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Performance Enhancement of Solar Still Using Lauric Acid–Al_2O_3 Nanoparticle-Enhanced PCM in a Tube-Based Absorber Design

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Abstract

Solar desalination is a common method which uses solar energy to make drinking water. Main advantages of solar stills are fresh water production is a renewable, sustainable, and economic activity. This green policy fulfills the necessary need in clean water, decreases environmental footprint, and offers financial benefits. The shape of the absorber in solar still system is very important because an inefficient absorber leads to reduced water productivity and thermal performance. This paper reviews absorber design which comprises container made out of tubes and packed with Phase Change Material (PCM) which is made up of lauric acid. The fact that PCM is encapsulated in still improves heat transfer and shows thermal energy especially when radiation changes occur. Moreover, thermal characteristics of phase change material was improved through the utilization of scattered aluminium oxide nanoparticles. Experiments were conducted for five consecutive sunny days under identical climatic conditions. The 0.9 wt% Al_2O_3 PCM achieved a maximum water temperature of 72°C and productivity of 2.65 $kg/m^2{\cdot}h$. Thermal efficiency improved up to 79%, representing a 44.2% enhancement over the conventional still. Three concentrations of aluminium oxide (0.3, 0.6 and 0.9 wt%) was tested. Studies have shown that lauric acid that contains 0.9 wt% aluminum oxide nanoparticles has a high thermal performance when compared to the lauric acid itself. The lauric acid/aluminium oxide nanoparticles at the concentration of 0.9 wt% showed improvement in temperature thermal efficiency and water productivity by about 44.2, 57, 71.2, 74 and 79 %.

Keywords: Phase change material, Thermal efficiency, Water productivity, Solar still, Lauric acid.

1. Introduction

The increased world population has led to some challenges of meeting the basic needs of the human race. Safe drinking water is a necessity and the lack of this water due to environmental degradation poses significant problems. In many regions of the world, freshwater is a scarce resource. A latent heat storage system using paraffin wax with aluminium oxide nanoparticles was integrated into solar stills. The phase change material enabled thermal energy retention under solar radiation, enhancing water productivity and energy efficiency during extended operation [1]. CFD-based thermal optimization of solar stills using aluminium oxide nanofluid film cooling was performed. Improved heat transfer reduced glass temperature, increasing fresh water productivity, thermal efficiency, and CO_2 mitigation in solar desalination systems [2]. A modified dish-type solar still incorporating aluminium oxide nanoparticle-enhanced phase change material was developed. Optimized water temperature distribution significantly improved water productivity and thermal efficiency compared with conventional solar stills [3]. Hybrid aluminium oxide–titanium dioxide nanofluid glass cooling was numerically studied for solar stills. Enhanced thermal optimization increased temperature gradients, leading to higher fresh water productivity, energy efficiency, and improved solar desalination sustainability [4]. A micro- and nano-sized aluminium oxide additives in solar stills. Nano-enhanced phase change materials achieved superior water productivity and thermal efficiency, highlighting aluminium oxide's role in solar thermal optimization [5].

A PCM-based solar still integrated with nano-additives was experimentally evaluated under varying solar radiation. Lauric acid and paraffin wax showed superior thermal optimization, resulting in improved water productivity and energy efficiency [6]. A machine learning–based thermal optimization approach using Random Forest was applied to predict solar still performance. Key parameters influencing water temperature, productivity, and thermal efficiency were identified, enabling rapid solar desalination optimization [7]. Numerical analysis of nanoparticle-enhanced phase change materials revealed aluminium oxide–based composites as effective thermal storage media. Faster melting improved heat utilization, supporting higher fresh water productivity in solar stills [8]. A basin water depth effects in PCM-based solar stills using lauric acid and nano-enhanced paraffin wax. Optimized water temperature distribution maximized fresh water productivity and reduced thermal losses in solar desalination [9]. Organic phase change materials including lauric acid were combined with pin fins to enhance thermal efficiency in solar stills. Improved heat transfer under solar radiation increased water productivity and reduced freshwater production costs [10].

This article enhanced thermal efficiency of solar still by adding use of phase change material at tubular container installed in the absorber plate. The PCM used was lauric acid and thermal property of PCM was improved with the use of aluminium oxide nanoparticles. The concentration of graphite/graphitic oxide nanoparticles was used at three different levels (0.3, 0.6 and 0.9 %). The analysis of experimental data evaluated such factors as temperature of water, water productivity and thermal efficiency of the solar still in comparison a traditional still system. Finally, the solar still with lauric acid with 0.9 % concentration of aluminium oxide nanoparticles exhibited good thermal performance as compared to other system setups of a still system.

2. Materials and Methods

2.1. Blending of Lauric acid/Aluminium oxide Nanoparticles Blending

Lauric acid is widely used as an phase change material in the storage of thermal energy because of its desirable thermal and physical properties. The resulting lauric acid melts at a temperature of between 58-62°C, contains latent heat of fusion of between 200-220 kJ/kg, and has thermal conductivity of 0.3-0.35 W/m K at solid state. The material is chemically stable, non-hazardous and has insignificant supercooling effects, which propagate the continued thermal use. Poor thermal conductivity rating of the lauric acid products limits their thermal performance. The selected concentrations were based on stability and thermal enhancement limits. The 0.3 wt% provides baseline improvement. The 0.6 wt% represents moderate enhancement. The 0.9 wt% was identified as the optimal limit before viscosity and agglomeration effects occur.

Aluminum oxide (Al_2O_3) nanoparticles are unique as they are generated out of graphite and therefore have both thermal and mechanical properties. The lateral extent of the Al_2O_3 nanoparticles ranges between 200 nm and 250 nm with a thickness of 1-2 nm with specific surface areas more than 400 m2/g. Al_2O_3 nanoparticles have a heat conductivity of 5 W/m K which were much higher than lauric acid. Hydrophilic nature of Al_2O_3 is due to the functional groups present in the form of oxygen in the molecule that ensues effective dispersion in lauric acid, organic and polymeric substances. The lauric acid compound combined with the Al_2O_3 improves the thermal conductivity, therefore, promoting better heat transfer and faster energy storage throughout the process e.g.solar stills. The provided samples of the Al_2O_3, in powder and aqueous dispersion form, are above 99% pure and the carbon to oxygen faction of 3:1. Copper was avoided due to high cost and corrosion concerns.

