Performance of single slope solar stills: a comparative study of conventional and modified stills with nanofluid and reflectors

Vishwanath Kumar Panangipalli[1*], *Mani* Saraswathi Hallika Pindiprolu[2], *Divya* Maharana[1], *Naveen* Ghanapuram[1]

[1]Department of Mechanical Engineering, Anurag University, Hyderabad, Telangana, India
[2]Department of Mechanical Engineering, G. Narayanamma Institute of Technology and Science (for Women), Hyderabad, Telangana, India.

Abstract. Nature has naturally desalinated water for centuries through the process of solar heating, where oceanic water transforms into vapor and then returns to Earth as freshwater precipitation. Freshwater is vital for sustaining life, but growing populations, industrial expansion, and increased agricultural production have created a rising demand for it. Desalination has emerged as a potential solution to address water scarcity. Existing desalination technologies fall into two categories: single-phase processes like reverse osmosis and electro-dialysis, and phase-change processes such as distillation and solar stills. While single phase processes provide freshwater, some rely on non-renewable fossil fuels for energy, indirectly contributing to greenhouse gas emissions. Solar distillation, in contrast uses renewable energy from the sun, offers a promising and sustainable alternative for freshwater production. Solar stills employ shallow water basins within enclosed structures, as moisture collects on the interior surface of the glass cover, cooled by natural airflow. In this study, two 250 X 250 mm^2 single slope solar stills were designed, one conventional and the other modified with nanofluids and reflectors. The experiment assessed their performance in Hyderabad's typical climate, with a glass cover slope of 17.45°. Both stills operated with a 1 cm water depth (500 ml) to observe the water distillate output. Readings were recorded for two different nanofluid concentrations (considering 0.08% and 0.1% of Cerium Oxide nanoparticles by volume mixed with water) allowing for a comparison of their cumulative hourly yields and effectiveness in increasing freshwater output.

Keywords. Solar desalination, Solar still, Nanoparticles, Nanofluids, Reflectors.

1 Introduction

The solar still used for distilling the salty/brackish water, employs a process reminiscent of the hydrologic cycle's evaporation and condensation [1]. Utilizing green energy from solar radiation, the still facilitates the transformation of impure water into freshwater. The process

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[*] Corresponding author: vishwanathmech@anurag.edu.in

involves evaporation of the filled basin water by the solar radiation passing through the glass cover. Subsequently, water vapor condenses on an inclined glass cover, and the resulting “contamination-free droplets” due to gravity fall and get collected into a “distillate trough” [2,3]. Consequently, solar still productivity relies entirely on “incident solar radiation” [4]. Abdallah et al. [5] explored three modified configurations for a "single basin single slope solar still," aiming to enhance its performance. These adaptations included: (a) integration of 'internal reflective mirrors,' (b) substitution of the stepped water basin with a flat basin design, and (c) inclusion of a 'sun tracking mechanism' into the stepped solar still. These alterations significantly boosted the distilled water production of the single-slope solar still. Experimental results indicated a 30% enhancement in thermal efficiency with the incorporation of internal mirrors. Moreover, the utilization of a step-wise basin improved performance by up to 180%. Combining the stepwise basin with the sun tracking system yielded the highest thermal efficiency, averaging at 380%. Dev and Tiwari [6] conducted experiments to evaluate the effectiveness of single slope passive solar stills with varying inclinations of the condensing cover (15º, 30º, 45º) at a water depth of 0.04m. Results showed that the glass cover tilted at 45º yielded the highest water output in both summer and winter conditions. During summer, investigating the performance of the solar still at a 30º angle, experiments were conducted with water depths ranging from 0.04 m to 0.16 m, with the most favorable outcomes observed at 0.04 m depth. At a 15° inclination and water depths of 0.01 m and 0.04 m, the optimal output was achieved at 0.01 m water depth. Velmurugan [7] conducted experiments on a single basin solar still, introducing enhancements such as fins, sponges, and wicks to augment evaporation and elevate distilled water production. These improvements resulted in productivity gains of up to 45.5%, 15.3%, and 29.6%, respectively, compared to a standard solar still. The maximum deviation between theoretical predictions and experimental analyses was found to be 10%, indicating close alignment. Further enhancement of the wick-type solar still involved positioning a reflector or flat mirror above it to enhance productivity. This resulted in a 25% increase in distillate output during summer and a 10% increase during winter, achieved by directing sunlight onto the evaporating wick using the bottom reflector. Moreover, adding a charcoal absorber quickens the rate of evaporation, although floating wick solar still produces the highest output when compared to other kinds [8]. Stepped and weir stills yield 60–80% more distillate than traditional stills do. When the location's latitude angle and the glass inclination angle coincide, maximum productivity is attained. In addition, the weir-type continues to be more productive than the stepped type. These results highlight the efficiency of stepped and weir stills in increasing the amount of distillate produced, especially when they are in line with regional factors such latitude and inclination angles [9]. Sharma and Modi [10] employed various techniques to improve the performance of a Spherical solar still. They did experiments on the still in combination with parabolic reflector, which led to improved performance. In addition, the authors used Jute on the basin for effective water absorption. Omaara et al. [11] conducted an extensive review of various solar stills with internal and external reflectors. The authors reported that tilting the reflectors according to the Sun movement would enhance the distillate yield throughout the day irrespective of the climatic condition.

