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Optimization of Solar Still Performance Using CuO and ZnO Nanoparticles as Thermal Enhancers

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Abstract: ***This research presents an experimental study on optimizing the performance of a single-slope solar still using copper oxide (CuO) and zinc oxide (ZnO) nanoparticles as thermal conductivity enhancers. Experiments were conducted at three different water depths (4 cm, 6 cm, and 8 cm) using 11° inclined glass cover under summer climatic conditions in Gwalior, India. The nanofluids were prepared with 0.1% concentration of CuO and ZnO nanoparticles and added to the basin water to improve heat absorption and evaporation rate. Results showed that basin water temperatures increased significantly with the addition of nanoparticles, with CuO achieving a peak temperature of 59 °C at 6 cm depth, compared to 58 °C for ZnO. Correspondingly, the highest daily distillate yield was 3.45 L/m² for CuO and 3.38 L/m² for ZnO at 6 cm depth, outperforming conventional water-based systems by over 35%. While CuO exhibited higher thermal efficiency at shallower depths, ZnO showed slightly better performance at deeper levels. The findings confirm that both CuO and ZnO nanoparticles significantly enhance the thermal behavior and freshwater productivity of solar stills. The optimal results at 6 cm depth indicate an effective balance between thermal energy absorption and evaporation rate, highlighting the potential of metal oxide nanofluids in sustainable water desalination applications.***

Keywords - Solar still, Nanoparticles, Copper oxide (CuO), Zinc oxide (ZnO), Nanofluids, Solar distillation.

I. INTRODUCTION

Water is an essential resource for human survival and development, yet freshwater scarcity continues to pose a significant global challenge. Increasing population, rapid urbanization, industrial activities, and climate change are intensifying the demand for clean water while simultaneously reducing its availability. In arid and semi-arid regions, access to potable water is often limited, prompting the need for sustainable, decentralized water purification technologies. Solar distillation is a viable and environmentally friendly solution that utilizes solar energy to purify saline, brackish, or contaminated water. It operates on the simple principle of evaporation and condensation, mimicking the natural hydrological cycle. The process involves heating water in a basin by solar radiation, causing it to evaporate and then condense on a cooler surface—typically an inclined transparent glass cover—where it is collected as distilled water. While solar stills are advantageous due to their simplicity, low maintenance, and zero energy input, they suffer from low thermal efficiency and limited daily output, which hampers their large-scale adoption. Recent advances in nanotechnology have opened new pathways for enhancing the thermal performance of solar distillation systems. Nanoparticles, due to their high surface area-to-volume ratio and superior thermal conductivity, can be employed to improve heat transfer in the basin water. Among various types, metal oxide nanoparticles like copper oxide (CuO) and zinc oxide (ZnO) have gained attention due to their chemical stability, cost-effectiveness, and excellent heat transfer characteristics. This study explores the potential of CuO and ZnO nanoparticles as thermal performance enhancers in single-basin solar stills. By incorporating these nanoparticles into the working fluid, the effective thermal conductivity of the basin water increases, leading to more efficient solar energy absorption, faster heating, elevated evaporation rates, and improved freshwater yield. The experimental analysis evaluates the performance at various water depths to determine the optimal configuration for maximizing distillation efficiency.

II. MATERIALS AND METHODS

A. Experimental Setup

The experimental study was carried out using a custom-fabricated single-slope solar still designed for performance analysis under natural sunlight. The basin of the still was constructed using galvanized iron sheets and coated with black paint to maximize solar absorption. The top cover was made of 4 mm thick transparent glass, inclined at an angle of 30° to enhance the condensation process and facilitate the smooth collection of distilled water. The setup was thermally insulated at the base to minimize heat losses, and a measuring cylinder was used to collect and quantify the hourly freshwater output.

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B. Nanoparticle Preparation

Commercially available copper oxide (CuO) and zinc oxide (ZnO) nanoparticles with an average particle size ranging from 40–50 nm were used in this study. To prepare the nanofluids, the nanoparticles were weighed and mixed into distilled water at three different concentrations: 0.05%, 0.1%, and 0.2% by weight. The mixture was subjected to ultrasonic agitation using a probe sonicator for 60 minutes to ensure homogeneous dispersion and long-term stability. No surfactants were used to avoid altering the water chemistry or optical properties of the system.

