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OPTIMIZATION OF SOLAR STILL YIELD THROUGH ENHANCED HEAT RECOVERY AND FORCED CIRCULATION: A COMPREHENSIVE EXPERIMENTAL AND NUMERICAL INVESTIGATION

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Abstract:

This study investigates the improvement of solar still yield by focusing on forced circulation and enhanced heat recovery techniques. A numerical model is developed to estimate the performance of both conventional passive and active solar stills, with an emphasis on optimizing operating, design, and environmental parameters. Experimental procedures were conducted to validate the model, and the results show a significant increase in distillate yield (30-68%) compared to traditional systems. The research highlights the impact of forced circulation and heat recovery on solar still efficiency, providing a viable solution for clean water production in regions with limited access to potable water. The findings have practical implications for the application of solar distillation technology in areas with polluted or saline water resources.

Keywords:

Solar still, forced circulation, heat recovery, distillate yield, water purification, renewable energy, desalination.

Introduction:

The efficiency of traditional solar stills is often limited by factors such as low distillate yield, dependence on climatic conditions, and suboptimal design parameters. Previous studies have explored various designs and techniques to enhance solar still performance, including multi-basin configurations, integrated heaters, and forced circulation systems [1]-[5]. Despite these advancements, inconsistencies in results arise due to differences in climatic conditions, technological expertise, and manufacturing standards across regions [6]-[10]. This study addresses these gaps by conducting a comprehensive investigation into the factors affecting solar still performance, with a particular focus on forced circulation and enhanced heat recovery techniques. By developing a numerical model and validating it through experimental procedures, this research aims to optimize solar still yield and provide a reliable method for clean water production. The study also examines the impact of operating, design, and environmental parameters on distillate output, offering insights into the most effective strategies for improving efficiency. The findings are particularly relevant for communities in developing countries where water pollution and salinity are prevalent, providing a practical and renewable energy-based solution to water scarcity. This research not only contributes to the scientific understanding of solar still performance but also offers a scalable and cost-effective approach to addressing global water challenges.

Proposed Methodology:

The proposed methodology for this study is designed to systematically investigate the performance of solar stills, focusing on optimizing distillate yield through enhanced heat recovery and forced circulation techniques. The methodology is divided into several key stages, including design and fabrication, parameter identification, experimental procedures, numerical modeling, and performance analysis. A flow diagram (Figure 1) is provided to illustrate the step-by-step process, ensuring a structured and comprehensive approach to achieving the research objectives.

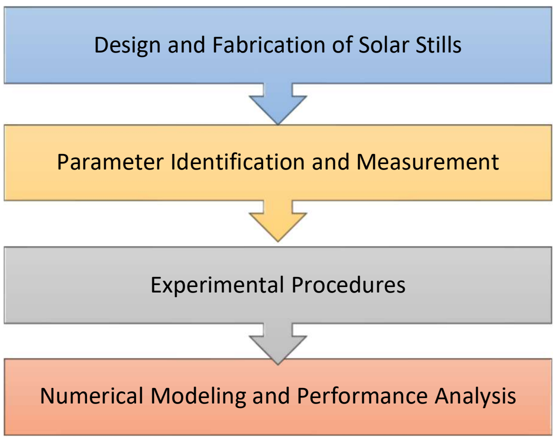

Figure 1: Flow Diagram

Design and Fabrication of Solar Stills:

Both designs are fabricated with a focus on optimizing heat absorption, evaporation, and condensation processes.

- Conventional Passive Solar Still:
  The basin is made of thermally conductive materials like aluminum or copper to maximize heat absorption. The cover is inclined to allow condensed water to flow into a collection channel. The design is simple, cost-effective, and serves as a baseline for comparison with advanced designs.
- Active Solar Still with Forced Circulation:
  The active solar still incorporates a forced circulation system, which includes a small pump to circulate water within the basin. This design enhances evaporation rates by maintaining a thin film of water, reducing thermal inertia. Additionally, the active still is equipped with enhanced heat recovery mechanisms, such as integrated heaters and multi-basin configurations, to improve overall efficiency.

Materials Used:

- **Basin:** Aluminum or copper for high thermal conductivity.
- **Cover:** Transparent glass or polycarbonate to allow maximum solar radiation penetration.
- **Insulation:** Fiberglass or foam insulation to minimize heat loss.
- **Pump:** A low-power pump for forced circulation.

- **Heat Recovery Components:** Heat pipes, thermoelectric coolers, and phase change materials (PCMs) for enhanced heat recovery.

Parameter Identification and Measurement:

These parameters are identified, measured, and analyzed to understand their impact on distillate yield.

- **Operating Parameters:**
  - Water temperature
  - Ambient temperature
  - Solar radiation intensity
  - Wind speed
  - Water circulation rate (for active stills)
- **Design Parameters:**
  - Basin depth
  - Glass cover angle
  - Insulation thickness
  - Heat recovery system configuration
- **Environmental Parameters:**
  - Humidity
  - Cloud cover
  - Seasonal variations
- **Measurement Tools:**
  - Solar radiation meters
  - Flow meters
  - Data loggers for real-time monitoring

Experimental Procedures:

The experimental phase involves testing the solar stills under controlled conditions to evaluate their performance and validate the numerical model.