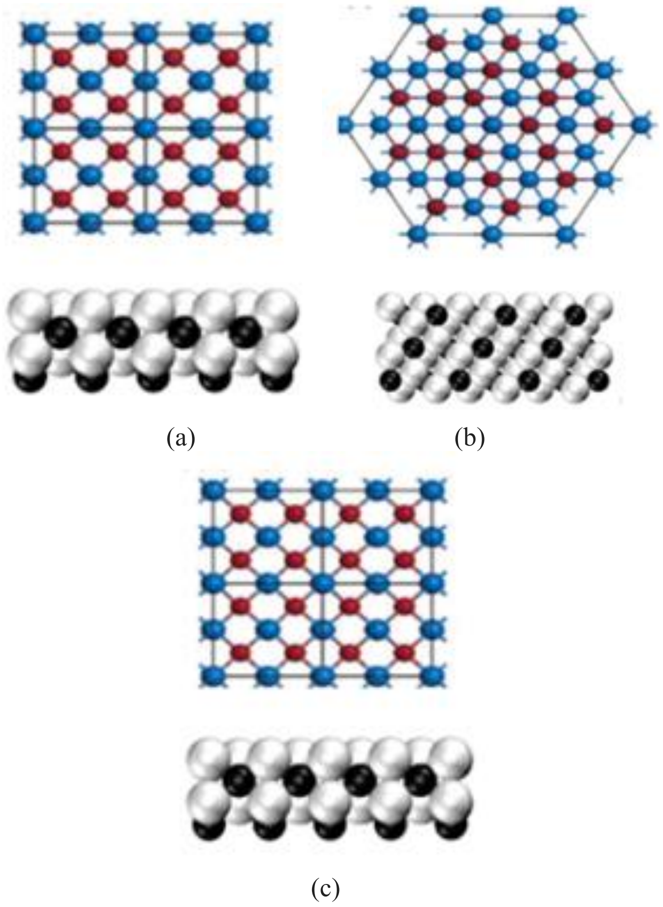
Nanofluids Application in Solar Stills. Operating solar still with nanofluids is one of the innovative ways of enhancing distillate productivity. Nanofluid is a suspension of nanoparticles in the base fluid. Due to the higher thermal conductivity properties of these nanoparticles, the nanofluid has better heat absorption and enhanced evaporation rates compared to conventional stills. Kabeel et al. [12] compared the efficiency of the conventional solar still with that of the still incorporated with nanofluid under vacuum. They used copper oxide (CuO) and aluminum oxide (Al_2O_3) particles of thermal conductivities 76.5 and 46 W/m-K respectively. The authors reported an efficiency increase of 133.64%