In the present study, lauric acid is used as the phase change material and it was purchased in Star Scientific, Erode, Tamilnadu, India. The PCM had a melting temperature of about 45°C. Also, the aluminium oxide was chosen as a way of enhancing thermal performance and were purchased at Matrics Enterprises, Nagercoil, Tamilnadu, India. The nanoparticles are used as additives in enhancing thermal performance. The nanoparticle (PCM and Aluminum oxide) was added and placed in a container made up of a tube. Therefore, synthesis of the lauric acid/aluminium oxide took place in the lab and a process that was followed in the synthesis of this compound is shown in Figure 1.

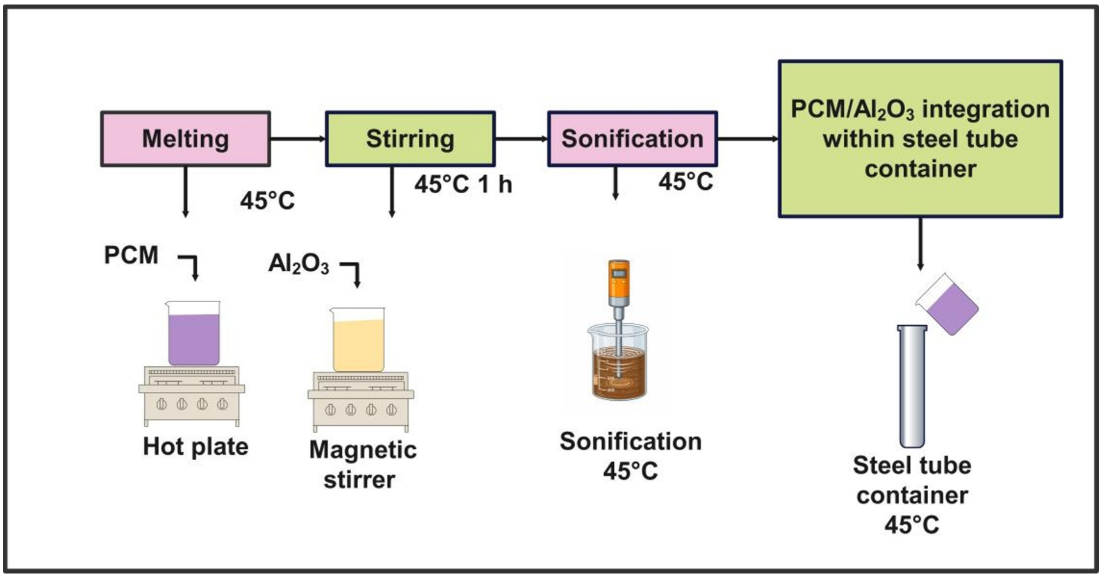


Figure 1 Preparation of lauric acid/aluminium oxide PCM

The dispersal of aluminium oxide nanoparticles in lauric acid can be done using a comprehensive method through accurate methods which guarantee homogenous distribution of nanoparticles and stable suspension within the PCM. Addition of aluminium oxide in the preparation is aimed at improving thermal conductivity and lauric acid performance because of its outstanding heat transfer capabilities.

Preparation begins by measuring the amount of aluminium oxide nanoparticles with a weight of 0.3 and 0.6 and 0.9wt% of lauric acid respectively. After dispersing the Al_2O_3 nanoparticles in distilled water or ethanol solution, the treated solvent is required to separate the agglomerates of the Al_2O_3 nanoparticles in order to achieve a higher quality of dispersion. Ultrasonication is done by subjecting the suspension to acoustic waves between 30 to 60 minutes. In the ultrasonication method, liquids are subjected to intense sound waves to create bubbles of cavitation in liquids, which lead to the dispersion of nanoparticles into uniform particles of nanometer size. Ultrasonication prevents nanoparticle agglomeration. It ensures uniform dispersion within the PCM. This improves long-term stability.

In the heating of lauric acid under controlled temperature water bath between 60°C and 70°C, exceeding its melting point, an Al_2O_3 suspension under ultrasonic stirring is converted into a liquid form before slowly being added to the continuously stirring molten lauric acid. The mixing process involves a mechanical or magnetic stirrer to maintain the agitation process of 1-2 hours until the nanoparticles are uniform and to avoid their sedimentation. One more ultrasonication step is essential to enhance the stability of aluminium oxide / lauric acid nanocomposite, particularly in cases of solvent use to make the inclusion of Al_2O_3 in the lauric acid. Under the solvent-evaporation method, a uniform lauric acid-Al_2O_3 compound is obtained once the mixture reaches high temperatures, and its pressure is reduced without ceasing to stir it.

This method ensures the even distribution of the aluminium oxide nanoparticles in the lauric acid, ensuring the consistency of thermal performance and eliminating such issues as nanoparticle sedimentation or uneven heat transfer. The efficiency of Al_2O_3 dispersion in lauric acid is of paramount importance to the desired improvements in thermal conductivity, latent heat storage and the general efficiency of solar thermal systems such as solar stills.

This paper has chosen three individual concentrations of Al_2O_3 nanoparticles, namely, 0.3 wt, 0.6 wt and 0. 6 wt, considering the previous research results, the possible improvement of the thermal properties, and experimental issues. The influence of the changes in the concentrations of the nanoparticles in the solar still at 0.3 wt, 0.6 wt, and 0.9 wt was also investigated with the aim of analyzing the properties of lauric acid-based phase change materials used in the solar still. In this study, 0.3 wt% was chosen as the lowest possible concentration of Al_2O_3 additive to investigate the nature of thermal conductivity and heat retaining of lauric acid without causing any morphological or structural changes in the matrix. Throughout the performance improvement at this low concentration, it is possible to attribute it mainly to the Al_2O_3 because there was no other physical or rheological characteristic that changed. The experimental group that has 0.6 wt% nanoparticles can shed a lot of light on the changing of thermo-physical properties owing to the moderate distribution of nanoparticles. Data review will identify whether the improvement in thermal efficiency characterized by the rise in water temperature and productivity is in a linear or non-linear correlation with the concentration levels. The median concentration value was needed to set standards in the measurement that exhibited performance dynamics among various ratios of loading. High levels of nanoparticles create a high viscosity and sedimentation in the nanocomposite substance, which reduces stability and thermal performance. The most suitable effective dispersion was determined to be at 0.9 wt where the concentration was maximum before stability declined and results were not consistently reproducible and at the same time, imparted processability and stability. By making these three concentrations, the study tried to identify an optimal dosage that can add heat storage and transmission characteristics without affecting the stability of the material and processing efficiency.