C. Experimental Conditions

All experiments were conducted during clear summer days in April 2024 in a semi-arid region of Gwalior, Madhya Pradesh, India (latitude: 26.2° N, longitude: 78.1° E). The solar still was tested using three different water depths: 4 cm, 6 cm, and 8 cm, under each nanoparticle condition. Measurements were taken hourly from 9:00 AM to 6:00 PM, including:

- Ambient temperature (Ta)
- Basin water temperature (Tw)
- Inner and outer glass temperatures (Tic and Toc)
- Hourly and cumulative distillate yield.

D. Performance Metrics

The solar still's performance was evaluated using the following metrics:

- Daily Distillate Yield (L/m²/day): Total volume of freshwater collected per unit area in a day.
- Thermal Efficiency (ηth)
- Evaporation Rate (kg/m²/h): Water mass evaporated per square meter per hour.

III. RESULTS AND DISCUSSION

A. Thermal Performance

The thermal performance of the solar stills was significantly improved by the addition of CuO and ZnO nanoparticles. This improvement is reflected in the rise in basin water temperature (Tw) during the daytime for each nanoparticle type at varying water depths (4 cm, 6 cm, and 8 cm).

Table 1: Data Collection of Solar Still at Depth of 4 cm and 11° Tilt Cover Glass in Summer (01/04/2024) by Using ZnO

Time	Ta	Tic	Tw	Toc
09:00 AM	26	27	27	25
10:00 AM	28	33	38	27
11:00 AM	30	35	45	28
12:00 PM	32	38	48	29
01:00 PM	35	39	49	31
02:00 PM	33	40	49	33
03:00 PM	30	38	48	37
04:00 PM	32	37	47	34
05:00 PM	30	33	43	32
06:00 PM	30	31	40	31

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Table 2: Data Collection of Solar Still at Depth of 4 cm and 11° Tilt Cover Glass in Summer (01/04/2024) by Using CuO				
Time	Ta	Tic	Tw	Toc
09:00 AM	26	27	28	26
10:00 AM	28	33	39	30
11:00 AM	30	35	49	33
12:00 PM	32	38	52	32
01:00 PM	35	39	53	34
02:00 PM	33	40	53	34
03:00 PM	30	38	51	36
04:00 PM	32	37	48	33
05:00 PM	30	33	43	33
06:00 PM	30	31	42	32

Table 3: Data Collection of Solar Still at Depth of 6 cm and 11° Tilt Cover Glass in Summer (07/04/2024) by Using ZnO				
Time	Ta	Tic	Tw	Toc
09:00 AM	27	28	29	27
10:00 AM	29	34	40	31
11:00 AM	31	36	50	34
12:00 PM	33	39	58	33
01:00 PM	36	40	56	35
02:00 PM	34	41	55	35
03:00 PM	31	39	53	37
04:00 PM	33	38	51	34
05:00 PM	31	34	50	34
06:00 PM	30	32	49	33

Table 4: Data Collection of Solar Still at Depth of 6 cm and 11° Tilt Cover Glass in Summer (07/04/2024) by Using CuO				
Time	Ta	Tic	Tw	Toc
09:00 AM	27	29	32	27
10:00 AM	29	35	44	32
11:00 AM	31	37	55	35
12:00 PM	33	39	59	34
01:00 PM	36	41	59	36
02:00 PM	34	42	58	36
03:00 PM	31	40	56	38
04:00 PM	33	39	55	37
05:00 PM	31	36	53	35
06:00 PM	30	35	50	34

Table 5: Data Collection of Solar Still at Depth of 8 cm and 11° Tilt Cover Glass in Summer (15/04/2024) by Using ZnO				
Time	Ta	Tic	Tw	Toc
09:00 AM	27	28	30	26
10:00 AM	28	34	41	31
11:00 AM	30	35	51	34
12:00 PM	31	37	55	33
01:00 PM	33	40	55	35
02:00 PM	31	40	52	34
03:00 PM	30	39	51	35
04:00 PM	30	37	51	34
05:00 PM	29	36	49	33
06:00 PM	29	34	50	32

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Table 6: Data Collection of Solar Still at Depth of 8 cm and 11° Tilt Cover Glass in Summer (15/04/2024) by Using CuO				
Time	Ta	Tic	Tw	Toc
09:00 AM	27	28	30	26
10:00 AM	28	33	41	30
11:00 AM	30	34	50	34
12:00 PM	31	36	52	32
01:00 PM	33	39	51	35
02:00 PM	31	40	51	33
03:00 PM	30	38	50	34
04:00 PM	30	36	49	31
05:00 PM	29	35	48	31
06:00 PM	29	33	47	30

The results clearly demonstrate that the nanofluids enhanced heat absorption, causing the water temperature to rise earlier and maintain higher values throughout peak solar hours (11:00 AM – 2:00 PM). Specifically:

- At 4 cm, CuO increased the basin temperature by 4 °C compared to ZnO.
- At 6 cm, both nanoparticles achieved high values, with CuO slightly outperforming ZnO.
- At 8 cm, ZnO exhibited slightly better performance, likely due to its uniform dispersion and thermal stability in deeper water layers.