and 125% for Al_2O_3 and 93.87% and 88.97% for CuO with and without the fan respectively. In addition, Kabeel et al. [13] studied the performance of solar stills with nanofluids along with external condensers. They reported an efficiency increase of 116% as compared to conventional still. Elango et al. [14] compared the single slope still performance with different nanoparticles Al_2O_3, Zinc Oxide (ZnO), and Tin Oxide (SnO_2). The results indicate an increase in the distillate output of 29.95%, 12.67% and 18.63% with these respective nanoparticles as compared to conventional still. Elfasakhany et al. [15] in their experiments, employed CuO along with paraffin wax as a phase change material (PCM). They compared the still performance under three cases - with only CuO, with only PCM, and with PCM-CuO particles. It was reported that the first and second case led to an efficiency increment of 125% and 106%. Similarly, Rufuss et al. [16] combined PCM with CuO nanoparticles and reported 60% increase in the distillate output. Elavarasi et al. [17] investigated the performance of two stills, one with paraffin wax and the other with a combination of silicon oil and CuO nanoparticles. The authors reported a 25% increase in distillate output using combined configuration. Nazari et al. [18] examined the performance of a single slope solar still employing CuO nanoparticles along with thermoelectric cooling channels. It was reported that 0.08% CuO nanoparticles led to an 81% increase in the yield and 80.6% improvement in the efficiency. Behura et al. [19] performed tests with CuO nanoparticles and paraffin wax in a solar still with a corrugated absorber plate with a basin area of 0.25 m^2. Varying the nanoparticles in weight concentrations of 0.1%, 0.2%, and 0.3%, the authors found daily distillate yields of 440 ml, 455 ml, and 510 ml respectively. A maximum increase of 62.74% fresh water production was reported by the authors. Somanchi et al. [20] explored the usage of two distinct PCMs in a single slope solar still experiment: magnesium sulphate hexahydrate and a combination of sodium sulphate and titanium oxide (TiO_2) nanoparticles. Results indicated that the combination of sodium sulphate and titanium oxide nanoparticles exhibited lower efficiency compared to magnesium sulphate hexahydrate. Dsilva et al. [21] conducted a numerical analysis on a solar still incorporating nanoparticles and latent heat storage material. Utilizing paraffin wax and titanium oxide nanoparticles, the study found that using titanium oxide with paraffin wax raised the still's daily output to 6.6 l/m^2, which is 88% more than conventional solar still setups. Sathyamurthy et al. [22] focused on a stepped solar still coated in black paint with fumed silica nanoparticles. Concentrations ranging from 10% to 40% were tested, revealing a 27.2% increase in output with 10% nanoparticle concentration compared to normal black paint. Although no significant effect on output was observed with a concentration increase beyond 20%, higher concentrations still demonstrated improved performance. Panchal et al. [23] conducted experiments on a stepped solar still using Magnesium oxide and Titanium oxide nanoparticles at concentrations ranging from 0.1% to 0.2%. Magnesium oxide at 0.1% concentration resulted in a 33.33% increase in fresh water output, while Titanium oxide at the same concentration produced a 4.1% increase. Higher concentrations, particularly for Magnesium oxide, led to even greater fresh water output, highlighting the impact of thermal conductivity and specific heat capacity on still performance.

The current study aims to follow a similar approach in utilizing nanofluids to enhance the performance of solar stills. Cerium oxide nanofluids, in particular, exhibit superior thermal conductivity compared to conventional fluids [24]. This characteristic facilitates improved heat transfer within the solar still, leading to higher temperatures and increased evaporation rates.

2 Materials and Methodology

Cerium Oxide Nanoparticles belong to the lanthanide metals group on the periodic table. In its oxide form, cerium adopts a fluorite structure. Even at the nanoscale, cerium oxide nanoparticles maintain this fluorite structure, especially when they possess oxygen deficits. This results in the formation of cerium oxide nanoparticles with vacancies ($CeO_2{-}x$), providing sites for reactions involving reduction and oxidation. The catalytic activity of these nanoparticles in reactions is heavily influenced by the surface structure of the fluorite lattice. Optimal surfaces for catalytic activity on cerium oxide nano crystals include (100), (110), and (111), as depicted in Figure 1. Table 1 provides an overview of the thermophysical properties of Cerium Oxide nanoparticles.


(a) (b)

(c)

Fig. 1. (a) CeO_2 (110), (b) CeO_2 (111), and (c) CeO_2 (100) surfaces [24]

Table 1. Thermophysical of Cerium Oxide nanoparticles [25]

S.No	Properties	Value [units]
1	Density	7.132 [g/cm^3]
2	Specific heat	460 [J/kg-K]
3	Thermal conductivity	12 [W/m-K]

Preparation of Nanofluid. The chosen nanoparticle is cerium oxide, denoted as CeO_2 or Ceric Oxide. Fig. 2 shows the cerium oxide powder and it exhibits a pale-yellow color.