The copper was not used because of its high cost and also because it allowed holding structural integrity and supporting lauric acid as a phase change material in the steel tube container. Copper has the advantage of being a better conductor of heat than steel; however, it is much more expensive, which makes the cost-efficiency of solar desalination systems more difficult. Stainless steel tubes provide reliable operation in thermal and corrosion resistance and they remain stable in the presence of moisture and change in temperature. The mechanical properties of steel protect the encapsulating structure as they take into account rise and fall of thermal expansion and contraction throughout the freezing and melting of PCM. The material properties of steel make it an adequate sustainable alternative to be used in practical applications of solar stills.

The thermophysical properties of lauric acid/aluminum oxide mixture were analyzed through the following equations. The equations below (1-6) were used to compute the density, latent heat capacity, specific heat capacity, thermal conductivity and dynamic viscosity [11].

$$\rho_{\text{nepcm}} = \emptyset_n \rho_n + (1 - \emptyset_n)\rho_{pcm} \tag{1}$$

$$\left(\rho C_p\right)_{\text{nepcm}} = \emptyset_n \left(C_p\right)\rho_n + (1 - \emptyset_n)\left(\rho C_p\right)\rho_{pcm} \tag{2}$$

$$(\rho L)_{\text{nepcm}} = (1 - \emptyset_n)(\rho L)\rho_{pcm} \tag{3}$$

$$k_{\text{nepcm}} = \frac{k_n + 2k_{pcm} - 2\left(k_{pcm} - k_n\right)\emptyset_n}{k_n + 2k_{pcm} + \left(k_{pcm} - k_n\right)\emptyset_n} k_{pcm} + f b \gamma \emptyset_n \rho_{pcm} C_{p,pcm} \sqrt{\frac{KT}{\rho_n d_n}} f(T, \emptyset_n) \tag{4}$$

$$\gamma = 8.4407(100\emptyset_n)^{-1.0724} \tag{5}$$

$$\mu_{pcm/g} = 0.938\mu_{pcm} \exp\,(12.95\emptyset_n) \tag{6}$$

The conventional equations helped in the evaluation of the thermo-physical characteristics of the lauric acid/aluminum oxide composite. The properties of this matter depend on the specific parameters such as the density, latent heat capacity, specific heat capacity, thermal conductivity and dynamic viscosity. These values were calculated using a set of equations (1) through (6) with the help of the fundamental variables: b (5 × 10^{4}), which is the Brownian motion constant, k (1.381 × 1023 J K^{-1}) the Boltzmann constant, and dn the diameter of aluminium oxide nanoparticles. The computations used a mean experimental operational temperature of the lauric acid/ alumnium oxide nanocomposite in the course of the testing cycle. Specific heat determines the energy storage capacity of the PCM. Dynamic viscosity affects nanoparticle stability and heat transfer behavior. Both properties influence evaporation performance.

The encapsulation process was done using 2.5 kg of lauric acid as the experimental setup. The researchers chose the use of lauric acid as a phase change material (PCM) due to its beneficial characteristics that include chemical stability, large latent heat of fusion, cost-effectiveness, and non-toxicity. The change of state of lauric acid between solid and liquid states during energy uptake preserves stored thermal energy, which the system then emits during the solidification process and, therefore, contributes to a higher solar still energy storage.

Addition of aluminium oxide nanoparticles in three different mass ratios, ranging between 0.3% to 0.9% increased the thermal conductivity of lauric acid. The concentrations were selected as a result of research studies because of its capability in increasing efficacy of heat transfer in phase change substances (PCS). A stability test was conducted as a two-hour continuous testing to test the stability of lauric acid and aluminium oxide nanoparticles. The duration of the observation (two hours) showed no apparent changes, whether visual or structural, which proves the admirable short-term stability of the nanocomposite structure.

The level of different types of analyses of pH levels established the ideal stable environment of the nanofluid. To maintain a uniform performance of the nanofluid and to prevent sedimentation or agglomeration of nanoparticles that can hinder heat transfer, the current experiment maintained the nanofluid at pH 8.

2.2. Experimental Method

Figure 2 depicts the design of the solar still and phase change material encased still absorber. A one-slope solar collector was designed with a glass cover and insulation on one side and experiments carried out. The surface of the absorber plate of conventional solar still which is 0.9 m long and 0.65 m wide was made of mild steel. The topmost surface of the absorber was coated with black material which had an absorptivity of about 0.91 and emissivity of 0.89 to maximize absorption of the radiation. Body thickness of solar desalination equipment is 0.006m, top glass cover thickness is 3 mm and the slope is 30°. The PCM encapsulation lauric acid was put in a stainless-steel tube that had a diameter of 0.015 m. The tube containers were sealed on both ends. The large area of approximately 80% area covered with PCM helps in increasing the thermal energy storage efficiency. The introduction of the free space is essential to the reduction of pressure build-ups during the melting process, and therefore prevent the harmful effects on characteristics of phase change material in the sealed tube container.

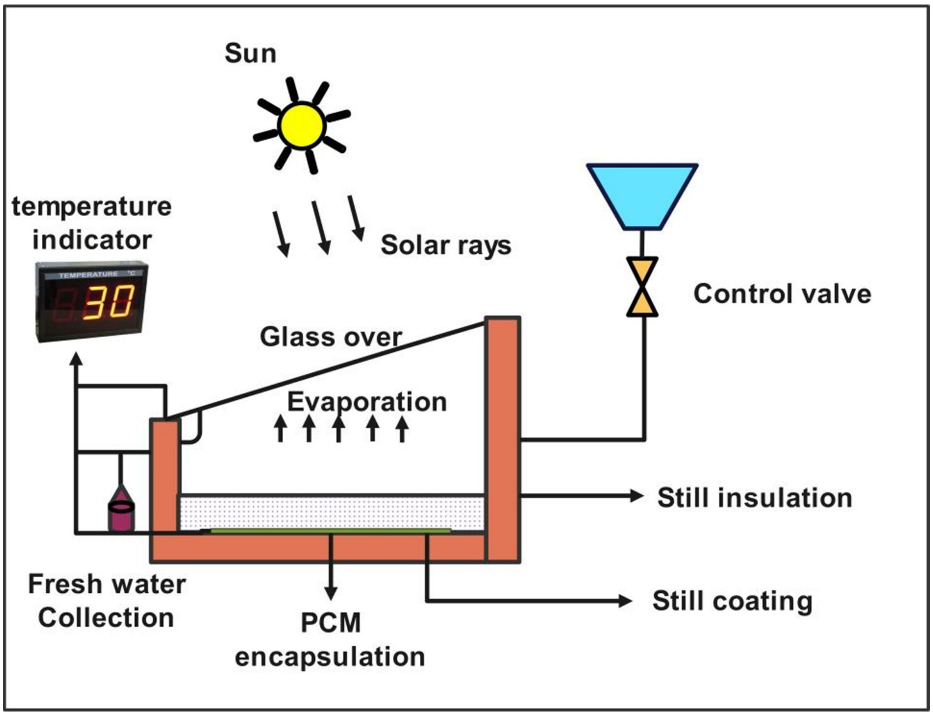


Figure 2 Experimental of solar still setup with encapsulated PCM

The weather conditions in Tamil Nadu, India (13.067439, 80.337617) were disturbed and all experiments on traditional solar still used. Five thickly encapsulated lauric acid absorbers were tested to determine the effectiveness of the solar still such as Case 1: conventional still without phase change material (CS), Case 2: still with encapsulated lauric acid absorber (SEPA), Case 3: still with encapsulated lauric acid and 0.3% aluminum oxide (SEP0.3GA), Case 4: still with encapsulated lauric acid and 0.6% aluminum oxide

