of film cooling parameters on the daily productivity of the still. The presence of glass cover water film cooling can boost the daily productivity of stepped stills by roughly 8.2%, and the right set of film cooling parameters can have a big impact on output. **Shoeibi S et.al., [13],** The purpose of the study was to use porous media, nano-enhanced phase change material (NEPCM), and nano-enhanced absorption (nano-coated) to improve the efficiency of solar desalination. The productivity of solar stills was raised by 55.8% and 49.5%, respectively, with the addition of CuO and Al2O3 nanoparticles in the NEPCM, while the rate of water production was increased by about 5.7% with CuO nanocoating. sun desalination is a practical and sustainable way to use sun energy to produce drinking water. The performance of solar stills was strengthened by the use of porous media, nano-enhanced phase transition material, and nano-coated surfaces, which raised their output and water production rate. **Mahian O, et. al., [14**], The study delves into the exploration of a solar still equipped with a heat exchanger, employing nanofluids, with a keen focus on aspects such as freshwater production, energy efficiency, and exergy efficiency. Diverse sets of experimental data are meticulously gathered, encompassing varying nanoparticle volume fractions, nanoparticle dimensions, water depths, and nanofluid mass flow rates, all within the context of differing weather conditions. What becomes evident from the findings is the substantial influence of weather conditions, notably the intensity of solar radiation, on the overall performance of the solar still. To comprehensively assess the impact of nanofluids, a mathematical model is not only conceived but also rigorously validated through the integration of the experimental data. The analysis unfolds an intriguing revelation: employing a heat exchanger at temperatures below 60°C does not confer significant advantages. However, the introduction of nanofluids into the system results in a noteworthy performance enhancement of approximately 10%. Conversely, at higher temperatures, the utilization of a heat exchanger proves advantageous, although the augmentation achieved with nanofluids is relatively modest, hovering around 1%. **Raju VR et. al., [15],** The distillate yield and functionality of an active solar still under the coastal climate of India are examined in this research in relation to the impact of connecting flat plate collectors (FPCs) in series. The studies were place at Kakinada, India, over the course of 24 hours in the summer. According to the findings, compared to a still with a single FPC, utilising two FPCs connected in series boosts the distillate yield by 41% and the still efficiency by 0.47%. The distillate yield is enhanced by 89% when three FPCs are connected in series, although the still's efficiency drops by 0.48% as a result of the larger radiation area. The achievement of high-water temperature is responsible for the rise in distillate yield. **Omidi B, et. al., [16**], In this research, a novel humidification-dehumidification desalination (HDD) system is presented. It consists of a hybrid solar collector and two working fluids, ethylene glycol and air. The system is outfitted with thermoelectric cooling modules, and it is tested in Tehran, Iran, in local weather conditions. Investigations are conducted into how various factors, such as collector outlet air velocity, volumetric flow rates of ethylene glycol and saline water, and the usage of thermoelectric cooling, affect the system's efficiency and performance. The experimental outcomes demonstrate improvements in water production with higher collector outlet air velocity and higher ethylene glycol and saline water volumetric flow rates. A smaller gap between the glass cover and the absorber plate increases productivity as well. **Patel SK, et.al, [17],** In order to enhance the desalination process and create drinkable water from tainted river water, the study provides an integrated system that combines a modified solar still with a partial cooling coil condenser. The system's maximum daily yields throughout the summer and winter seasons, respectively, were 11,499 ml/day and 8,212 ml/day, with system efficiencies of 76.66% and 54.74%. The produced water's physicochemical characteristics were found to be in good compliance with EPA and WHO requirements. The cost of acquiring potable water, according to economic study, was Rs. 0.63 per litre and Rs. 2.06 per kWh. **Jathar LD et. al., [18**], The paper reviews the factors affecting the performance of solar stills and provides researchers with methods to enhance their productivity. It highlights the importance of solar radiation intensity, solar still type, temperature, water depth, absorber plate design, reflector plates, gap distance, and sun tracking system in improving the productivity of solar stills. **Rubio E, Porta MA et. al., [19],** The report includes an experimental investigation into the effects of shade and evaporative cooling of the glass cover on the performance of a solar still enhanced with an evacuated tube collector and a heat exchanger. The experiment results demonstrate a considerable improvement in freshwater productivity with partial shade and cooling of the glass cover, which is how the study hopes to improve the productivity and efficiency of the solar still. **Bhargva M, Yadav A et. al.**

[20], The goal of the study is to raise the temperature differential between the water and glass cover of a solar still by simultaneously applying thermoelectric cooling and heating. In comparison to a passive solar still, this innovation increased productivity by 2.32 times and produced 76.4% efficiency, according to trials carried out in Tehran, Iran.

3. SOLAR STILS MATHEMATICAL CALCULATIONS

Solar stills are devices that utilize solar energy to purify or desalinate water through the processes of evaporation and condensation. The design and operation of a solar still involve various mathematical calculations to estimate parameters such as water production rate, heat transfer, and system efficiency. Here are some key mathematical calculations commonly associated with solar stills:

3.1. Water Evaporation Rate:

The rate at which water evaporates from the solar still's surface can be calculated using the following equation:
Evaporation Rate=Solar Intensity×Absorptivity×AreaEvaporation Rate=Solar Intensity×Absorptivity×Area
Where:

- Solar Intensity: Solar energy incident on the solar still surface (W/m^2)
- Absorptivity: Absorptivity of the solar still surface
- Area: Surface area of the solar still (m^2)

3.2. Heat Loss from Solar Still:

The heat loss from the solar still can be estimated using the heat transfer equation:
$Qloss=U\times A\times \Delta T$
Where:

- Qloss: Heat loss (W)
- U: Overall heat transfer coefficient ($W/m^2\cdot K$)
- A: Surface area of the solar still (m^2)
- ΔT: Temperature difference between the inside and outside of the solar still (K)

3.3. Distillate Production Rate:

The rate of distilled water production can be determined by calculating the volume of condensed vapor:
Distillate Production Rate=Condensation Rate/Density
Where:

- Condensation Rate: Rate at which vapor condenses (kg/s)
- Density: Density of water (kg/m^3)

3.4. Solar Still Efficiency:

The following equation can be used to determine the solar still's efficiency:

Efficiency=Useful Output (Distillate) Energy/Input Solar Energy×100
Where:

- Useful Output Energy: Energy content of the distilled water (J)
- Input Solar Energy: Solar energy incident on the solar still (J)

3.5. Temperature Profile:

Mathematical modelling of the temperature profiles within the solar still involves solving heat transfer equations and energy balances for different components.

These calculations are generally based on principles of heat transfer, fluid dynamics, and thermodynamics. It's important to note that the actual mathematical formulations can become more complex depending on the specific design, assumptions, and considerations of the solar still system. Additionally, experimental validation and iterative refinements may be necessary to accurately predict the performance of solar stills.

4. CONCLUSIONS

In conclusion, the integration of computational fluid dynamics (CFD) analysis and thermal investigations has proven to be instrumental in advancing the design, performance optimization, and understanding of solar still technology. This review paper has provided a comprehensive overview of the contributions of these methodologies to the field of solar stills, highlighting their significance in addressing global water scarcity and promoting sustainable water production. In essence, this review paper has shed light on the transformative potential of integrating CFD analysis and thermal investigations in the realm of solar stills. By harnessing the power of these tools, researchers and engineers are poised to drive innovation, optimize system performance, and contribute to a more sustainable and water-secure future. As the demand for fresh water continues to grow, the insights garnered from this review hold the promise of significantly shaping the trajectory of solar still technology and its global impact.

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