Fig. 2. Cerium Oxide extrapure AR, 99.99% nanoparticles

The mass of CeO_2 nanoparticles was determined through the utilization of a Digital Weighing Machine. To convert concentration values to milligrams per liter (mg/l), the conversion factor is established as follows: 1 part per million (PPM) is equivalent to 0.0001% or 1 mg/l. Fig. 3 and Fig. 4 shows the mass of cerium oxide considered to prepare volume concentrations of 0.08% and 0.1% respectively.

Fig. 3. Mass of CeO_2 for 0.08% concentration

Fig. 4. Mass of CeO_2 for 0.1 % concentration

To prevent the sedimentation of nanoparticles, a nanofluid preparation approach is employed, following a two-step method as illustrated in the accompanying figure. In this procedure, the initial step involves the measurement of the weight of CeO_2 nanoparticles mixed with a base fluid. Subsequently, the mixture is subjected to agitation for a duration of 5 minutes using a glass rod as seen in Fig. 5. This process aims to ensure a homogeneous distribution of CeO_2 within the fluid, thereby enhancing the stability and uniformity of the resulting nanofluid.

Fig. 5. Stirring the nanoparticles and base fluid (water) with a glass rod

Fig. 6. Sonication of the nanofluid mixture in an ultrasonic cleaner

Following the initial mixing step, the CeO_2-water mixture undergoes a further treatment by being placed in an ultrasonic sonicator for a duration of 1 hour as seen in the Fig. 6. Throughout this process, a consistent temperature of 50°C is maintained, and the sonicator operates at a speed of 1000 revolutions per minute (rpm). Subsequently, the treated mixture is transferred to a mechanical stirrer and stirred for an additional 10 minutes as seen in Fig.7.

Fig. 7. Mixing the nanofluid mixture in a mechanical stirrer

Following this, an additional base fluid is introduced into the system and stirred for an extended period of up to half an hour, with the stirring speed set at approximately 1200 rpm. This intricate sequence of ultrasonication, mechanical stirring, and prolonged stirring at a specific speed is designed to optimize the dispersion and stability of CeO_2 nanoparticles within the nanofluid, ensuring a uniform and well-mixed final product. Fig. 8 and Fig. 9 shows CeO_2-water nanofluid with 0.08% and 0.1% CeO_2 concentrations respectively.

Fig. 8. 0.08% concentration CeO_2 Nanofluid

Fig. 9. 0.1% concentration CeO_2 Nanofluid

Mirrors as Reflectors. Internal reflectors concentrate solar radiation and are ideal for weak sunlight or low temperatures. External reflectors redirect solar beams, especially useful for vertical absorber plates to recover vapor latent heat. Both internal and external reflectors boost solar irradiation on the basin liner, increasing productivity and distillate yield. Reflectors are most practical in areas with weak solar radiation and lower ambient temperatures [26]. Fig. 10 shows the solar still modified with Internal Reflectors.

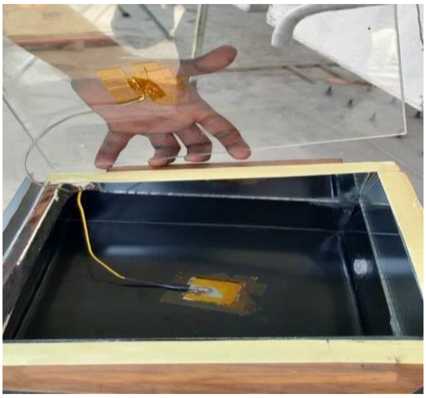


Fig. 10. Modified Still with Internal Reflectors

3 Results and Discussion

The experimental procedures were carried out over a three-day period, specifically from February 28th to March 2nd, within the SOLAR LAB. To ensure the proper dispersion of CeO_2 nanoparticles in the base fluid (either distilled or deionized water) and to prevent sedimentation, the nanofluid was prepared one day prior to the commencement of the experiments. Each day, the experiments were conducted during a seven-hour window, from 9:00 am to 5:00 pm.

On the first day of experimentation, thermocouples and RTDs (Resistance Temperature Detectors) were strategically connected to measure temperatures at four distinct locations: at the bottom of the basin (utilizing an RTD sensor), within the water itself, at the inner surface of the covering glass (employing an RTD sensor), and in the ambient atmosphere. For the initial experiment, 500 ml of tap water was carefully introduced into both the conventional and modified solar stills as seen in Fig. 11. To prevent any potential leaks, meticulous sealing of all edges and endpoints was executed.