(SEP0.6GA), and Case 5: still with encapsulated lauric acid Table 2 also forms the broad outlines of the numerous cases being examined, with detailed information. In order to provide uniform ambient temperature and sunlight radiation conditions in the experiments, measurements were performed in 5 consecutive sunny days, that is between 09/5/2025 and 13/5/2025. Five consecutive sunny days ensured consistent radiation. This improved repeatability and reduced climatic variation. The solar weather station that was installed with an anemometer and a pyranometer was used to obtain data on ambient wind velocity and incoming radiation that is crucial in determining the thermal performance of the solar stills. The pyranometer measures incident solar radiation. The anemometer records wind speed affecting convective losses. These measurements ensure reliable performance evaluation. The records were taken of data on sun intensity, water temperature, hourly water production, PCM temperature, PCM/Aluminium oxide temperature, and ambient temperature between 09:00 and 15:00 on the test day and the data was recorded every 30 minutes. The PCM-filled tubes were placed beneath the absorber plate. Heat from the absorber is transferred to the PCM and stored as latent heat. The stored heat is gradually released during cooling periods.

Table 1 Date of measurements, and name of still

Date of measurements	Still name	Specification
09/5/2025	CS	Still with plain absorber
10/5/2025	SEPA	Absorber with encapsulated lauric acid
11/5/2025	SEPO.3GAN	Absorber with encapsulated lauric acid and 0.3% aluminium oxide
12/5/2025	SEPO.6GAN	Absorber with encapsulated lauric acid and 0.6% aluminium oxide
13/5/2025	SEPO.9GAN	Absorber with encapsulated lauric acid and 0.9% aluminium oxide

The investigation was aimed at the performance evaluation of the solar still operated under different circumstances of the absorber (absorber and absorber with encapsulated lauric acid). A control valve was then used to bring water in the storage unit into the basin to achieve the required level of the desalination process. The control valve maintains constant basin water depth. Uniform depth ensures fair comparison among cases. The temperature was measured through a K-type thermocouple and the values were displayed through a channelized temperature meter.

2.3. Uncertainty Analysis

In experimental endeavors, testing uncertainty is a vital issue because apparatus, measurement inconsistencies, and calibration errors adversely affect this study. A well-established level of tolerance of uncertainty is 5 % in engineering. To obtain the uncertainty value, this study uses the formula described in Equation (7) as the Holman formula.

$$\omega_x = \sqrt{\left(\frac{\partial X}{\partial x_1}\right)^2 \omega_{x1}^2 + \left(\frac{\partial X}{\partial x_2}\right)^2 \omega_{x2}^2 + \cdots + \left(\frac{\partial X}{\partial x_n}\right)^2 \omega_{xn}^2} \tag{7}$$

Here the ω_x indicates the uncertainty of X, the ω_{xn} indicates the uncertainty of x_n and the $\partial X/\partial x1$ indicates the partial derivative of X with regard to $x1$. Using the Holman equation of the efficiency Equation (2) and the energy Equation (2) together with the errors of the measures known to us and the variables in Table 3 we can determine a 2.1 percent difference in solar still efficacies. Similarly, Figure 3 also shows the graphical description of the current investigation.

Table 2 Measured instruments and accuracy

Device	Model	Range	Accuracy (%)
Thermocouples	RTD PT-100	−200 °C	±0.6
Pyranometer	RS485	0–2000 W/m²	±3
Anemometer	SKU: 28669	0–30 m/s	±3
Temperature indicator	RT1004	−200 °C to 1371 °C	±10

