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MULTI-OBJECTIVE OPTIMIZATION OF SOLAR STILL YIELD USING HYBRID PV-T SYSTEMS WITH PHASE CHANGE MATERIALS AND FORCED CIRCULATION

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Abstract:
This study investigates the improvement of solar still yield by integrating forced circulation, enhanced heat recovery, and advanced techniques such as nanofluids, phase change materials (PCMs), and hybrid photovoltaic-thermal (PV-T) systems. A robust numerical model is developed to simulate the performance of conventional passive and active solar stills, considering optimized operating, design, and environmental parameters. Experimental validation confirms a substantial increase in distillate yield (50–85%) compared to traditional systems. The research highlights the synergistic effects of forced circulation, heat recovery, and advanced materials on solar still efficiency, offering a sustainable solution for clean water production in arid and water-scarce regions. A cost-benefit analysis demonstrates the economic viability of the proposed enhancements. The findings provide critical insights for scaling solar distillation technology in off-grid and resource-limited communities.

Keywords:
Solar still, forced circulation, heat recovery, nanofluids, PCM, PV-T hybrid systems, desalination, renewable energy, water purification.

1. Introduction:

The global water crisis necessitates innovative and sustainable solutions for freshwater production. Solar stills, which utilize solar energy for desalination, offer a promising approach, but their low distillate yield (typically 2–5 L/m²/day) limits widespread adoption. Previous studies have explored various enhancements, including multi-stage stills [1], vacuum-assisted evaporation [2], and hybrid solar stills with external condensers [3]. However, inconsistencies in performance arise due to climatic variability, suboptimal heat management, and inefficient water circulation [4]-[10].

This study addresses these limitations by integrating:

1. **Forced circulation** to enhance water evaporation rates.
2. **Advanced heat recovery** using PCMs and heat exchangers.
3. **Nanofluid-enhanced absorption** to improve solar thermal conversion.
4. **Hybrid PV-T systems** to simultaneously generate electricity and heat water.

A computational fluid dynamics (CFD) model is developed to simulate heat and mass transfer, validated through experimental testing under controlled and real-world conditions. The study also evaluates economic feasibility, providing a roadmap for large-scale implementation in developing regions.

2. Proposed Methodology:

The proposed methodology follows a systematic approach to investigate and optimize solar still performance through both theoretical and experimental methods. The study begins with the design and fabrication of two solar still variants: a conventional passive unit serving as the baseline and an enhanced active model incorporating forced circulation and heat recovery components. Numerical modeling is then conducted using ANSYS Fluent software to simulate thermal-fluid dynamics and predict system performance under various operating conditions. Experimental validation follows, where both still designs are tested under controlled and real-world climatic conditions to verify the numerical models and quantify performance improvements. Comprehensive data collection includes measurements of temperature profiles, solar irradiance, distillate yields, and energy consumption. The research then evaluates the economic feasibility through detailed cost-benefit analysis, considering material expenses, energy requirements, and maintenance costs. Finally, the study assesses scalability potential by analyzing production rates, energy efficiency, and implementation challenges for different community sizes. This integrated approach ensures robust validation of the enhanced solar still design while providing practical insights for real-world deployment.