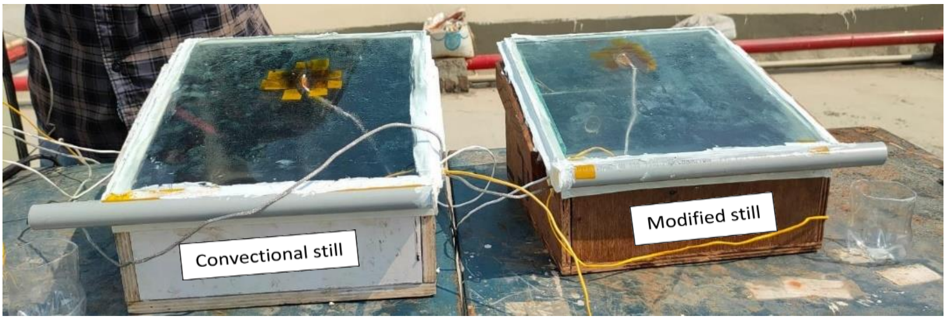


Fig. 11. Day 1 Experimentation: Conventional and modified solar stills with 500 ml water

Preparation for the subsequent day's experiment included the formulation of a CeO_2 nanofluid with a concentration of 0.08%, utilizing a two-step method. This nanofluid would be utilized in the Day 2 experimentation. On the second day of experimentation, the 0.08% CeO_2 nanofluid underwent a mixing process at 1200 rpm for 5 minutes to ensure homogeneity and prevent sedimentation of particles that may have settled at the base of the container. Following this mixing step, the prepared nanofluid was introduced into the modified solar still, equipped with reflectors. The water depth is set to 1 cm which translates to 500 ml in volume. Fig. 12 shows the conventional and modified stills for day 2 experimentation. Throughout the day (from 9:00 am to 5:00 pm), the pyranometer was connected to the server, facilitating continuous monitoring of humidity, solar radiation values, and the accumulation of distillate yield. Table 2 compares the hourly distillate yield from the conventional solar still and modified solar still (0.08% of CeO_2 and mirror reflectors).

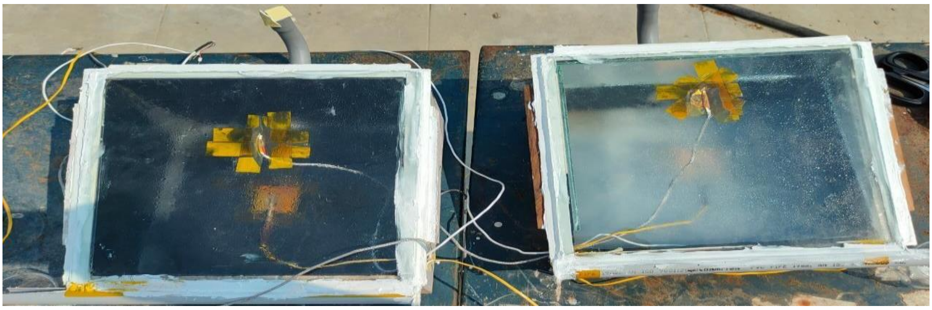


Fig. 12. Day 2 Experimentation: Conventional still with 500 ml water and modified still with 500 ml water and 0.08% CeO_2 nanoparticles

Table 2. Comparison of hourly distillate yield from the conventional and modified solar still on Day2

S. No	Time [hr]	Solar Intensity [W/m^2]	Ambient Temperature [^{o}C]	Distillate yield (conventional still) [ml]	Distillate yield (modified still) [ml]
1	9:00 am	644.40	32.74	0	0
2	10:00 am	789.31	34.55	5	7
3	11:00 am	870.25	35.98	13	18
4	12:00 noon	882.60	36.75	18	24
5	1:00 pm	737.53	36.53	20	30
6	2:00 pm	626.29	36.94	24	32
7	3:00 pm	382.11	35.02	30	38
8	4:00 pm	255.46	33.26	32	39

Simultaneously, in anticipation of the subsequent day's experiment, a 0.1% CeO_2 nanofluid was formulated using a two-step method. On the third day of experimentation, mirroring the procedures of the previous day, the 0.1% CeO_2 nanofluid underwent a 5-minute mixing procedure at 1200 rpm to uphold particle dispersion and prevent settling. Following this meticulous mixing, the well-prepared nanofluid was introduced into the modified solar still, which was equipped with reflectors. Fig. 13 shows the conventional and modified stills for day 3 experimentation.