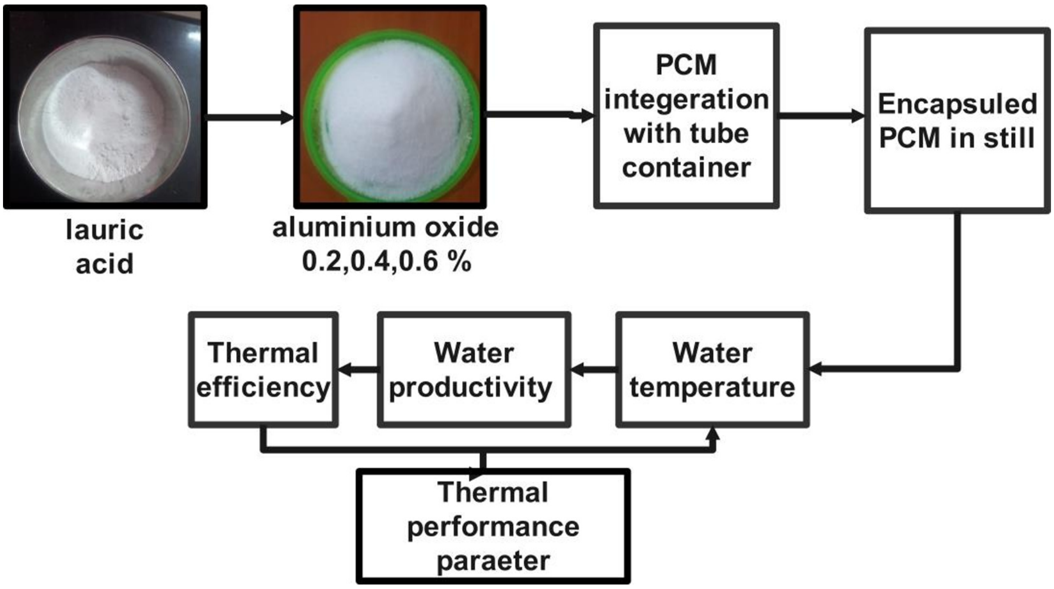


Figure 3 An overview of this investigation

3. Results and Discussion

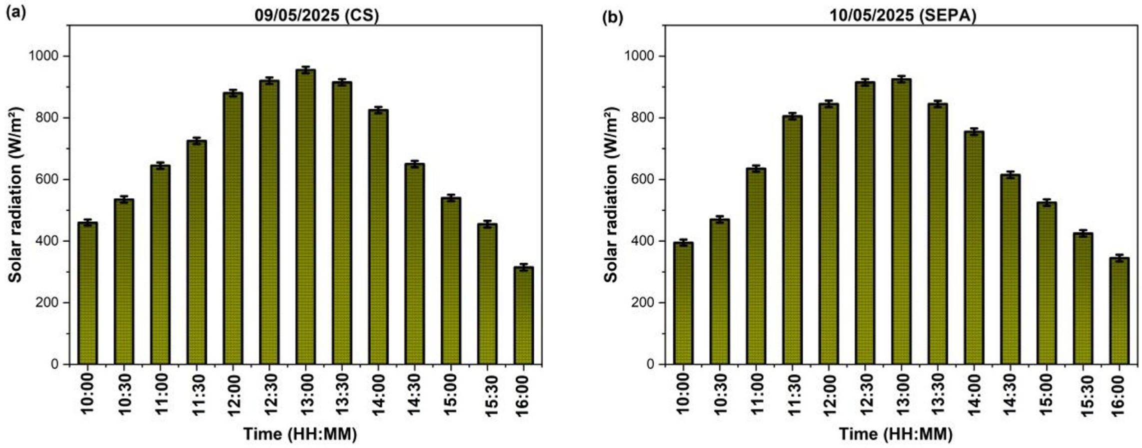
This research was conducted to determine the thermal efficiency of a solar still working in varying absorber conditions. The different absorbers were contained in a steel tube enclosure of PCM. The lauric acid along with the combination of lauric acid and alumina oxide nanoparticles was encapsulated. The experiment was started at 10:00 and ended at 16:00, and the readings were made every half an hour. Three different mass concentrations of the alumina oxide nanoparticles were used in increasing thermal properties of PCM to 0.3, 0.6, and 0.9%. The experiment results were used to determine the thermal performance of CS, SEP, SEP0.3GAN, SEP0.9GAN and SEP0.9GAN. Each of the types of observations was done five times and the average rounded off was recorded to be analyzed.

3.1. Solar Radiation

The solar radiation is made up of visible light, ultraviolet radiation and the infrared radiation. In solar desalination experiments, the solar radiations are the main source of energy that are used to enable the evaporation and condensing process of the desalination process. The solar still which is usually covered with a transparent cover enables sunlight to enter yet preserves the heat produced by it, and the glass cover has an increased absorptivity. The higher the temperature of the saline water due to the absorbed solar energy, the more the evaporation that takes place in the still.

Therefore, the effectiveness of the process of desalination is directly related to the intensity and term of the sun radiation, and it is a critical factor that needs to be tracked and evaluated in such studies. Moreover, the absorption and use of solar radiation can be enhanced by the involvement of researchers in exploring new materials or by modifying design, which could help to maximize the effectiveness of the solar still in general. The best strategy to improve the thermal performance involves the introduction of PCM to the absorber system. The process has proved to be more effective when compared to other methods. Figure 4a-e represents the changes in solar radiation on the basis of the time measurements on the experimental periods 09/05/2025-13/05/2025 relating to CS, SF, SEP, SEP0.3GAN, SEP0.9GAN and SEP0.9GAN respectively. The solar radiation ranged between 100-1000 W/m 2. All error bars were reflected at a 95% confidence interval and at ±1 and the standard deviation (SD).

Looking at Figure 4a, it can be seen that the highest level of solar radiation was registered at 13:00 noon and was about 955 W/m^2 when the CS condition occurred. Figure 4b shows that the highest radiation of the SEP experimentation was about 925 W/m^2. Figure 4c shows the highest value of about 940 W/m^2 which was obtained during the SEP0.3GAN tests. In the same manner, Figure 4d displays the radiation of SEP0.6GAN experiments with the highest value of about 922.5 W/m^2. Also, in Figure 4e, the highest radiation reading of SEP0.9GAN experimentation was approximately 934.1 W/m^2. In prior studies, thermal optimization of solar stills using aluminium oxide nanoparticle-enhanced phase change material to improve solar desalination performance. Enhanced water temperature retention under solar radiation significantly increased fresh water productivity and thermal efficiency, particularly during post-sunset operation [12].



