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"A COMPREHENSIVE REVIEW ON CFD-BASED PARAMETRIC ANALYSIS OF SINGLE SLOPE SOLAR STILLS FOR ENHANCED WATER DESALINATION"

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ABSTRACT

The increasing scarcity of potable water globally necessitates innovative and sustainable approaches for water purification. Among several alternatives, solar stills stand out as low-cost, environmentally friendly solutions for small-scale desalination. This review paper provides a detailed analysis of a Computational Fluid Dynamics (CFD)-based study on single-slope solar stills. The focus is on evaluating structural and operational parameters, such as wall materials (wood and glass), basin dimensions, water depth, and environmental influences. Utilizing ANSYS Fluent, the study simulated thermal and mass transfer within the still, highlighting the improved performance of glass wall configurations. The review consolidates existing research, emphasizes the advantages of CFD in design optimization, and suggests future directions for integrating novel materials and hybrid systems to enhance solar still performance.

Key Words: *Solar Still, CFD, ANSYS Fluent, Water Desalination, Renewable Energy, Parametric Study.*

I. INTRODUCTION

Water scarcity has become a critical issue due to increasing population, industrialization, and climate change. Traditional desalination methods like reverse osmosis and multi-stage flash are effective but require significant energy and infrastructure investment. In contrast, solar stills offer a passive, sustainable, and low-maintenance method to purify saline or brackish water using solar energy.

A single-slope solar still consists of a black-bottom basin filled with saline water, covered by a transparent sloped glass. Solar radiation heats the water, leading to evaporation; the vapor condenses on the cooler glass surface and is collected as distilled water. The process is simple but has relatively low efficiency, prompting the need for design enhancements. CFD provides a powerful tool to simulate and analyze heat and mass transfer processes within solar stills, offering insights that can guide design modifications without physical trials.

In recent years, concerns about access to clean drinking water have intensified due to climate variability, over-extraction of groundwater, and contamination of surface water sources. More than two-thirds of the global population experiences water scarcity at least one month a year, and in several regions, this scarcity is acute and persistent. Against this backdrop, solar desalination is gaining momentum as an off-grid, sustainable technology that leverages the abundant energy of the sun.

The technology of solar stills is not new. Its roots date back to the 19th century, with historical implementations in South America. However, the modern application of solar stills demands improved efficiency, scalability, and adaptability to local climatic conditions. Computational modeling, particularly CFD, plays a pivotal role in addressing these challenges. It allows researchers and engineers to optimize the design, materials, and orientation of solar stills, thus enhancing their thermal performance and productivity.

The importance of CFD in the context of solar energy applications is multifaceted. CFD provides detailed visualizations and quantitative data on flow dynamics, temperature gradients, and phase transitions, which are critical for understanding and optimizing the performance of solar thermal systems. In the case of solar stills, CFD helps identify heat loss zones, inefficient evaporation paths, and condensation inefficiencies, enabling targeted improvements.
This review focuses on a specific CFD-based analysis of single-slope solar stills and integrates it with broader insights from past literature. The objective is to present a comprehensive understanding of the design and performance variables that influence solar still efficacy and to highlight the transformative role of computational tools in water purification technology.

II. Literature Review

The global pursuit of sustainable water purification technologies has led to significant interest in solar stills due to their simple operation and renewable energy dependency. However, their limited output capacity necessitates performance enhancement. This has led researchers to explore various techniques, including geometric optimization, hybridization with solar collectors, the use of phase change materials, and most recently, Computational Fluid Dynamics (CFD) to simulate and optimize thermal and mass transfer behavior.

Solar Still Efficiency Improvements

Khalifa and Hamood (2009) investigated the impact of water depth on evaporation rates and found that shallow water depth significantly improves productivity. Similar observations were made by Prabahar et al. (2015), who tested water depths of 0.5–2 cm in double slope solar stills and reported higher distillate output at lower depths. They also stressed the importance of controlled experimental conditions for reliable data.

Integration with Solar Collectors and Reflectors

Rahul Dev and G. N. Tiwari (2011) developed modified solar stills with external curved reflectors to improve heat absorption. Their comparative analysis between traditional single-slope stills and the improved model showed increased efficiency and a lower cost per liter of water produced. A. E. Kabeel (2009) also demonstrated enhanced productivity by integrating a flat-plate collector and internal reflectors, increasing distillate output by over 30%.