Throughout the experimental period, extending from 9:00 am to 5:00 pm, continuous recordings were made for solar radiation and the hourly distillate yield. These measurements facilitated a thorough evaluation of the system's performance and provided insights into the influence of nanofluid concentration on the distillation process. Table 3 compares the hourly distillate yield from the conventional solar still and modified solar still (0.1% of CeO_2 and mirror reflectors).

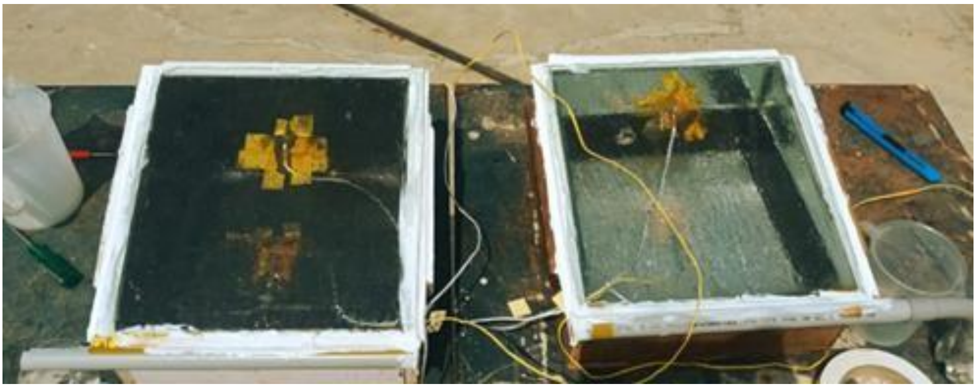


Fig. 13. Day 3 Experimentation: Conventional still with 500 ml water and modified still with 500 ml water and 0.1% CeO_2 nanoparticles

Table 3. Comparison of hourly distillate yield from the conventional and modified solar still on Day3

S. No	Time [hr]	Solar Intensity [W/m^2]	Ambient Temperature [^{o}C]	Distillate yield (conventional still) [ml]	Distillate yield (modified still) [ml]
1	9:00 am	514.53	29.07	0	0
2	10:00 am	700.25	33.04	5	4
3	11:00 am	835.59	35.89	7	10
4	12:00 noon	866.59	37.25	10	17
5	1:00 pm	853.82	37.32	15	30
6	2:00 pm	759.72	37.33	24	40
7	3:00 pm	584.02	37.46	26	44
8	4:00 pm	387.55	35.99	27	46

Fig. 14 shows the variation of ambient temperature with time on Day 2 and Day 3 of experimentation. Fig. 15 shows the variation of daily solar radiation intensity with time. Fig. 16 shows the variation of daily cumulative distillate yield with time for conventional and modified solar stills for Day 2 and Day 3 of experimentation. From Fig. 16, it can be observed that for a 1 cm depth of 500ml water with 0.1% CeO_2 concentration, the distillate productivity increased by 53.33% when compared with the conventional solar still. Furthermore, it can also be concluded that the concentration of CeO_2 increases the output level.