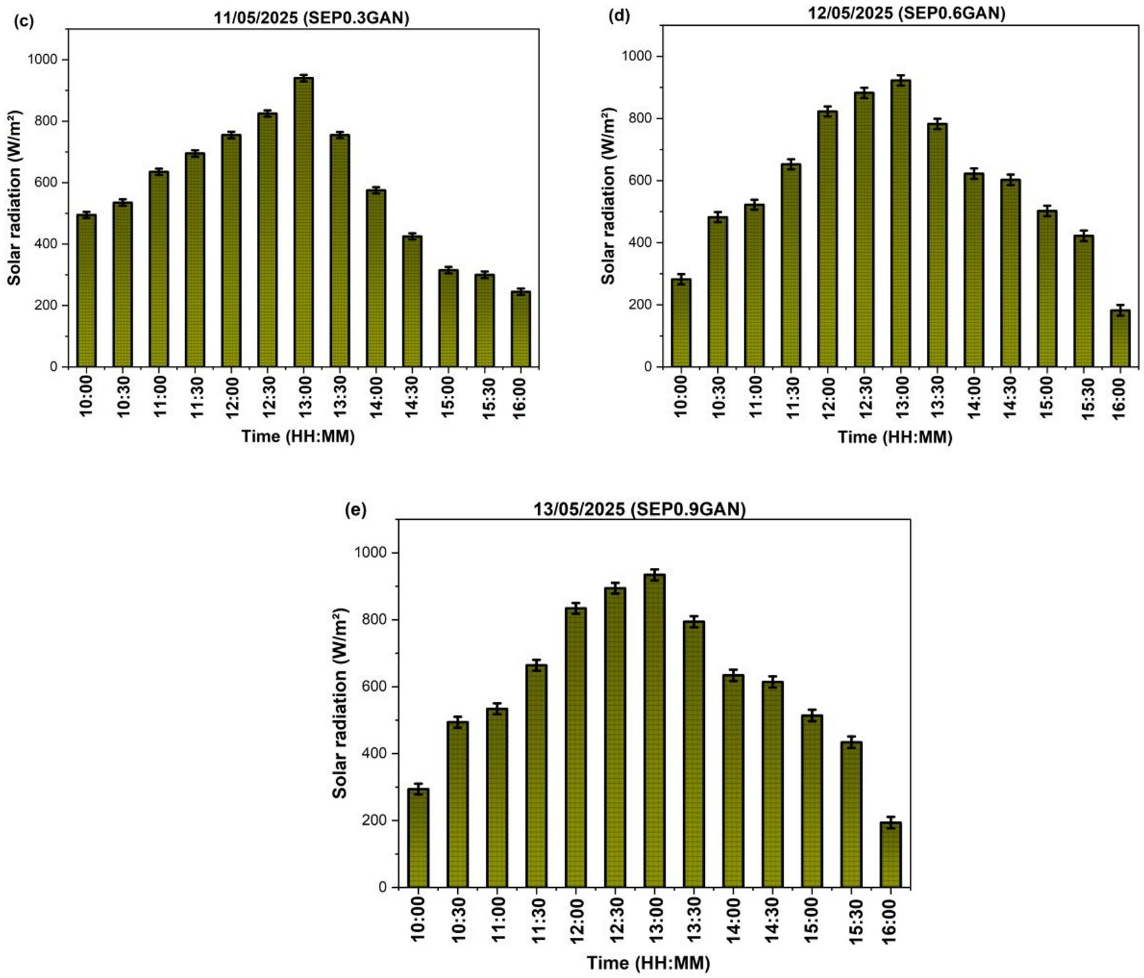


Figure 4 Solar radiation profiles on the days of testing over daytime for: Testing with (a) CS; (b) SEP; (c) SEP0.3GAN; (d) SEP0.6GAN; (e) SEP0.9GAN

Therefore, it can be seen that the radiation of the sun rises up to the midday and then declines towards the dusk following its maximum value. The input of the solar still varied with the sun radiation statistics. When the efficiency measurements were taking place the input of the solar radiation was kept at a constant level to compensate the changes in the input and the output of the still. Therefore, the ability of the solar still to improve thermal efficiency is attributed to the ability to maximize the absorption of photons through the absorber. Changes in the radiation caused by the atmosphere conditions result in low efficiency of the system. The encapsulated PCM is therefore a latent heat storage provision mechanism to the desalination process, which leads to increased thermal performance.

3.2. Water Temperature

Both the traditional and encapsulated PCM solar stills have an absorber, whose water temperature is identical to the temperature of the particular water in the absorber. When sunlight gets trapped by the absorber, the water inside the absorber experiences growth in temperature. The high temperature plays a key role at process of evaporating water and this were why it is important to separate it with the contaminated water and salts during the desalination process. Solar energy were absorbed and causes temperature of water in the absorber to rise leading to the liquid water changing to vapor. Ambient temperature affects convective heat loss. Lower ambient temperature reduces basin water temperature.

The vapor is then condensed on a cold surface within the solar still and hence distilled water is produced. The efficiency of the solar still greatly depends on the depth of the water in the still. Therefore, solar still system has improved efficiency as the water depth reduces and deteriorates as depth increases in the water. Figure 5 shows the temperature of water when it is being experimented with CS, SEP, SEP0.3GAN, SEP0.9GAN, and SEP0.9GAN.

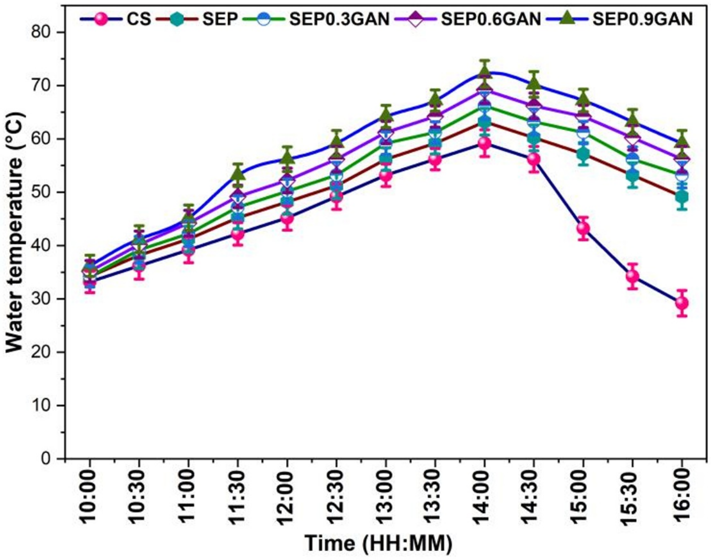


Figure 5 Water temperature profile when using conventional and encapsulated PCM systems

The recorded maximum water temperatures were approximately 59.2°C, 63.2°C, 66.2°C, 69.2°C, 72°C of the CS, SEP, SEP0.3GAN and SEP0.9GAN respectively. Water temperatures were approximately 29.2°C, 49.2°C, 53°C, 56°C and 59°C. It is therefore evident that the higher the levels of solar energy, higher temperature of water. The water temperature in traditional still was consistently low throughout the entire experiment compared to the absorber with encapsulated PCM (SEP) where the water temperature was significantly lower. In addition, the temperature of water in the standard still exhibited a sharp decrease once that temperature reached its maximum level. The differences of peak and average water temperature of different solar still conditions and CS, SEP, SEP0.3GAN, SEP0.9GAN, and SEP0.9GAN may be explained by a large number of factors that contribute to them.

The type of absorber and the use of PCM have a significant impact on the differences realized. Systems based on encapsulated PCM like SEP and variants of it offer better thermal performance as they have better thermal retention and release characteristics. The CS is always found to record lower temperatures in the course of the experimentation, and it is assumed that this is due to its limited thermal inertia, as well as its low ability to retain heat. Moreover, the fact that the temperature in the CS dropped suddenly after its peak suggests increased heat loss. The water temperature could still be enhanced by an encapsulated PCM. The lauric acid with 0.9% of aluminum oxide nanoparticles has improved the performance of water temperature. According to prior demonstrates the solar still performance was enhanced using lauric acid, paraffin wax, and stearic acid phase change materials combined with aluminium oxide and copper oxide nanoparticles. Improved water temperature regulation led to higher fresh water yield and thermal efficiency [13].