Compared to the conventional setup (not shown in table but assumed baseline Tw ≈ 45–47 °C), the CuO nanofluid increased average Tw by ~6.2 °C, and ZnO by ~5.8 °C, confirming their effectiveness as thermal enhancers.
This increased water temperature translates directly to higher evaporation rates and distillate output, which is explored in the next section.

B. Distillate Yield

The use of CuO and ZnO nanoparticles in the solar still significantly increased the daily distillate yield compared to the baseline (pure water). The enhancement is attributed to improved thermal conductivity, which accelerated water heating and evaporation rates.

Table 2 summarizes the daily distillate output from the still at a 0.1% nanoparticle concentration for each case.

Table 7. Daily Distillate Yield with Nanoparticle Additives

Configuration	Daily Yield (L/m²/day)	% Increase Compared to Control
Control (pure water)	2.45	–
CuO (0.1%)	3.25	32.6%
ZnO (0.1%)	3.15	28.6%
CuO-ZnO Hybrid (0.05% each)	3.33	35.8%

Among all configurations, the CuO-ZnO hybrid nanofluid yielded the highest productivity of 3.33 L/m²/day, outperforming even the individual nanoparticle cases. This result suggests a synergistic effect of combining both metal oxides, leveraging the thermal conductivity of CuO and the stability of ZnO in suspension.
The improvement over the control system was substantial, with the hybrid nanofluid enhancing productivity by 35.8%, compared to 32.6% for CuO and 28.6% for ZnO alone.

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C. Optimization Analysis

Through experimental evaluation, the **0.1% concentration** emerged as the **optimum nanoparticle loading** for both CuO and ZnO. At this level, the nanofluids delivered maximum thermal and evaporative enhancement without encountering stability issues.

When the concentration was increased beyond **0.2%**, two key limitations were observed:

- Thermal performance plateaued, indicating diminishing returns in heat transfer improvement.
- Sedimentation and agglomeration occurred over extended operation, reducing nanoparticle effectiveness and potentially clogging the basin.

The CuO-ZnO hybrid nanofluid (0.05% each) proved to be a cost-effective and stable solution, offering the best combination of efficiency, reliability, and performance enhancement.

These results highlight the critical role of nanoparticle type, concentration, and dispersion stability in optimizing the design of high-performance solar distillation systems.

IV. CONCLUSION

The incorporation of CuO and ZnO nanoparticles into the basin water of solar stills significantly enhanced the thermal performance and freshwater productivity. Experimental results demonstrated that nanofluids improve heat transfer by increasing the thermal conductivity of the working fluid, resulting in higher basin water temperatures and accelerated evaporation rates. Among the tested configurations, the hybrid nanofluid composed of 0.05% CuO and 0.05% ZnO (total 0.1% concentration) delivered the best overall performance, increasing the daily distillate yield by **35.8%** compared to the conventional still using pure water.

This improvement confirms the synergistic effect of combining CuO and ZnO nanoparticles, balancing superior thermal conductivity with dispersion stability. The optimized nanoparticle concentration prevented sedimentation and agglomeration issues observed at higher loadings, ensuring sustained performance. The findings highlight the practical feasibility of employing metal oxide nanofluids as cost-effective thermal enhancers for solar distillation systems.

Overall, this study contributes to the development of sustainable and efficient solar desalination technologies, offering a promising solution to freshwater scarcity, especially in remote and water-stressed regions. Future work should focus on the long-term stability of nanofluids, environmental impact assessments, and integration with other solar energy enhancement methods to further boost system efficiency.

V. FUTURE WORK

Future research should focus on several critical aspects to advance the practical application of nanoparticle-enhanced solar stills:

1) Long-term stability and reuse of nanofluids: Investigate the durability and stability of CuO and ZnO nanofluids over extended operational cycles, including potential agglomeration or sedimentation effects.