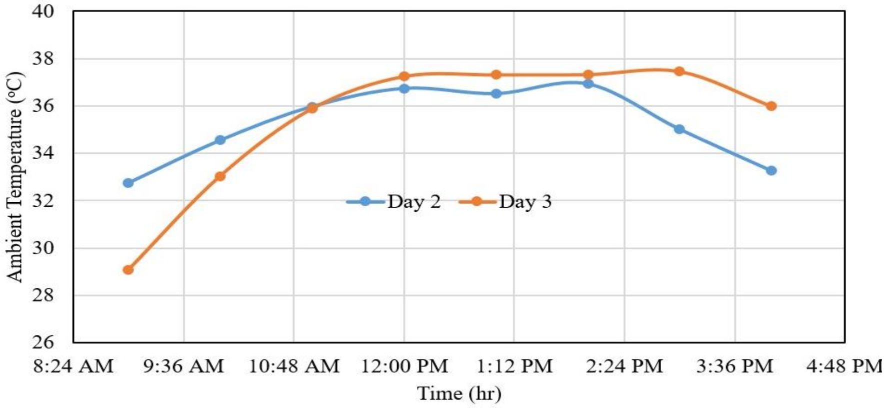


Fig. 14. Variation of daily ambient temperature with time

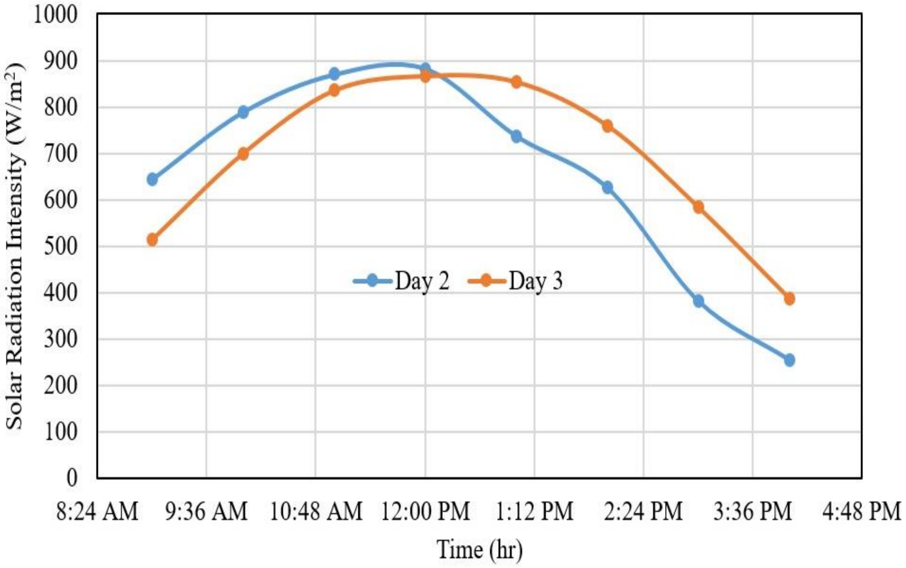


Fig.15. Variation of daily solar radiation intensity with time

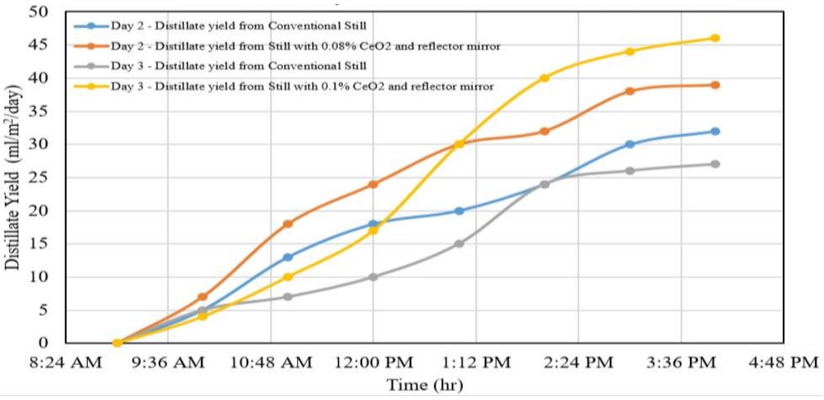


Fig.16. Variation of daily cumulative distillate yield with time

4 Conclusion

Solar stills, offering a simple and energy-efficient alternative, require minimal maintenance expertise and are versatile in various environmental settings. Key operational factors impacting solar still performance include wind speed, climate conditions, solar radiation, water depth, and cover material maintenance. Integrating solar stills with photovoltaic thermal systems and solar ponds aims to boost water yield. This study investigates solar stills to analyze factors enhancing efficiency, ultimately addressing water scarcity in underserved areas.

In a world emphasizing sustainable development for a green and healthy environment, renewable energy resources are crucial. Solar stills, powered by abundant, pollution-free green energy, can provide a solution to water contamination in deprived communities lacking access to electricity or conventional water treatment. Technological advancements hold promise for more effective water purification in the future.

Solar stills are particularly valuable for electrified rural areas facing water impurity challenges. This research involved designing two solar still prototypes, one conventional and the other equipped with internal reflectors, and conducting preliminary experiments in Hyderabad. Higher concentrations of CeO_2 nanoparticles in the nanofluid resulted in a significant 53.33% increase in hourly yield, demonstrating the potential for improved freshwater production.

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