3.3. Water Productivity

The amount of distilled water or desalinated water which is generated by the solar still system over a given time is known as freshwater productivity in a sun. There are several parameters, including radiation reaching the absorber, the layout of the absorber, water depth, environmental factors and use of encapsulated materials, that greatly influence the productivity of the still. The appraisal and enhancement of freshwater productivity is imperative to the evaluation of how well a solar still system will achieve a sustainable and dependable supply of clean water particularly in regions with limited availability of freshwater resources. The way the productivity changes with still conditions is shown in figure 6. Hourly productivity reflects evaporation–condensation dynamics. It allows direct correlation with solar radiation intensity.

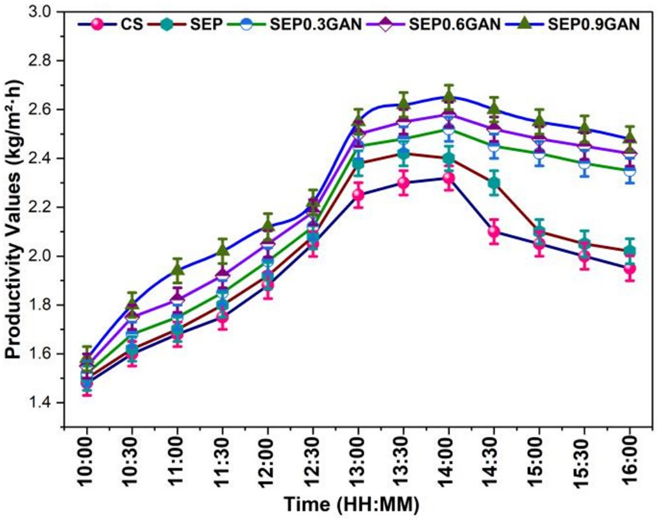


Figure 6 Productivity profile when using different setups of solar stills such as CS, SEP, SEP0.3GAN, SEP0.9GAN, and SEP0.9GAN over daytime

The maximum value of freshwater productivity was recorded to be approximately 2.32, 2.4, 2.52, 2.58, and 2.65 kg/m^2/h of CS, SEP, SEP0.3GAN, SEP0.9GAN, and SEP0.9GAN respectively. The mean values of productivity were about 1.48, 1.5, 1.52, 1.55, and 1.58 kg/m^2/h, respectively. Accordingly, the encapsulated phase change material still (SEP) was found to be more productive compared to the traditional still (CS). Formulations in which lauric acid was incorporated with 0.9% aluminium oxide nanoparticles showed better water productivity as compared to those that incorporated 0.3% and 0.6% aluminium oxide nanoparticles. There is an improvement in the evaporation-condensation cycle which leads to increased fresh water productivity. With the condition of SEP0.9GAN, the use of lauric acid with 0.9% concentration of aluminium oxide nanoparticles shows high productivity as compared to low concentration of atoms (0.3% and 0.6% concentration) which shows an effect of concentration on the absorption of heat and energy. As reported in previous analyses, nanoporous copper structures were introduced into solar stills to enhance solar radiation absorption and evaporation rates. Optimized anodization time resulted in improved water temperature and a 22.22% increase in water productivity, strengthening energy-efficient solar desalination [14].

3.4. Thermal Efficiency

Solar stills have a thermal efficiency determined by the ratio of the evaporative heat transfer which is a measure of the transmission of thermal energy by the solar radiation to the system. This is denoted by Equation (8) as shown in the reference.

$$\eta = \frac{m/(N\times 3600)h_{fg}}{I_b A_b} \tag{8}$$

Here m is the hourly production of the distillate, N is the number of experimental hours, $h$fg is the latent heat of water vaporization and I is the radiation, and Ab is the area of the basin. The solar still system efficiency in thermo-efficiency was only dependent on the solar radiation that was coming in and the water productivity achieved by the stills. Figure 7 represents the oscillations of thermal efficiency in different stationary conditions.

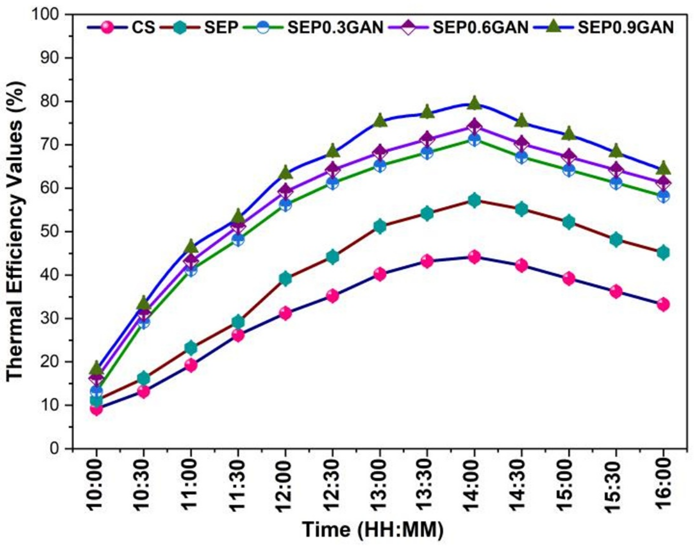


Figure 7 Thermal efficiency profile of solar still with different absorber conditions over daytime

The maximum thermal efficiency is recorded as 44.2, 57, 71.2, 74 and 79 % of CS, SEP, SEP0.3GAN, SEP0.9GAN and SEP0.9GAN respectively. The situation with the highest peak thermal efficiency is the one with SEP0.9GAN. Moreover, it is observed that the CS system experiences a precipitous decrease in efficiency at the optimum value of this parameter, whereas the lauric acid/aluminium oxide nanoparticles mixture shows a minor decline in efficiency. The adjustment in average thermal efficiency of CS, SEP, SEP0. 2GAN, and SEP0. 4GAN, as well as SEP0. 6GAN is shown in Figure 8.