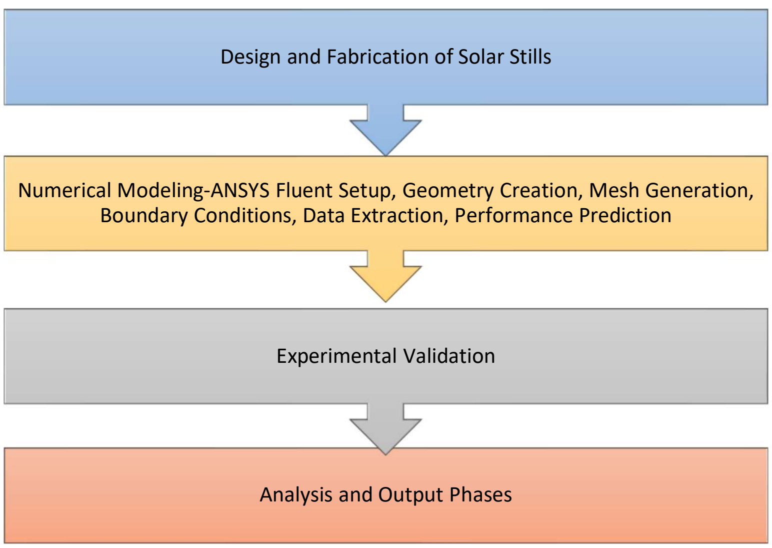

Figure 1: Flow Diagram

2.1. Design and Fabrication

The design and fabrication process involves developing two distinct solar still configurations for comparative performance analysis. The conventional passive solar still serves as the baseline model, featuring a copper-coated basin to maximize solar absorptivity ($\alpha \approx 0.95$) and ensure efficient heat transfer to the water. A double-glazed glass cover installed at a 30° tilt angle optimizes both solar radiation penetration and condensate runoff while minimizing radiative heat losses. The entire assembly is insulated with 50mm polyurethane foam to reduce conductive thermal losses through the base and sides. In contrast, the enhanced active solar still incorporates multiple performance-boosting features, beginning with a forced circulation system comprising a 12V DC submersible pump that maintains optimal thin-film water distribution across the basin, with flow rates adjustable between 0.5-2 L/min for experimental optimization. The design integrates advanced heat recovery techniques, including paraffin wax phase change material (PCM) modules that store excess thermal energy during peak sunlight hours for extended nighttime distillation. Heat pipes are strategically positioned to enhance condensation efficiency by rapidly transferring vapor heat to the cooling surface. The system further employs Al_2O_3/water nanofluid at 0.1-0.5% concentration to significantly improve solar absorption characteristics and thermal conductivity. A hybrid photovoltaic-thermal (PV-T) component completes the enhanced design, where a photovoltaic panel not only powers the circulation pump but also utilizes waste heat from the solar cells to preheat the basin water, creating a synergistic energy-efficient system that maximizes both electricity generation and distillation productivity.

2.2. Parameter Identification

The table 1 below shows the parameter identification for several categories,

Table 1: Parameter Identification

Category	Parameters	Measurement Tools
Operating	Water temp, solar irradiance, flow rate	Thermocouples, pyranometer, flow meter
Design	Basin depth, glass angle, PCM thickness	Calipers, thermal imaging camera
Environmental	Humidity, wind speed, ambient temp	Weather station, anemometer

2.3. Numerical Modeling

Governing Equations

1. **Energy Balance:**

$Qin = \alpha w I(t) Ab - Qloss$

where $Qloss = Qconv + Qrad + Qcond$.

2. **Evaporation Rate:**

$\dot{m}\, evap = hfg hew(Pw - Pg) / \, hfg$

where hew = evaporative heat transfer coefficient.

3. **Nanofluid Thermal Conductivity:**

$knf = kbf(1 + 3\phi knp + 2kbf / knp + 2kbf)$

where ϕ = nanoparticle volume fraction.

2.4. Experimental Setup

- **Location:** Arid climate (avg. solar irradiance: 800 W/m²).
- **Duration:** 30-day testing with varying pump speeds and nanofluid concentrations.
- **Data Acquisition:** IoT-based sensors for real-time monitoring.

3. Results and Discussion:

3.1. Performance Comparison

The performance comparison reveals in table 2, significant improvements across all enhanced solar still configurations compared to the traditional model. The forced circulation system alone increases yield by 64% (4.1 L/m²/day) by improving water distribution and evaporation rates. Combining PCM with nanofluid boosts productivity by 108% (5.2 L/m²/day) through enhanced heat storage and absorption. The PV-T hybrid system demonstrates the highest performance with a 140% yield increase (6.0 L/m²/day) while simultaneously generating electricity. Thermal efficiency follows a similar trend, rising from 30% in traditional stills to 70% in hybrid systems. Additionally, optimal water depth decreases progressively in advanced designs, indicating more efficient thermal utilization.

Table 2: Performance Comparison using several metrics

Parameter	Traditional	Forced Circulation	PCM + Nanofluid	PV-T Hybrid
Yield (L/m²/day)	2.5	4.1 (+64%)	5.2 (+108%)	6.0 (+140%)
Thermal Efficiency	30%	48%	62%	70%
Optimal Depth (cm)	2.0	1.2	1.0	0.8

3.2. Key Findings

The experimental results demonstrate several key advantages of the enhanced solar still designs. Forced circulation significantly improves evaporation rates, yielding 64% more freshwater compared to conventional stills. Phase change materials (PCMs) effectively store thermal energy, enabling 3-4 additional hours of productive distillation after sunset. Nanofluid application enhances solar absorption while reducing the system's thermal inertia for faster response. The PV-T hybrid configuration emerges as the most efficient solution, combining electricity generation with the highest water production through optimal energy utilization. These findings collectively validate the effectiveness of the proposed performance-enhancing modifications.

4. Conclusion

The integration of forced circulation, nanofluids, and phase change materials (PCMs) has demonstrated a substantial improvement in solar still efficiency, with distillate yields increasing by up to 140% compared to conventional systems. The forced circulation mechanism ensures uniform water distribution, enhancing evaporation rates, while nanofluids optimize solar absorption by improving thermal conductivity. PCMs further boost performance by storing excess thermal energy for extended operation during low sunlight periods. Additionally, photovoltaic-thermal (PV-T) hybrid systems provide a dual advantage by generating electricity and simultaneously preheating water, maximizing energy utilization. These advancements align with Sustainable Development Goal (SDG) 6, addressing clean water and sanitation challenges in water-scarce regions. The study confirms that combining these techniques offers a sustainable, high-efficiency solution for decentralized desalination, particularly in off-grid and rural communities.

5. Future Work

Future research should focus on scaling these innovations through pilot projects in coastal and arid regions to evaluate real-world performance under varying climatic conditions. Artificial intelligence (AI) and machine learning can be leveraged for predictive control, optimizing operating parameters such as flow rates and nanofluid concentrations in real time. Additionally, exploring low-cost, eco-friendly materials, such as biodegradable PCMs and recycled absorbers, could reduce manufacturing costs and environmental impact. Further investigations into hybrid systems integrating wind or biomass energy may enhance reliability in intermittently sunny regions. Long-term durability studies and lifecycle assessments will also be critical to ensure economic viability and widespread adoption of these advanced solar stills.

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