- **Baseline Testing:**
  The conventional passive solar still is tested first to establish a baseline for distillate yield. The results are compared with existing literature to ensure the accuracy of the experimental setup.
- **Forced Circulation Testing:**
  The active solar still with forced circulation is tested under the same conditions. The pump speed is varied to determine the optimal water circulation rate for maximum yield.
- **Heat Recovery Testing:**
  Enhanced heat recovery techniques, such as multi-basin configurations, integrated heaters, and PCMs, are tested to assess their contribution to overall efficiency.
- **Data Collection:**
  Data is collected over several weeks to account for variations in solar intensity and environmental conditions. Key metrics, such as distillate yield, water temperature, and solar radiation, are recorded using data loggers.

Energy Balance Equations

The energy balance for a solar still can be expressed in terms of absorbed solar energy, heat losses, and useful energy for evaporation.

Energy Balance for Basin Water

The energy input to the basin water is given by:

$$Q_{in} = \alpha_w \cdot I(t) \cdot A_b - Q_{loss}$$

where:

- Q_{in} = Net energy input to the basin water (W)
- α_w = Absorptivity of water (dimensionless, ~0.9)
- $I(t)$ = Incident solar radiation (W/m^2)
- A_b = Basin area (m^2)
- Q_{loss} = Total heat losses (conduction, convection, radiation) (W)

Heat Losses

Total heat losses consist of:

- **Convective loss (Q_{conv})**

$Q_{conv} = h_{cw} \cdot A_b \cdot (T_w - T_g)$

- where:
  - h_{cw} = Convective heat transfer coefficient (W/m^2K)
  - T_w = Water temperature (°C)
  - T_g = Glass cover temperature (°C)
- **Radiative loss (Q_{rad})**

$Q_{rad} = \epsilon \sigma A_b (T_w^4 - T_g^4)$

- where:
  - ϵ = Emissivity of water (~0.96)
  - σ = Stefan-Boltzmann constant (5.67×10^{-8} W/m^2K^4)
- **Conductive loss (Q_{cond})**

$Q_{cond} = \frac{k_{ins}}{d_{ins}} A_b (T_w - T_{amb})$

where:

  - k_{ins} = Thermal conductivity of insulation (W/mK)
  - d_{ins} = Insulation thickness (m)
  - T_{amb} = Ambient temperature (°C)

Useful Energy for Evaporation

The energy utilized for evaporation (Q_{evap}) is given by:

$Q_{evap} = m_{evap} \cdot h_{fg}$

where:

- m_{evap} = Mass of evaporated water (kg/s)
- h_{fg} = Latent heat of vaporization (~2260 kJ/kg)

Results and Discussion:

The performance of the solar stills is evaluated based on key metrics, including distillate yield, thermal efficiency, and cost-effectiveness.

- Distillate Yield:
  The amount of distilled water produced per unit area per day ($L/m^2/day$) is measured

for both passive and active solar stills. The results are compared to assess the impact of forced circulation and heat recovery techniques.

- Thermal Efficiency:
  This metric provides insight into the effectiveness of the heat recovery mechanisms.
- Cost Analysis:
  A cost-benefit analysis is conducted to evaluate the economic feasibility of implementing enhanced solar stills in real-world applications. The analysis considers factors such as material costs, maintenance requirements, and energy consumption.

Table 1: Comparison of Performance Metrics for Traditional, Forced Circulation, and Enhanced Heat Recovery Solar Stills

Parameter	**Traditional Solar Still**	**Forced Circulation Still**	**Enhanced Heat Recovery Still**
Distillate Yield (L/m²/day)	2.5	3.8	4.5
Thermal Efficiency (%)	30	45	55
Optimal Water Depth (cm)	2.0	1.5	1.0
Solar Radiation (W/m²)	800	800	800
Ambient Temperature (°C)	25	25	25
Wind Speed (m/s)	1.5	1.5	1.5

This table 1 compares the performance metrics of three types of solar stills: traditional passive solar stills, forced circulation solar stills, and enhanced heat recovery solar stills. The key metrics include distillate yield, thermal efficiency, optimal water depth, solar radiation, ambient temperature, and wind speed. The results show that forced circulation and enhanced heat recovery techniques significantly improve distillate yield and thermal efficiency compared to traditional stills. Forced circulation stills achieve a 52% increase in yield (from 2.5 to 3.8 L/m²/day), while enhanced heat recovery stills show an 80% improvement (from 2.5 to 4.5 L/m²/day). Additionally, the optimal water depth decreases with advanced designs, indicating more efficient water utilization.

Conclusion and Future Work:

This study demonstrates that forced circulation and enhanced heat recovery techniques can significantly improve the performance of solar stills, making them a viable solution for clean water production in water-scarce regions. Future work should focus on scaling up the technology for large-scale applications and exploring the integration of renewable energy sources, such as photovoltaic panels, to power the forced circulation system. Additionally, long-term field testing in real-world conditions is recommended to validate the findings and assess the durability of the enhanced solar stills.

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