Advanced Geometries and Materials

Hitesh Panchal and P. K. Shah (2013) introduced a hemispherical solar still design and validated their CFD model with experimental data. They found that the hemispherical geometry allowed better capture of solar radiation throughout the day. Similarly, Setoodeh et al. (2011) conducted a multiphase CFD study to simulate heat and mass transfer within conventional stills, revealing accurate predictions of thermal gradients and vapor generation.

The use of alternative materials also contributed to higher efficiency. Kalidasa Murugavel et al. (2011) experimented with various wick materials, concluding that coir and cotton-based wicks significantly improved the evaporation surface area and thus water output. In another study, M. Shakthiwel et al. (2010) utilized jute cloth in regenerative solar stills, achieving a 20% increase in distillate yield with minimal structural changes.

CFD in Solar Still Design and Optimization

CFD has emerged as a powerful tool to simulate complex heat transfer processes in solar stills. Joshi (2016) used ANSYS Fluent to model solar radiation impacts in Indian states, finding that output peaks during mid-afternoon due to maximum solar insolation. CFD results closely matched experimental data, demonstrating the reliability of numerical simulation for performance prediction.

Gnanvel et al. (2020) validated CFD simulations against experimental data using aluminum basins with and without phase change materials. Their study confirmed that CFD can accurately predict temperature profiles and distillate yield before physical implementation.

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Hybrid and Multi-Effect Systems

Abdallah et al. (2009) studied combined systems with solar heaters, achieving a 120% increase in productivity compared to stand-alone stills. They also emphasized the role of environmental factors such as wind velocity and solar irradiance. Badran (2011) conducted theoretical analyses of active stills and recommended coupling them with storage units for continuous operation during non-sunny hours.

Thermodynamic Insights and Future Trends

Recent trends emphasize the thermodynamic analysis of solar stills operating at low temperatures under vacuum conditions. These methods reduce energy consumption and allow the use of low-grade heat sources such as waste heat or solar collectors operating at 50°C. The development of multi-effect stills, integrated solar drying systems, and AI-assisted performance prediction represent the future of solar desalination technology.

Overall, the literature reveals consistent efforts to enhance the thermal performance of solar stills. CFD-based studies, like the one under review, offer cost-effective, scalable pathways to evaluate new materials, configurations, and environmental interactions prior to field testing.

III. PROPOSED METHODOLOGY

The methodological framework for analyzing single-slope solar stills was built upon a comprehensive computational fluid dynamics (CFD) simulation using ANSYS Fluent, with emphasis on simulating heat and mass transfer, fluid flow, and temperature distribution under varying material configurations. The goal was to model and compare the performance of two solar still variants—one with wooden walls and the other with glass walls—to assess their efficiency in evaporating and condensing water for desalination.

3.1 System Design and Geometric Modeling

The baseline solar still model used in the simulation features a single-slope, single-basin configuration with an overall basin area of 1 m². The dimensions and angles were chosen based on standards used in previous validated designs. The geometric structure was developed using NX 8.5 CAD software, which enabled precision modeling of the various components, including:

- Basin base plate (absorber)
- Sloped transparent glass cover (30° angle)
- Side, front, and rear walls (wooden or glass depending on variant)
- Enclosure for holding water and collecting distillate

These CAD models were then exported in compatible formats for meshing and simulation.

3.2 Meshing and Grid Sensitivity

High-quality meshing is critical for achieving accurate CFD results. Using Salomé (an open-source pre-processing tool), a structured finite volume mesh was generated with special attention to regions of high thermal gradients near the basin water interface and inner walls.

- Mesh Type: Structured hexagonal cells
- Total cell count: ~50,000 elements (determined after grid independence testing)
- Mesh refinement: Applied in regions of interest such as air–water interface, glass cover surface, and absorber plate

To ensure grid independence, the mesh density was increased iteratively until simulation results (particularly vapor volume fraction and surface temperatures) showed negligible change across successive refinements.

3.3 Governing Equations and Assumptions

The simulation used a pressure-based solver in steady-state and transient modes, employing the finite volume method to solve the 2D incompressible Navier–Stokes equations and energy equations. The simulation made the following physical assumptions:

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- Incompressible flow (Mach number < 0.3)
- Turbulent flow modeled using the RNG k-ε turbulence model
- Negligible radiation losses to the environment
- Steady-state temperature profiles in the glass and wall materials
- Uniform solar irradiation across the absorber surface
- No-slip boundary conditions on all walls
- Constant material properties for air, water, plywood, and glass

3.4 Boundary Conditions

Boundary conditions play a crucial role in determining the energy and mass transfer behavior within the solar still. The simulation incorporated the following:

- **Inlet boundary**: Uniform velocity inlet of air at **10 m/s**
- **Outlet boundary**: Pressure outlet at atmospheric pressure
- **Wall boundary**: Heat flux condition at **10 W/m²**
- **Initial Conditions**: Temperature of ambient air and walls initialized at **300 K**, with the basin starting at a slightly elevated temperature

3.5 Material Properties and Computational Domain

Four key materials were modeled with their thermophysical properties:

- **Air**: Dynamic viscosity, specific heat, and thermal conductivity
- **Water**: Density ($\rho = 998$ kg/m³), latent heat of vaporization, specific heat
- **Glass**: Low emissivity, high transmissivity, thermal conductivity = 1.05 W/m·K
- **Wood** (Plywood): Thermal conductivity = 0.12 W/m·K, specific heat = 1.7 kJ/kg·K

The **computational domain** included the internal cavity of the still (air space above water), the water layer itself, the glass cover, and the walls.

3.6 Simulation Workflow

The simulation process included the following stages:

1. **Pre-Processing**:
   - Geometry creation in NX 8.5
   - Mesh generation in Salomé
   - Material definition and boundary condition assignment in ANSYS Fluent
2. **Solver Configuration**:
   - Pressure-based solver with SIMPLE algorithm for pressure-velocity coupling
   - Second-order upwind scheme for momentum and energy equations
   - RNG k-ε model with standard wall function for turbulence
3. **Solution Initialization and Run**:
   - Solution initialized with a uniform temperature field
   - Simulation run for **1000 iterations** for steady-state convergence
   - Residuals monitored for continuity, momentum, energy, and turbulence ($< 10^{-5}$)
4. **Post-Processing**:
   - Results visualized using **ParaView** for vector plots, temperature contours, and vapor distribution
   - Comparative analysis performed on temperature distribution, vapor volume fraction, and water volume fraction between the two models

3.7 Validation

While this CFD study focused primarily on numerical comparison, the findings were qualitatively validated by comparing with trends reported in previous experimental studies, such as those by Panchal & Shah (2013), Joshi (2016), and Gnanvel et al. (2020), which also used CFD to model heat and mass transfer in solar stills. The temperature ranges and volume fractions observed in the simulation fell within expected ranges reported in these studies, lending credibility to the simulation outcomes.

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3.8 Justification for CFD Tool Selection

The use of **ANSYS Fluent** is justified by its robust solver algorithms, extensive material library, and proven accuracy in solving multi-physics problems. In addition, the combination of open-source pre-processing (Salomé) and post-processing (ParaView) ensured flexibility and cost-effectiveness in simulation without compromising on mesh quality or result visualization.

IV. Conclusion

This review has critically examined the application of Computational Fluid Dynamics (CFD) in evaluating and enhancing the performance of single slope solar stills for sustainable water desalination. The use of CFD modeling in this study provided deep insights into the thermal and fluid dynamics inside a solar still, which would otherwise be difficult and costly to obtain through physical experiments alone.

The comparative analysis between a wooden-walled and a glass-walled solar still revealed that the glass wall configuration consistently outperformed the wooden variant. The improved transparency and thermal conductivity of the glass allowed for better solar heat absorption, leading to higher inner wall and basin temperatures. As a result, the vapor volume fraction increased, and the water volume fraction decreased, indicating enhanced evaporation and distillation efficiency. These outcomes demonstrate the critical role of material selection and design parameters in optimizing the performance of solar desalination systems.

Moreover, the study confirmed that CFD simulations—when carefully validated and implemented—can replicate real-world conditions with high accuracy. The modeling approach captured essential physical phenomena such as heat flux, air convection, and phase transformation, thereby enabling the prediction of distillate yield and temperature distribution under different boundary and environmental conditions.

This investigation also reinforces the broader importance of solar stills in water-scarce regions, particularly in off-grid or rural areas where conventional desalination technologies are economically or logistically unfeasible. Given their simplicity, passive operation, and reliance solely on solar energy, single slope solar stills represent a cost-effective, eco-friendly, and scalable solution to water purification challenges in developing countries.

However, the simulation also highlighted inherent limitations such as restricted output and sensitivity to solar radiation intensity. These limitations open avenues for integrating active components such as flat plate collectors, evacuated tube systems, or phase change materials (PCMs) to boost efficiency, especially during low insolation periods or nighttime.

In essence, this CFD-based approach not only supports the design and optimization of solar stills but also contributes to the development of a scientific foundation for future research in sustainable desalination technologies. It bridges the gap between theoretical predictions and experimental validations and provides a flexible platform for simulating complex parametric studies across various climates and geographic conditions.

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