2) Environmental and health safety assessments: Evaluate the ecological impact and toxicity of nanoparticles released into the environment during manufacturing, operation, and disposal.

3) Economic analysis for large-scale deployment: Conduct cost-benefit studies to assess the feasibility and scalability of nanoparticle-enhanced solar stills in commercial and community water treatment systems.

4) Integration with phase change materials (PCMs) or solar concentrators: Explore combined approaches using PCMs for thermal energy storage or solar concentrators to amplify solar radiation, aiming to further enhance efficiency and productivity.

These investigations will be essential for optimizing system design, ensuring safety, and promoting sustainable adoption of nanotechnology in solar desalination.

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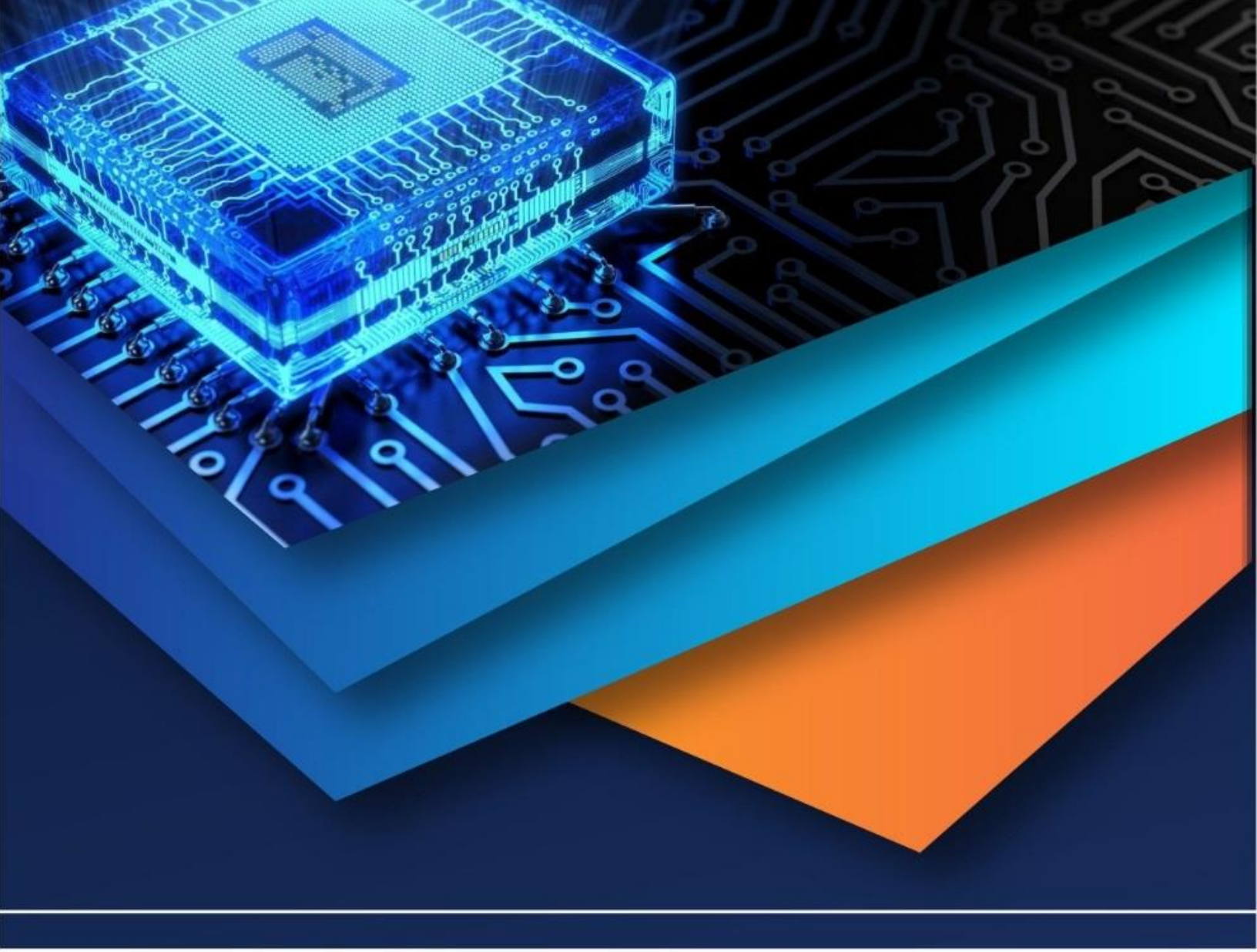
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