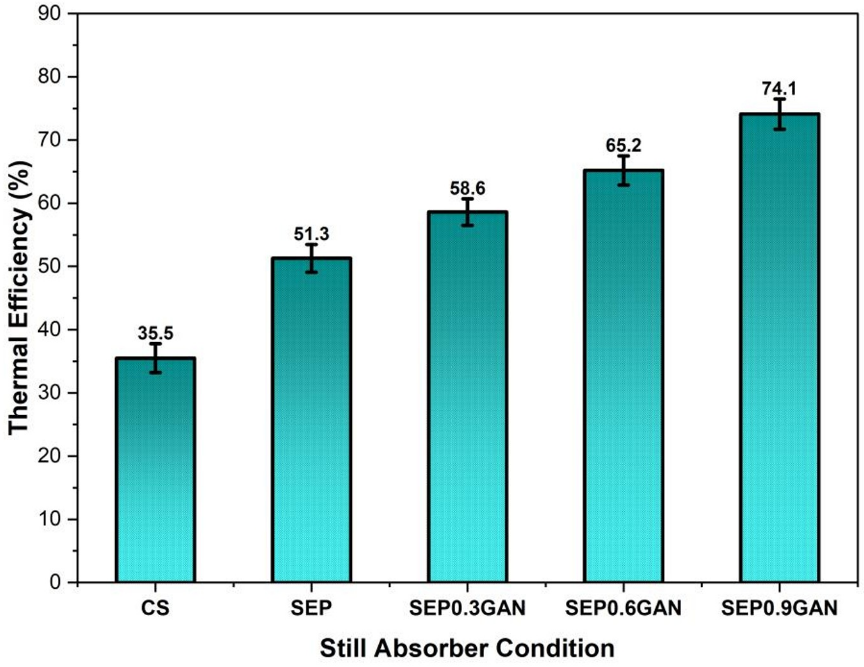


Figure 8 Average thermal efficiency of the solar still over a day with different absorber conditions

The thermal efficiencies are on average 35.5, 51.3, 58.6, 65.2, and 74.1 percent of CS, SEP, SEP0.3GAN, SEP0.6GAN and SEP0.9GAN respectively. This implies that integrating PCM into the solar still improves the thermal performance and efficiency in comparison to the CS. Application of 0.9 percent of aluminium oxide nanoparticles in lauric acid PCM has a higher thermal efficiency as compared to the formulations that are 0.3% and 0.6% of concentrations. In prior studies demonstrated that, the nanoparticle-assisted solar thermal desalination using aluminium oxide, copper oxide, and zinc oxide fluids. Improved thermal conductivity enhanced water temperature and fresh water yield, achieving up to 66.6% overall thermal efficiency improvement [15].

The increased thermal efficiency observed in solar stills of PCM encapsulation (SEP), can be attributed to the fact that it has better heat retention and release, and as such, the evaporation-condensation process is optimized. Introducing 0.9% aluminium oxide nanoparticles into lauric acid PCM of SEP0.9GAN outperforms the performance of lower concentrations (0.3 and 0.6%), which demonstrated that the effect on the heat transfer was concentration-dependent. There is a possibility that the abrupt drop in efficiency among the CS is a result of minimal thermal energy storage. The incorporation of PCM and concentration of the aluminum oxide nanoparticles play an essential role of enhancing thermal efficiency and the overall system performance.

The outstanding performance of 0.9 % of aluminum oxide (Al_2O_3) concentration in lauric acid-based phase change materials (PCM) is associated with improved thermal conductivity, improved energy storage dynamics as well as advanced nanoscale heat transfer processes. It is the rate of this particular concentration that allowed achieving the significant improvements in the temperature of water, the productivity, and thermal efficiency of the solar still systems, promoting the distinct physical processes and scientific mechanisms. Al_2O_3 nanoparticles form conductive pathways within the PCM. Phonon transport enhances heat diffusion. Brownian motion contributes to micro-convection effects.

The key reason behind this advantage is the much greater heat conductivity of aluminium oxide that is many times higher than the heat conduction of lauric acid. The presence of nanoparticles of Al_2O_3 scattering uniformly throughout the lauric acid matrix forms thermal paths that improve the spread of heat throughout the phase change material (PCM). The thermal energy handling of the material is enhanced with an increase in the concentration of Al_2O_3 to range between 0.3% and 0.9 % as the concentration of the thermally conductive channel that improves absorption, storage and release phenomena. The percolation network is created by a connected dispersion of the aluminium oxide particles with a weight fraction of 0.9wt%, to solid-state phonon transmission. An aluminum oxide network is used as a thermal conductor, which allows the transfer of heat between the solar absorber and lauric acid components to be rapid, thereby enhancing rapid melting during the day and slowing down cooling during the night or on a humid day. This mechanism keeps the water temperature high over a long period of time, and increases the level of water production.

Widespread distribution of lauric acid molecules is also enhanced by the big surface area and high aspect ratio of Al_2O_3 which increase interfacial heat conductivity between the particles. The properties of Al_2O_3 and lauric acid are optimized at a concentration of 0.9 as it renders the most effective interaction between the two as well as reducing the adverse effects of viscosity or particle aggregation observed with higher concentrations. The compound gets a greater latent heat storage and with freezing; the thermal output is efficiently solidified resulting in a long span of thermal application. The presence of aluminium oxide functional groups such as hydroxyl, carboxyl and epoxy groups increase the stability of the lauric acid solutions because they increase the suspension properties and guarantee the compatibility of the constituents. The consistency of nanofluid formations during consecutive heating and cooling cycles is due to the chemical interactions of the elements. At a 0.9 wt% concentration of Al_2O_3, the thermal conductivity, stability and high dispersion quality are at their maximum and thus the heat absorption, retention, and transfer properties are excellent.

4. Conclusions

This paper set out to determine the thermal performance of a solar still in various absorber conditions. The phase change material (Lauric acid) was wrapped in a tubular container that was installed in the still to enhance the rate of heat transfer and the thermal efficiency. Also, the aluminium oxide nanoparticles were used to improve the thermal characteristics of the PCM in three different mass fractions, which were 0.3 wt, 0.6 wt and 0.9 wt. The thermal performance of the still was studied at different absorber settings and compared to a standard absorber in the solar still system. The following conclusions were drawn through the current study.

The highest temperatures recorded in water were approximately 59.2°C, 63.2°C, 66.2°C, 69.2°C, 72°C of CS, SEP, SEP0.3GAN and SEP0.6GAN and SEP0.9GAN respectively. Therefore, when lauric acid/aluminium oxide nanoparticles were used at the concentration level of 0.9%, better water temperature was achieved.

The use of SEP, SEP0.3GAN, SEP0.6GAN and SEP0.9GAN resulted in water productivity improvement in the order of 2.32, 2.4, 2.52, 2.58, and 2.65 kg/m 2 /h respectively compared to CS.

Application of SEP, SEP0.3GAN, SEP0.6GAN and SEP0.9GAN resulted in an increase in the thermal efficiency to approximately 44.2, 57, 71.2, 74 and 79 compared to the CS system.

Finally, the combination of lauric acid phase change material and aluminium oxide nanoparticle has better thermo-physical characteristics and better thermal performance as compared to other nanoparticles. Importantly, high levels of aluminium oxide nanoparticles, especially 0.9%, exhibit a high rate of desalination and thermal efficiency. This suggests that further research can be conducted on the use of solar stills with the use of varied nanoparticles to encapsulate PCM in future studies. Future studies may explore hybrid nanoparticles.

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